A MULTIDISCIPLINARY FRAMEWORK FOR MISSION EFFECTIVENESS QUANTIFICATION AND ASSESSMENT OF MICRO AUTONOMOUS SYSTEMS AND TECHNOLOGIES

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A MULTIDISCIPLINARY FRAMEWORK FOR MISSION EFFECTIVENESS QUANTIFICATION AND ASSESSMENT OF MICRO AUTONOMOUS SYSTEMS AND TECHNOLOGIES

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Dedicated to...

[...my parents, siblings and their children.]
[...everyone who loves you at their own time.]

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It's been quite a journey since that strangely remarkable day in the fall of 2007, when I attended Doc's rather spontaneous lecture at METU, my undergrad college in Turkey. Without a doubt, that fateful meeting changed the course of my life. I learned. I experienced. I made some new friends. I lost some old friends. Most of all, I made memories to cherish for the remainder of time. And here, after 5 years, I finished; and not on my own, for sure. So, thank God!

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SUMMARY

During the past two decades, there have been dramatic changes in the way wars are fought. They have evolved from being based on traditional war-fighting elements of mass, will, patience, and raw firepower dominance from afar to knowledge, precision and accuracy of Information-Age. For instance, the first gulf war in 1991 lasted less than seven months to complete operations. The allied forces experienced less than 400 soldier casualties. The key war winners were superior fire power and the ability to aim at an organized army. However, today, such fire power is rarely able to aid over the many fronts at which the wars are being fought. The soldiers are required to fight at close quarters and most often in urban environments. These paradigm changes in today's wars have necessitated the need for integration of autonomous robots to aid the Warfighter.

One such initiative is Army Research Laboratory (ARL) sponsored project 'Micro Autonomous Systems and Technologies (MAST)'. It is based on a consortium of revolutionary academic and industrial research institutions working together to develop new technologies in the fields of microelectronics, autonomy, micromechanics and integration. The overarching goal of the MAST consortium is to develop autonomous, multifunctional, and collaborative ensembles of microsystems to enhance small unit tactical situational awareness in urban and complex terrain. Although unmanned systems are used to obtain intelligence at the macro level, there is no real-time intelligence asset at the squad level. MAST seeks to provide that asset. Consequently, multiple integrated MAST heterogeneous platforms (e.g. crawlers and flyers) working together synergistically as an ensemble shall be capable of autonomously performing a wide spectrum of operational functions based on the latest development in micro-mechanics, micro-electronics, and power technologies to achieve the desired operational objectives. The design of such vehicles is, by nature, highly constrained in terms of size, weight and

power. Technologists are trying to understand the impacts of developing state-of-the-art technologies on the MAST systems while the operators are trying to define strategies and tactics on how to use these systems. These two different perspectives create an integration gap. The operators understand the capabilities needed on the field of deployment but not necessarily the technologies, while the technologists understand the physics of the technologies but not necessary how they will be deployed, utilized, and operated during a mission. This not only results in a major requirements disconnect, which represents the different perspectives between the Warfighter and the technologists, but also demonstrates the lack of available quantified means to assess the technology gap. The requirements disconnect also represents the difference of perspectives between soldiers and researchers. The researcher are working at the fundamental scientific level, developing independent critical technologies. Meanwhile, the soldiers know what capability they need to satisfy their missions, but can't necessarily define how to use the latest technologies.

This necessitates the quantification and resolution of the requirements disconnect and technology gap leading to re-definitions of the requirements based on mission scenarios. A research plan, built on a technical approach based on the simultaneous application of decomposition and re-composition or 'Top-down' and 'Bottom-up' approaches, was used for development of a structured and traceable methodology. The developed methodology is implemented through an integrated framework consisting of various decision-making tools, modeling and simulation, and experimental data farming and validation.

The major obstacles in the development of the presented framework stemmed from the fact that all MAST technologies are revolutionary in nature, with no available historical data, sizing and synthesis codes or reliable physics-based models. The inherently multidisciplinary, multi-objective and uncertain nature of MAST technologies makes it very difficult to map mission level objectives to measurable engineering metrics.

It involves the optimization of multiple disciplines such as Aero, CS/CE, ME, EE, Biology, etc., and of multiple objectives such as mission performance, tactics, vehicle attributes, etc. Furthermore, the concept space is enormous with hundreds of billions of alternatives, and largely includes future technologies with low Technology Readiness Level (TRL) resulting in high uncertainty.

The presented framework is a cyber-physical design and analysis suite that combines Warfighter mission needs and expert technologist knowledge with a set of design and optimization tools, models, and experiments in order to provide a quantitative measure of the requirements disconnect and technology gap mentioned above. This quantification provides the basis for re-definitions of the requirements that are realistic in nature and ensure mission success. The research presents the development of this methodology and framework to address the core research objectives. The developed framework was then implemented on two mission scenarios that are of interest to the MAST consortium and Army Research Laboratory, namely, Joppa Urban Dwelling and Black Hawk Down Interior Building Reconnaissance.

Results demonstrate the framework's validity and serve as proof of concept for bridging the requirements disconnect between the Warfighter and the technologists. Billions of alternative MAST vehicles, composed of current and future technologies, were modeled and simulated, as part of a swarm, to evaluate their mission performance. In-depth analyses of the experiments, conducted as part of the research, presents quantitative technology gaps that need to be addressed by technologist for successful mission completion. Quantitative values for vehicle specifications and systems' Measures of Performance were determined for acceptable level of performance in the given missions. The consolidated results were used for defining mission based requirements of MAST systems. In conclusion, the developed methodology and framework provides a unique platform to evaluate System of Microsystems, consisting of vehicles built from existing and forecasted future technologies, for complex terrain mission scenarios.

CHAPTER I

INTRODUCTION

During the past two decades, there have been dramatic changes in the way wars are fought. They have evolved from being based on traditional war-fighting elements of mass, will, patience, and raw firepower dominance from afar to knowledge, precision, and accuracy of Information-Age. For instance, the first gulf war in 1991 lasted less than seven months [1] to complete operations. The allied forces experienced less than 400 soldier casualties [2]. The key war winners were superior fire power and the ability to aim at an organized army; however, today, such fire power is rarely able to aid over the many fronts at which the wars are being fought. The soldiers are now required to fight at close quarters and most often in urban environments. It is rather difficult to differentiate between guerrilla hostiles and civilians. Nearly two-thirds of soldier casualties in second Iraq war have been caused by Improvised Explosive Devices or IEDs [3]. These paradigm changes [3] in today's wars have effectively reduced the once complete situational awareness to a game of 'Battleship' [4].

Even though the aerospace industry has seen a trend surge of high altitude Unmanned Aerial Vehicles (UAVs), such as Predator [5] and Global Hawk [6], and satellites to acquire intelligence at macro level for surveillance and reconnaissance missions, these platforms are considered strategically too important and expensive to provide close-to-the-ground intelligence, especially at squad level. As shown in Figure 1, these platforms are implemented at many different command levels in the military enabling anywhere intelligence views from 50,000 feet up in the air to all the way close to ground. However, these systems are not used at the squad level resulting in a major intelligence gap for soldiers on the field. Various levels can be defined as following [7]:

- Brigades: 3000-5000 personnel; colonel typically in charge

- Battalion: 300-1000 personnel; lieutenant colonel typically in charge
- Squad: 9-10 personnel; sergeant to staff sergeant typically in charge

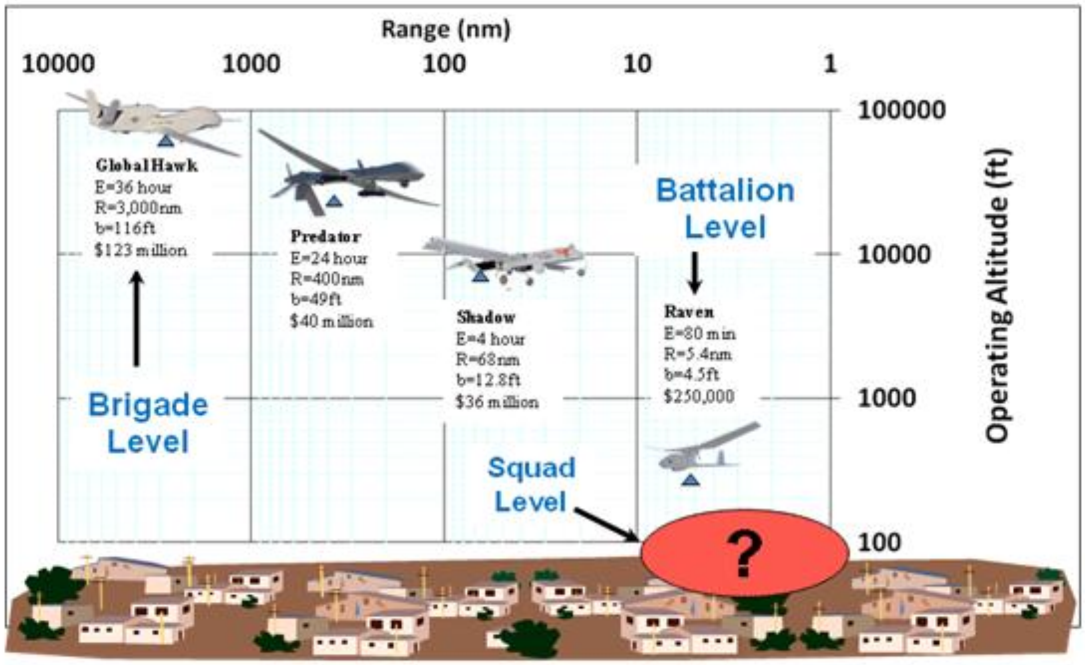


Figure 1: Operation Level of Different UAVs

Even though Global Hawk can fly from San Francisco to Maine, spend a day surveying a 230 square mile block, then fly back [8], the information is rarely available for soldiers in the field. As apparent from the following quotation [8]:

> "Because they rarely see the Global Hawks, officers in the field joke that these pictures are mainly used to fill the PowerPoint briefings for generals back in D.C." (ibid)

This has resulted in integration of robots into the military squads at an exponential rate, as apparent in Figure 2 . PackBot [9] and Talon [10] were introduced as search and rescue systems during 9/11 attacks [11] but are now widely utilized by ground units of U.S. Army [12].

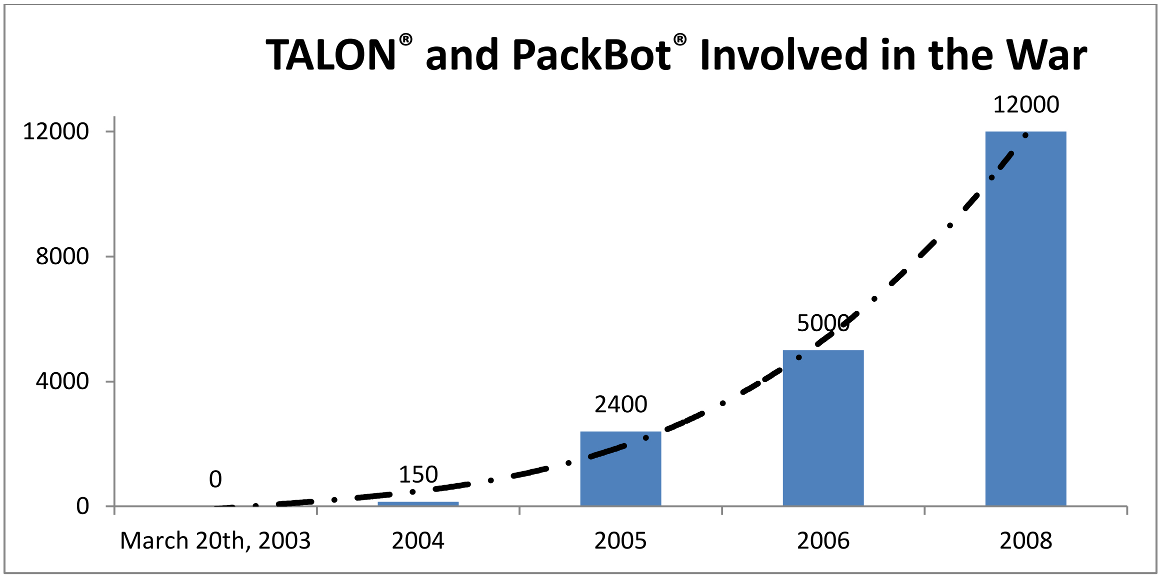


Figure 2: Robots in War [8]

However, the current systems (including robots) are neither small enough nor capable of stealthily maneuvering indoors (i.e. interiors of buildings, caves, jungle) for small unit operations, where the intelligence is almost non-existent. The importance of intelligence information at squad-level was highlighted in a Gedanken Experiment conducted at Fort Benning, GA [13]. A major conclusion drawn about the necessity of information for soldiers on from the experiment is well summarized in the following statement [14]:

"Soldiers felt that persistent surveillance and reconnaissance for mission planning support were more important capabilities than making the MAST systems lethal..."

In order to address the squad-level intelligence gap, United States Army Research Laboratory (ARL) formed, in February 2008 [15], a Collaborative Technology and Research Alliance (CTA) with industry and academia to pursue the Micro Autonomous Systems and Technologies (MAST) project. According to ARL, MAST CTA is defined as the following:

"Collaborative Technology and Research Alliances are partnerships between Army laboratories and centers, private industry and academia that are focusing on the rapid transition of innovative technologies to the Warfighter to enable the Army's Future Force." [16]

"Perform enabling research and transition technology that will enhance Warfighter's tactical situational awareness in urban and complex terrain by enabling the autonomous operation of a collaborative ensemble of multifunctional, mobile microsystems." [17]

1.1. MAST Overview

Micro Autonomous Systems and Technologies (MAST) is an Army Research Laboratory (ARL) sponsored project [18] based on a consortium [19] of advanced academic and industrial research institutions working together to develop new technologies in the fields of microelectronics, autonomy, micromechanics and integration [20]. The disciplinary fields were later renamed as the following three thrusts: Mobility, Control and Energetic (MCE); Sensing, Perception and Processing (SPP); Communication, Networking and Coordination (CNC) [21]. The overarching goal of the MAST consortium is to develop autonomous, multifunctional, and collaborative ensembles of microsystems to enhance small unit tactical situational awareness in urban and complex terrain [22]. Systems developed under MAST are expected to bridge the gap of real-time intelligence at the squad level by enabling several capabilities: (1) reconnaissance and surveillance of complex terrain such as urban areas building interiors, (2) real time planning to adapt to mission changes, (3) tactical situation assessment by obtaining and interpreting data from various sensors such as optical, acoustic, or chemical, and (4) emergent behavior of a group such as swarming. A depiction of MAST network synergizing with a squad to achieve superiority over hostile force is shown in Figure 3 [23]. A MAST network is expected to provide total situational awareness, giving the Warfighter an edge on the enemy by: knowing who the enemy is, where the enemy is located and what the enemy is planning.

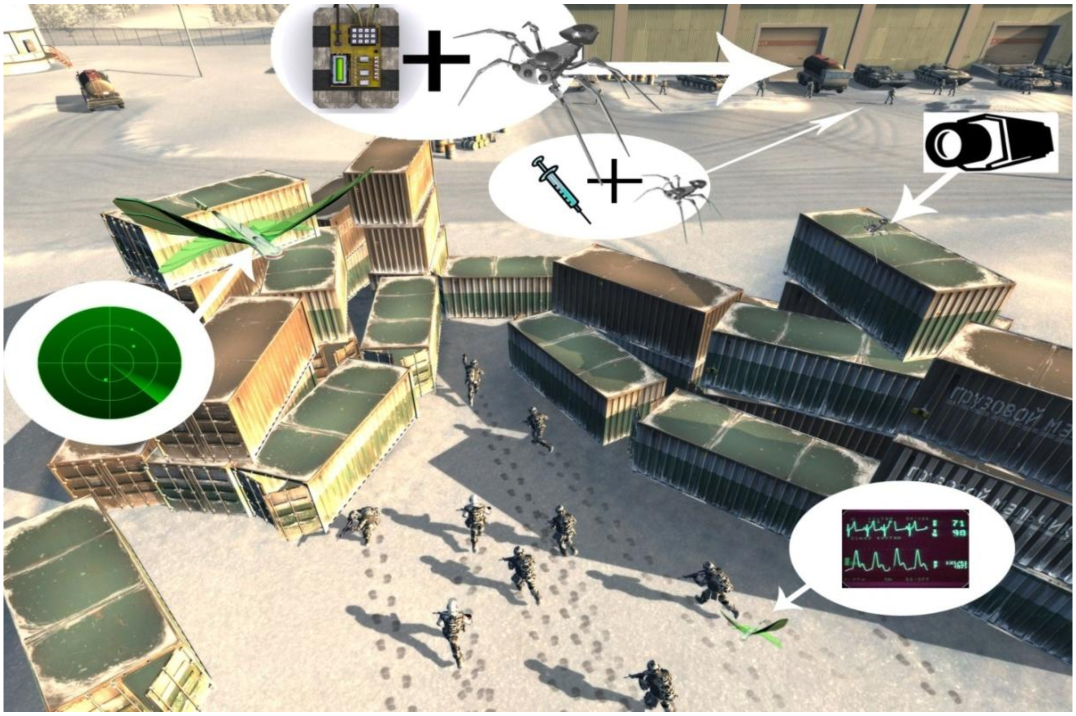


Figure 3: Depiction of MAST Technologies Aiding Soldiers in Battle [23]

1.2. Motivation

In order to achieve outlined goals, multiple integrated MAST heterogeneous platforms (e.g. crawlers and flyers) will be working together synergistically as an ensemble capable of autonomously performing a wide spectrum of operational functions based on the latest development in micro-mechanics, micro-electronics, and power technologies to achieve the desired operational objectives. The design of such vehicles is by nature highly constrained in terms of size, weight and power. Technologists are trying to understand the impacts of developing state-of-the-art technologies on the MAST systems while the operators are trying to define strategies and tactics on how to use these systems.

The motivation of the research emerges from the major operational requirements disconnect and integration gap created by these two different perspectives and independent sources of data. The requirements disconnect represents the different perspectives between the MAST end-users (Warfighter), and the researchers and technologists. The technologists are working at the fundamental scientific level, developing independent MAST-critical technologies. They understand the physics of the technologies but not necessarily how they should be deployed and operated during a mission. Meanwhile, the Warfighter knows what capability they need to satisfy their missions, but don't necessarily understand or are able to define how to use the latest MAST technologies. Figure 4 [24] illustrates this disconnect.

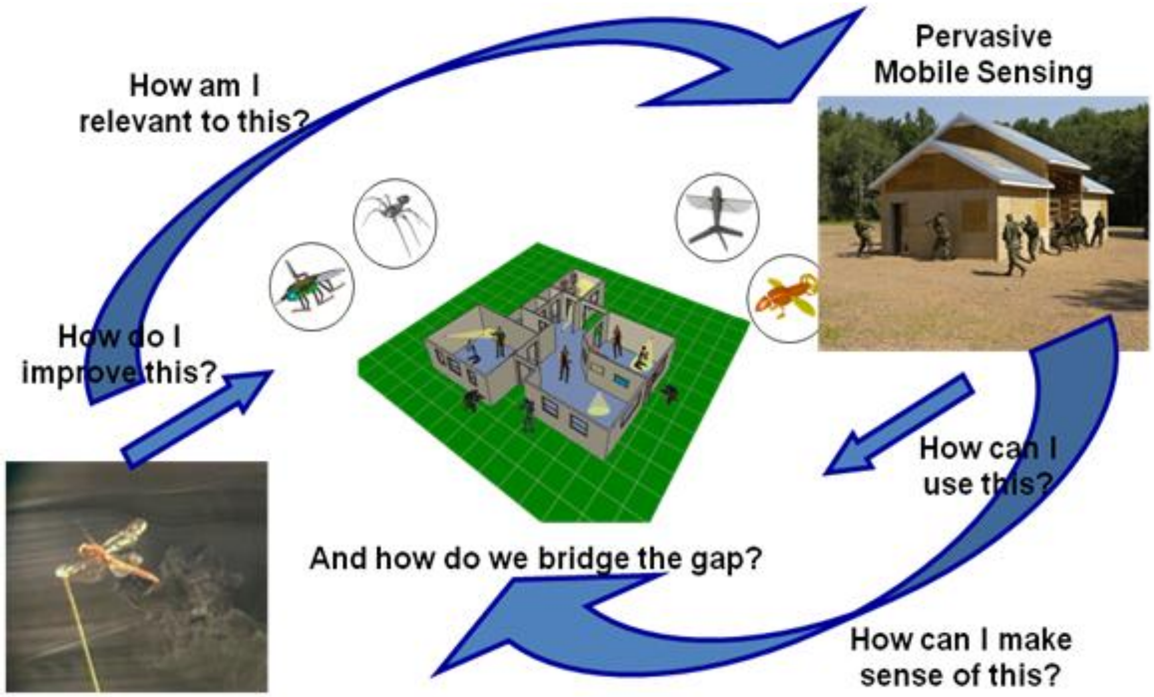


Figure 4: Motivation - Requirements Disconnect [24]

As shown, the operators require capabilities such as "pervasive mobile sensing" based on a mission scenario while the technologists are improving the current state of micro-systems, without particularly understanding the exact metrics that need to be improved upon in order to enable such capability. It is apparent that there needs to be a structured framework in order to create comprehensible relationships between required operational capabilities and technology development for given mission scenario. And individually, neither operators nor stakeholders can implement such a relationship without a presence of an integrated framework. Moreover, such a framework will also enable analysis of technology gap, which is meant to quantify the difference between the required capabilities for a given MAST scenario and the available capabilities provided by state-of-the-art technologies.

Therefore the overarching research objective of this dissertation is to develop a structured methodology and framework that will enable quantification of requirements disconnect and technology gap. This will include formulation and development of accompanying decision making and optimization tools and modeling and simulation (M&S) environments along with its experimental validation for the latest MAST technologies. This will not only bridge the gap between the Warfighter and the technologists, it will also result in defining new and much more realistic technology requirements in order to achieve required operational capabilities.

1.3. Challenges

Development of the aforementioned methodology and framework is no easy task and riddled with plethora of challenges. Some of the major challenges are explained below:

Revolutionary Technologies: Lack of Existing Models and Data

The major issues stem from the fact that all of MAST technologies are of revolutionary nature with no available historical data, sizing and synthesis codes or reliable physics-based models. Development of any rigorous design principles for technologies under consideration is currently at its dawn. Moreover, the inherently multidisciplinary, multi-objective and uncertain nature of MAST makes it very difficult to map mission level objectives to measurable engineering metrics. It involves multiple disciplines (such as aerodynamics, computer science/engineering, mechanical engineering, electrical engineering, biology etc.), multiple objectives (such as mission performance, army goals, etc.), and an enormous design space that largely includes future technologies with low Technology Readiness Level (TRL) [25] resulting in high uncertainty.

Massive Concept Space

The concept space entailing technologies that are relevant to MAST vision is astronomically large. The problem is further aggravated by lack of reliable physical models and data for these technologies. Just to name a few, the technologies of interest include vehicle platforms (e.g. rotary wing, fixed wing, ground, water, ambulating), sensors (e.g. chemical, radioactive), power sources, communication platforms, and processing components. It will be later shown in this dissertation that the possibilities range in hundreds of billions of possible family of alternatives resulting in a massive concept space.

Physical and Virtual Testing

In order to down-select between different technologies for any given mission scenario requires, in essence, the ability to either physically test or virtually analyze them in a simulation environment. Aside from the fact that physical testing is extremely costly, it goes without saying that a technology that doesn't exist cannot be physically tested. And without testing these developing technologies, it is rather difficult to forecast the attributes that would be required from these technologies for achieving desired operational capabilities. Hence as time progress, this results in an increasing gap between mapping of what is current technology level and what level these technologies need to be in future.

This dissertation serves as a solution to the problem of requirements disconnect between the Warfighter and the technologist and presents a technology gap quantification methodology for current and revolutionary technologies. The solution consists of a methodology formulation and development and implementation of framework for few selected mission scenarios. These scenarios include interior building reconnaissance, jungle surveillance and cave exploration. These missions are of two types and defined by two sources: 1) benign missions - are based on physical experimental setups at Joppa, MD [26], designated by MAST consortium for benchmarking technologies; 2) hostile missions - are defined by Vehicle Technology Directorate of ARL and based on the Movie "Black Hawk Down" [27]. The implementation of developed methodology and framework will enable quantification of requirements disconnect and technology gap for the above mentioned mission scenarios.

CHAPTER II

BACKGROUND AND LITERATURE REVIEW

The premise of the research has been introduced and motivations have been defined in the previous chapter. Before exploring fundamental research objectives and devising a plan to address them, it is necessary to conduct a detailed background and literature review. This chapter documents the background research undertaken to gather information on MAST project, consortium members and technologies. A detailed understanding of goals of technologist and Warfighter, in terms of technologies and capabilities needed, is of paramount importance for laying ground work. Upon which, a methodology and framework can be build to address the fundamental issue of requirements disconnect.

2.1. Overview

The literature search presented in this chapter focuses on two categories of information: metrics and technologies. The metrics for defining Measures of Performance (MoPs) and Measures of Effectiveness (MoEs) are necessary for evaluating success of any mission scenario to be accomplished through MAST Systems of Microsystems. These metrics are basic building blocks for setting up a measurement system to quantify the capabilities required by the Warfighter and technology levels achieved by technologist. Since the key enablers for MAST vision are revolutionary technologies that are being currently developed or planned to be achieved in future, it is only logical to thoroughly research and understand the specific technologies that are relevant to MAST vision and their specifications. These will also serve as foundations for exploring concept space and modeling and simulating MAST missions and technologies.

With the basis of literature review established, the next step is to present the information gathered through this exercise. First, the structure and members of MAST consortium, specifically technical centers and thrusts, will be briefly discussed to understand the major technological goals being highlighted by the MAST vision. Then, current efforts, if any, being undertaken to address the requirements disconnect between technologists and Warfighter will be explored. It will also provide an opportunity to note the gaps in the current approach. Then system of systems level thought experiments and workshops carried out by the Warfighter and Subject Matter Experts (SMEs) will be explored to understand the metrics deemed to be of utmost importance. Moreover, it will also shed light on capability needs and requirements of soldiers in the battlefield. Finally, an extensive survey on technologies that are relevant to the MAST vision will be presented along with available specifications.

2.2. MAST Technical Centers and Thrusts

The MAST consortium consists of four main technical centers focusing on different aspects of research thrusts divided into three categories. The technical centers are Microsystem Mechanics, Processing for Autonomous Operation, Microelectronics and Integration. The primary source of information for this section is MAST's annual program plan [28]. The thrusts grouping the research conducted by these centers are defined as following [29]:

- Mobility, Control and Energetic (MCE): focuses on research for developing micro scale systems capable of flexible and autonomous mobility and control.
- Sensing, Perception and Processing (SPP): focuses on development of hardware, software and algorithms for monitoring, interpretation and processing of state and sensor data for navigation, intelligence, surveillance and reconnaissance.
- Communication, Networking and Coordination (CNC): focuses on development of communication issues and capabilities required for optimized execution of

missions and enabling connectivity between heterogeneous ensembles of microsystems.

The Microsystem Mechanics center is tasked with research into the fundamental understanding of mechanics for mobility of small aerial and ground unmanned platforms. The Processing for Autonomous Operations center primarily develops fundamental understanding of autonomous operations for micro scaled and multi-agent mobile systems. The Microelectronics center works on small scaled electronic systems to develop revolutionary approaches for meeting stringent constraints on size, weight, and power. The last technical center, Integration, is tasked with focusing on system analysis, experimentation research, and other integration issues such as defining and implementing vision to enable integration of research performed by MAST consortium [28].

It is apparent that the research focus of Integration Center is relevant to the motivation of the research presented in this thesis. Although the basic description of Integration Center looks quite appealing to address the requirements disconnect, a more detailed analysis of their tasks is warranted to understand the gaps in the approach and lack of framework to bridge the gap between Warfighter and technologists. The defining the tasks for vision of Integration Center are [28]:

- Use of model-based system analysis and scalability studies to develop parametric models for air and ground vehicles for studying efficiency and endurance. The focus is on vehicles that are being currently under development, but also aims to generalize models for other types of vehicles.
- Address the issues of fusion of inertial and visual sensors with commercially available processors.
- Conduct studies to address gust response of several MAST aerial vehicles.
- Improve joint experiments through means of integrating sensing and processing units on MAST platforms.

Considering the above defined overall research tasks of Integration Center, it is evident that none of them are addressing the system of systems level issues outlined in the previous level. Although the model based system analysis and scalability task only appears as one of the research issues to be addressed, it only deals with individual systems analysis and only for the ones that are currently under development. This means that there aren't any specific tasks scheduled or outlined to be accomplished by Integration Center for system level analysis. They are not expected to analyze future technologies that are not currently available.

The above analysis leads to defining observations for the motivation of research behind this thesis:

- There is a clear lack of any approach or methodology within MAST consortium to evaluate systems of systems level issues.
- There are no system level approaches defined for evaluating revolutionary integrated technology systems, which are either not currently under development or with no available historical data and physical models, and their influence on mission scenarios.
- There is no framework or methodology to address the Warfighter's capability needs in terms of technology level goals for technologists.
- Finally, there is no method for assessing mission based systems of systems level technology gaps to understand the attribute levels needed to achieve capability needs.

Without these methodologies, it is not possible to define requirements for technologist that explicitly map Warfighter goals to technical attributes for mission scenarios under consideration. Before contemplating on research issues and questions stemming from these observations and developing a research plan to address them, a closer look is warranted towards the Gedanken Experiment, mentioned in Chapter 1, conducted to understand Warfighter needs from MAST. Furthermore, a literature survey on technologies relevant to MAST is presented in following sections.

2.3. Thought Experiment and Workshops

The technologies are under consideration of MAST CTA are not only of revolutionary nature and currently conceptual but are also expected to be integrated in a synergistic manner that as systems or systems of systems would be beneficial for Army needs. In the early days of MAST CTA, it was important for the Army to assess the military benefits of such a science and technology investment initiative. A methodology based on a study conducted by Center of Technology and National Security policy (CTNSP), documented in reference [30], was utilized to evaluate future capabilities expected to be offered by MAST efforts Army. The demonstration and results of this exercise were later documented in Defense and Technology Paper (DTP) [14] entitled " Assessing Military Benefits of S&T Investments in Micro Autonomous Systems Utilizing a Gedanken Experiment," as an application of the methodology. These results are studied and analyzed for the purpose of the research presented in this thesis as the knowledge gained forms the foundations of the background information required to understand MAST technologies and their possible applications for benefit of the Warfighter. Moreover, a series of workshops were also conducted by ASDL to gather SMEs and Warfighter opinions and recommendations for the following: technology areas, technology attributes, operational activities, and operational functions.

The data obtained was used extensively in the development of a methodology and framework proposed to provide solution of requirements disconnect and quantification of MAST SoMs. The consolidated data will be referenced and discussed in later chapters of this thesis and the concentration of this section will be on the details of the Gedanken Experiment. As mentioned previously, the current conceptual nature of technologies under consideration necessitates the need to study their future benefits without the ability to physically test the hypothesis. Therefore, a Gedanken Experiment or a thought experiment was conducted. A Gedanken Experiment [31] is the process of considering a hypothesis or theory under question, primarily through a series of 'thinking' exercises. The hypotheses for this experiment were put forth by Subject Matter Experts (SMEs) [32] and tested through feedback from participation of technologist and Warfighter as they explored the use of the technologies for various mission scenarios. The end result was the exploration of operational benefits of MAST technologies for Army needs through means of low fidelity simulations.

The Gedanken Experiment was conducted at Fort Benning, GA over a period of three days, with a different set of agendas for each day. The focus of the first day was to expose technologists and Warfighter to small units operations together and conduct exercises that mimic squads clearing rooms and buildings. This sets up a platform for all participants to gather data, develop an understanding, discuss thoughts and be surveyed on the second and third days. The questions that led the discussion will be explored in next chapter. This not only exposed researchers and technologist to Warfighter operational tactics, processes and possible integration of MAST systems into small army units, but also to brainstorm on answering capability needs of the Warfighter. The results and conclusions gleaned from this experiment are fundamental to understanding the connection and developing a bridge between perspectives of technologists and Warfighter. Moreover, it also points to operational needs and technical capabilities that will be required to address them. These conclusions are now presented.

Capability Needs Priorities

The highest priority capability needs are the ability to navigate complex terrain, stealth and reasonable fidelity level of the information obtained through sensing. The emphasis is placed on stealth. This is accomplished by reducing visual, through camouflage, and auditory signals rather than conventional figure of merits of minimizing electromagnetic and radar signatures.

Tactics and Processes

The Warfighter needs a user friendly interface for supporting soldiers and MAST systems interactions from a command and control perspective. The interface should not only enhance the Warfighter's situational awareness and allow setting up of missions, but also enable dynamic changes in operational details while the mission is being executed. It was also learned that soldiers prefer the systems to be used for intelligence gathering and planning phases of the mission only and not during the execution of a combat operation. At least for now, soldiers do not want to be teamed with MAST systems when a combat operation is in progress or there is a firefight ensuing. Finally, the results bolstered the idea that, at least for present time being, it is not a reasonable approach to expect that autonomous systems should clear rooms or building.

Lethality of MAST Systems

The Warfighter is more inclined towards employing non-lethal MAST systems to obtain capabilities for creating diversions and deceptions during missions, even for offensive ones. Moreover, MAST systems should be capable of aiding in reducing civilian casualties in hostage and non-hostage situations.

Scalability and Variety

One of the most important results of this exercise was to highlight the need of the Warfighter command and control to provide different levels of information in terms of scale, fidelity and type to platoon and squad leaders. In order to achieve this capability need, various sizes and types of MAST systems with varying level of autonomy will be required, depending on mission scenario.

The major conclusions, summarized above, from the Gedanken Experiment are the key guide points for researchers to serve as guides for developing systems and SoM design approaches. Furthermore, these conclusions can serve as fundamental basis for developing a methodology and framework to bridge the requirements disconnect. With the premise of technologists and the Warfighter interactions defined and analyzed, it is now time to survey the technologies that are likely to serve as key enablers for development of MAST systems.

2.4. Technology Survey and Research

This section presents the technologies researched and surveyed that are expected to be relevant to MAST vision. The data compiled through this exercise will be used through the research to develop major modules of the proposed framework and serve as baseline and future level of technology capabilities for modeling and simulation and gap analysis. Some of the technology research presented in this section was conducted by author as part of MAST ASDL Grand Challenge 2008- 2009 team, compiled in reference [33].The section will be divided in to subsections based on category of technologies being researched. The main categories are sensors, robotic navigation, power systems and communication systems.

2.4.1. Sensors

For MAST systems, sensors will determine their capability envelope by defining their probability of detection at a given distance, which is a fundamental requirement for successfully achieving a mission scenario. Visual and audio sensors will be required for detecting obstacles and humans while chemical sensors will be needed to detect IEDs. The major technology attributes for quantifying sensors are defined by quality, power required and weight of the sensors, computation power required and bandwidth for sending and receiving information. Starting with sensor research is helpful in understanding the resultant requirements for processor, power supply, communication system and platform size and shape. The models for relating sensor technologies to probability of detection are also required to be obtained through the literature review.

2.4.1.1. Visual

The research into visual sensors is focused on cameras and required minimum quality for reasonable level of surveillance. A study was conducted by The Institute of Telecommunication Sciences conducted to determine the required minimum video quality that would be usable for first respondents such as police or firemen. Experiment was conducted by allowing the first responders to watch sequences of videos on which they remarked whether or not the quality was acceptable. Data was collected from 35 first respondents [34]. For purpose of the study, the video was considered reasonable if the acceptability from the viewers was above 70% and the results are compiled in Table 1.

Table 1: Requirements for Tactical Video [34]

Maximum One-Way Video Delay	**Coder Type and Minimum Bit Rate**		**Maximum Packet Loss Percentage**	
1 sec	1.5 Mbps for MPEG-2	768 kbps for H.264 (advanced video compression)	0.5% for MPEG-2	0.1% for H.264

As apparent from the data, lower-bit rate allowed by advance video compression uses less bandwidth but the video quality is more susceptible to packet losses.

<u>Cameras</u>

The primary types of cameras being considered are: Charge coupled device (CCD) and complementary metal oxide semiconductor (CMOS). The image sensors in both of these are pixilated metal oxide semiconductors [35]. However, CCD cameras are larger in size and require more power but also provide better image quality [35]*. In order to quantitatively assess these camera types with respect to MAST applications, the attributes to consider are minimum amount of light needed for exposure and resolution of the resulting image.

Lux [36], SI unit, is conventionally used for measuring the required minimum light for exposure resulting in a reasonable image. Lux is defined as the luminous flux density [36], or also known as illuminance, on a given surface is measured in lumens per square meter. A lumen is defined as a Candela, the standard candle, that emits one lumen per steradian [37]. In order gauge the measurement levels of Lux, approximate levels of the unit at different lighting conditions are compiled in Figure 5.

Sky Condition	**Approx. Levels of Illuminance – lux (lm m^{-2})**
Direct sunlight	1-1.3 x 10^{5}
Full daylight (Not direct sunlight)	1-2 x 10^{4}
Overcast day	10^{3}
Very dark day	10^{2}
Twilight	10
Deep twilight	1
Fullmoon	10^{-1}
Quartermoon	10^{-2}
Moonless, clear night sky	10^{-3}
Moonless, overcast night sky	10^{-4}

Figure 5: Illuminance Levels at Different Lighting Conditions [37]

Moving on, the resolution of an image is defined as the extent of which it is possible to see the details of an image. Generally speaking, the number of horizontal lines in image defines the resolution of a camera. They are specified using monitor height [38]. The number of vertical lines, or scanning, is constraint by the image scanning system to produce the captured picture and thus is not considered for determining camera’s resolution. For instance, PAL format utilizes 625 lines scanning at 50 Hz and NTSC format uses only 525 lines at 60 Hz frequency [39]. An example of this concept is shown in Figure 6 (one pixel is represented by one cell), where horizontal lines are the elements of the image across the screen from left to right.

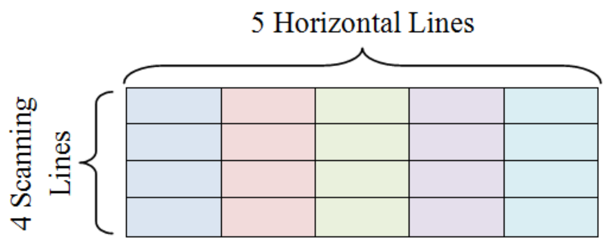


Figure 6: Image Resolution [33]

Using the aforementioned attributes, a list of Commercial Off the Shelf (COTS) cameras is complied in Table 2.

Table 2: List of Some COTS Video Cameras

Model Name	Weight (oz)	Min. Lux	Horizontal Lines	Current	Voltage	Dimensions (in)
RC Mini Cam [40]	3.17	3				.59 x .87 x 1.3
Fingercam [41]		3	380			.59 x .59 x .59
Spyeye [42]		1.5	380			
SpyCam [43]		2	382	50mA		
Miniature Camera ProSeries [44]	7.05		380		5-12 V	.71 x 1.3 x .79
Pencil Eraser Cam [45]		1.5	380		7-12	.32 x .32 (w x h)
KX-131G [46]	7.76	1		120 mA	5V	.87 x 1.0 x 1.1
KX-121 [47]	2.12	5	330	120 mA	5V	.87 x 1.0 x .59
Micro Color Camera [48]	0.35	1.5	380	30 mA	7-12V	.31 x .31 x .39
Micro B/W Camera [49]	0.32	0.5	380	15 mA	7-12V	.31 x .31 x .39
Micro Analog [50]	4.23	0.19	480			
Sony CC-1SBHR [51]	10.23	0.2	550	65 mA	9 – 14.5 V	1.3 x 1.3 x 1.1
Sony CC-1XHRM [52]	10.23	0.05	480	120 mA	9 – 14.5 V	1.4 x 1.4 x 1.4

Considering the currently available cameras, it is apparent that size is not an issue with respect to MAST systems. They are sufficiently small and light but resolutions at this scale need further improvements, especially for ability to detect humans and obstacles. Another issue at this size is lack of provision of variable focal length. This feature would enable the camera to dynamically adjust the viewing angle to optimize the image being captured based on the distance to object of interest. For instance, wide angle viewing can be used for scanning larger portions of area and it can be decrease to focus on an object of interest, thereby increasing the number of pixels in the image being captured.

2.4.1.2.Audio

A complementary sensor type to visual sensors is audio capturing device. Not only it helps in capturing conversations and other voice based information, it also helps in surveillance and reconnaissance by determining enemy locations through noises such as footsteps. The primary device researched for audio sensor type is microphone. The major issue in integrating on MAST systems would be interference cause by ambient noises and vibrations of the platforms. However, these concerns need to be addressed to physical experimentation at a later stage in MAST CTA development.

Microphones

Microphone is a device that captures sound waves converts them into electric signals that can be electronically interpreted. The two main types of microphones are dynamic and variable capacitor, or condenser. The variable capacitor, also known as condenser, microphones contains a fixed back-plate and a diaphragm. The capacitor is created by polarizing charge using electrets, or polarized material on the back-plate, which is located on the rear of the diaphragm [53]. The sound waves cause the diaphragm to move back and forth, which results in variation of the space between itself and the capacitor causing a change in the voltage. The change in voltage is then interpreted as sound. In order to convert the resulting high electrical impedance to a value reasonable for signal transmission, a preamp is wired in parallel with the diaphragm. Although the use of electret material ensures that microphone doesn't require power to function, the preamp still requires power to operate. Figure 7 shows a schematic drawing of a capacitor based microphone.

On the other hand, the dynamic microphones contain a diaphragm that has an aluminum coil attached and moves back forth (as in capacitor microphone) from the plan of a magnetic field. The stimulus for this movement is sound waves and causes an electric current to be induced in the coil [53], which can then be interpreted. Figure 8 shows a schematic diagram of a dynamic microphone.

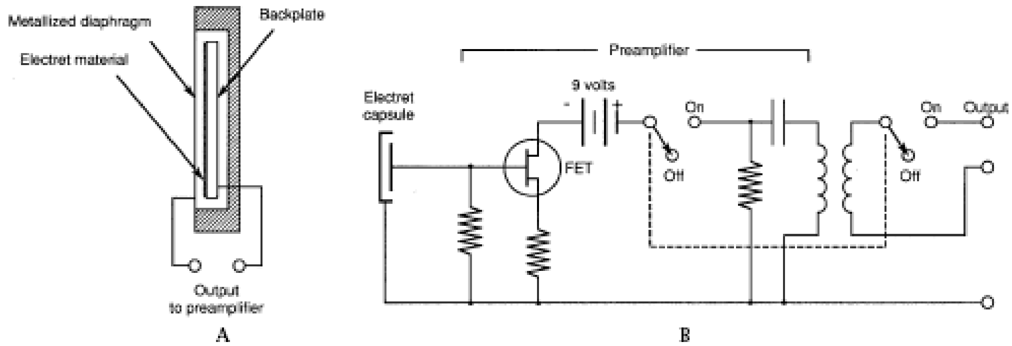


Figure 7: Electret Based Variable Capacitor Schematic with a Preamplifier [53]

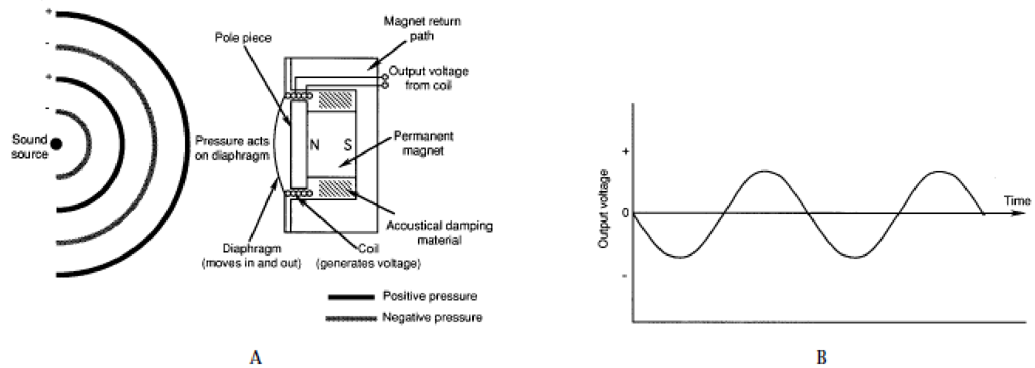


Figure 8: Schematic of a Dynamic Microphone. a) The sound waves and the diaphragm b) Output Voltage [54]

Another important attribute for selecting a type of microphone is its 3D pickup pattern, which is a fundamental characteristic [53]. Majority of the microphones are either omnidirectional or cardioids [53]. Omnidirectional ones respond to sound coming from any direction equally, while Cardioid microphones are designed to focus on sounds coming from a certain direction, usually the front of the microphone. There are three types of cardioid: cardioid, supercardioid, and hypercardioid [53]. The difference is in acceptance angle and capturing distance of the microphone and is graphically shown in Figure 9.

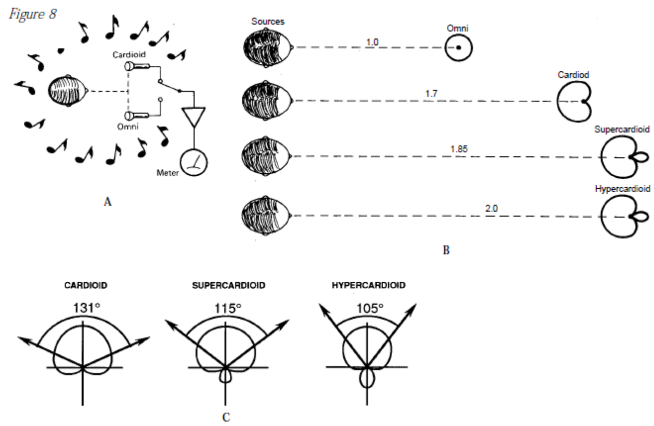


Figure 9: Relative Range and Acceptance Angle for Microphone Pickup Patterns [53]

The selection of the microphone directionality type depends on application such as directed hearing from an object of interest or capturing anything over a larger area. Moreover, technical attributes that quantify performance of a microphone should also be considered for mission scenario. Some of these primary attributes are: equivalent acoustic noise, or self noise level, sensitivity, overload sound level and frequency response. Equivalent acoustic noise level is the sound produced and captured by the microphone itself. However, it can be ignored in most cases as the ambient noise is much louder than the self noise of the microphone [53]. Sensitivity is the measure of microphone's output voltage when placed in a sound pressure field level of 94 dB at 1000 hertz, which is equivalent to one Pa (Pascal) [53]. The overload sound level is the limit that defines maximum sound pressure level that can be handled by the microphone. For speech detection purpose, overload sound level is rarely reached and thus not an issue. The last attribute to consider is frequency response, which is defined as the range of frequencies that the microphone can capture [53].

A list of COTS microphones that are relevant to MAST systems is shown in Table 3. Due to confidentiality issues, specifications of most advanced miniature microphones are not publicly available and thus difficult to compile for research purposes.

Table 3: List of COTS Microphones

	Pickup Pattern	Weight (oz)	Voltage (V)	Current (mA)	Frequency Response (Hz)	Sensitivity (mV/Pa)	size
PA3-IL [55]		0.501	6 - 15				
Countryman WCB6 Micro-Lavalier [56] [57]	Omnidirectional	0.071	1 - 2	0.5	20 - 20k	7	.1" Diameter
Tram TR50 Lavalier Electret [58]	Omnidirectional		1.5	0.03	40 - 16k		.18" x .3" x .55"
TMM-1 [59]			1.5 - 10		20 - 20k	5.6	.35" x 1"
Matchstick Label [60]			1 - 9			5.6	.125" Diameter
CMM-1 [61]						5.6	
PRAM 1 Preamp Electret [62]	Omnidirectional	1.517	1.5 (inc)		20 - 20k		
Shure WL51 Condenser Electret Wireless [63]	Cardioid	0.741	5	0.13	20 - 20k	3.2	
AT Pro 37 Condenser [64]	Cardioid	1.728	11 - 52	2	30 - 15k	7.9	3.9" x .83"
AT898 Condenser Lavalier [65]	Cardioid	0.032	1.5	.4	200 - 15k	5	.91" x .21"
Countryman Isomax 2-H Choir [66]	Hypercardioid	0.035	9	1	40 - 18k	10	
Countryman B6 Lavalier [67]	Omnidirectional	0.071	1 - 2	0.5	20 - 20k	12	.1" Diameter
Countryman B3 Lavalier [68]	Omnidirectional	0.012	9	4 @ 48V	20 - 20k	10	.23 " x .18"
AKG CK 98 Condenser Electret Shotgun [69]	Directional	2.822	9		20 - 20k	25	.4" x 10.2"
AKG CK 55 L Lavalier Condenser [70]	Cardioid	0.088	1.5 - 10	2	15 - 18k	8.8	
AKG CK 97-0 Condenser Electret [69]	Omnidirectional	0.106	9		20 - 18k	10	.3" x .7"

2.4.1.Navigation Sensors

One of most fundamental operational functions required by MAST systems to perform is to navigate an unknown terrain. A class of sensors that enable navigation and guidance for unmanned vehicles is navigation sensors. These sensors are used in conjunction with navigation algorithms to improve accuracy and enable path planning. For MAST systems, the challenge is to make sensors smaller and lighter while maintaining reasonable level of accuracy. There are many different types of navigation sensors available and ones most relevant to MAST systems are researched below.

Sonar

Sonar based sensors enables navigation by emitting a sound wave that echoes or bounces off an object or obstacle and returns to the sensor. The distance to the object can then be calculated by taking into consideration amount of time it took for the sound wave to return and properties of the air it propagated through. And thus enables unmanned systems to map surroundings and determine its relative location. Sonar sensors are not capable of determining global location. However, there are some disadvantages of sonar based sensors. First, they are relatively larger compared to sensors such as gyroscopes and accelerometers. Moreover, they can also be detected, by detecting the signals being emitted, and jammed, by emitting a counter signal of a similar frequency to create extreme data noise [71]. Table 4 lists some the sonar based sensors, and their specifications, available in market today.

Table 4: List of COTS Sonar Sensors

	H (in)	**W (in)**	**L (in)**	**Weight (oz)**	**V (DC)**	**Avg. Current (mA)**	**Min Range (in)**	**Max Range (in)**	**Accuracy (% of range)**
Maxbotix LV-EZ1 [72]	0.79	0.87	0.65	0.15	5	2	6	255	0.4
Devantech Sonic Range Finders [73]	1.7	0.54	0.78	0.4	5	30	1.1811	118.11	1.01
Ultra-Sonic Range Finder 28015 [74]	0.84	1.8	0.6		5	25	0.787	118.11	
F42 Series [75]	1.34	3.15	3.15		5	5	3.543	78.740	

Another drawback of sonar sensors is that they require much more processing power than gyroscopes or accelerometers [76]. In opinion of the author, sonar sensors can be best utilized by unmanned aerial systems for maintaining altitude indoors.

Laser Range Finders and LIDARs

Laser Range Finders (LRF) and LIDARs (LIght Detection And Ranging) utilize a laser ranging technique to find distance to object by measuring the properties of the light scattered by the object. Generally, the distance to an object is calculated by using pulses of laser. The primary difference between laser ranging and sonar based sensors is that former uses light, usually around the spectrum range of ultraviolet or infrared, and latter uses sound. Similarly to sonar, laser ranging based sensors can enable unmanned vehicles to map their surroundings and determine their relative location [77].

Some of the biggest drawbacks of LIDAR or LRF are their size and requirement of high processing power. Moreover, they can also be detected and jammed in a manner similar to that for sonar [78]. Nevertheless, LIDARs are very capable sensors that enable very precise mapping capabilities, especially when data from Inertial Measurement Unit (IMU) is combined using a navigation algorithm. Table 5 shows some of the currently available of LRF devices, and their specifications, in the market.

Table 5: List of COTS LRF

	H (in)	**W (in)**	**L (in)**	**Weight (oz)**	**V DC**	**Avg. I (mA)**	**Min Range (in)**	**Max Range (in)**	**Accuracy (% of range)**
Micro-Laser [79]	1.75	1.5	4	20	1.5		984.3	59055	0.067
BOD 63M-LA01-S115 [80]	1.1	2.7	3.5	9.17	25	4	19.69	236	0.036
SureShot™XP SSXP [81]	.			88	25	100	12	600	0.204
Opti Logic [82]	3.3	3.1	1.2	7.9	8	14.4			

Ideally speaking, if LIDARs can be minimized to sizes similar to that of sonar units and require less power they can become one of most effective assets for navigation of unmanned vehicles.

GPS

Perhaps one of the most widely used sensors in the world is a Global Positioning System receiver or GPS. It is a global navigation satellite system that determines the location of a receiver by using the current location of satellite and time taken for communication. The location determined is usually very accurate and the receivers have shrunk to extremely small sizes over the years [83]. Table 6 lists several GPS receivers, and their specifications, currently available in the market. The major drawback of a GPS receiver is that it only works outdoors and movement of the unit causes the accuracy to decrease. The outdoor requirement is due to the fact that GPS receivers need to receive satellite signals in order to operate. This limitation renders GPS receiver units useless for indoor environments or locations with obstruction above such as forest [84]. However, solutions for enabling GPS units to work indoors are being explored and are expected in the future. These indoor GPS units are known as Assisted-GPS (A-GPS) [85]. Although, the location of an unmanned vehicle equipped with GPS receiver can be determined quite accurately, this position can only be related to other nearby objects whose locations are known previously. Meaning that the vehicle can know its own location but it won't know the location of surrounding objects. Therefore, navigation in unknown terrain is impractical by sole use of GPS localization [83].

Table 6: List of COTS GPS Receivers

	h (in)	w(in)	l(in)	Weight (oz)	V (DC)	Avg. I (mA)	Max Range (in)	Resolution	Accuracy (% of range)
MN1010 [86]	0.39	0.4	0.1	0.2	1.8	35	360000	-152dBm	0.0328
Lassen iQ [87]	1.02	1	0.2	0.23	3.3	26	360000		0.0546
EM-406A [88]	1.18	1.2	0.4	0.56	5	60	360000	-159dBm	0.109
Copernicus [89]	0.75	0.7	0.1	0.07	3	40	360000	-160 dBm	0.0273

IMU

A fundamental component of inertial guidance systems is an Inertial Measurement Unit, or IMU. It is an electronic package that primarily consists of accelerometers and gyroscopes that are capable of sensing vehicle's motion in terms of rate, type and direction. Table 7 shows some of the currently available IMU units, and their specifications, in the market.

Table 7: List of COTS IMUs [90]

Model	**Manufacturer**	**Gyro**		**Acceleration**		**GPS**	Weight (oz)
		#	deg/s	#	G		
ADIS16355	Analog Devices	3	300	3	10		0.6
3D-Bird	Ascension	3	1000				1.0
INU	Atair Aerospace	3	300	3		yes	1.1
Micro INS	Athena Rockwell	3	200	3	7	yes	4.1
SensorPac	Athena Rockwell	3	200	3	7	yes	35.3
SilMU 01	Atlantic Inertial Systems	3	1000	3	50		8.8
MMQ-G	BEI Systron Donner	3		3		yes	8.1
C-MIGITS III	BEI Systron Donner	3	1000	3	15	yes	38.8
Crista	Cloudcap	3	300	3	10		0.7
Terrella 6	Clymer Tech.	3	2000	3	2		0.6
NAV 420	Crossbow	3	200	3	10	yes	20.5
NAV 425EX	Crossbow	3	200	3	10	yes	20.5
IMU440	Crossbow	3	200	3	4	yes	20.5
IMU700CB	Crossbow	3	200	3	4		56.4
HG 1700	Honeywell	3	1000	3	50		31.7
ISIS-IMU	Inertial Science	3	3000	3	500		8.8
InertiaCube3	InterSense	3	1200	3			0.6
Micro IMU	Memsense	3	1200	3	5		5.3
Nano IMU	Memsense	3	1200	3	5		0.5
MIDG II	Microbotics	3	300	3	10	yes	1.9
MP 2028g	MicroPilot	3	150	3	2	yes	1.0
3DM-GX1	MicroStrain	3	300	3	5		1.1

By integrating various sensors in one package, IMU provides a compact platform in terms of size, weight and power required [91]. The data obtained is utilized for determining location and usually employs a technique known as dead reckoning. It is a technique for determining current position based on previous position by using motion data, thus providing a comprehensive report on vehicle's location [92]. The major drawback of IMU stems from accumulation error those results from individual sensors continuously changing position information. Over time, the small errors in measurements accumulate to significant errors causing reduced accuracy of IMU data [93].

2.4.2. Navigation Techniques

In order for an unmanned vehicle to successfully navigate, a combination of sensors and algorithms is required. Previously, literature review on navigation sensors was presented and navigation techniques and algorithms will now be discussed. The fundamental function that an unmanned vehicle is required to perform for navigation is to determine its position relative to some fixed point in a map, also known as pose. The localization types can be grouped into four categories, according to reference [94]:

- **Local or Global:** For local positioning, the unmanned system is aware of its initial position and the uncertainty arises from sensor errors and vehicle movements. On the other hand, for global position, the unmanned system is not aware of its starting position at all. MAST systems will need to be capable of handling both types of problems to ensure full autonomy.
- **Single or Multi Vehicle:** Position localization can be achieved either by a single vehicle or multiple vehicles operating in a collaborative fashion. The cost of multi-vehicle operation is reliable communication system and increase complexity.
- **Passive or Active:** The difference between passive and active localization is that in former, the vehicle doesn't change positions to acquire new data for achieving localization. On the other hand, for active localization, the vehicle actively seeks to change position for the purpose of acquiring new data for the possibility of improving localization.
- **Static or Dynamic:** Static or dynamic conditions refers to the type of environment where former is constant. In dynamic environment, the state of obstacles and other objects may change. MAST systems will needs to be capable

of handling dynamic environments as would be expected of war mission scenarios.

With fundamental categories of localization defined, several navigation algorithms will now be explored.

Dead Reckoning

As previously mentioned, Dead reckoning is a navigation technique that determines vehicle's current position using sensor data for previous locations. IMU are primary source of data that enables integration of acceleration over time to determine changes in velocity and position over time. The major advantage of this algorithm is that it solely relies on data from internal sensors. However, the accumulation error makes this navigation algorithm less accurate over time.

Simultaneous Localization and Mapping (SLAM)

For autonomous systems to explore a truly unknown environment, it is required that only localization is achieved but the terrain is also mapped. Such a technique is called simultaneous localization and mapping or SLAM. It is a very important algorithm for indoor exploration as 'a priori' maps are usually not available for such environments and thus necessitates unmanned systems to not only navigate but also map the terrain. If either location or map information is available, the other piece of information can be determined using simpler techniques such as Dead Reckoning and lower computational power. However, in case of SLAM, both pieces of information are mission thus making the task complicated and computationally demanding. In fact, the processing requirements for SLAM based algorithms increases as the square of the number, also known as order N squared - O(N2), of features, such as landmarks - represented as points, in the map under consideration [95]. Figure 10 shows a graphical representation of SLAM algorithm.

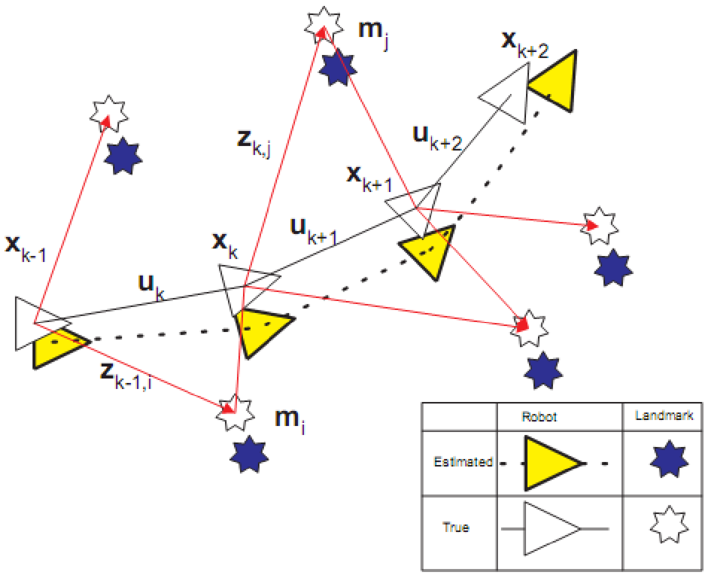


Figure 10: Graph Based Representation of the SLAM Problem [96]

Currently, there are number of solutions or algorithms available for SLAM based navigation that have been implemented and tested on autonomous systems. Nevertheless, complexity needs to be reduced much more to lessen computational burden [96].

Path Planning

Another important piece of algorithm required for navigation of autonomous systems is path planning. After localization and mapping, a vehicle needs to plan trajectory to use a path for navigating. There are a huge number of various path planning algorithms for different applications. The choice of algorithm depends on considerations of processing power limitations. Complex algorithms can be simplified in a number of ways such as adopting heuristics. However, such methods sacrifice optimality for reduced processing power requirements [97]. A popular path planning algorithm considered for application to MAST systems modeling and simulation in this research is known A* [98], which searches for path likely to lead to goal by plotting route between notes. An important characteristic is that it also considers the distance to be traveled when considering path options.

2.4.3. Power Systems

The role of power systems in unmanned vehicles is twofold: provide mechanical power to propulsion systems and provide electrical power to other subsystems (i.e. sensors, etc.). The energy needed to power these systems can be either stored on board or harvested/collected during execution of the mission. These two different mechanisms define the very board categories of power systems that are of interest for MAST vehicles. And due to the sizing limitations for MAST systems, most researched or implemented propulsion systems currently, as evident by MAST consortium members' technology research portfolio, are electric motors. Batteries and fuel are platforms for storing energy and powering propulsion systems. The primary difference is that a generator will be required to produce electrical energy from fuel if needed but it can be directly obtained from batteries. On the other hand, the energy collection systems are exemplified by solar cells or biomass harvesting, which recharge batteries on the go.

The largest component in micro autonomous vehicles, especially for aerial platforms, is most often a power system [99] [100]. Therefore, the type of power system selected for the vehicle under consideration needs to be optimized for the mission, in terms of maximizing specific energy and power output. This enables the vehicle to achieve required performance level and reduce overall weight. Figure 11 [101] shows different types of power sources and their trade-offs, in terms of high power density versus high energy density.

As apparent from the Figure 11, capacitors and inductor provide high power density at the cost energy density. Although not shown, energy harvesters would occupy the space alone left most edge of the chart as they have high energy density at the cost of power density [102] [103]. The selection of the power system is dependent on the requirements set by the mission scenario. Some of the power systems mentioned above will be discussed in detail below.

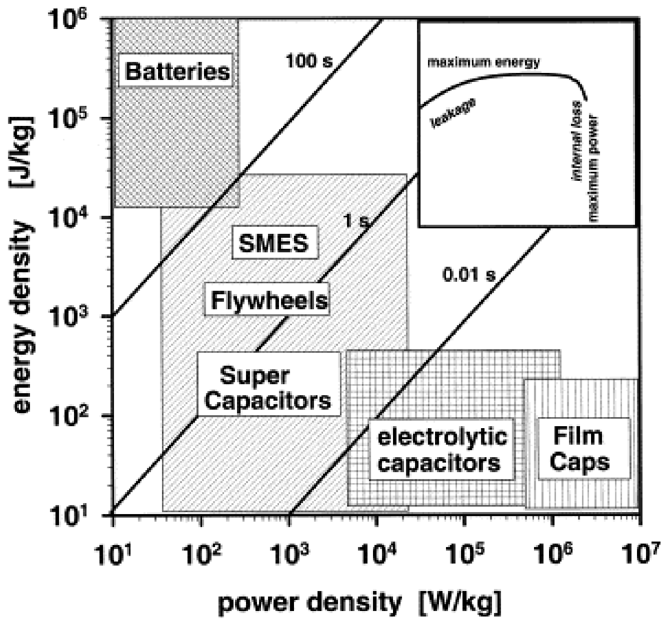


Figure 11: Ragone Plot of Different Energy Sources [101]

2.4.3.1.Motors - Electric Motors

As mentioned, the most common propulsion system for micro autonomous vehicles, especially aerial platforms, is an electric motor. The advantages are that electric motors come in very small size, are not very loud and they are reliable. However, the power output of electric motors is low [104] [105]. A rather large database of electric motors, specifically for aerial applications, is provided in a commercially available software called MotoCalc 8.07, developed by Capable Computing Inc [106]. Using the database and selecting a sample of the motors that have lowest weight and highest efficiency, a plot is created and shown in Figure 12, along with each motor's maximum power output.

Fitting a trend line using the selected data points, it becomes apparent that currently available electric motors have average specific power of 0.36 W/g. Some high end motors even have specific powers as high as 0.8 W/g. These values can be used for developing sizing relations for micro autonomous vehicles.

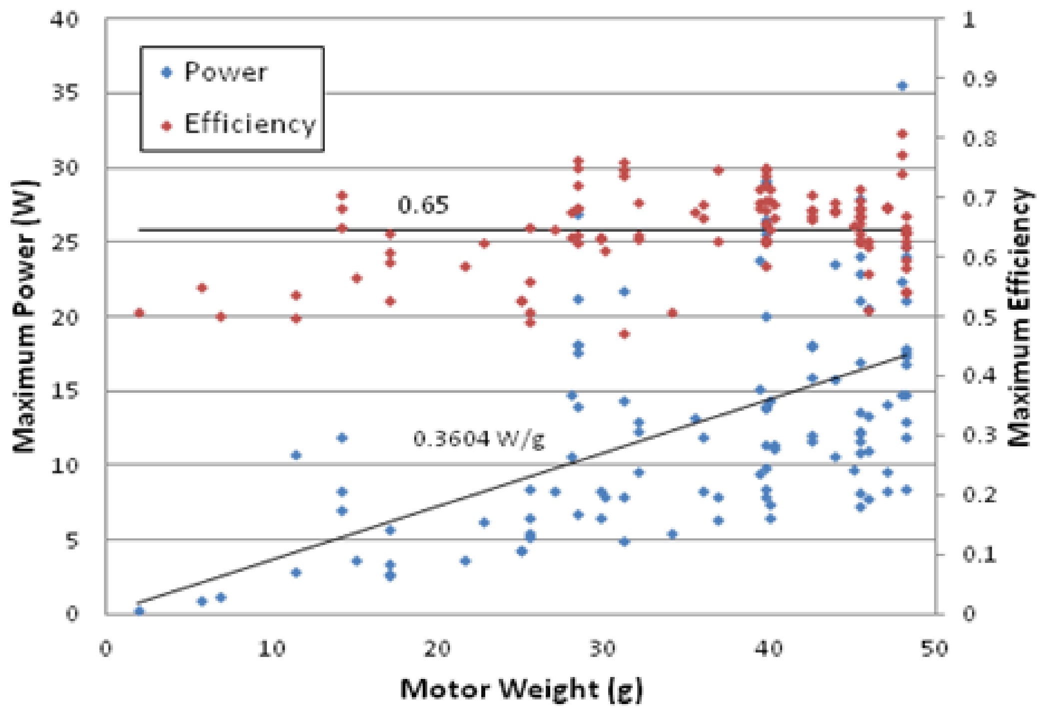


Figure 12: Electric Motors: Maximum Power vs. Mass [106] [33]

2.4.3.2.Energy Storage - Batteries

Due to size and weight limitations imposed by micro autonomous platforms, batteries are most researched and common form or power systems employed. Batteries are electrochemical devices or cells that convert stored chemical energy into electrical energy. The main technical attributes of batteries are energy and power. Moreover, the capacity of the battery is characterized as the amount of electric charge that can be stored in it and typically measure in Amp-hr. The power output of a battery is measured as the current being at given operating voltage (i.e. multiplied). The limitations on continuous power output is limited by the amount of current that can be drawn safely for a sustained period of time.

The three main types of batteries that are relevant to MAST systems are: Primary, secondary, and mechanically rechargeable. Primary batteries are of disposable nature as they cannot be recharged and also, generally, the cheapest. On the other hand, the defining characteristics of secondary batteries are their ability to be recharged. The cost of having higher power density for secondary batteries is lower specifications of energy density. The less used and less applicable battery type is mechanically rechargeable battery. They are quickly recharged by just replacing a component, usually anode, of the battery [103]. Figure 13 [107] shows the Ragone plot for various primary and secondary batteries along with their performance metrics.

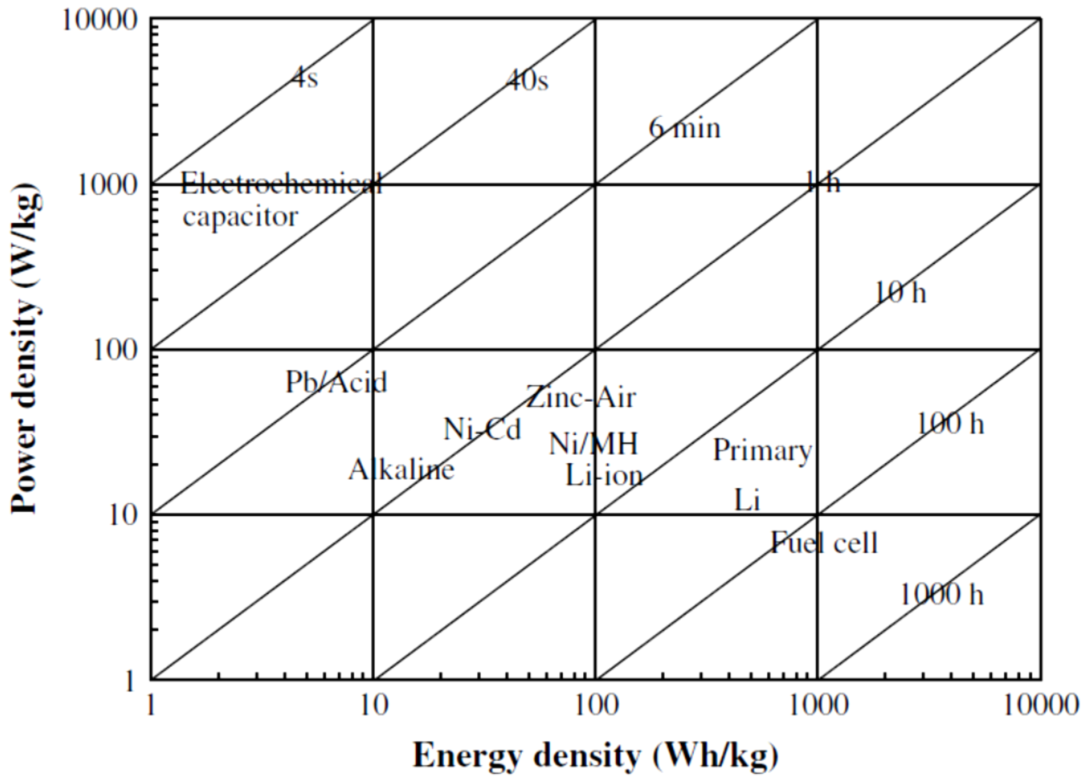


Figure 13: Ragone Plot: Primary and Secondary Batteries [107]

The power and energy densities are depicted using the lines of constant battery lifetime in the plot. Depending on the use, the most applicable battery type can be selected by plot and the list (not comprehensive) of specific batteries, and their specifications, shown in Tables 8 and **9**. Considering the data in the tables, a very notable type of battery is thin film lithium that has recently entered the market. The inherent design of these batteries allows much higher current draw than others resulting in very high power density. Thin film batteries can be custom built to accommodate space requirements and even be constructed using flexible material such as polymer substrate.

This is can lead to building these batteries to be incorporated as structural components on a vehicle resulting in substantial weight reduction. Another advantage of thin film lithium batteries is that unlike most other batteries, the increase in cost as size decreases towards micro scale is relatively much less [103].

Table 8: Performance of Primary Battery Systems

Primary Battery Systems	Nominal Voltage (V)	Specific Energy (W-h/g)	Specific Power (W/g)	Energy Density (W-h/L)	Power Density (W/L)
Lithium/Sulfur Dioxide	2.8	0.151	0.0438	230	67
Lithium/Manganese Dioxide	3.0	0.100	0.0200	195	39
Lithium/Carbon Monofluoride	3.0	0.322	0.0556	572	99
lithium/Iron Disulfide	1.3	0.324	0.0953	631	186
Lithium/Copper Oxide	1.5	0.285	0.0041	484	7
Lithium/Silver Vanadium Oxide	2.0	0.150	0.1439	405	388
Zinc Chloride	1.0	0.020	0.0200	36	36
Magnesium/Manganese Dioxide	1.6	0.160	0.0032	272	5
Alkaline/Manganese Dioxide	1.0	0.100	0.0273	289	79
Silver Oxide	1.6	0.139	0.7117	545	2794
Lithium/LiI, PbI2, PbS	1.9	0.092	0.0003	4671	13

Table 9: Performance of Secondary Battery Systems

Secondary Battery Systems	Nominal Voltage (V)	Specific Energy (W-h/g)	Specific Power (W/g)	Energy Density (W-h/L)	Power Density (W/L)
Sealed Nickel-Cadmium	1.2	0.034	0.0365	99	107
Nickel/Metal Hydride	1.2	0.055	0.1100	175	349
Zinc/Silver Oxide	1.4	1.246	0.4154	1834	611
Cadmium/Silver Oxide	1.0	0.046	0.1522	74	247
Lithium/Molybdenum Disulfide	1.8	0.050	0.1250	135	338
Lithium/Manganese Dioxide	3.0	0.141	0.3529	272	681
Lithium/Niobium Selenide	2.0	0.102	0.1486	276	401
Lithium/Lithium Cobalt Dioxide	3.8	0.090	0.3619	224	895
Lithium/SPE/S-based Polymer	2.1	0.215	0.8000	349	1300
Lithium-Aluminum/Carbon	3.0	0.003	0.0002	6	0.48
Li-Titanium Dioxide/Li-Mn2O4	1.5	0.016	0.0006	52	1.87
Lithium Thin Film	4.0	0.300	6.0000	959	19180
Lithium-Ion Thin Film	4.0	0.250	2.5000	1041	10410

2.4.3.3.Energy Collection - Solar Power

Power generation mechanisms that rely on harvesting energy have the potential to theoretically provide unbounded energy [102] [103]. However, the drawback is that the power output is relatively low and power production is unpredictable and even sporadic, depending on the specific type of harvester. A popular example of such power system is solar cells, also known as photovoltaic cells. These devices use photovoltaic effect to convert light energy into electrical energy directly. It is easily observable that there can be a number of hurdles to effective use of solar cells such as indoor environments, lack of sunlight due to clouds, vehicle moving in shadows, etc. Thus limiting the scenarios where implementation of solar cells will be ideal [108]. Solar cells can be used as part of hybrid power systems where a different type of mechanism, such as batteries, is used for supplying power where light is not available for harvesting. However, during that time solar cells will only act as dead weight, unless they can be built to serve as structural members of the vehicle.

2.4.4. Communication Systems

The final class of technology systems to be considered for literature survey is communication systems. The objective of communication system is enable transmission of data and information between two or more systems, which includes generating signals from data, their processing, and transmitting and receiving these signals. Communication systems that don't utilize wires or other electrical conductors are categorized as wireless communication. A telecommunication system is consist of three main components: 1). Transmitter: for conversion of data into digital or analogue signal, 2). Receiver: for receiving and decoding the signal into data, 3). Medium: through which the signal travels. Some fundamental attributes components of communication systems are discussed below.

Signal

Communication signals are of two types: digital or analogue. Digital signals consists of information encoded as a set of discrete packets (i.e. 0,1) while in analogue signals, information is encoded and varied in form of a continuous wave such as a cosine wave. The quality and strength of signals degrade due to noise caused by external interferences. The advantage of digital signals over analogue signals is that unless a certain threshold of noise is exceeded, the digital signal remains intact.

Channels

In order to avoid interference between multiple streams of information transmitted over communication systems, divisions in the frequency, known as channels, are utilized. This enables simultaneous transmission of different information lines without resulting in distortion of one another.

Modulation

Modulation is the shaping of a signal to convey information and can be utilized to represent a digital message as an analogue waveform. There are several modulation techniques including the following: 1). Amplitude modulation**:** This varies the strength or amplitude of the signal being transmitted, 2). Frequency modulation: varies the frequency of the signal being transmitted, 3). Phase modulation: varies the instantaneous phase of the wave.

Network

In terms of communication system, a network is a set of transmitters, transceivers and receivers with communication between one another. Moreover, routers may be utilized in networks to direct the path of communication. If signal strength needs to be amplified due to distance, then repeaters are generally employed.

Methods of Communication Systems

Considering the autonomous nature of MAST systems, it is imperative that the communication systems employed are of wireless nature. Therefore, the final aspect to consider for communication systems is the different methods available for wireless communication systems and include the following: 1) Infrared: transmits pulses of infrared light, 2). Laser: transmits pulses of laser beam, 3). Narrow-Band Radio: transmits signals using bandwidth of 25 kHz or lower [109], 4). Spread-Spectrum Radio: transmits signals spread over wide band of frequencies [110], 5). Ultra Wide Band Radio: transmit signals over even wider frequency than spread spectrum radio making them quite difficult to be detected [111].

2.5. Chapter Summary

This chapter documented the background research into the structure and research focus of MAST CTA, to observe and understand the need for methodology to address requirements disconnect between Warfighter and technologists. The Integration Center's vision and tasks were analyzed to put forth observations providing evidence for a need of framework to map Warfighter capability needs to technology attributes for mission scenarios. A Gedanken experimented was conducted in the early days of MAST CTA and its results were analyzed to understand the needs and the capabilities required by soldiers from MAST systems. Finally, a literature search was conducted to explore technologies relevant to the MAST vision.

With background information available and observations validating the need for this research laid out, the next chapter will discuss the research issues and objectives and formulate research questions. A research plan will put forth for addressing the formulated research questions.

CHAPTER III

RESEARCH OBJECTIVES

This objective of this chapter is to present a research plan based on the background and literature survey conducted in previous chapter and deliberation of the problem defined in the first chapter. From these considerations, a series of fundamental research questions are formulated that will be answered through the remainder of this thesis. The research questions put forth are answered in form of methodology and framework that enables quantification of requirements disconnect and technology gap.

3.1. Research Issues and Objectives

The main objective of this research stems from the fact that there is a need to address the established requirements disconnect between Warfighter and technologist, especially in context of MAST technologies. MAST poses a very comprehensive and complex problem in terms of system of systems design requiring highly integrated interactions of technical nature between a myriad of communities and organizations arising from a board range on technical spectrum. Academic institutions, government laboratories and industry are researching technologies from various disciplines. It results in a very complex working environment making integration task rather challenging as it is very difficult to understand how all the pieces fit together to form an overall solution. As apparent from previous chapter, the core focus of MAST consortium members is development of prototype technologies that may serve as key enablers in future to synthesize MAST systems for various missions. Developments of these technological capabilities are based on platform dependent metrics or Measures of Performance (MoPs) [112]. For instance, technologies are working to answer questions such as “What energy density do the batteries need to have?". However, the Warfighter is more concerned with answering questions from a System of Microsystems (SoM) perspective that are evaluated in terms of mission Measures of Effectiveness (MoEs) [113] [112]. According to MAST Initial Program Plan, System of Microsystems (SoM) is defined as an integrated ensemble of heterogeneous MAST microsystems interoperating to accomplish mission goals. The Warfighter, for instance, is interested in asking a question such as "For a given mission scenario X, what type of platforms will be able to stealthy map out an interior of a building of interest in least amount of time?". Considering the questions being asked two distinct perspectives, there is a clear capability gap or a design singularity between the expectations of operators and the vision of the technologists that needs to filled and solved in order to design and develop integrated MAST systems.

This presents an urgent need to create a methodology and framework that will be capable of addressing the research issues based on motivation presented earlier and the following observations:

- Need for an overall SoM architecture for an ensemble of MAST systems capable of accomplishing missions scenarios that are of interest to Warfighter
- Need for a methodology to systematically assess the effect of existing, new and emerging technologies on specified mission scenarios
- Need for capability to assess and modify technology transition goals for MAST mission scenarios
- Ability to create mappings between SoM level goals for achieving desired MoEs and technology attributes based on MoPs
- Ability to explore the complex and astronomically large concept and design space of MAST systems and technologies in a manner that is quantitative, traceable, dynamic and repeatable
- Ability to assess and define constraints and ranges based fundamental technology limits, models and metrics in order to understand and evaluate factors impacting

mission based performance. Which factors have the most impact to system performance?

- Need to evaluate, predict and optimize SoM level mission performance based on MAST existing and developing MAST technologies
- Need to define precise and updated technology requirements through evaluation of SoM consisting of MAST technologies for various mission scenarios
- Ability to promote and synchronize consortium wide interdisciplinary and collaborative research effort
- Need for a comprehensive methodology and framework to connect developing and existing consortium wide MAST technologies with capabilities defined by the Warfighter's needs.

Therefore the primary research objective is to address the aforementioned research issues required for the integration of the MAST from a System of Microsystems perspective. It should be achieved through development of a structured framework capable of creating comprehensible and quantifiable relationships between the required operational capabilities and MAST technologies under development.

3.2. Research Questions

From the research issues mentioned above, several fundamental research questions can be formulated to guide this research. They all arise from the need for an integrated framework to address the gap created by requirements disconnect between Warfighter and technologist. This research plans to address these research questions by creating a structured framework including systems functional breakdown, architecture design and evaluation, technology prioritization and goal optimization.

The formulated research questions and corresponding hypotheses are presented below with an explanation of each immediately following it.

Research Question 1

How to explore and evaluate the enormous combinatorial space consisting of integrated systems, technologies, and scenarios?

The MAST program is greatly focused on technology development and research due to the fact that advanced technological capability will be required to perform the missions. As previously mentioned the concept space bounding the technologies being researched is enormous and coupled with various possibilities of mission scenarios results in exponential growth of available combinations of microsystems. Moreover, the number of technologies that can be integrated into a single platform is very constraining as only few can be selected from a very large pool of alternatives, making it quite challenging to address research question 1. Nevertheless, it is imperative that research question 1 to be answered in a systematic and repeatable manner in order to bind the concept and design space to make it practical for analysis in context of mission scenarios.

The fundamental issue to be addressed is how mission level success can be mapped to direct performance of microsystems. The missions Measures of Effectiveness (MoEs) must be developed to quantify effects of microsystems for a given mission scenario. Relating them to technologies Measure of Performance (MoPs) of given concept of operation can enable the assessment of required capabilities for accomplishing a mission. It should be noted that since the performance of any microsystem depends on specifications and capabilities of technologies that it is built from, there has to be multi-level mappings to answer the following sub-question: *which MoPs drive which MoEs?*

Research Question 2

Can various MAST technologies be evaluated rapidly for mission specific scenarios?

Considering the astronomical size of the concept space to be evaluated for each mission scenario, it is vital, in terms of practicality, that billions of technologies are assessed from mission level perspective in a rapid manner. The analysis at this point doesn't have to be detailed but rather rely on questions such as *what are technical constraints for each technology (i.e. power limitations, communication ranges, etc)* or w*hat constraints are the limiting factors in the microsystems' design*. The answer to this research question lies in the art of filtering down technologies based on the specifications of a given missions. The fidelity level of such analysis will have to depend on the quality of information regarding each technology concept available such as mass, speed, size, etc. The core idea of the methodology to address research question 2 is to enable the capability that can answer the following sub-question: *What combination of technologies integrated into a microsystem will 'best' enable the accomplishment of a given mission based on associated MoEs?* The fundamental characteristics of the method addressing this question should include repeatability, traceability, and the ability to update as new information becomes available. This ensures that over time, the fidelity level of analyzing billions of technologies combination rapidly will improve.

The hypothesis to answer the first two research questions is stated as:

<u>Hypothesis 1</u>

If missions can be quantified in a systematic manner in terms of operational functions then combinations of technologies can be mapped to them and rapidly evaluated by means of a mathematical scoring scheme.

<u>Research Question 3</u>

How can integration effects of various platforms be modeled, and how are the resulting emergent behaviors identified within the microsystem ensemble?

The complexity of any MAST mission stems in part from the integrated heterogeneous platforms operating in an ensemble. Due to the size and power constraint individual microsystems can perform relatively simple functions. However interacting with each other in an ensemble gives rise to synergistic relationship between different types of microsystems. And when coupled with autonomous behavior, it leads to emergent behavior [114], which are complex patterns resulting in complex behavior and functions. Therefore, the impact of integrating heterogeneous platforms into an ensemble requires assessment of emergent behavior in terms of when and how such patterns occur and effect a given mission scenario..

In order to address research question 3, it is vital that mission scenarios can be modeled and simulated along with MAST microsystems with the capability to discover and observe emergent behavior as missions are run. Agent based modeling (ABM) [115] should be an integral part of the simulation to assess swarm behavior. It will also lead to address sub-questions such as following: *How do integrated systems of heterogeneous microsystems interact? And what combinations of microsystems would maximize the given mission's probability of success?* These questions may also lead to answers regarding effect communication platforms between microsystems and mission operators and evaluation of nature and types of microsystems in an ensemble in context of mission scenario based on factors such as: number of microsystems, types of sensors, and so on.

Research Question 4

How can specific mission scenarios be simulated from start to end in a virtual world that is reasonably accurate?

As evident from research question 3, there is a need for capability to model and simulate mission scenarios in order to assess mission level performance that not only takes into account MoPs and specifications of microsystems, but also interactions and emergent behavior. And this serves as justification for applicability of research questions 4 and 5, which must be addressed together.

A given mission scenario should be modeled and simulated at a reasonable level of fidelity in order to evaluate the performance of the autonomous microsystem ensemble for that mission. As technologists are currently developing various technologies and their underlying models, it is of paramount importance to acquire the capability of mission level modeling and simulation to bridge the gap between the Warfighter and the technology researchers. Addressing this issue requires development of a modeling and simulation environment based agent based modeling logic resulting in a virtual world to simulate various mission scenarios. It will lead to evaluation of robust combinations of microsystems that can successfully accomplish the various operational scenarios. It should also take into account operational constraints such as: number of microsystems, deployment, types of sensors equipped, and environment variables. The technology modeled simulated can be either based on current state of the art or some modeled future technologies. Therefore, technical feasibility of various technology levels can be assessed. Other sub-questions that may be answered using such a modeling and simulation environment include the following: *What is the effect of different navigation algorithms on mission outcomes? What is the benefit or disadvantage of using a complicated navigation algorithm?*

The hypothesis for addressing third and fourth research question is formulated as:

Hypothesis 2

If missions and multiple MAST systems (current and future) can be modeled and simulated in a virtual world without the existence of physical based technology specific models then integration effects and emergent behavior can be identified and analyzed.

Research Question 5

How can modeling and simulation environments for System of Microsystems be validated to ensure that the accuracy is reasonable?

A very important issue that arises from use and implementation of modeling and simulation environments is whether or not it can be trusted to replicate real world behavior of MAST microsystems at a reasonable level of accuracy. Without confidence in the developed modeling and simulation environment, it is not practical to apply the results obtained through such analysis. Therefore, it is critical to validate the modeling and simulation environment to address research question 6. As there is no substitute to real-world validation, experimentation involving simulation of a controlled mission (i.e. same vehicles and mission environment) in real life and the modeling and simulation environment. Comparing the outcomes and performing any necessary fine tuning to the virtual environment will result in its validation. Knowing that virtual world mimics real world at a reasonable level of accuracy will enable the analysis to be used for overall purpose of closing the gap between Warfighter and technologist.

The solution to fifth research questions is hypothesized as:

Hypothesis 3

If virtual simulation missions can be physically simulated in real world then the comparison of outcome can either validate virtual world or guide its calibration.

Research Question 6

How can technical feasibility of the microsystems in modeling and simulation environment be evaluated based on current state of the art technologies?

The core issue raised by this research question stems from need to feedback into the previously addressed virtual world in terms of platform specifications. This feedback aids evaluation of the technical feasibility of the technologies being modeled. Design parameters dictate the individual performance of the platform and provide the final sizing result for the given mission. These parameters are, constrained by the physical and logistical limitations of the subsystem technology components such as power sources, size, payload, actuators etc. determined to give the lightest and smallest platform to complete the mission. However, the mission requirements are determined for sizing based on the simulation results from the virtual experimentation. Therefore, a process for utilizing sizing relations needs to be an iterative in nature and operated in conjunction with modeling and simulation of microsystems. In order to address research question 6, it is necessary to integrate platform dependent sizing relations or model in the solution framework.

The sixth research question is expected to be addressed by the following hypothesis:

Hypothesis 4

If simplified sizing relations for power and mass can be developed for different platforms and technologies then model and simulated integrated systems can be sized and checked for technical feasibility.

Research Question 7

How can technology gap be quantified, while considering all aspects of a mission scenario including swarm and emergent behavior, and lead to re-definition of requirements for MAST systems?

The core motivation behind this research is to quantify requirements disconnect between Warfighter and technologist in order to minimize this existing gap. A fundamental implication of this research is to quantify of the technological gap between the current, existing, or emerging MAST technologies based on their capabilities that are applicable to Warfighter's needs with the technology level that must be achieved in order to achieve the goals set forth by those needs. It is important to note that the gap will depend on the specified mission. This will enable technologists to quantitatively evaluate the level and direction of advancement required to meet the MAST mission level goals and enable Warfighter to re-define requirements that are realistic for MAST vision.

Addressing research question 7 requires compilation of development defined for all of the previously mentioned research questions into a comprehensive integrated framework that will consist of the following: Quantification of requirements disconnect through utilization of system based decomposition methodology, evaluation of concept and design space, and development of an iterative closed loop between modeling and simulation and advanced concept synthesis and analysis. This will enable quantitative assessment of the current capabilities of MAST technologies and the required capabilities to achieve the MAST missions. The following hypothesis captures the essence of the proposed answer to research question 7:

Hypothesis

Once requirements disconnect is bridged through implementation of previous modules then mission based requirements can be defined and compared with current state of the art to quantify technology gap.

In an effort to consolidate the requirements of all the fundamental research questions put forth in this section, a research objective statement is formulated as following and will serve as mission statement for this research:

Research Objective:

Develop a structured methodology and framework capable of creating comprehensible & quantifiable relationships between the required operational capabilities & MAST technologies.

3.3. Research Plan

With the research issues, the objectives, and the questions established, it is now necessary to put forward a research plan to address them. The aim of this research is to address the issues and questions and achieve objective set forth by developing a structured a methodology and an integrated design, analysis and experimentation framework. It will include the following features: system-level functional breakdown, operational architecture design and evaluation, concept and design space exploration and evaluation, modeling and simulation, sizing relations, and physical experimental validation. Once developed, it will be implemented on number of MAST and ARL specified mission scenarios to test and obtain results. The findings will also be documented in this thesis.

3.3.1. Technical Approach

The existence and significance of requirements disconnect between Warfighter and technologists have been previously well established. In brief, it stems from end-user and Warfighter working on different ends of the spectrum. The technologists are working in laboratories on fundamental development of technologies such as motors or antenna while the Warfighter or soldiers are operating in a battlefield to achieve specific mission goals. Without a clear understanding of other side's perspectives, it creates an operational gap and requirements disconnect and require the need to implement SoM approach. The goal is to create a framework to integrate two main components of MAST vision: *Technology driven:* Development and advancement of the state-of-the-art of individual technologies. *Warfighter focused:* Integrated SoM solutions based on MAST technologies for implementation on the battlefield.

In order to develop a methodology and framework that would provide a structured, dynamic, traceable, and transparent “living” approach for quantification and solution of requirements disconnect and technology gap, an integrated technical approach will be implemented that is a combination of *Top Down and Bottom Up* approaches [116] simultaneously. Figure 14 shows details of this technical approach and information flow from one end to the other and back. These two fundamental approaches to design depend on the starting perspective. Starting with Warfighter, on the left, and coming down towards technologist is a top-down approach to design. Top-down design consists of decomposing the problem based on goals and needs into fundamental technologies. And starting from technologist level is a Bottom up design approach and consists of synthesizing fundamental technologies and working up to system of systems level goals and capability needs. Moreover, the 'explosion' symbols shown in the Figure 14 signify a gap or disconnect between each level requiring the proposed framework to provide a solution through modeling, simulation, and experimentation. Warfighter represents army goals and needs for MAST. For instance, a representative army goal can be to provide situational awareness to a squad of soldiers on mission to infiltrate an urban two-level building.

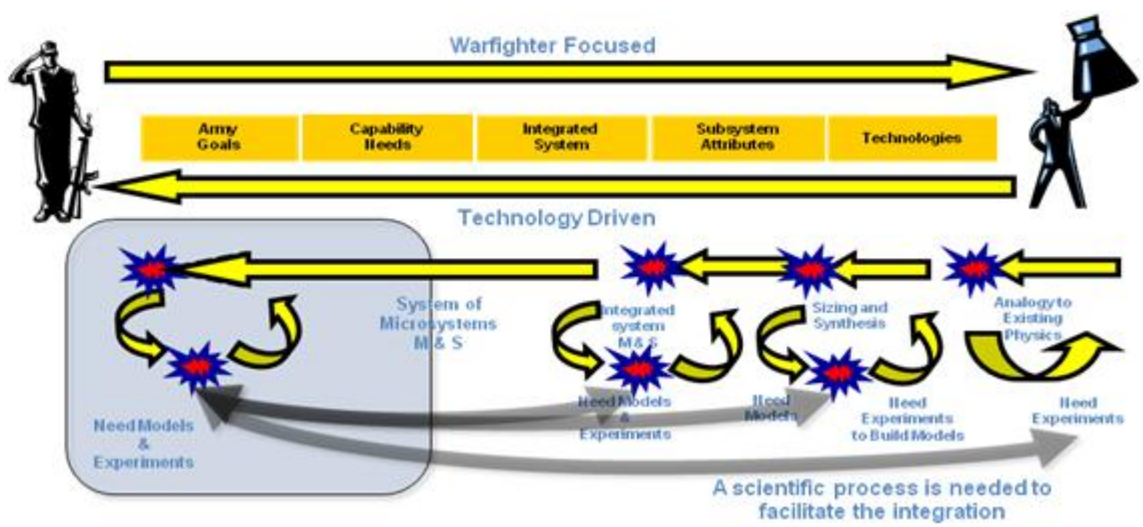


Figure 14: Integrated Approach Based on simultaneous Application of Top-down and Bottom-up Approaches

These army goals can be decomposed into capability needs which will enable accomplishment of those goals. An example of a capability need is the ability to explore the building of interest building without being detected by enemies inside. This capability need is can be broken down into integrated system that will possess this capability. An integrated system can be either individual MAST systems of system of systems working together as an ensemble. For the former case, the decomposition at this level is in two parts: system of systems and then individual system. An example of this level is a swarm of micro flyers or a carrier unmanned ground vehicle deploying other unmanned systems. Each integrated system consists of subsystem technologies that are specified by technological attributes. These subsystems are dependent on integration of fundamental technologies (i.e. flapping-wings, rotary wing, sensors, etc.) which dictate these attributes, such as mass, power consumption, speed, etc. For instance, a flapping wing subsystem will consist of enabling technologies such as advance actuation mechanisms capable of flapping wings at 150 degrees of angles without little losses. And this is the level where technologists are working at and attributes concerned with in terms of development.

Now going back the other direction, technologists start with very little fundamental knowledge due to revolutionary nature of MAST technologies. For instance, to design a flapping-wing micro aerial vehicle, it is necessary to construct analogies to existing physics and develop new physics based models. This along with corroboration is achieved through experimentation. It eventually leads to development of new sizing and synthesis codes, which fills the gap between the technologies and the subsystem attributes. Going up a level, disconnect between subsystem attributes and integrated systems is solved through development and implementation of modeling and simulation codes and environments. Again, it is necessary to create new models and conduct experiments to develop a modeling and simulation environment. Moving further up, the quantification and solutions to information disconnects at various levels starts to synthesize into an understanding of the army goals and capability needs. Information fed-back from modeling and simulation of the system-of-microsystems level plays a crucial role in mapping the top level goals to bottom level technological attributes, thereby forming a relationship among all levels of information flow.

Simultaneously applying these two design approaches in integrated manner, as explained above, forms the backbone of this research plan for this thesis. Developing and implementing a methodological framework based on this research plan will enable quantification and solution of requirements disconnect and technology gap. The next chapter explains in detail the developed methodology and framework to address the research issues and questions mentioned in this chapter and to achieve research objectives put forth.

CHAPTER IV

METHDOLOGY AND FRAMEWORK

Micro Autonomous Systems and Technologies (MAST) is an Army Research Laboratory (ARL) sponsored project composed of a consortium of cutting edge academic and industrial research institutions working together to develop revolutionary technologies in the field of microelectronics, autonomy, micromechanics and integration. The primary goal of the MAST consortium is to develop autonomous, multifunctional, and collaborative ensembles of microsystems to enhance tactical situational awareness of small units in urban and complex terrain. In order to achieve such enhanced situational awareness, it is necessary that heterogeneous set of MAST vehicles built on revolutionary technologies to operate in a synergistic ensemble capable of autonomously conducting intelligence, reconnaissance and surveillance missions. Technologists are tasked with developing new technologies to enable advance MAST capabilities, while Warfighter is more concerned with defining strategies and tactics on implementation of these systems. These two distinct groups within MAST Consortium are working on the same problem but at different ends of the perspective spectrum and hence creating a requirements disconnect.

The importance and necessity to quantify and solve this requirements disconnect has been established in previous chapters. In Figure 14 (of chapter 3), a research plan, built on a technical approach of simultaneous application of decomposition and re-composition or 'top-down' and 'bottom-up' approaches, was laid out. The research presented proposed development of a structured and traceable methodology for the quantification of requirements disconnect and technology gap. The implementation of this methodology through an integrated framework consists of development of various decision making and modeling and simulation tools along with a process for experimental data farming [117] and validation. Following the laid out research plan, this chapter will document the development of an integrated multidisciplinary framework for quantification, assessment, simulation, optimization and experimentation of MAST. It will describe overall framework developed to answer the previously formulated research questions and present details of its components. The framework will be used as a roadmap for this chapter. The theory, models and tools that have been utilized for development of each component will be presented and explained.

4.1. Methodology Overview

The research approach taken for development of a methodology to address the fundamental problem of requirements disconnect between the technologists and the Warfighter and quantification of technology gap is based on the fundamental challenges described earlier. The existence of information disconnects between operators and scientist stems from two major obstacles defined in this dissertation. First, all of the MAST technologies, current and future, are of revolutionary nature with no currently available and reliable historical data, sizing and synthesis codes or physics-based models. The inherently multidisciplinary, multi-objective and uncertain nature of MAST technologies makes it very difficult to map mission level objectives to measurable engineering metrics. It involves multiple disciplines such as aerodynamics, computer science/engineering, mechanical engineering, electrical engineering, biology, etc. There are also multiple objectives such as mission performance, vehicle attributes, etc. Second, the concept and design space is enormous with hundreds of billions of alternatives and largely includes future technologies with low Technology Readiness Level (TRL) resulting in high uncertainty.

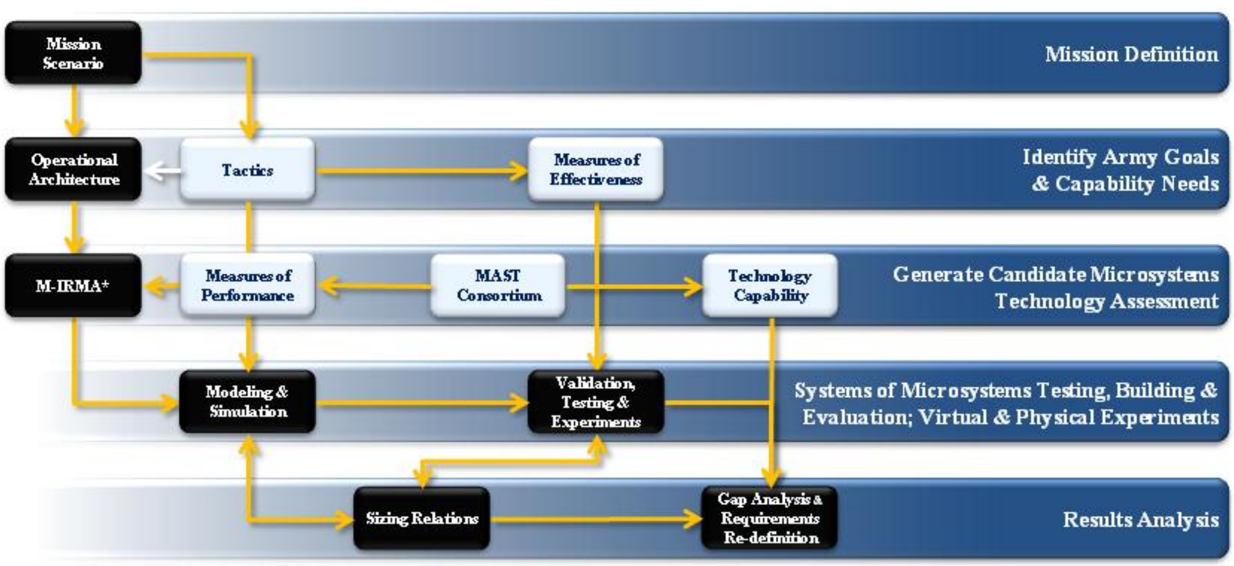
Therefore, the fundamental problem to be addressed is to find a way that will enable the researchers to do the following:

- Assess current and future technologies in context of mission scenarios, tactics and requirements without sizing and synthesis codes or complete physics based models.
- Assessment should be rapid and/or proportional to the number of technologies being evaluated to make it practical. The assessment should take into account the mission level objectives and MAST operational architecture.
- Model and simulate mission scenarios with current and future MAST technologies and future technology capabilities of existing technologies.
- Model and simulate representative technological capabilities that may be available and/or required in future.
- Modeling and simulation should be complemented through hardware-in-the-loop [118] [119] experimentation.
- Optimize heterogeneous swarms of MAST vehicles for modeled mission scenario.
- Assess sizing and technical feasibility of the optimized ensemble based on current and future technologies.
- Quantify technology gap if it exists and dictate updated requirements to close the gap.

It is important to note that all of the above tasks are to be accomplished without the luxury of having access to reliable historical data available for most MAST technologies. There should also be some level of automation available for these tasks to ensure practicality of the approach. The data input should be of flexible format and be able to accept both qualitative and quantitative. It should be traceable, structured, and "live" so that it can be updated once new information becomes available. The ability to input experimental data directly into decision making tools and modeling and simulation environments at any point in process is necessary. It ensures that if there is lack of certain type of information that may become a show stopper for designer, then it can be obtained through experimental means. Moreover, it will enable hardware-in-the-loop analysis capabilities. Finally, the end result must not always be a point solution (unless the current technology level is able to accomplish mission with reasonable level of probability of success) but rather a set of requirements that guides the technological advancements necessary for accomplishing specific mission scenarios.

4.2. Framework Overview

In order to address the research issues put forth previously while keeping in mind the basic methodology specifications defined in the previous section, the framework to be developed and implemented should comprise of components enabling quantification, assessment, modeling and simulation, optimization and experimentation of MAST technologies and mission scenarios simultaneously. The proposed framework is schematically shown in Figure 15. For brevity, it will be referred to as MAST quantification framework from here onwards. It depicts the information flow-down along with critical components and their relationships to each other.



* Interactive Reconfigurable Matrix of Alternatives

Figure 15: MAST Quantification Framework

This framework is a cyber-physical design [120] and analysis suite that combines Warfighter mission needs and expert technologist knowledge with a set design and optimization tools, models and experiments in order to provide a quantitative measure of the requirements disconnect and technology gap between current capability and future objectives. The fundamental features of this framework are:

- **Modular:** Each component is a separate module that can be replaced or removed without affecting overall flow of information. For instance, if information provided by one of the component is obtained by some other means rendering its use redundant, then it can be skipped over. Moreover, each component can be utilized individually and without having to re-run previous level components in information flow-down.
- **Generalization and adaptability:** The methodology of the framework is built upon generalized assumptions so that it can also be adapted to problems other than MAST if needed. Therefore, it is adaptable to any multidisciplinary, multi-objective optimization problem that lacks fundamental theoretical and physical models and spans enormous design space.
- **Flexible data input:** User can input qualitative, quantitative and experimental data.
- **Software platform independent:** Each component is independent of any specific software platform. Although, the author uses a specific set of software for implementation of this framework to MAST, other users are free to utilize any other software platform of their choice. The only caveat is that it should be compatible with the type of the framework's input and output data.
- **Traceable, structured, and dynamic:** The information flow-down is traceable and structured. It is also dynamic and information can be update at any point in the process and to any component.

- **Fidelity level:** The fidelity level of the analysis depends on the fidelity of the information available. Therefore, marching forward in time, the fidelity level of the framework improves as more reliable information becomes available.

With the structure and features of the developed framework presented, the following sections will describe in detail the general information flow-down and development of each component along with its methodology.

4.3. Information Flow-down and Component Description

Referring to Figure 15, the specified mission scenario is broken down into operational blocks comprised of required functions obtained largely from the Army tactics manual, which are constituted in the operational architecture [121]. Operational architecture defines the primary activities, sub-activities, and fundamental operational functions to be accomplished by MAST systems. This functional breakdown, along with information on current state-of-the-art within the MAST consortium, is fed into the MAST Interactive Matrix of Alternatives (M-IRMA) [122]. With this information in hand, M-IRMA evaluates the entire design space (> 250 billion possible combinations) [123] and finds the highest performing technologies according to the selected mission functions and subsystem choices. M-IRMA utilizes qualitative and quantitative measures such as Subject Matter Expert (SME) rankings and available physical data to calculate an aggregate score for a single vehicle.

M-IRMA then passes the family of concepts to the Agent-Based Modeling Environment for rapid scenario evaluation at a higher level of detail than the qualitative and quantitative measures used within M-IRMA. This level of analysis includes factors such as swarming effects and emergent behavior. The top performing technologies from the Agent-Based Modeling [124] environment are passed into even more detailed Unified System for Automation and Robot Simulation (USARSim) [125] environment for analysis. At this level, the analysis is three dimensional in nature and each mission scenario can be modeled and simulated from start to finish in great detail. The final output is a family of concepts that performs the mission most effectively out of an initially unwieldy design problem. This family of concepts is analyzed by using the Sizing & Synthesis (S&S) environment, which attempts to take performance characteristics exhibited by the final family of concepts through an iterative process to converge on a physical system with the same capability based on currently existing technology. However, if convergence is not reached, this implies the current state of technology is not sufficient to perform the mission according to the requirements defined. In the subsystems that prevent convergence, a gap in technology exists. Therefore, the quantitative data obtained will result in gap analysis, which answers the following two questions for each mission scenario: What is the state of the art in the pertinent technologies? What level of technology capability is needed to build a MAST system? The quantified gaps dictate new and more realistic requirements for technologies. Identifying and quantifying these gaps, along with re-definition of requirements is the fundamental research goal of this dissertation. Overall, the framework provides a powerful, integrated system of tools for designing, simulating, analyzing, and predicting the behavior of experimental micro autonomous vehicles.

Considering the presented cyber-physical framework, there are five major levels of quantification and analysis that categorizes each of the components.

1. Quantitative Technology Assessment (QTA)
2. Mission level Modeling and Simulation (MLMS)
3. Sizing Relations
4. Experimental Validation
5. Gap Analysis and Re-definitions of Requirements

For the remainder of this chapter, the focus of discussion will be on methodology behind the five major categories listed above and their sub-components.

4.4. Quantitative Technology Assessment (QTA)

Quantitative Technology Assessment (QTA) is a term being used here to describe the evolution of tools and methods to guides the researchers towards necessary level of technology attributes for mission scenarios of interest. The core purpose is to develop relations between desired high-level capabilities of end user and the projected abilities of technologies under development. It consists of developing a traceable process providing top-down and bottom-up path between system level capabilities and fundamental technology level Measures of Performance (MoPs). The process starts with conceptual level sensitivity studies to quantifying effect of key technology measures of performance on system level Measure of Effectiveness (MoEs).

QTA enables determination of robust combinations of technologies that promise high probability of success for a mission scenario under consideration. Quantification of these relationships is essential in answering two critical questions: 1) from Warfighter's perspective, “what can be done?” to enhance the capabilities of small combat units in complex terrain. This fundamental question defines the MoEs for various mission scenarios 2) from technologist perspective:, “how can it be done?” by implementing existing and future technologies based on their MoPs This will enable researchers to quantitatively observe the level and direction of advancement required to meet the MAST system level capabilities and goals for a given mission scenarios. In essence, QTA provides a methodology to form quantified relationships between MoEs and MoPs using the hybrid approach of top-down and bottom-up approaches defined in research plan previously.

In context of this framework, the simultaneous combination of top-down and bottom-up approaches is shown in detail in Figure 16 [24].

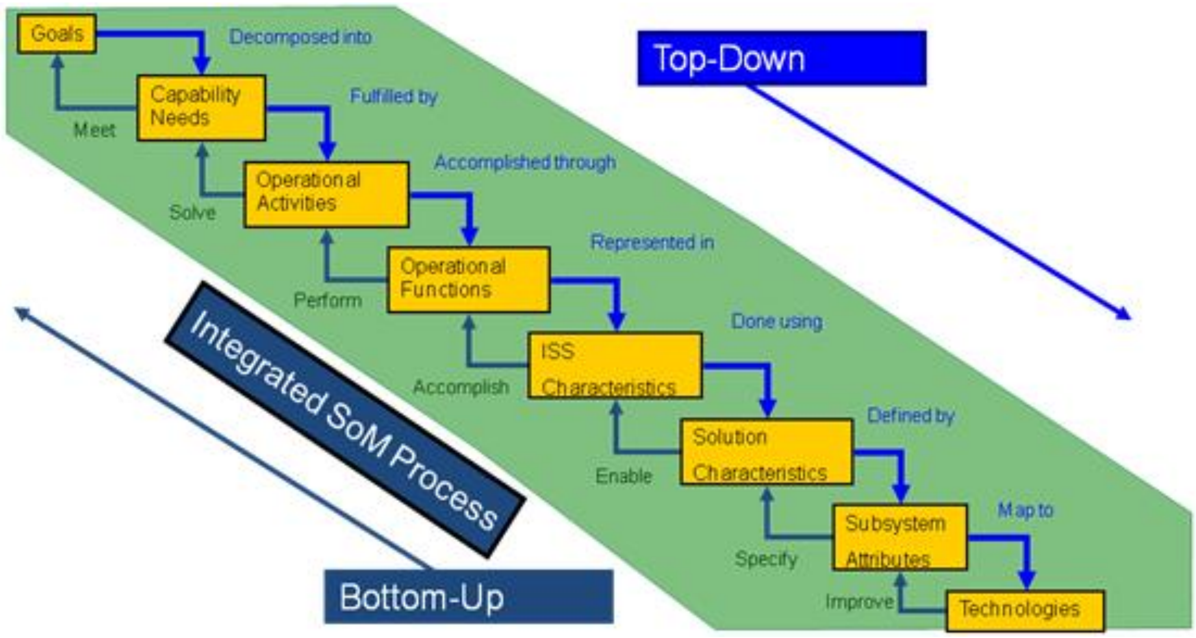


Figure 16: Decomposition and Re-composition [24]

Considering the depicted information flow down above, the terms shown are described as following:

- **Top-down process:** Decomposition of operational capabilities to fundamental technologies
- **Bottom-up process:** Re-composition of fundamental components based on functional categories using MAST technologies to complete integrated system of systems accomplished defined mission scenario.
- **Goals:** Main aims of Warfighter such as surveillance inside a building.
- **Capability Needs:** The required abilities that will enable achievement of desired goal under specified conditions such as determine enemy locations.
- **Operational Activity:** A major level action to be performed for fulfilling a capability need. It depicts operational action and not system functions based on hardware or software. Multiple operational activities enable a capability need.

- **Operational Function:** A lowest level function that needs to be performed to accomplish an operational activity. Multiple functions enable an operational activity.
- **Integrated Solution Set Characteristic (ISS):** A set of characteristics defining a system of systems that undertake operational functions.
- **Solution Characteristics:** A set of attributes that define a single microsystem consisting of different technologies and is a member of system of systems. These attributes consists of operational performance parameters such as precision, etc. and intrinsic parameters such as mass etc.
- **Subsystem Attribute:** A defining characteristic of an individual technology and usually defines a performance parameter such as speed etc.
- **Technologies:** Current and future subsystem technologies under consideration such GPS.

Referring back to Figure 15, QTA forms the backbone of following sections of the defined framework: mission definition, identification of Army goals and capability needs and generation of candidate microsystems. Starting with several designated MAST mission scenarios and army tactics, overall Army goals and capabilities are identified in form of MoEs. Operational architecture for MAST showing operational activities and function is then developed to quantitatively relate them to mission scenarios. These all are then related to MoPs of MAST technologies currently available and under development through layers of traceable and quantifiable parameter mappings. Analyzing these mappings in a structured manner enables generation of candidate microsystems for each mission scenario from a defined concept space. The output of this major level of analysis is set of homogeneous microsystems consisting of MAST technologies that are quantitatively shown to be desirable candidates for mission scenario under consideration and warrants further analysis.

The following subsections will describe each step and tool developed and implemented under QTA in detail.

4.4.1. Missions, Tactic, Requirements and Definitions

The major inputs in the defined framework are mission scenario definitions and tactics and requirements for utilization of MAST SoMs by army squads. These two inputs are of different types and therefore need to be incorporated into the framework in a structured and traceable manner. Considering that MAST SoMs will need to conform to Amy tactics already defined for soldiers in order to be beneficial, a standardized process for defining missions scenarios in terms of current army tactics is put forth. The mission scenarios are quantified through decomposition in terms of capability needs defined by Warfighter as overall army goals and required tasks, to achieve those capabilities, using the 'Army Universal Task List' [126]. The process is depicted in Figure 17. As shown, the major MAST capability needs such as "provide autonomous zone, area, and route reconnaissance" are broken down, using the universal army task list, into specific tasks such as "conduct surveillance". These tasks are then used to decompose each and every mission scenario, such as interior reconnaissance, that is either of interest of representative of a board range of possible mission scenarios to be undertaken by MAST systems. The decomposition of these mission scenarios are in terms of operational activities and functions as defined above.

The driving capability needs, operational activities and operational functions are defined as part of an operational architecture defining MAST. The details are given in subsequent sections and for now, it will be assumed that these terms are already defined well for decomposing mission scenarios. The major tactics laid out by Army Universal Task List are first defined for each mission scenario and then are quantified by further breaking them down into specific tasks that current and future state of the art MAST systems will be required to accomplish. Moreover, these tasks may also serve as definitions for tactics to be used in developing autonomous navigation logic and algorithms by researchers. By gaining better understanding of what lower level tasks accomplishment will be required by MAST systems, a more refined and realistic set of requirements and goals can be laid out for researcher to aim for in order for the MAST systems to be practical in real world mission scenarios.

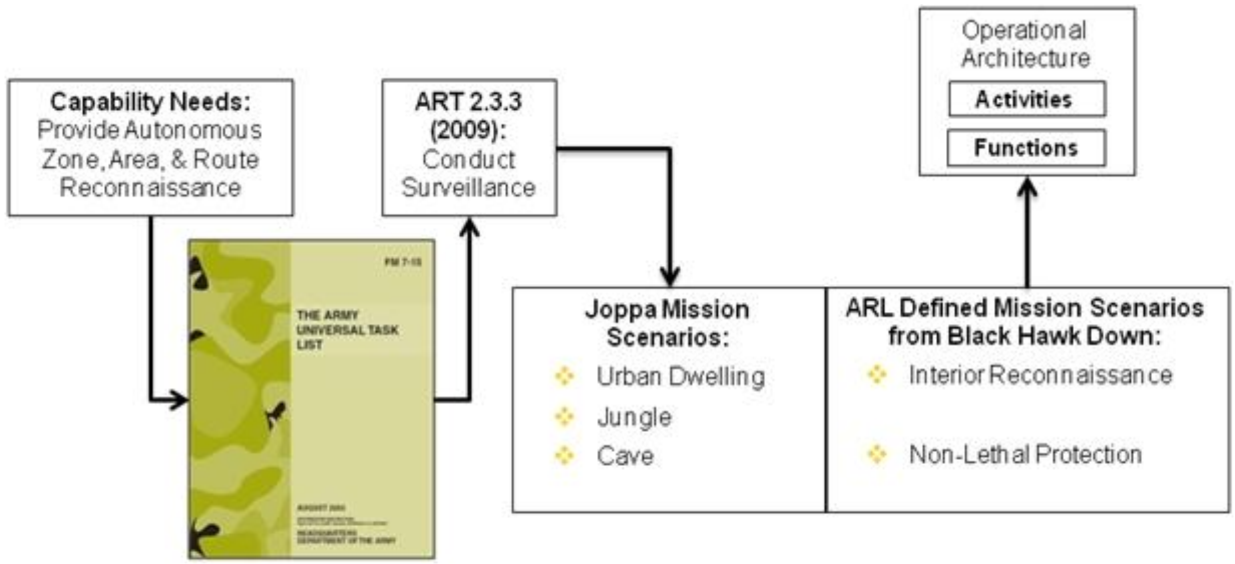


Figure 17: Mission Definition

The next section describes quantification of some specific mission scenarios and tactics associated with each.

4.4.1.1.Mission Scenarios and Tactics Quantification

The quantification, assessment, simulation and optimization of MAST integrated systems are dependent on the selected mission scenario. As previously explained, the solutions are generated, assessed and optimize based on the major inputs in the beginning for this framework, which are definition of a selected mission and tactics associate with it. Each mission scenario is expected to lead to a different solution set of integrated system of systems. The various mission scenarios and tactics are input into the framework by defining them in terms of operational functions and mission MoEs, which forms the core set of metrics for evaluating mission success.

The first step is to define several types of mission scenarios are representative of the ones of interest to MAST researchers and Warfighter. There are two primary sources of these mission scenarios: 1) MAST experimentation facility in Joppa, MD [26], and 2) Vehicle Technology Directorate of Army Research Laboratory [127]. The primary difference between the mission scenarios purposed by these two sources is whether the environment is benign (i.e. no enemies) or hostile. These environments can also be considered as idealized cases of MAST systems having complete stealth capability and thus rendering presence of hostiles irrelevant to mission success. The Joppa mission scenarios are based on physical experimental platforms that have been built to conduct MAST technologies experiments while ARL mission scenarios are based on the movie Black Hawk Down [27]. All of these missions are referenced to specific high level army tasks to define their scope. For the remainder of this thesis, these mission scenarios will be referred to as Joppa missions and Black Hawk Down missions respectively. There are a total of five mission scenarios, three from Joppa and two from ARL, to be considered and are described in detail below. Not all of these mission scenarios will be implemented for every step in this framework as part of this thesis. Some of these will be chosen to demonstrate major capabilities and show proof of concept. The five mission scenarios are:

- Joppa Missions:
  - Urban Dwelling
  - Jungle
  - Cave
- Black Hawk Down Missions:
  - Interior building reconnaissance
  - Non-lethal area protection.

Each mission scenario is described in detail below that include mission details, associated tactics, which drives operational functions (further discussed in sections related to system architect), and defining MoEs.

Joppa: Urban Dwelling (JU)

This Joppa based mission scenario is designed to simulate small squads infiltrating a building located in an urban environment. MAST microsystems are expected to enter the building by locating doors and windows and map it as extensively as possible. It may involve delivering sensory payload that will transmit audio and visual data throughout the building. Soldiers will use the data to plan their infiltration by knowing exactly where everything is located. The actual physical platform is shown in Figure 18.

Figure 18: Urban Dwelling Platform

Joppa: Jungle

The Joppa jungle platform is built as a MAST mission scenario to test the capabilities of microsystems to disperse and navigate into different paths without colliding with trees randomly located in the area. The data of audio and visual nature transmitted during navigation should map the area extensively to provide real time coverage to army units. Microsystems are expected to return to based once mapping is complete without crashing into obstacles. The jungle physical platform is shown in Figure 19.

Figure 19: Jungle Platform

Joppa: Cave

The cave platform at Joppa is designed to simulate reconnaissance and surveillance of an environment that consists of multiple caves. Army units need up to date and/or real time information regarding the layout and occupants of caves in hostile territory. The primary feature of cave environment is irregular interior layouts and hard to find entrances. MAST microsystems are expected to enter different caves without crashing and create a map of interior layout that includes obstacles and occupants. Multiple caves present in a given area must be explored by microsystems before returning to base. The cave physical platform is shown in Figure 20.

Figure 20: Cave Platform

Black Hawk Down: Interior Building Reconnaissance (ARL IBR)

The IBR mission scenario is defined by universal Army task, specifically ART 2.3.3.2 (2009) Interior Reconnaissance. The major goal of this mission scenario is for microsystems to explore and map an interior of a building while avoiding detection. It is quite similar to Joppa: an urban dwelling but includes the presence of hostiles and thus is categorized as a hostile mission. MAST systems are required to stealthily enter a building and provide soldiers with real information on obstacles and enemies present. Soldiers should be able to initiate microsystems to begin mission. A secondary capability to explore for microsystems would be to provide soldier with cover during extraction. IBR mission scenario is depicted in Figure 21 [128].

Figure 21: Black Hawk Down: Interior Building Reconnaissance [128]

Black Hawk Down: Non-Lethal Protection (NLP)

The NLP mission scenario is defined by universal army task, specifically ART 2.3.3.3 (2009) Non-Lethal Protection. This last mission scenario to be considered is a very specialized case in which few soldiers are stranded in middle of enemy territory without reasonable cover. Moreover, the enemy is expected to be aware of the stranded soldier is and en route to lethally engage them. MAST systems are required to set up perimeter defense in about fifteen minutes and oversee approaching enemies from multiple directions. The defense of soldiers from enemy by microsystems should be of non-lethal nature. NLP mission scenario is depicted in Figure 22 [129].

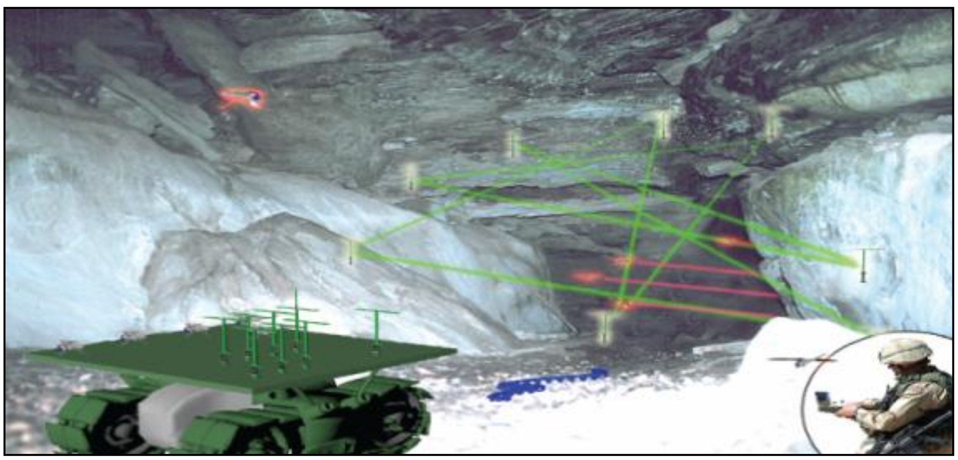


Figure 22: Black Hawk Down: Non-Lethal Protection [129]

With all of the mission scenarios defined, tactics laid-out, and other details presented, the next step is to define relevant MoEs and quantify the values for mission. These are presented in the following Tables 10 and 11. The MoEs are quantified based on requirements set forth for similar tasks in the Army Universal Task List and on engineering judgment of the author. The values presented are expected to be updated over the years as newer information becomes available.

Table 10: MoEs - Joppa Missions

MAST Measures of Effectiveness	Urban	Cave	Jungle
Entry Points Identified	> 80%	> 80%	N/A
Routes through Building	>1	N/A	N/A
Routes through City	N/A	N/A	N/A
Enemies Identified	> 95%	> 95%	> 95%
Enemies Analyzed	> 25%	> 25%	> 25%
Enemies Immobilized	N/A	N/A	N/A
Interior Coverage	> 90%	> 90%	N/A
Weapons Identified	> 80%	> 80%	> 80%
Hazards Identified	> 80%	> 80%	N/A
Counter-Surveillance Identified	> 50%	> 50%	> 60%
Data Transmitted to Soldier	> 95%	> 50%	> 50%
Data Transmitted to Base	> 70%	>50%	> 50%
False Negatives	< 10%	< 5%	< 5%
False Positives	< 10%	< 10%	< 10%
Total Area Coverage	> 90%	> 90%	> 90%

Table 11: MoEs - Black Hawk Down Missions

MAST Measures of Effectiveness	Interior Building Reconnaissance	Non-Lethal Protection
Entry Points Identified	> 80%	N/A
Routes through Building	> 1	N/A
Routes through City	N/A	N/A
Enemies Identified	> 95%	> 95%
Enemies Analyzed	> 25%	N/A
Enemies Immobilized	N/A	> 95%
Interior Coverage	> 90%	N/A
Weapons Identified	> 80%	> 80%
Hazards Identified	> 80%	N/A
Counter-Surveillance Identified	> 50%	N/A
Data Transmitted to Soldier	> 95%	> 10%
Data Transmitted to Base	> 70%	> 95%
False Negatives	< 10%	< 5%
False Positives	< 10%	< 5%
Total Area Coverage	> 90%	> 90%

The final step in defining mission scenarios and tactics is to decompose them into operational functions that must be carried out by MAST SoMs to accomplish a mission. Therefore, it is now time to discuss and present the development of MAST operational architecture that leads to definition of critical overall operational functions for MAST systems. Once a framework for operational architecture is developed, it will be possible to decompose any given mission scenario in terms of operational functions to generate candidate microsystems, as will be presented in subsequent sections.

4.4.2. Operational Architecture

Operational Architecture of a system or system of systems is essential in determining relationships components and enable mapping of capability needs to operational functions. As defined for the Army, "Operational Architecture or OA is a description of the tasks and activities, operational elements (such as commanders, staff, and frontline soldiers), and the quantity and quality of information flows required to support an operation. In other words, it describes who talks to whom and what they talk about." [130]. Similarly applicable to MAST, operational architecture will enable decomposition of this complex system of systems in a set of operational views. These views will serve as a starting point for Warfighter's requirements definitions and allow traceability between the operational architecture and the MAST technologies. Moreover, it also defines roles for individual systems. One important benefit of analyzing operational functions of a system is that it reveals interrelationships and understandings that would otherwise be missed.

There are several well establish methods in literature for designing operational architecture of a system of systems. For the purpose of this research, those methods are applicable and will suffice for achieving the goal relation operational functions with capability needs. The issue at this point is to make an inform decision and select a method that offers most benefits in context of this framework. The foundations for definition of selection criteria to evaluate the available architecting frameworks are determined to be the following:

- Level of traceability of information flow
- Flexibility and capability to easily update the architecture as new information becomes available
- Dynamics of relationships generated between components of the architecture.

The architecting frameworks selected from literature search for further evaluation before implementation are: Zachman Framework for Enterprise Architecture (ZF) [131], 4+1 View Model of Architecture [132], Federal Enterprise Architecture Framework (FEAF) [133], The Open Group Architecture Framework (TOGAF) [134] and Department of Defense Architecture Framework (DoDAF) [135]. These architecting frameworks are evaluated using Pugh selection method [136] and the results are summarized in Table 12 [137]. The '+' symbol signifies reasonable fulfillment, '-' symbol signifies partial fulfillment and '0' points to lack of fulfillment of the criterion.

Table 12: Architecting Frameworks Comparison [137]

Selection Criteria	DoDAF	TOGAF	ZF	4+1	FEAF
Architecture Definition	+	+	0	0	+
Architecture Process	+	+	-	-	+
Architecture Models	+	+	+	+	+
Standardization	+	+	-	-	0

Considering the results presented in Table 12, it is apparent that both TOGAF and DoDAF are appropriate for context of the framework developed in this thesis. However, considering DoDAF's established use for Department of Defense's war-fighting operations and processes [135], capability to establish explicit relations between operational activities and functions and author's familiarity with it, DoDAF was selected as the architecting framework for the purpose of the research presented in this thesis.

DoDAF serves as a standard for the specification of different architecture views of an integrated system of systems or even individual systems. The process of “architecting” means that relationships between system elements are formulated such that overall capabilities for accomplish missions are achieved. Not only general structure of these elements and their relationships are defined but also their behavior over time is described, if applicable. For this framework, high level behavior of MAST system of systems through operational activities and operational functions of individual systems needs to be defined. Therefore, the relevant views developed with DoDAF architecture are Operation View - 5 (OV-5) and Systems View - 4a (SV-4a) [135] . The process for developing OV-5 and SV-4a views primarily involved thorough design understanding of MAST systems-of-systems in context of it operational requirements [138] [139]. It requires analysis and answering of considerations that include following: Independence of systems versus their interdependence, available resources within the systems of systems, and roles that each system is required to fulfill.

In order to explain the development of the proposed operational architecture, several important levels of components previously defined will be re-iterated here:

- Operational Activity: A major level action to be performed for fulfilling a capability need. It depicts operational action and not system functions based on hardware or software. Multiple operational activities enable a capability need.
- Operational Function: The lowest level function that needs to be performed to accomplish an operational activity. This level cannot be further broken down into more activities or functions. Multiple functions enable an operational activity.

The first step in developing operational architecture was to outline the major activities to be performed by MAST SoMs. The defining analogy utilized in this context was that MAST SoMs are to an enclosed space to be explored just as army small units are to a designed area, such as an urban terrain. Therefore, the operational activities (first two levels) in OV-5 view were primarily defined using US Army Field Manuals/Army Universal Task List 126. In this manner a hierarchy of activities was developed comprising of progressively lower-level actions to be performed by MAST systems. The next step was to define the lower level functions and it was based on two sources of information: 1). Background and literature search on MAST technologies currently available and under development. The functions and roles of individual systems were defined by considering stated or expected profiles for deployment of these technologies by researchers. The results of literature review were extensively documented in Chapter 2 of this thesis. 2). Engineering judgment (of several ASDL MAST researchers[1]) and context of operations.

Once all components of the architecture were defined, SQL as database a commercial off shelf software for frontend, IBM's Telelogic System Architect [140], was used to implement the views for practicality and convenient access and viewing. The graphical frontend provided by System Architect also enables automated queries to the backend SQL database. The complete list of architectural activities is available in Appendix A, along with definition of all the terms used. A sample view of the top most level of OV-5 view is shown in Figure 23.

Considering the top level operational view shown in the Figure 23, it can be observed that the top-level tasks of MAST SoMs are to perform activities that will enable capability needs for achieving MAST goals of intelligence, reconnaissance, and surveillance for small army units in complex terrain. The data gathered and generated are analogous to activities performed by manned intelligence teams and analyzed by tactical officers. A set of operational activities represent top level capabilities such as the ability to 'perform reconnaissance of a zone'. As stated previously, these sets of operational

[1] ASDL MAST Research Team 2008 - 2009; ASDL MAST Grand Challenge Team 2008 - 2009

activities are recursively broken down to the lowest level possible, which is represented by operational functions. An example of operational functions is shown in Figure 24.

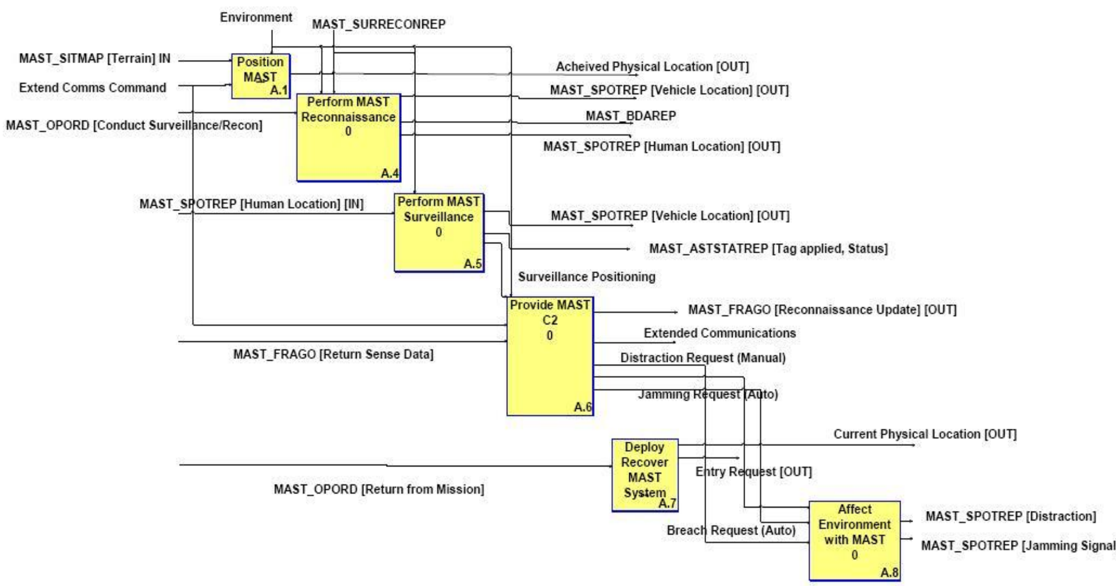


Figure 23: OV-5 Top Level View

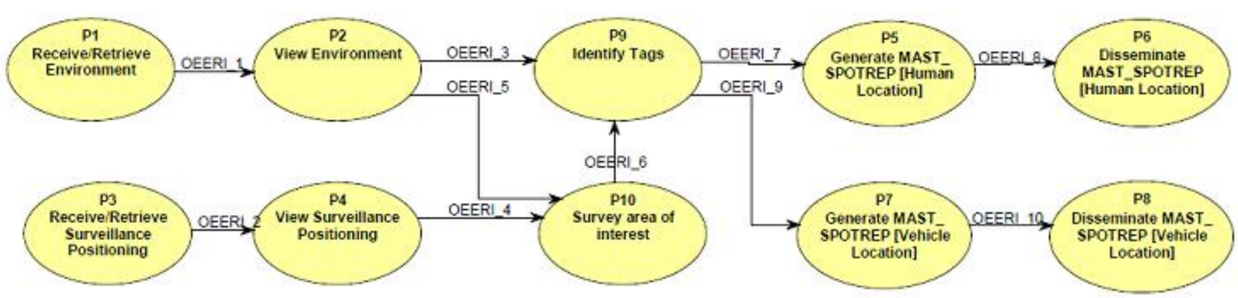


Figure 24: OV- 5 Operational Functions View

These are the operational functions that each mission scenario and associated tactics are decomposed into. Moreover, these operational functions also serve as a mapping level individual MAST technologies and will explained later. Referring to the presented framework in Figure 15, the next step is to consolidate the information and results obtained until now into an interactive platform that will enable concept space exploration and generation of candidate microsystems for each mission scenario. The next section described the methodology and development of the aforementioned interactive platform.

4.4.3. M-IRMA: Concept Space Exploration and Generation of Candidate Microsystems

This section discusses the construction of a specialized tool designed to practically analyze the enormous concept space for MAST specific missions, consolidation of information and results obtained through mission scenario and tactic quantification and analysis of operational architecture. The eventual output of this tool is generation of candidate microsystems for specified mission scenario(s).

4.4.3.1. Overview

The basic foundations of proposed tool are based on a generic decision making framework developed at Aerospace Systems Design Laboratory (ASDL) known as an Interactive Reconfigurable Matrix of Alternatives (IRMA) [141]. It provides a structured methodology based on morphological analysis [142] for integrating objective and implicit information into the concept selection process. IRMA enables functional decomposition of the problem to allow exploration and traceable reduction of the design space from an astronomical number of combinations to a manageable quantity. This generic framework was utilized to develop specialized decision making architectures for application to MAST mission scenarios. This new MAST specialized decision making tool will be denoted as M-IRMA from here onwards to prevent ambiguity from the original tool.

The major developments include multi-layer mappings that enable determination and creation of relationships among technologies, technology attributes and operational functions. With this level of complexity, the use of tools such as Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [143] to compare a limited number of alternatives is no longer necessary. Instead, a scoring scheme based on multi-layer mappings is used for numerically scoring each possible alternative concept. Additionally, technology models qualitative in nature and of very low TRL can be included and evaluated using Multi-Attribute Decision Making (MADM) Criteria [136], which is defined by aforementioned mappings. Finally, the capability to sweep concept space in an automated manner has been achieved through coded MATLAB scripts, also defined as M-IRMA analysis and automation tools.

In order to improve systems engineering processes for MAST researchers, a database-driven web-based implementation of M-IRMA was developed to aid online problem definition and solution conceptualization. WM-IRMA (Web-based MAST Interactive Reconfigurable Matrix of Alternatives) will provide a dynamic online platform for all researchers in MAST consortium to access, view, modify, and evaluate alternatives from any geographic location at any time. It not only greatly improves convenience for researchers, but also provides real time database update capability, thereby allowing researchers to instantly update technology attributes and enable other members to access the updated data immediately. The development and implement of WM-IRMA is neither in the scope of this thesis and nor individual work of the author. It is merely mentioned to demonstrate expansion capabilities of M-IRMA. More information can be found in reference [144] .

4.4.3.2.Motivation and Current Methods

Before going into details of development of M-IRMA, it is essential to explore the motivation behind it and why implementation of current methods wouldn't suffice for this research. A central problem of systems engineering is evaluating alternative based on based on a set of qualitative or quantitative effectiveness measures. Over the years, many methods have been developed to address the problem of decision-making and each comes with set of strengths and weaknesses depending on application context.

The first method to be considered is a Tree Diagram [136]. It is a pictorial network diagram of all the possible outcomes of every possible decision. Even though it is useful for enumerating every possible alternative, the decision branches are usually created under the assumption of mutual exclusivity. It implies that only a set of specific series of decisions will result in a specific alternative reached.

Another useful method to be considered was developed by Thomas L. Saaty in the 1970's known as the Analytical Hierarchy Process (AHP) [145]. In this method, the decision under consideration is broken down into sub-decisions representing necessary criteria of a decision alternative. They are then analyzed independently and assigned numerical weights or priority in form of a hierarchy based on decision attributes. Reaching a decision using AHP method requires comparison of all possible decision alternatives against the criteria defined by each sub-decision. AHP has been demonstrated to be suited well for helping a group come to a collective decision, as the weights assigned to each sub-decision can be the combination of opinions of the participants. The drawback of this method is assumption that the salient characteristics which defines any possible decision alternative desirable are to be known beforehand, which is not the case for MAST.

The last decision making method to be considered is the Pugh Selection Process (PSP) [146], which was earlier implemented in this research to select a suitable architecting framework. PSP decision making method is similar to AHP as a decision to be made is broken down into criteria that is scored and summed. The difference is that PSP does not attach weights to the criteria. The benefit is that the process is much quicker but at the cost of assuming that each criterion is equally important.

Based on the discussion of current method described above, there are few major disadvantages common to each. First, all of these methods are static meaning that addition of a new possible alternative or criteria necessitates that the entire process be repeated. Second, these decision making techniques are severely limited by the number of alternatives that can be accommodated, as their complexity rises quickly and efficiency decreases with increasing number of criteria and possible alternatives. Lastly, these techniques are not capable of creating any sort of mapping between system components due to the limitation of their architecture. Therefore, it is necessary to develop a customized decision making and concept space exploration platform for this research.

4.4.3.3.Functional Decomposition Vs Physical Decomposition

In order to address complicated problems, it is important to decompose them into smaller and ideally, non-interacting components. The two widely used methods are functional and physical decomposition. In functional decomposition, a system is resolved into its constituent parts based on functional relationship between components that can be reconstituted by composition of its functional parts. On the other hand, physical decomposition results in division of a system into it smaller physical parts [147].

For a problem such as MAST where mission level performance is emphasized, it is more useful to decompose the systems functionally rather than physically. Functional decomposition avoids the pitfall of defining alternatives for each component based on physical similarity to the whole system. An example can be put forth by considering a baseline design of a tiger. Its physical decomposition would consist of the following: eyes, nose, fur, claws, legs, and so on. Such decomposition will result in alternatives that will be physically similar to a tiger such as lion, bear, or wolf. However, if a tiger is functional decomposed, then the components would as following:

- Sensing- eyes, ears, nose
- Mobility- legs
- Protection- fur
- Hunting mechanism- claws, teeth

This decomposition will result in alternatives capable of achieving those functions such as hawk, shark, hornet, along with the physically similar ones previously mentioned. Considering this simple example, it is evident that functional decomposition of possible alternatives to accomplish given MAST mission scenario is necessary to avoid unintentional limitation of design space and solutions. Therefore, the basis of decomposition in M-IRMA is functional.

4.4.3.4.Defining Characteristics of M-IRMA

There are a number of unique characteristics of M-IRMA that define its role as a major decision making tool in context of complex combinatorial problems such as presented by MAST. They enable M-IRMA to be a dynamic platform capable of analyzing quantitative and qualitative data for vast number of alternatives. These characteristics are summarized below [122]:

- **Bottom-up approach:** A problem is addressed starting with individual technologies at functional levels and building up to a complete solution.
- **Flexible and reconfigurable:** The interface is dynamic and formatted to be easily updatable and adaptable to new problems of any category.
- **Multi-level mappings:** There are multiple levels of mappings between technology alternatives and mission scenarios.
- **Evaluation in context of mission scenarios:** A specific mission scenario is a qualitative or quantitative input to evaluation of alternatives.
- **Compatibility relations:** Interdependencies of alternatives are defined using symmetric matrix to filter out incompatible solutions.
- **Calculation of number of alternatives:** Total number of possible solution families is automatically calculated.
- **MADM:** Each family of concept as an alternative is evaluated using mappings in terms of multi-attribute decision making.
- **Scoring and ranking of Alternatives:** Each possible solution family can be numerically scored and ranked both manually or automatically.
- **Filters:** Number of combinations can be reduced by employing filters such as desired TRL.

- **Collaborative:** Real time calculations enable collaborative design and trade studies to be performed with subject matter experts.
- **Possible web-based complementary interface:** An online interface that allows all members of MAST consortium to access M-IRMA remotely (not part of this thesis).
- **M-IRMA analysis and automation tools:** Allows for automated analysis of design space.

4.4.3.5.Methodology and Tool Architecture

M-IRMA's architecture is based on Fritz Zwicky's Morphological Analysis Method [148] and the process of generating a matrix of alternatives. Each component of functional decomposition is listed in a vertical column, divided in basic categories, with a matrix of alternatives for each component next to it. The matrix contains alternatives in form of solutions, subsystems, or methods in each horizontal row corresponding to a specific functional component. Selecting a single alternative in each row will constitute a single family of concepts capable (considering compatibilities and feasibility) of functionally accomplishing the tasks required by the solution.

Building on this architecture, M-IRMA incorporates definition of mission scenario (through input of qualitative or quantitative data for operational functions), technology attributes, and subsystem technologies to develop a multi-layer mapping that allows the designer to visually evaluate alternatives in terms of multiple attributes that make traceable decisions. As an alternative in each row is selected, incompatible choices are automatically eliminated and multi-level mappings based on multiple attributes in the background update a numerical score of the defined solution. This allows a designer to numerically compare different combination of technologies. Definitions of mission scenario, mappings and scoring methodologies are explained in subsequent sections.

4.4.3.6.Information Flow-down

In order to explain the multi-level mappings in M-IRMA, it is important to understand how information flows between its components and how it is utilized in making design decisions. As M-IRMA is a bottom-up approach, the information input starts at lowest level, namely subsystem technologies. Each technology subsystem is first defined based on functional decomposition of MAST systems as described above. For instance, a locomotion functional category can contain flapping wing. These technologies are mapped to a number of technology attributes such as power, mass, speed, etc. These technology attributes are mapped to operational functions such as detecting openings or generating paths. Operational functions are the lowest levels of functions that must be performed for a given mission. In essence, any mission scenario can be broken down to low level functions and then numerically defined. The technologies and attributes are defined through surveys and literature search which have been extensively documented in Chapter 2 of this thesis.

Each functional component of the system is related to a pool of alternatives through the mappings. For example, locomotion sources may include flapping wings, rotors, wheels, etc. These alternatives are further broken down into detailed options such as active shaping wings, folding wings, and so on under flapping wings. And each option in the lowest branch has either a qualitative or quantitative score in terms of technology attributed, which is used for its evaluation. Figure 25 illustrates mappings of alternatives and their sub-alternatives for each functional component to technology attributes.

The formulation of each level of mapping is explained in next subsection. The mapping can be quantitative (e.g. certain grams for mass) or qualitative (i.e. on a defined scale) in nature. Quantitative mappings will be based on a certain model depending on the level of fidelity required and available. Qualitative mappings are based on engineering judgment and experience of subject matter experts and usually defined in collaborative workshop sessions. Therefore, the fidelity of M-IRMA is dependent on the underlying models used in the background. The information obtained through these models flows through each mapping level all way to interface level to provide a decision making platform for designers. As newer information becomes available, the underlying models are dynamically updated and the fidelity of M-IRMA is improved. This makes the tool a dynamic platform that becomes more accurate over time.

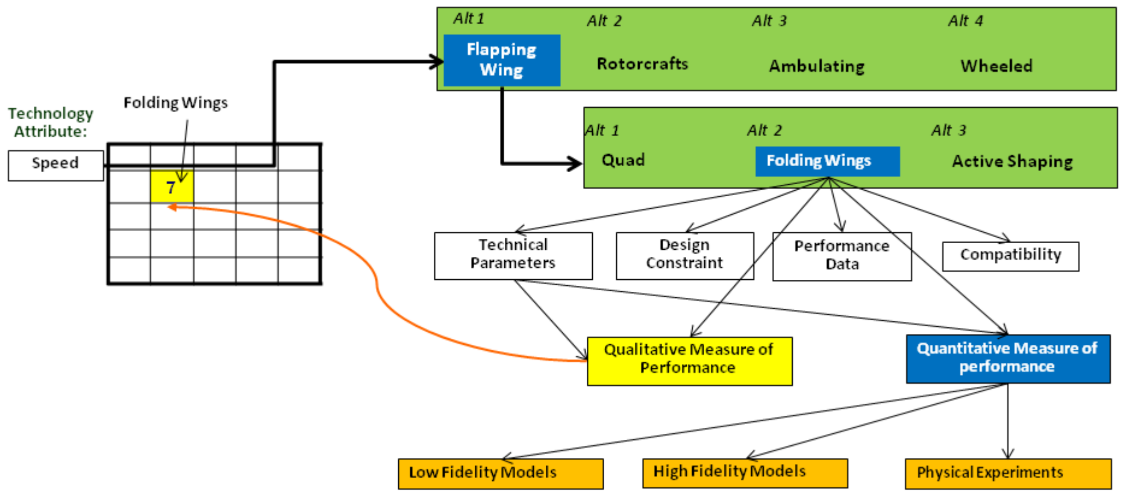


Figure 25: M-IRMA Information flow-down

4.4.3.7. Basic Components and Mappings

M-IRMA is a suite of several components and scripts that form the user interface, underlying models, mappings and automation and analysis tools. The primary programs used for development are MS Excel and MATLAB. Each of the components, mappings and scoring formulation are explained below:

- **M-IRMA dashboard:** Graphical User Interface (GUI) for selection of technologies and concepts.
- **First level of mapping - T vs. TA:** The first level of mapping is between each subsystem technologies (T) and technology attributes (TA). It is a quantitative/qualitative numerical score of each technology relative to every technology attribute. For instance, active shaping wing vs. mass. Currently, the mappings are qualitative and based on a relative scale of 1 to 10, with 1 being

lowest and 10 highest quantitatively. Table 13 illustrates this level of mapping. The values are based on workshop conducted with subject matter experts, literature and engineering judgment.

Table 13: Subsystem Technologies vs. Technology Attributes Mapping

Subsystem Technologies	Mass	Power Required	Speed
Active shaping wing	6	5	6
Quad-rotor	8	7	8

- **Mission scenario definition:** In order to evaluate alternatives with respect to a given mission scenario, it needs to be broken to down to lowest level operational functions that needs to achieved in order to accomplish the mission. These operational functions are an input into M-IRMA and weighted for importance. The weighting is based on a normalized scale of 1 to 10. The number of times each functions needs to be executed or invoked it enumerated and then normalized over 10. This value is then keyed into M-IRMA. Table 14 shows sample operational function and weightings:

Table 14: Technology Attributes vs. Operational Functions Mapping

Operational Functions	Weighting
Generate planned path	7
Perform system warm-up/check	1

- **Second level of mapping - TA vs. F:** The second level of mapping is between technology attributes (TA) and each operational function (F). It is a qualitative interrelationship numerical score of each technology relative to weight operational function. For instance generate current physical location vs. power required. The qualitative scale utilized for mappings at this level is as following:

    - -5: Strong Negative

- -3: Negative
- 0: Neutral
- 3: Positive
- 5: Strong Positive

The values are based mission specifications, literature and engineering judgment. Table 15 shows this level of mapping.

Table 15: Mission Scenario Definition

Operational Functions	Mass	Power Required	Speed
Generate planned path	-3	-3	3
Perform system warm-up/check	0	-3	0

- **Alternative Scoring:** With all required information added to M-IRMA, a score for each technology alternative is calculated based on the mappings between technology and technology attributes and between functions and technology attributes. Since mapping is qualitative, higher score means better alternative. Equation 1 defines the calculations:

Equation 1: M-IRMA Scoring

Alternative Score = ΣScoretech. Vs. ScoreTA + FWeight * (ScoreTA vs. ScoreF * Scoretech. Vs. ScoreTA)

Figure 26 a schematic of M-IRMA components, mappings and scoring. The analysis and automation scripts are explained in next subsection.

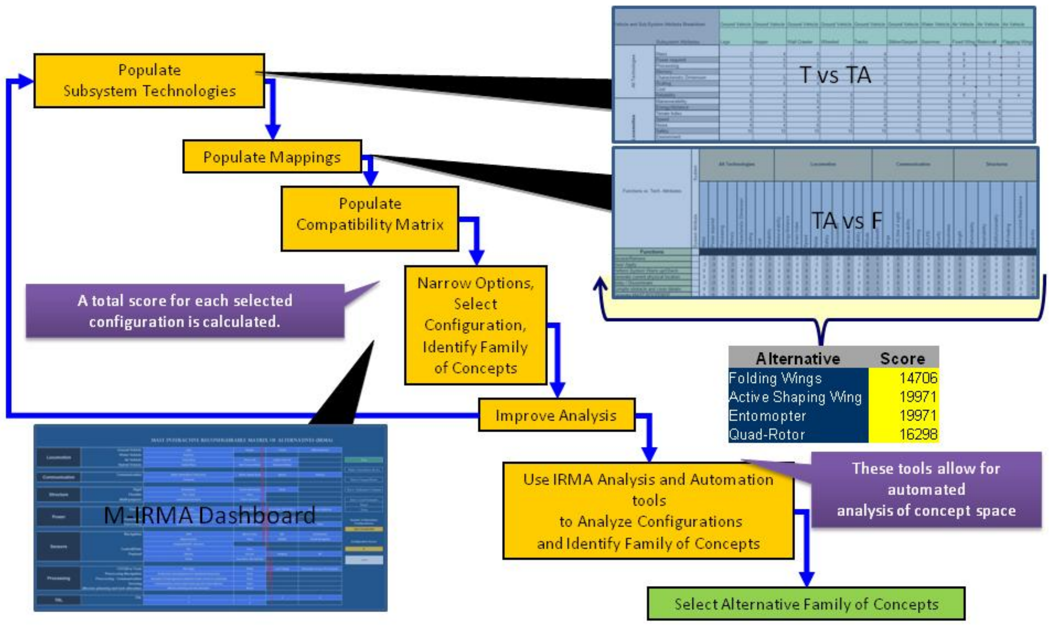


Figure 26: Concept selection process using M-IRMA

4.4.3.8.M-IRMA Analysis and Automation Scripts

A major challenge in implementing M-IRMA for concept selection is that even with all the mappings completed, it is quite difficult to actually analyze every possible combination and compare one to another manually. It is simply not practical to manually undertake such a task involving billions of possible alternatives. In order to overcome this challenge, a set of analysis codes were written using MATLAB software package to develop an automation tool. It generates and compiles all possible combination of alternatives within the defined concept space that have no compatibility issues. Once generated, each alternative combination is scored and ranked. The mathematics behind the tools is based on the fact that each incompatibility shrinks the concept space. In the 3D concept space, one incompatibility eliminates a line of alternatives, while in 4D concept space a plane would be eliminated. Similarly, if the concept space is 5D, a volume would be eliminated, and so on [149]. This mathematical concept is leveraged in the tool by generating two matrices in binary form, one consisting of compatibility matrix of the alternatives and the other contains the available alternatives. The multiplication of the two will then filter out invalid or incompatible solutions. Repeating this process for every possible combination will generate all possible compatible combination of alternatives. The next step is to compute the score of each combination of alternatives which enables the ranking of each one relative to another. These two steps are implemented using the automation tool and are dynamically linked to M-IRMA. Therefore, any changes in M-IRMA will be reflected in the analysis when the tools are executed. Moreover, the two steps can be executed independently; hence, any change in data related to only one of the steps will not warrant execution of the other step.

The qualitative mappings between subsystem choices and mission activities, outlined previously, are applied to each compatible alternative using the combined compatibility matrix and matrix of alternatives. This results in a score which is a ranking of potential mission effectiveness that can be compared to other possible alternatives. However, even after elimination of all incompatible combinations there is still a very large concept space to analyze. Therefore progressive down-selection technique is employed to determine top performers. This technique can be summarized as following: The user indicates the number of top performers to consider. Based on it, the script analyzes and adds possible alternatives to an array until the desired number is reached. Then, a second array is created which similarly adds alternatives up to the desired number. Using these two arrays, the alternatives are combined and ranked according to their scores. Based on the rankings, the original array is then cut down to the desired number by filling it with top performers thus creating an array of best alternatives found until now. The second array is emptied out and this marks end of a single loop. The script repeats in this fashion by filling up a temporary array with newly analyzed alternatives, attaching it to the array containing the current best alternatives, ranking them based on their scores, and then eliminating the alternatives that rank below the number initially set by the user. This continues until every possible alternative has been evaluated or until the user terminates the process.

At the end of the process, the set of best performing alternatives are read into an Excel table from the designated array. Then, an alternative by alternative analysis calculates the number of times each candidate subsystem technology appeared as a top performer. This enables the most effective subsystem choices to be quantitatively shown as a percentage of the top performing entries and thus forming set of suitable candidates for given mission.

4.4.4. Summary

The output from this step is the consolidation of results in form of generation of candidate microsystems for mission scenarios of interest. This also sums up the process of QTA in context of this framework. At this point, the major systems of systems level considerations have been analyzed, mission and tactics have been quantified, operational architecture developed, astronomically large concept space has been explored and several possible solutions have been selected for defined missions.

However, it is important to understand that the results consist of homogenous systems while swarm behavior and resulting synergy and emergent behavior were not taken into consideration. The next step in the proposed framework is to model, simulate, and optimize the generated microsystems at system of microsystems level for given mission scenarios. The following section describes the methodology and development of this next major level of MAST quantification framework.

4.5. Mission Level Modeling and Simulation (MLMS)

Following the road map laid out in the beginning of this chapter, the next major level of MAST Quantification to be discussed is Mission Level Modeling and Simulation (MLMS). As previously presented, the primary objective of QTA was to explore concept space and generate homogeneous candidate microsystems for specified missions based on Warfighter capability needs and operational considerations of MAST, that maximize mission probability of success. It was accomplished through construction of MAST's operational architecture, definition of missions and tactics in terms of MoEs and operational functions, and a systematic concept space sweep to rank alternatives based on scoring of their technology attributes to operational function. With candidate microsystems generated using alternatives down-selected from an astronomically high number to a reasonable order of magnitude, it is now necessary to further analyze these alternatives to quantify their effect on mission probability of success when being operated in a heterogeneous ensemble along with considerations of resulting emergent behavior impact. The quantification involves determining relations of technology attributes on operational functions of the mission in context of SoMs. This is the primary objective of MLMS level presented in MAST quantification framework.

4.5.1. Motivation and Characteristics

The need for MLMS arises from two primary issues that not accounted for in QTA level analysis: 1) emergent and swarm behaviors of SoMs, and 2) SoMs consisting of heterogeneous solutions. This necessitates the need for more in-depth evaluation to quantify mission effectiveness of heterogeneous SoMs. Several options are available to accomplish quantification of the aforementioned issues and are listed in the Table 16, along with their pros and cons.

Table 16: Evaluation Options for Heterogeneous SoMs.

Options	Pros	Cons
Historical Data	Time efficient, reliable	Non-existent for MAST technologies
Physical Experiments	Realistic results for top level parameters	Requires technologies to be built first; Resource intensive
Modeling and Simulation	Model emergent and swarm behavior	Results dependent on model fidelity

Considering the information presented, it is apparent that use of historical data option is out of question and physical experiments option, although necessary, is severely crippled by the need to have the technologies to be analyzed built first. But considering that MAST technologies are developing prototypes for physical experiments, it is logical to pursue the path of modeling and simulation that would feed into future physical experiments. This research model is schematically shown in Figure 27.

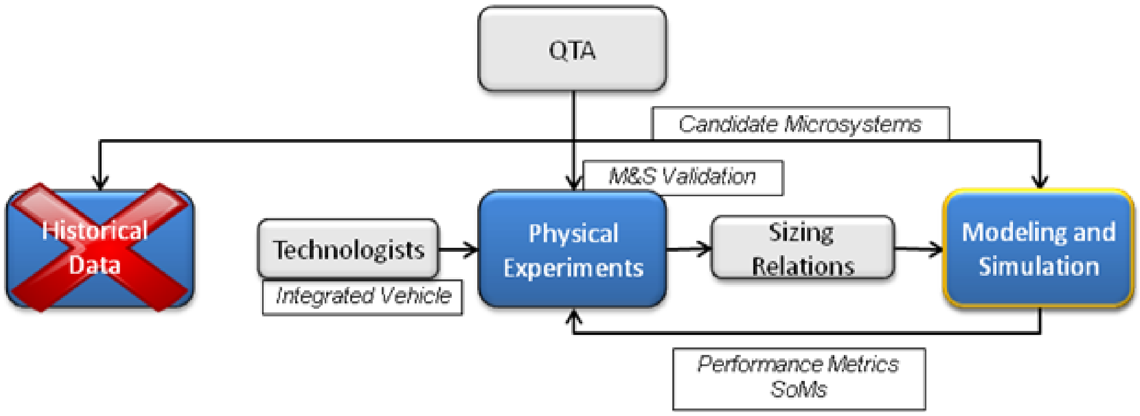


Figure 27: Evaluation of Heterogeneous SoMs

The output of QTA will be analyzed and quantified using modeling and simulation framework. The virtual experiments conducted will complement the physical experiments in terms of down-selection and direction. Technologist will develop integrated vehicles for physical experiments and the results will be fed back into the modeling and simulation environment through sizing relations (will be discussed in later sections of this chapter) to improve its fidelity.

Therefore, MLMS should consist of modeling and simulation of the following for each specified mission scenario: MAST concept of operations, technologies researched by the MAST consortium, mission scenarios, emergent, and swarm behavior of heterogeneous ensembles of microsystems, platform sizing relations, and various autonomy algorithms. This enables modeling of a mission from start to end the ability to quantify MoEs and MoPs, and analyze mission segments in detail. The modeling and simulation of the operations starts with the deployment of the microsystem ensemble by a small combat unit. These microsystem platforms then autonomously perform their mission in the given complex environments (e.g. urban, jungle, etc.). It models a mission from start to end quantitatively. In order to ensure practicality and repeatability of MLMS level in MAST quantification framework, it is imperative that the following characteristics are intrinsic to modeling and simulation framework:

- **Architecting mission scenarios:** The framework should be capable of modeling major types of mission scenario in detail. It should provide a standardize process and platform to model mission scenarios.
- **Structure and traceability:** The process and methodology defined by the framework should be structured and traceable to enable user to follow the flow of information with high transparency level.
- **Dynamic:** The framework should be dynamic to allow user to update underlying models as newer ones are developed and become available.
- **Parametric:** The types of vehicles, MoEs (e.g. time to complete mission), MoPs (e.g. vehicle speed), and sensors (e.g. sonar) should be modeled and their defining characteristics parametrically variable.
- **Representative technology modeling:** Since considerable number of MAST technologies are under development or lack existing physical models, the framework should be capable of modeling technologies to be simulated in mission based on their anticipated performance characteristics.
- **Framework modularity:** The type of mission and simulation environment should be independent of the framework, including any software utilized. As long as any alternative environment fulfills the minimum required specifications set forth by the framework (in terms of inputs, outputs, controllers, etc.), the user should be able to plug it into the framework.
- **Vehicle behavior definition:** The controller, autonomy or other behavior scripts should be modular in nature to allow modification and/or replacement. This

ensures that any algorithm defining vehicle or SoM behavior can be actively modeled and simulated within the framework.

- **Hardware-in-the-loop testing compatibility:** The presented MAST quantification framework is cyber-physical in nature and therefore requires that modeling and simulation frameworks provides the ability to include hardware in evaluating simulation results through hardware experimentation. The signature requirement would be to have standardized controller scripts that can be plugged into both virtual and physical vehicles.
- **Fidelity level:** The framework should provide reasonable level of fidelity in order to evaluate performance and perform optimization of autonomous microsystem ensembles operating in a mission that sufficiently captures the real world behavior. It is acceptable to allow successive modeling and simulation at varying level of fidelity that builds upon the previous results.

A modeling and simulation framework consisting of aforementioned characteristics will allow Warfighter and other end-users to conduct concept and design level exploratory experiments consisting of various heterogeneous MAST platforms operating in systems of systems manner in virtual interactive environments that mimic real world MAST missions. It will also enable probabilistic and statistical studies of various mission scenarios that are essential in analysis of swarms because of resultant emergent behavior. The data obtained through modeling and simulation will be utilized to explore and evaluate and candidate microsystems generated by QTA in heterogeneous swarms within a variety of concepts of operations to quantify and determine the combinations and their MoPs that are most effective for the successfully completing mission scenarios based on defined MoEs. This is an essential step in defining quantifying requirements disconnect and specifying MAST systems requirements that will be fill the gap between technologists and Warfighter by quantitatively specifying technology gap, which is also includes the trade-off space between realistically achievable advances in certain technology and the desired mission capabilities from it, and the direction needed to minimize it. MLMS supports MAST technology development from conceptual design through development and testing of hardware and software. Once sufficient fidelity of modeling and simulation is achieved, MLMS framework will serve as a virtual experimental test-bed, similar to the concept of Computational Fluid Dynamics (CFD) [150] software being "virtual wind tunnels". This will complement field tests by serving as pre-testing environment for encompassing evaluations of MAST SoMs in various mission scenarios. Another benefit of a MLMS framework would be allow Warfighter and end-users to conduct operational "gaming" experiments and exercises through simulation to explore and evaluate different mission tactics and CONOPS. The data obtained can become a valuable source of information for technologists in terms of needed system functionalities to achieve desired capability needs.

4.5.2. Framework and Methodology of MLMS

The defining characteristics of the MLMS framework have been defined and set forth above. Following them as a road-map, a two level modeling and simulation framework is proposed to evaluate heterogeneous MAST SoMs. The primary difference between the two levels is fidelity level and computation time. The proposed and developed two-level for MLMS are: 1) Screening Level (SL) for rapid assessment, and 2) Detailed Level (DL) for in-depth assessment. The output from QTA consists of microsystems based on current and future MAST technologies, which are a reduced pool of combination of solutions but can still be a very large number, can be rapidly evaluated using screening level simulation that primarily assesses top-level MoEs of a specified mission based on very general MoPs. The behavior of microsystems is based on representative algorithms that would mimic actual algorithms at a reasonable level. The evaluation is quantitative in nature and takes into account emergent and swarm behavior. The fidelity level is such that the evaluation is rapid so user can assess thousands of runs in a practical timeframe. Running these many cases at a very detailed level of analysis will be impractical in terms of time and computation power. However, the results output from this level of modeling and simulation will be a mission based down-selected pool of microsystems, by removing the less viable alternatives that can be practically assess at much higher level of fidelity. The choice of modeling and simulation environments for each level will be user dependent as the framework is set up to be modular. Any software or platform that is in compliance with modularity of the framework can be plugged in practically. And thus the second level of MLMS framework will quantitatively assess alternatives in context of mission scenario in much greater depth. This two-level MLMS framework information flow-down and typical number of alternatives to be evaluated are shown in Figure 28.

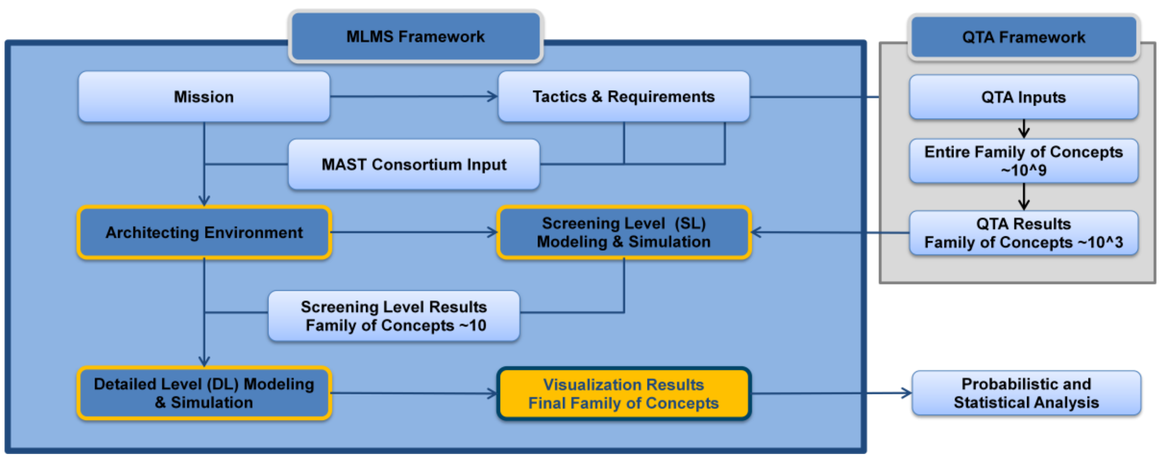


Figure 28: MLMS Framework and Information Flow-down

The aforementioned MLMS framework will be capable of achieving the goal of primary modeling MAST concepts of operations, mission scenarios, effectiveness of SoMs in successfully accomplishing missions while accounting for emergent and swarm behaviors. It also fulfils the characteristic requirements of MLMS framework set forth in the previous section. With overall MLMS framework defined, the next step is to discuss and select the overall type methods/paradigms for both levels of modeling and simulation.

4.5.2.1.Modeling and Simulation Methods

There are three widely used methods/paradigms for modeling and simulation available and were considered for implementation for proposed MLMS framework. They are summarized below:

- **Physics-Based Modeling** [151]
    - Very high fidelity but requires existence of physics based models of technologies being modeled.
    - Computationally and time intensive with steep learning curves.
    - Suitable for modeling and simulating a very small number of well defined technologies.
- **Discrete Event Simulation** [152] **(e.g. Manufacturing processes)**
    - For non-continuous time simulations; hard-coded event list
    - Suitable for modeling and simulating well understood phenomena, such as a manufacturing and shipment process where time is assess at discrete points.
- **Agent-Based Modeling (ABM)** [115] [153] **(e.g. Biological swarms)**
    - No physical required and models capabilities, actions and interactions.
    - Not computationally or time intensive; possibility of rapid development and analysis.
    - Suitable for modeling and simulating interactive behavior of platforms that lack well developed physical models.

These three options can be evaluated using Pugh selection method. It is summarized in Table 17. The '+' symbol signifies reasonable fulfillment, '-' symbol signifies fulfillment and '0' points to partial fulfillment of the criterion.

Table 17: Modeling and Simulation Methods

Selection Criteria	Physics	Discrete	ABM
Fidelity Level	+	+	-
Learning Curve Steepness	-	0	+
Programming Time	-	+	+
Setup Time	-	0	+

Considering the evaluation above and the fact that MAST simulation have to be based on continuous time, it is tempting to pick ABM as the method for modeling and simulation. However, for pure ABM based environments, major drawback is level of fidelity and lack of physics of the world. Therefore, it would appropriate to follow a paradigm that would build upon strengths of physics based and ABM methods. And this lends itself quite nicely to the proposed two level MLMS frameworks. It is appropriate to base the SL of modeling and simulation purely on ABM and DL on a combination of physics based and ABM method. To elaborate, the DL modeling and simulation will entail a physics based world (i.e. gravity, collision, etc will exist) and the vehicle capabilities and behavior will be driven by ABM in a parametric and modular fashion.

4.5.2.2.Agent-based Modeling (ABM)

ABM is a modeling approach that studies behavior of an individual within a simulation in terms of its actions and interactions with other individuals. The effects of individuals' behavior are evaluated for their impact on the global environment. Each individual or 'agent' behaves based on some pre defined behavioral rules and has a defined intelligence. It is also permitted to communicate with other agents, depending on defined communication protocol (i.e. if within defined range of other agents) and share data. ABM is specifically developed for modeling and simulating the "properties of the whole" that emerge as a result of the characteristics of individuals in the scenario. A real world example include the behavior of overall stock market is based on the prices of individual stocks bought and sold [154]. The scenes of battle in the movie Lord of the

Rings were simulated using ABM for behavior of many orcs [155]. Figure 29 shows a screenshot of Massive [156] software modeling such scenes.

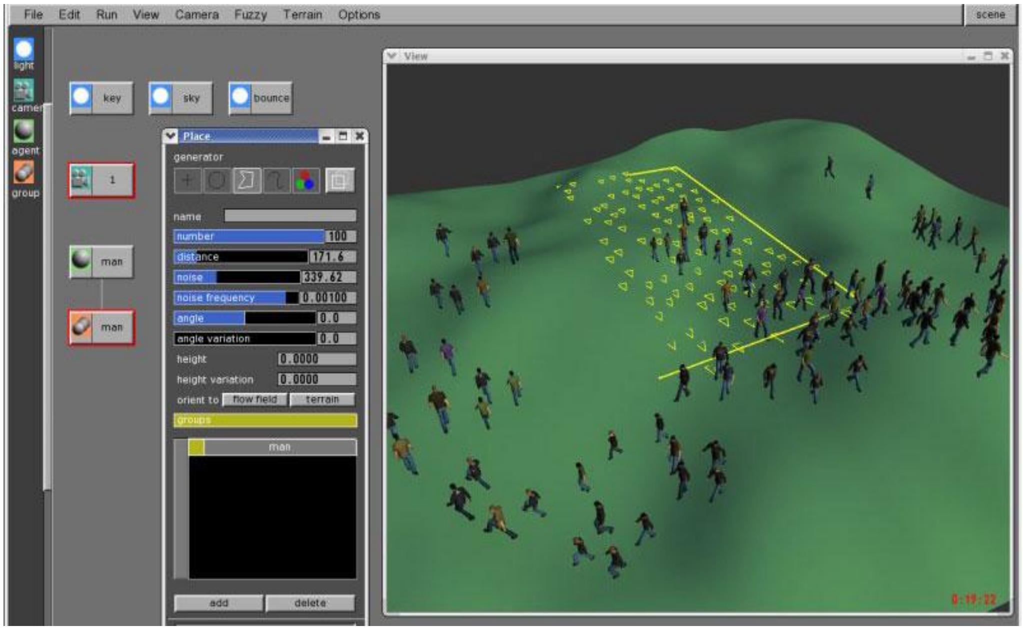


Figure 29: ABM of Lord of the Rings Movie Battle Scene [156]

There are five major components of ABM environment:

- Agents: MAST vehicles, soldiers, enemies, etc.
- Non-agent environment: Mission scenario including the buildings or other structures to be explored.
- Decision-making heuristics: Rules governing the basic behavior of the agents. For a MAST vehicle, it will include navigation and mapping algorithms, etc.
- Learning rules: Rules that govern how agents behave when new knowledge is gained. For instance, if a new passage ways is discovered, explore and map it while keeping track of area explored.
- Interaction topology: Rules governing interaction of agents with each other. For instance, share the discovery of enemies with other agents.

In context of MAST, ABM can be used to evaluate the impact of various MAST platforms and technologies operating in swarms on the mission MoEs, based on their

MoPs. This will also enable the analysis of emergent and group behaviors of the SoMs operating in a mission. Emergent collective intelligence and swarming are complex behaviors that biology has mastered to high degree. In order to realistically mimic the resulting emergent behaviors from the virtue of interaction between various MAST vehicles and quantifying them in context of their effect on mission MoEs, it is necessary to define capabilities, MoPs and agent interaction and communication rules. These rules will need to account for heterogeneous capabilities in a dynamic environment and will be based on information obtained for different MAST technologies from technologist. The communicating interactions, either direct or indirect, will be modeled based on MAST communication platforms. Overall, several important quantifications for assessment of MAST SoMs on mission MoEs can be obtained including the effect of individual capabilities and technology, collective behavior, and the number and type of vehicles operating in a mission. Before going into details of each level of modeling and simulation, a generalized set of inputs and outputs for both levels will be first established.

4.5.2.3.Inputs and Outputs

The inputs of for each modeling and simulation environments will consist of mission definition parameters (e.g. building layout), SoMs level configuration variables (e.g. number of microsystems in a swarm), and MoPs (e.g. speed) that define technology attributes of the technologies being modeled. The outputs will be the level of each MoE (e.g. mission completion time) achieved during simulation of a mission upon which success or failure of a mission will be judged. Figure 30 schematically shows major representative inputs, along with sources, and outputs.

As shown, there are three major sources for input and output variables: 1) Mission scenarios: for mission parameters to set up the environment and define SoMs; 2) technologists: for technology MoPs. The breakdown of sources for technologist has been previously documented in Chapter 2 of this thesis; and 3) Warfighter: for MoEs and acceptable levels of each for mission success.

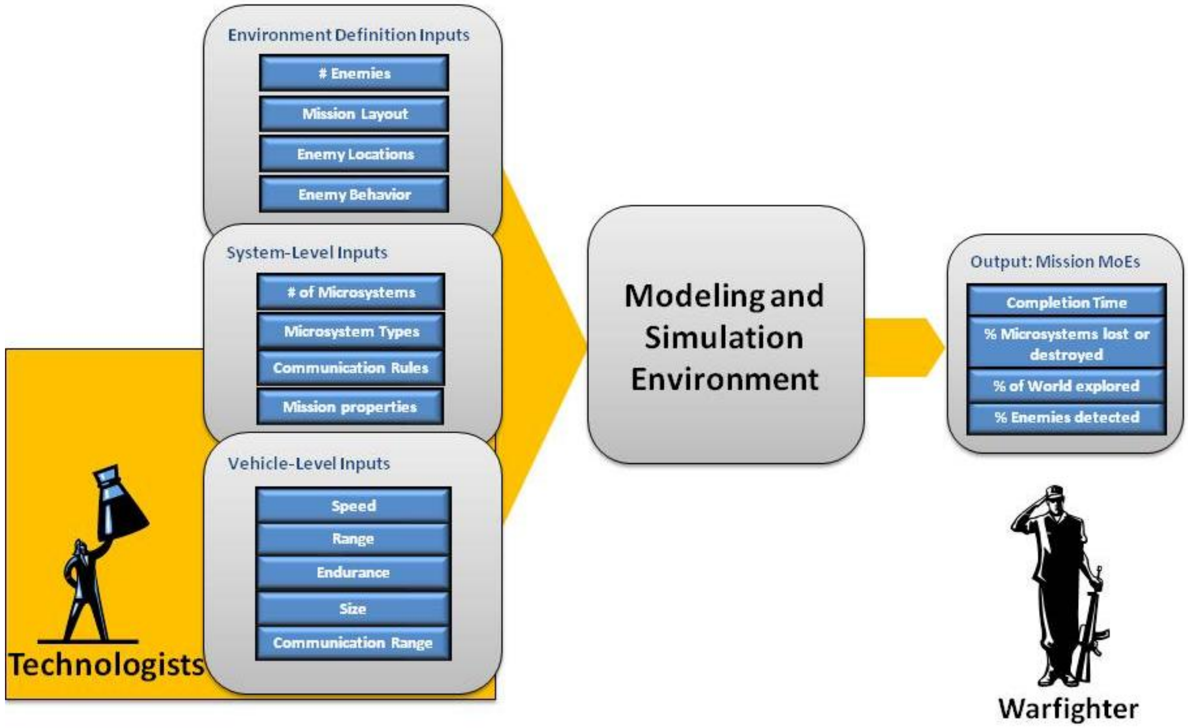


Figure 30: Modeling and Simulation Inputs and Outputs

In order to model and simulate various levels of MoPs and quantify their effect on mission MoEs, the inputs will be varied using an applicable Design of Experiments (DoE) [157]. The specific design and number of runs will depend on the type of mission scenario during the time of implementation. The simulation cases will be stochastic [157] in nature due to the variability of the model which is caused presence of emergent behavior. This means that it is expected to get different results each time even with same input levels. Therefore, each run will have to be repeated in order to this variability.

This section has documented the definition and set up of MLMS framework including selection of modeling and simulation methods for both levels and definition of inputs and outputs. This paves the path for specific discussion of each level of modeling and simulation environments. In the following sections, SL environment will be presented and discussed first followed by DL environment. The specific presented environments are not mandatory for implementation for the proposed framework. They are chosen by the author based on certain criteria (explained later) to implement the framework. Therefore, the development of each specific environment will be only as extensive as required to implement or test certain features of the framework. The end-users can either further develop these environments to the required level or replace them with ones of their choice.

4.5.3. Screening level (SL) Modeling and Simulation Environment

The goal of screening level modeling and simulation environment is to utilize agent based logic to rapidly evaluate heterogeneous MAST SoMs in modeled mission scenarios. It would utilize behavior and control logic that closely mimics the actual autonomy control and communication algorithms to accomplish missions. This would allow the evaluation of technologies and systems to be rapid while maintaining reasonable accuracy for mission based technology down-selection. It will enable determination of mission-level and technology-level characteristics that are necessary to sufficiently assure mission success or meet the required level of probability of success. The down-selected set of technologies will then be modeled and simulated in great detail using a detailed analysis level environment.

The screening level modeling and simulation environment is to be designed to provide a first level parametric quantitative assessment of MAST SoMs for a given mission. This serves as initial filter to more detailed levels of modeling and simulation, which will be discussed in next section, by providing a smaller set of alternatives. Moreover, the screening level environment enables designers to evaluate emergent and swarm behaviors of MAST systems. Collective ensemble behavior resulting from emergent intelligence and swarming that greatly benefits a communal mission can be observed in biological swarms [158] at a level that is masterful and sets the bar for non-biological systems to mimic. So the relevant question in an effort to address the quantification of this behavior in MAST SoMs is, "How to map individual system behavior to collective mission performance?" The answer lies in definition of capabilities, rules, and communication interactions for individual systems. These rules should be able to account for heterogeneous swarms as their capabilities, individual behavior and complex interactions with the environment will vary. Moreover, the communication between individual systems, direct or indirect, should be modeled based on MAST technologies currently available or being developed. The quantification of multi-agent MAST systems' emergent and swarm behavior in their influence on mission MoEs is necessary in analyzing the required technology levels, control logics, and behavioral rules for successfully accomplishing different missions. Designers can also use screening level environment to conduct sensitivity studies of different technology parameters resulting from mission implementation in a rapid manner. Finally, the screening level environment is an important contributing module towards gap analysis as it provides a platform to investigate both current state of the art and future technologies from context of mission scenarios. This leads to quantification of ideal levels of technologies required for mission success and can be compared to current levels to determine existing gaps in technology MoPs.

Before selecting an environment for screening level, the details of the framework for this level of modeling and simulation will be laid out to ensure that it is platform or software independent. In the required modeling and simulation environment, MAST SoMs will attempt to enter and search buildings, caves and other structures and also locate enemies, obstacles, booby traps, etc. Enemy soldiers may be present inside or around the structure being explored. The enemies should follow certain defined patrolling logic (e.g. stationary or following a way path) to follow so that if they encounter a MAST system, they will be able recognize it as an intruder and attempt to intercept and destroy it. On the other hand, if a MAST system is able to detect an enemy without being detected, it will report the enemy to other systems in range. Depending on exploration logic being explored, they may retreat completely to base or only from that specific area. The MAST systems will explore unknown terrain using potential field theory [159] logic.

This dictates that MAST systems are more likely to explore regions of the map that have not been discovered yet which increases the likelihood of entering structures like buildings and unfamiliar areas within. Obstacle and wall avoidance will prevent these MAST systems from crashing into walls and mapping present obstacles. At this level of analysis, 2D or 'looking down from top' environment is sufficient to model and quantify mission level MoEs based on technology level MoPs. Structures can be modeled as a set of walls or boundaries that physical barriers to passing through. Doors, windows and other passages ways will be modeled as openings of varying size in the defined boundaries. Once certain mission accomplishment (e.g. percent of map explored) criteria are met, MAST systems should utilize path-planning algorithms (e.g. A-star) rather than exploration logic to return to base. MAST systems should be able to be equipped with certain types of sensors that mimic the ones under consideration for the purpose of MAST, with their capabilities parametrically defined. Some important types include: 1) distance-ranging sensor (i.e. LIDAR) to detect obstacles and guide navigation to avoid collisions with walls. 2) Vision based sensors such as camera for enabling identification of other agents including enemies. These generally have broader viewing angle than the distance ranging sensors. 3) Communication sensors to allow sharing of information between MAST systems in an ensemble, depending on parametrically controlled range.

Ultimately, the aforementioned ground rules enable MAST systems to be condensed down into black boxes that are represented parametrically defined MoPs and swarm level parameters. These variables can then used to effectively quantify all aspects of the systems individually and as a swarm such as number of systems, locomotion, sensors equipped communication capabilities, etc. Moreover, the mission scenarios can now be defined using their operational functions in context of physical objects, requirements on MAST systems navigation and mapping logic and interactions with the environment and other systems, and interactions with enemies. This results in simulation output as parameters relevant to mission effectiveness, which are defined by MoEs.

These MoEs quantify how a given set of MAST SoMs performs at the mission level for the scenario under consideration. Some of the major MoPs, swarm level parameters and MoEs are listed in Table 18.

Table 18: MoPs, Swarm Parameter and MoEs

Measures of Performance (MoPs)	Swarm Parameters	Measures of Effectiveness (MoEs)
Speed	Types of Platforms	% of World Discovered
Turn Rate	# of Systems	% of Interior Discovered
Sensor Detection Distance	Communication Range	Enemy Agent Detected
Sensor Viewing Angle		MAST Vehicle Lost
Avoidance Distance		

The developed modeling and simulation environment should be capable of handling one to six MAST systems with their capabilities varied parametrically. Enemies should range in number of one to four and terrain to be able to include structures up to 1000 square feet in area. Another important implication of environment featuring the aforementioned structure is the capability to conduct Design of Experiment (DoE) studies as laid out in previous sections.

Implementing the above defined environment allows user to quantity mission MoEs for various MAST systems from a large combinatorial pool. The ones that are able to accomplish mission at acceptable level of probability of success can now be down-selected for more detailed modeling and simulation at higher fidelity. Therefore the output of MAST systems from screening level becomes input into DL environment, which is the subject of next section.

4.5.4. Detailed Level (DL) Modeling and Simulation Environment

Following the laid out methodology for modeling and simulation, this section discuss development of DL environment. It has been already explained that the purpose of DL is exactly the same as that of screening level, which is to quantify MoEs for modeled mission based on MoPs MAST SoMs while taking into consideration emergent and swarm behavior. The primary different is fidelity level of simulation. With screening level rapidly analyzing a vast number of MAST systems for given mission scenario and down-selecting technologies to a reasonable number, it is at this step that increased computational time and power can be utilized to for an analysis that is much more detailed and at higher fidelity level. As mentioned previously, DL environment will include a physics based 3D world where MAST systems, using agent based logic, can be simulated. Therefore, the required and properties of the agent-based modeling for DL environment will be same as the ones laid out for screening level and will not be repeated here. The difference is that DL environment will not mimic control logic and algorithms but will be able to provide an interface for plugging these scripts directly into the simulation. This capability is an enabler for hardware-in-the-loop testing as same scripts can be used in both virtual and physical testing.

Once again, the choice of environment is user dependent as long as it fulfills the required features listed under screening level environment and the following:

- Presence of physics engine to model world and dynamics of objects interactions (i.e. gravity and collision).
- The ability to map architecture into physical domain
- Controller script interface should be independent of any platform to enable modularity of plugging in algorithms for navigation, mapping, vehicle behavior, etc. Also enables hardware-in-the-loop testing. For instance, scripts written in C++ and Python should be implementable in a simulation.
- 3-Dimensional to enable detailed mission level simulation of mission scenarios from start to end.
- Capability to design and model 3D mission scenarios
- Capability to design and model vehicles, sensors, enemies, etc.

- Capability to infuse agent based logic including modeling of integrated systems and parameter definition.
- Ability to run DoE on modeling and simulation environment.

With methodology requirements for defining, architecting and simulating mission and vehicle behavior, the DL modeling and simulation environment can now be developed and will be presented in the next chapter. The only concern left regarding is whether or not DL environment actually mimics real world behavior at the reasonable level. This requires validation of the environment and since there is no alternative to real-world testing, experimental validation is necessary. A simple methodology to accomplish basic validation is put forth in the next section.

4.5.5. Experimental Validation of DL Modeling and Simulation Environment

Validation of the modeling and simulation environment, especially for detailed mission level modeling and simulation, is of paramount importance in order to utilize it confidently. Therefore it is necessary to develop an experimental physical platform such as quad-rotor to serve as a test bed for physical evaluation of various autonomy algorithms, physical configurations, components, and tactics leading to eventual validation of the modeling and simulation environment. It will be similar, in terms of type, sensors equipped, and autonomy algorithms, to the one being flown or simulated in the modeling and simulation environment. Moreover the location used for testing this quad-rotor will be mapped virtually in the M&S environment. Thus this setup will effectively serve as real-world validation. Once the environment has been validated, it can then be used for testing of other vehicles in various other scenarios eventually leading to optimization of ensemble for that specific mission scenario. It will be utilized to conduct gap analysis for testing virtual designs of vehicle based on current state of the art and future technologies by adjusting its design and performance parameters. This will enable the determination of the minimum threshold values of technology attributes that need to be achieved in order to successfully complete the given mission scenario.

Finally, a provision that is provided through this module is the ability to input experimental data directly into simulation environment. The experimental validation sums up the MLMS level defined by MAST Quantification framework.

4.5.6. Summary

With development of screening level and DL modeling and simulation environments complete and a process to validate DL laid out, the MLMS framework is now defined and set up for MAST quantification framework. This concludes the next major level of analysis for quantifying requirements disconnect and providing a methodological approach to analyzing mission scenarios for various integrated heterogeneous MAST SoMs. The output of this level is simulated results of given mission scenarios that quantify the defined MoEs based on technology MoPs while taking into considerations for swarm and emergent behaviors. These results forms the foundations of quantified information that is needed to address research questions put forth for this research. However, before consolidating the results into gap analysis and requirements redefinition, sizing relations to map vehicle parameters to MoPs (and subsequently to MoEs) needs to be addressed. The following sections will define these methodologies and develop the remaining modules of MAST quantification framework, which are parts of results and analysis level as laid out in the beginning.

4.6. Sizing Relations

The final level of MAST quantification framework consists of analyzing the results obtained through QTA and MLMS by starting with development of sizing relations of specific MAST technology platform. Until now, mission MoEs have been quantified using defined MoPs of MAST technologies. However, it is important to relate functional and operational components of individual integrated platforms to mission

MoEs directly. The reasoning behind it is two-fold: 1) it generates vehicle definition for the required MoPs for a mission scenario, and 2) it sizes the vehicle either based on current technology levels or future technologies levels, defined by user. This serves the overall purpose of this module, which is to establish a relationship between vehicle platform parameters and mission MoEs through the means of MoPs.

The major obstacle in implementing this module is that there aren't any developed sizing codes for MAST technologies that either available or reliable. Therefore, it is imperative that some of sizing relations are developed during the course of the research. These developed relations will be preliminary in nature and can be updated in future, by the virtue of framework's modularity, as more information becomes available. Three primary platforms are to be explored for developing sizing relations: 1) fixed wing aerial platforms, 2) rotary wing aerial platforms, and 3) flapping wing aerial platforms. The reasoning behind selection of these three is based on author's engineering judgment and preliminary results from previous modules (discussed in next the chapter) show that these platforms are most capable for accomplishing defined mission scenarios. For the purpose of this research, the first set of sizing relations, for fixed wing and rotary aerial platforms, were developed/compiled by ASDL's MAST integration effort team, during 2008-2009, of which author was a member. The second set of sizing relations, for quad-rotor and flapping wing aerial platforms, were compiled into a code from various resources by the author and members of ASDL's Grand Challenge Team of 2012-2013. The team was led by the author himself.

The goal of these sizing relations is to define simplified power equations for the aforementioned platforms. Moreover, it is a concept demonstrator for developing similar power relations for other platforms. Ideally, such power relations would be developed, primarily by technologists, for all vehicle platforms that are under MAST consideration to enable relationship mapping between vehicle parameters, MoPs and MoEs.

Following subsections puts forth fundamental assumptions for simplified power equations followed by development of first order sizing relations that will used in the implementation of MAST quantification framework. The details of the implementation will be presented in the next chapter.

4.6.1. Assumptions

The fundamental assumptions made for development of sizing relations for both platforms are:

- The vehicles to be analyzed are of micro scale as defined in context of this research earlier.
- Each vehicle is considered to be a point mass.
- Each vehicle is considered to be of constant weight throughout the mission.
- Correction factors are utilized to fine tune the power equations for specific platforms. These will be determined based on results obtained from literature review.

4.6.2. Basic Concept

The fundamental difference between full size aerial platforms and micro aerial platforms is consumption of power and associated change in weight. Full size platforms are more often powered by consumable fuel source in terms of weight and thus requiring a detailed analysis of mission segments to account for changing weight. However, for smaller size platforms, the power source is usually of constant weight type (e.g. batteries) and therefore enables the development of single power equation to govern the size of the vehicle under consideration. The size can be conceptually determined based on the required propulsion system and power source that are dictated by calculated required power. With basic assumptions justified, the power relations for each platform will be simplified using the basic power relation show in Equation 2.

Equation 2: Simplified Power Equation

$$P = mgV$$

where:

m, mass (kg)

V, forward velocity (m/s)

Considering a point mass, the above equation related power required based on velocity of the mass. However, it doesn't take into consideration of additional power required due to parasite (primarily profile) drag associated with three dimensional shape of the vehicle. In order to account for it, the proposed method adds a correction factor, μ, which is directly proportional to forward velocity. A basic assumption being made here is that the power required due to drag associated with physical shape of the platform is directly proportional to velocity. For first order analysis, it is reasonable to make this assumption. Therefore, the generalized power equation now becomes:

Equation 3: Simplified Power Equation with Correction Factor

$$P = m \cdot g \cdot V \bullet \mu$$

The correction factor is specific to platform type and can be determined by equating and varying velocity in Equation 2 and specific power equation of the platform. A curve can be fitted through the generated data points to provide an empirical equation. Details for power equations for the two specific types of platforms are given in sections below. Two sets of equations are presented below. The first set of equations are primarily based on reference [160], while second set of equations are compiled from various resources and referenced at appropriate locations below.

4.6.3. Fixed Wing Aerial Platforms – Set 1

The power equation for fixed vehicle is shown in Equation 4.

Equation 4: Fixed Wing Power Equation

$$P = \frac{1}{2}\frac{\rho \cdot V^3 \cdot S}{\eta_{prop}}\left(c_{Do} + \frac{k}{\pi \cdot \Lambda}\left(\frac{Q}{S}\right)^2\left(\frac{2}{\rho \cdot V^2}\right)^2\right)$$

Using the literature searched conducted and documented in chapter, many of the parameters in above equation can be specified as constants. These are based on sizing limitations placed by MAST concepts and current levels of these parameters that are being considered by technologist and are summarized in Table 19.

Table 19: Fixed Wing Power Equation Parameters Values

Parameter	Values Assumed
ρ - air density (kg/m^3)	1.225
η_{prop} - Propeller Efficiency	0.8
C_{D0} - Zero Lift Drag	0.04
Λ - Aspect Ratio	2
m - Mass (kg)	0.1
k - Wing Efficiency; 1/e	e= 0.8; k =1.25

Fixing the values of aforementioned parameter only leaves three variables, namely Weight (Q [N]), Wing Area (S, [m^2]) and Velocity (V, [m/s]). Defining wing area based on limitations on the size of the vehicle enables the determination of the correction factor, by varying velocity in equations 3 and 4.

4.6.4. Rotary Wing Aerial Platforms - Set 1

Following a process similar to one for fixed wing, the power equation for rotary wing platforms is shown in equation 5.

Equation 5: Rotary Wing Power Equation

$$P = \frac{1}{8}\rho A \sigma V_T{}^3 c_{D0}\left(1 + 3 \cdot \mu^2\right) + DU + Tv_i$$

where:

D, drag (N)

T, thrust (N)

U, free stream velocity (m/s)

V_T, rotor tip velocity,

v_i, induced velocity of the rotor (m/s)

μ, advance ratio in rotor plane.

Again, some of the parameters in the previous equation can be defined using literature search and engineering judgment as shown in Table 20.

Table 20: Rotary Wing Power Equation Parameters Values

Parameter	Values Assumed
ρ - air density (kg/m^3)	1.225
σ - solidity	0.318
C_{D0} - Zero Lift Drag	0.04
C_D - Drag Coefficient	0.35
C_L - Lift Coefficient	1.5
A (m^2) – Rotor Area	0.0201
r - Rotor Radius (m)	0.08
c - Blade Chord (m)	0.04
N - # of blades	2

Considering Table 20, value selected for lift and drag coefficients warrant further explanation. They were estimated using the data provided in reference [160] and schematically shown in Figure 31 [160].

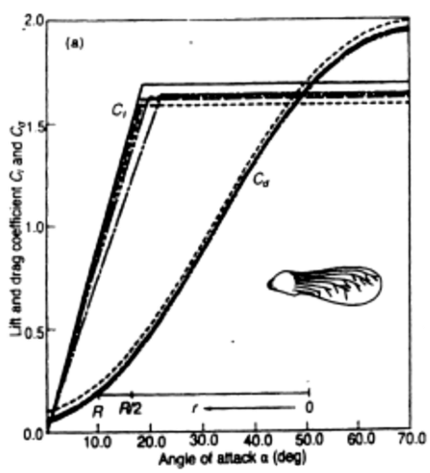


Figure 31: Lift and Drag of a Rotary Seed [160]

The major assumption being made here is that the vehicle under consideration is flying at a constant angle of attack and increases its collective thrust by increasing RPM of the propulsion motors. Therefore, vertical thrust component is countering weighting and horizontal component overcome drag caused for forward flight. For developing preliminary sizing relations, this assumption is reasonable to be made to simplify calculations. Another important aspect to consider before developing an equation to determine correction factor is effect of hovering flight, afforded by rotary wing platform, on power required. At this point, it is necessary to break away from the assumption of point mass put forth in the beginning of this section, allowing the use of actuator disc theory [161] to quantify hovering power required in a simplified manner. The primary parameter to be determined here is induced velocity is the result of power required to push certain amount of air down through the rotor to sustain flight. The basic equation resulting from actuator disc theory is shown in Equation 6. And power required to hover is defined by Equation 7.

Equation 6: Induced Velocity

$$v_i = \sqrt{\frac{mg}{2\pi\rho r^2}}$$

Equation 7: Power Required to Hover

$$P_h = m \cdot g \cdot v_i$$

Using the above equations, fundamental power equation and the parameters defined earlier, the simplified power equation can now be written as Equation 8.

Equation 8: Simplified Power Equation for Rotary Wing Platforms

$$P = m \cdot g \cdot (V + v_i)$$

Following the laid out method, remaining parameters can now be varied based on specific rotary wing platforms under consideration to obtain correction factor through Equations 3 and 8.

With simplified power equations defined for two platforms, the vehicle parameters can now be related to mission MoEs through platform specific MoPs. The results obtained from this module will be fed into gap analysis and requirements re definition to close the loop for quantification of MAST technologies, which is the topic of next section.

4.6.5. Quad-rotor Aerial Platforms – Set 2

The sizing relations for quad-rotor aerial platforms are basically extension of the one presented in rotary wing aerial platforms section above. It follows the application of fundamental principles of the Momentum Theory, Blade Element Theory, and Blade Element Momentum Theory on the four rotors [162], [163]. These theories have been widely documented, applied and validated in literature and therefore will not be repeated here. The primary references used for this section are Latorre [164] and Leishman [162]. The details of its application to a mission scenario will be presented in the next chapter. However, most helicopter theories require experimental correctional factors in order to get a reasonable agreement between analytical and experimental results. The approach developed by Latorre presents a Combined Momentum and Blade Element Theory (CMBT) corrected using empirical factors for quad-rotors at smaller sizes. A brief overview will be presented in this section on the theory behind Latorre's methodology. The equations and method is taken directly from Latorre.

The process starts with definition of rotor geometry including number of blades, rotor radius, twist and chord distribution, airfoil data or C_l and C_d values and root cutout. For the purpose of this research, the above mentioned parameters along with atmospheric conditions are listed in Table 21 [164]. Other required inputs include speed of sound and tip speed.

Table 21: Quad-rotor CMBET Input Parameters [164]

Parameter	Values Assumed
ρ - air density (kg/m^3)	1.225
Speed of Sound (m/s)	340.29
C_{d0} - Zero Lift Drag	0.0081
C_{d1} - Drag Coefficient	-0.014
C_{d2} - Drag Coefficient	0.4
C_l - Lift Coefficient	6α
θ - Rotor Twist (deg)	0
r_0 - (m)	0.04
N - # of blades	2
NR - # of rotors	4

With input parameters defined, the next step is to select a finite number of blade sections ranging between five and fifteen. Then, at each blade section, local Mach number, lift curve slope and local twist are calculated using the Equations 9 to 11.

Equation 9: Local Mach Number

$$M = r(\frac{\Omega R}{V_{sound}})$$

Equation 10: Lift Curve Slope

$$a = f(M) per\ radian$$

Equation 11: Local Twist

$$Local\ Twist = \Delta\theta$$

Then, collective pitch, θ_o, local inflow angle and local angle of attack are determined using Equations 12, 13 and 14.

Equation 12: Collective Pitch

$$\theta = \theta_0 + \Delta\theta - \alpha_{LO}$$

Equation 13: Local Inflow Angle

$$\frac{v_i}{\Omega y} = \frac{aN_b \frac{c}{R}}{16\pi r}\left[-1 + \sqrt{1 + \frac{32\pi\theta r}{aN_b \frac{c}{R}}}\right]$$

Equation 14: Local Angle of Attack

$$\alpha = \theta - \tan^{-1}\left(\frac{v_i}{\Omega y}\right)$$

The next step is to determine lift and drag using Equations 15 and 16.

Equation 15: Lift Coefficient

$$C_l = a\alpha$$

Equation 16: Drag Coefficient

$$C_d = C_{d0} + C_{d1}\alpha + C_{d2}\alpha^2$$

Then, running thrust loading, running profile torque loading and running induced torque loading can be calculated using Equations 17, 18, and 19. Integrating these equations will give the respective coefficients. At this point, tip loss factor can also be calculated using empirical relations.

Equation 17: Running Thrust Loading

$$\frac{dC_T}{dr} = \frac{N_b r^2 (\frac{c}{R}) C_l}{2\pi}$$

Equation 18: Running Profile Torque Loading

$$\frac{dC_{Q0}}{dr} = \frac{N_b r^3 (\frac{c}{R}) C_d}{2\pi}$$

Equation 19: Running Induced Torque Loading

$$\frac{dC_{Qi}}{dr} = \frac{N_b r^3 (\frac{c}{R}) C_l \frac{v_i}{\Omega R}}{2\pi}$$

Next, disc loading and the relation CT/σ are computed using Equations 20 and 21.

Equation 20: Disc Loading

$$D.L. = C_T \rho (\Omega R)^2$$

Equation 21: C_T/σ

$$C_T/\sigma = \frac{C_T}{\frac{N_b c}{\pi R}}$$

An empirical correction factor for the wake contraction as a function of (Disc Loading)/ (C_T/σ), as presented in Prouty [165], is shown in Figure 32.

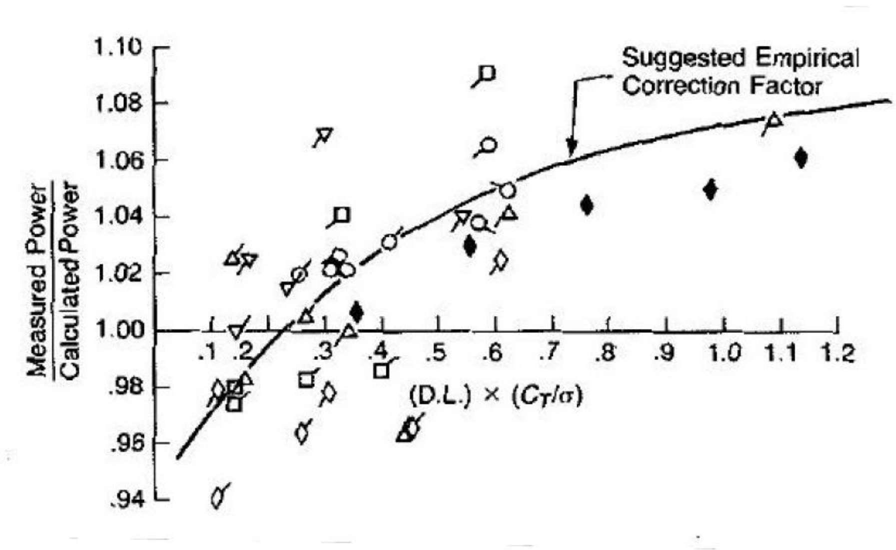


Figure 32: Correction Factor for Tip Vortex Interference [165]

And now the total torque coefficient can be determined using Equation 22.

Equation 22: Total Torque Coefficient

$$C_Q = \left(C_{Q0} + C_{Qi} + \Delta C_{Qi}\right)\left(\frac{Measured\ Power}{Calculated\ Power}\right)$$

Finally, the overall Thrust and Torque can be determined, as shown in Equations 23 and 24, and hence the total power consumption, using the power equation.

Equation 23: Overall Thrust

$$T = \rho A(\Omega R)^2 C_T$$

Equation 24: Overall Torque

$$Q = \rho A(\Omega R)^3 C_Q$$

This concludes the theory, adopted from Latorre, which will be used in this research for determining the power consumption of quad-rotor. The actual implementation will be presented in the next chapter.

4.6.5.1.Validation

Before the above mentioned method for sizing quad-rotor power requirements, it is necessary that the model is validated to perform at a reasonable level. Latorre performed several tests to compare the theoretical results with experimental results. The discrepancies between the two results ranged from 2% to 10% for thrust calculations with average being at 4.6%. For first principles' level analysis, these discrepancy levels are acceptable. Moreover, the compiled specification databases for motors, batteries, and rotors are expected to further improve the results' agreement with experimental data.

4.6.6. Flapping Wing Aerial Platforms – Set 2

The method, for determining sizing relations, is primarily taken from the one presented in VanGehucten [166]. The method heavily references the work of Shkarayev et al. [167]. For the purpose of this research, the above mentioned sizing equations are coupled with a maximum mass check equation presented by Shyy, et al. [168], and invokes the study by Pennycuick [169]. The major assumptions are:

- One-dimensional
- Quasi-steady
- Incompressible
- Inviscid

A composite method consisting of above resources was developed by the author and Arun Ramamurthy as part of the ASDL's 2012 - 2013 MAST Grand Challenge Team, under the guidance of the author. The mass check equation is a rearranged version of the equation for predicting wing-beat frequency if mass, wingspan, wing moment of inertia and wing area are known. It is shown in Equation 25.

Equation 25: Wing-beat Frequency

$$f = (mg)^{1/2} b^{-17/24} S^{-1/3} I^{-1/8} \rho^{3/8}$$

where:

S, wing area (m^2)

b, wingspan (m)

I, wing moment of inertia (kg m^2)

ρ, air density (kg/m^3)

For MAST systems of flapping wing nature, the wing beat frequency will be a design factor and thus will be known a head of time. Therefore, equation 25 can be easily rearranged to determine the maximum mass that can be carried given wing-beat frequency, wingspan and wing area. This will serve as a check on every generated flapping wing alternative for technical feasibility in terms of their ability to sustain flight.

The power required to hover and fly forward is determined on Shkarayev et al. method, which uses a partial actuator disk theory for aerodynamic estimation of flapping wing based aerial vehicles. This method has been implemented by VanGehucten and validated for some test vehicles. The flapping momentum based model is based on a partial actuator disk that accelerates flow through it, thereby transferring momentum to the fluid. Figure 33 shows the schematic of the disk actuator model.

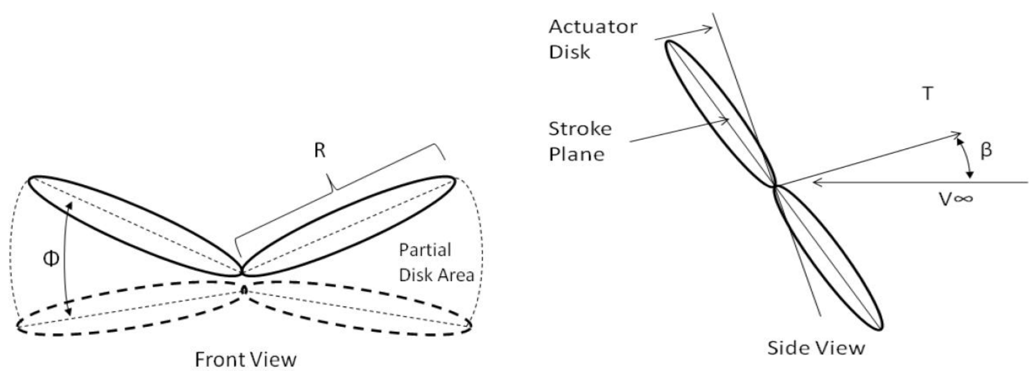


Figure 33: Actuator Disk Model [166]

Using the geometry as shown in Figure 33, the disk area and induced downwash velocity can be calculated from Equations 26 and 27 respectively. All subsequent equations in this subsection are taken from the above mentioned references and presented for coherence here.

Equation 26: Actuator Disk Area

$$A = \phi b^2/4$$

where:

b=2R

Equation 27: Induced Downwash Velocity

$$\omega^4 + 2\omega^3 V \cos\beta + \omega^2 V^2 = (\frac{T}{2\rho A})^2$$

where:

ω = induced velocity

β = stroke plane angle

Now, the ideal power can be calculated by multiplying normal velocity into the disk and thrust. It is shown in Equation 28.

Equation 28: Ideal Power

$$P = T(V\cos\beta + \omega)$$

The stroke plane angle and velocity becomes zero during hover and the induced velocity and power can now be determined using Equations 29 and 30 respectively.

Equation 29: Hover Induced Power

$$\omega_0 = \sqrt{\frac{T_0}{2\rho A}}$$

Equation 30: Hover Power Required

$$P_0 = T\omega_0$$

For forward flight, the major assumption is that the flight regime will be low speed. For horizontal flights, stroke plane angle will be small enough to safely assume β to be horizontal. The drag is also assumed to be zero, due to very low speed flight, and thus induce velocity and power required for forward flight can be found from Equations 31 and 32 respectively.

Equation 31: Forward Flight Induced Velocity

$$\omega = \sqrt{-0.5V + \sqrt{0.25V^2 + \omega_0^4}}$$

Equation 32: Forward Flight Power Required

$$P = T(V\cos\beta + \omega)$$

Finally, a metric is needed to account for non-ideal effects including efficiency losses and other variations in the model. Following Leishman, a Figure of Merit will be used in conjunction with power equations. The modified power required relations are shown in Equations 33 and 34.

Equation 33: Hover Power Required - Figure of Merit

$$P_{0C} = \frac{P_0}{FM}$$

Equation 34: Forward Flight Power Required - Figure of Merit

$$P_C = \frac{P}{FM}$$

These equations can now be used to size flapping wing based aerial vehicles. The results will not account for detail aerodynamic issues such vortices but is sufficient to provide first principles estimate.

4.6.6.1.Validation

It is mandatory to validate the code before utilizing it in the framework for quantification of MAST systems' mission performance. Although it is currently difficult to validate any flapping wing sizing code due to lack of available real world data and/or non-disclosed specifications, an effort was made by VanGehucten to compare the results of AeroVironment, Inc's hummingbird-like nano air vehicle [170]. His results show agreement on determined weight to be within 5% error. Considering that these first principle sizing relations are being used to discard alternatives that are not technically feasible, this bare minimum validation will suffice for now.

4.6.7. Summary

The sizing relations presented above will be utilized in conjunction with detailed mission level modeling and simulation environment to generate technically feasible alternatives for detailed mission level modeling and simulation. The alternatives can be generated based on technology year. This enables relating desirable MoPs to actual vehicle characteristics, even for those that are expected to be available in future.

4.7. Gap Analysis and Re-definition of Requirements

The final step in this framework is providing a solution for now quantified requirements disconnect by re-defined realistic requirements for the mission scenarios under consideration. In order to accomplish this step, it is necessary to quantify technology gap using the results obtained through all previous levels in the established framework.

Gap Analysis is a term that describes quantification of the ‘gap’ that exists between the MoPs required to accomplish a defined mission scenario and the MoPs that are currently available for MAST technologies. Moreover, it can also be utilized to observe what capabilities can be obtained for certain level of MoPs that will be available in the future.

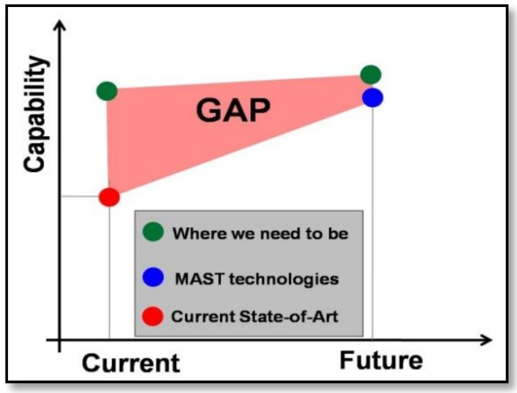


Figure 34: Technology Gap

This concept of technology gap is pictorially shown in Figure 34. At present time, there is a state of the art technology, but it maybe inferior in capability (based on its MoPs) to what is desired by the Warfighter. And at some time in future, it is expected that the technology's MoPs will improve as a function of time, what capabilities will be obtained in terms of mission scenarios. Representative examples are as following:

- At 20 years in future; suppose vision sensors can be made that are half the size of today's vision sensors, what capability does that give us?
- If a capability to search a 3,000 sq ft building in 5 minutes is required, based on current levels of technology improvement, how long will it take to mature to the required level?

In essence, the purpose of all levels of MAST quantification framework was to provide a methodology to obtain quantified data that will generate gap analysis. The units for each defined "gap" are the same as the units representing that specific MoP (e.g. m/s for speed). With gaps defined, requirements for MoPs can now be redefined. A representative example is as following:

- If a capability to search a 3,000 ft[20] building in five minutes is required and a soldier can only carry extra two pounds of weight for MAST technologies, the redefined requirements will be of the following form:
    - Types of platforms

- Number of platforms
- Minimum/Maximum speed of each vehicle
- Maneuverability required
- Stealth level required
- Endurance required

The exact types of definitions will be dependent on the mission being considered as will be evident in implementation of the framework in next chapter. At this point, if end-user needs to can apply standard requirements engineering [136] techniques and methods, which have been well developed and documented in systems engineering disciplines, to articulate and/or develop derivative requirements. Execution of this module is the last step in the developed MAST quantification framework and outputs two consolidated sets of information, technology gaps and redefined requirements, to address the research issues at the core of this research.

4.8. Chapter Summary

This chapter documented the development of methodology and framework to address the issues driving the research presented in this thesis. It answers the eight fundamental research question set forth in Chapter 3. The MAST quantification framework was propsoed and formulated following the research plan laid out in the beginning, motivated by discussion presented in the first chapter, and using knowledge gained from thorough background and literature review. The outcome of implementing the framework is quantification of MAST SoMs for given mission scenarios in their ability to achieve defined MoEs, evaluation and implications of emergent and swarm behavior, quantification of technology, and re-definition of requirements. Combined, these results provide a solution to the requirements disconnect between Warfighter and technologists.

The next chapter will test an implementation of this framework for two selected MAST mission scenarios. The results will be analyzed to present a conclusion on how each of the research questions were addressed through the developed MAST quantification framework.

CHAPTER V

DEVELOPMENT, IMPLEMENTATION, RESULTS AND ANALYSIS

This chapter documents the development and implementation of the MAST mission effectiveness quantification and technology assessment framework that was put forth, in the previous chapter, to address the core research issues presented in this thesis. The need for such a framework arises from the requirements disconnect created due to differences in the perspectives of the technologists and the Warfighter, viewing the problem from opposite ends of the spectrum, regarding the deployment of MAST SoMs in a mission environment. During the course of this chapter, each module of the framework is developed and executed for the selected MAST mission scenarios. The results from each step are analyzed to gain insight into the mission effectiveness quantification of the MAST SoMs in context of the mission scenario. The primary purpose of this implementation is to serve as a concept demonstrator for the developed methodology and the framework, and to verify that it is successful in closing the requirements disconnect. The results are expected to present validation of the developed method, tools and models. They are also expected to enable quantification of the technology gap for subsystems defining the mission optimized MAST SoMs leading to redefinition of requirements for the mission scenario considered. The framework's information flow-down shown in Figure 15 and is used as the roadmap for this chapter.

5.1. Overview, Operational Architecture and Mission Scenarios

The process starts by designating mission scenarios of interest, quantification of mission tactics and MoEs, and implementation of the operational architecture to generate operational functions. These tasks are defined by the first two modules of the framework, namely the ‘Mission Scenario’ and the ‘Operational Architecture’, and are addressed simultaneously.

First, the specific mission scenarios, which represent complex environments requiring signature capabilities needed from MAST SoMs, have been defined and presented in Chapter 4. These scenarios are analyzed in context of the mission tactics, defined by the Universal Army Task List, and the relevant mission MoEs. The level of each MoE required to deem the mission accomplished were also quantified. For the purpose of this research, the following two missions are selected for analysis: 1). Joppa Urban mission (JU) and 2). ARL Black Hawk Down - Interior Building Reconnaissance (ARL IBR) –These two mission scenarios, as defined in the previous chapter, represent two distinct perspectives and map types. The Joppa Urban is a small area map that is expected to be benign. Soldiers are to drop off the MAST systems close to the building and let them explore. On the other hand, the ARL IBR represents a map more closely resembling an urban warfare environment, which includes multiple buildings spread through a walled compound. The ARL IBR mission is anticipated to be hostile. However, benign and hostile versions of both missions are analyzed and compared.

Next, the operational architecture, specifically OV-5 view, for MAST SoMs, developed earlier in this research, is used for generating all required operational functions. As mentioned previously, these first two modules are only undertaken at the very first iteration of the framework's implementation. Their repetition or modification is only required if either of the following conditions is true at the next start of the next iteration:

1. A new mission scenario is defined and needs to be analyzed. Mission and tactics need to be re-quantified.
2. The concepts of operation for SoMs, as defined by the end user, change. Operational architecture needs to be modified or re-defined to accommodate additional activities and/or functions required to be performed by MAST systems.

If neither of these two conditions is invoked, then any subsequent iteration of the framework will not require re-execution of the first two modules. Therefore, the information, specifically the output of Mission and Tactics and Operational Architecture modules from the previous chapter, is used here to proceed to the next step in the framework. And as such the following subsection presents the setup and the execution of the M-IRMA module.

5.2. Concept Space Exploration and Concepts Selection: M-IRMA

With the mission scenarios selected and quantified for MoEs, tactics defined and operational functions generated, the next module consolidates this information with literature review and surveys data to provide a platform for concept space exploration. In order to enable systematic and traceable exploration of the concept space that contains an astronomically large number of alternatives, a specialized tool named M-IRMA was developed in the previous chapter. It is now implemented to conduct favorable alternative concepts selection, in form of homogenous integrated systems, for the selected mission scenarios of Joppa Urban and ARL – IBR. Essentially, the concept space is being explored to down-select from the available pool of alternatives to a number that can be practically analyzed in more detail. The down-selected alternatives are not individual systems, but families of concepts, which consist of MAST technologies that are most likely to be top performers and increase the chances of success for a given mission. The basic premise for further evaluation of the down-selected concepts is that these technologies, based on the required operational functions capabilities, are the only ones capable of accomplishing the mission being analyzed.

To re-iterate, the process begins with enumeration of each of the compatible configurations from the entire concept space. These configurations are then scored based on the mappings, generated from the literature review data and the expert knowledge, between subsystems technologies, technology attributes and operational functions [171]. The operational functions are weighted according to the mission scenario, considering the activities and functions required to be carried out by the MAST systems. Therefore, M-IRMA analysis needs to be conducted for each mission scenario.

Two different types of alternative generation and scoring schemes are implemented to minimize the chances of leaving areas of the concept space unexplored. The first scheme aims to keep the execution time reasonable by limiting the number of saved top scoring configurations, for determining effective subsystems, to 10,000. It uses a progressive down-selection method to find the top performers. The alternative generation script generates a compatible alternative combination, scores it and then adds it to an array. This process is repeated until the desired number of alternatives, *c* - defined by the user, within the array are generated and stored. Then, a second array is created in a similar fashion with next c alternatives. These two arrays are then combined into one (i.e. second array is appended to the first) and sorted, in a descending order, according to the scores of each alternative. The new array is then trimmed to *c* alternative numbers. The second array is now purged and the process is repeated with its re-population. This ensures that the top performers, from each iteration, are saved for the next generation. After desired number of iterations, the process is ended and results are saved in a comma separated values file. Next, an alternative by alternative analysis determines the number of times each candidate subsystem technology appears as a top performer, which quantitatively shows the most effective subsystem choices as the percentage of the top performing entries within a functional group. For the purpose of this research, the value of *c* was selected to be 100 with 1000 iterations.

The second scheme is a brute-force style technique where a very large number of alternatives are generated randomly from all over the concept space. They are then scored, ranked and saved in a comma separated values file. The top hundred alternatives can be then compared to find the most dominating technologies and can be quantitatively shown as % of top hundred. For current implementation, over a billion compatible alternatives were generated and scored.

Both schemes are applied for analyzing the Joppa Urban mission, while only the second scheme is implemented for analysis of the ARL – IBR mission. The results and specific experimental details for each mission scenario are presented in the subsections below:

5.2.1. Joppa Urban mission

Joppa Urban (JU) mission consists of an urban building structure that needs to be explored in the least amount of time, while mapping maximum percentage of the total area. For this step in the overall process, the mission is considered to be benign; no hostiles are present. Enemies are considered to be present during mission level modeling step implementation. The operational function weightings for this mission are shown in Appendix B. The weightings are selected as such to preferentially score technologies that improve path planning, obstacle and entry point detection and communication higher. With these mappings and weightings in place, each technology can be scored individually and provide bases for automated concept space sweep to generate and rank homogenous MAST systems. The top scoring subsystem combinations then represent the integrated MAST systems that have the highest probability of success to effectively perform this mission.

The technologies that consistently scored highest for Joppa Urban mission are listed in Tables 22 and 23, for schemes 1 and 2 respectively.

The results from both schemes are observed to agree with each other and strengthen the intuition that both can be equally effective depending on the mission under consideration. Quad-rotor and flapping wings platforms dominated the results, accounting for about 95% - 100% (depending on the analysis scheme) of top ranking alternatives.

Table 22: Scheme 1 - Top Performing Technologies for Joppa Urban

Category	Subsystem Technology	In top 10,000 performers	In top 10,000 performers (%)
Locomotion	Quad-rotor	2697	26
	Flapping Wings	6947	69
Structure	Flex Joints	6828	68
Power	Primary: Lithium - Ion	7530	75
	Secondary: Fuel Cells (Miniature)	8843	88
Sensors	IMU/LIDAR*	7713	77

Table 23: Scheme 2 - Top Performing Technologies for Joppa Urban

Category	Subsystem Technology	% appearance in top 100 performers
Locomotion	Quad-rotor	24
	Flapping Wings	76
Structure	Flex Joints	54
	Multi-purpose (i.e. Antenna, power)	25
Power	Primary: Lithium - Ion	75
	Secondary: Fuel Cells (Miniature)	100
Sensors	IMU/LIDAR*	100

* LIDAR was modeled as a future technology similar in size to GPS units.

* LIDAR was modeled as a future technology similar in size to GPS units.

Considering that scaling is one of the most important technology attribute for determination of mission success, it is not surprising to see the two platforms that promises to be the smallest and most maneuverable are ranked the highest. Moreover, these technologies are currently the most researched platforms in MAST and also show the most promise at meeting the MAST vision, which is a further validation of the results. Serving as complimentary technologies to these platforms, the most highly ranked structural technologies are flex joints and multi-purpose structural components (e.g. structure as antenna or power source). Flex joints are especially important for flapping platforms and multi-purpose structural components and greatly improve weight reduction. For the functional category of power, the top scoring technologies are Lithium-Ion/Poly batteries as the primary and fuel cells, size modeled as slightly larger than batteries (i.e. future technology), as the secondary sources. These technologies, as modeled, possess inherently superior technology metrics of energy density, size, and mass, which attributes to their top performance. The last category to be analyzed, sensors, produced the highest ranked technology alternative as a combination of IMU/LIDAR, where LIDAR is modeled as a conceptual future technology that is similar in size to today's GPS units with capabilities of a regular LIDAR. As the mission is to be performed indoors only, the LIDAR, at a much smaller size, is naturally the ideal technology to use. For the purpose of this research, it is an enabler technology that will allow MAST systems to position, plan path, and execute Simultaneous Localization And Mapping (SLAM) [96].

It is important to note that for the remainder of this document, the terms ‘quad-rotor’ and ‘rotorcraft’ will be used interchangeably, unless otherwise noted specifically.

5.2.2. ARL – IBR Mission

The ARL IBR (ARL) mission is geared toward providing a map that consists of multiple buildings situated in an open, yet walled complex. This requires the MAST systems to find an entrance to the complex and then explore the yard, while primarily aiming to find the buildings. The interior of these building are the most important areas for exploration. The primary mapping objective is to discover as much total area as possible in least amount of time. Furthermore, this mission map is much larger than Joppa Urban and is considered to be hostile, as enemies are expected to be present. Therefore, MAST systems should explore while trying to avoid detection by the enemy. The operational function weightings for this mission are shown in Appendix C. The weightings are selected as such to preferentially score technologies that improve path planning, obstacle and entry point detection, enemy avoidance and communication higher. Similar to the previous mission, these weightings are used in scoring Scheme 2 to generate and rank a pool of compatible alternatives in terms of homogeneous MAST systems. Again, the top scoring subsystem combinations represents the integrated MAST systems that have the highest probability of success for mission performance in ARL – IBR map.

The technologies that consistently scored highest for this mission are listed in Table 24.

Table 24: Scheme 2 - Top Performing Technologies for ARL - IBR

Category	Subsystem Technology	% appearance in top 100 performers
Locomotion	Quad-rotor	22
	Flapping Wings	78
Structure	Flex Joints	55
	Multi-purpose (i.e. Antenna, power)	28
Power	Primary: Lithium - Ion	86
	Secondary: Fuel Cells (Miniature)	100
Sensors	IMU/LIDAR*	100

* LIDAR was modeled as a future technology similar in size to GPS units.

The results demonstrate that quad-rotor and flapping wings platforms scored highest among the options and accounted for 100% of top 100 performers. The primary metrics for their success included scaling, size and maneuverability. Not surprisingly, these are complimented by flex joints and multi-purpose structural components to aid in weight reduction and efficient actuation mechanisms (i.e. wing actuation for flapping wing platforms). Since, the requirement for endurance is extremely high for this mission, Lithium-Ion/Poly batteries ranked highest as the primary power source and fuel cells (size modeled as slightly larger than batteries - i.e. future technology) top scored as the secondary power source. As before, the most influential technology attributes included energy density, size, and mass. Finally, IMU/LIDAR (with LIDAR modeled as a conceptual future technology that is similar in size to today's GPS units) combination was again ranked the highest considering that the mission requires SLAM capabilities along with the need to explore indoor environment, thus rendering GPS sensors ineffective.

The results for this mission are quite similar to the ones obtained for Joppa Urban. The primary reason for similar alternatives ranking highest is twofold: 1). both missions are similar in nature in terms of the mission tactics and require same operational functions to be carried out, albeit, some are more difficult in ARL IBR mission. 2). the highest ranked technologies are excellent in providing smallest, most maneuverable and long lasting alternatives. Furthermore, the approach provided by M-IRMA is to analyze the astronomically large concept space from systems level perspective and doesn't take into account the navigation logic and details, such as how technologies compare at avoiding enemies. These aspects are analyzed further down the presented process, specifically in mission level analysis module.

The output from this module has down-selected from billions of possible alternatives to a few families of alternatives that can now be further analyzed in-depth using the modeling and simulation modules.

5.3. Screening Level Modeling and Simulation: Netlogo

The next step in the process is to perform mission level modeling and simulation for each of the selected mission scenarios, starting with the screening level analysis. The down-selected families of alternatives, obtained from concept space exploration and the concepts selection, can now be quantitatively analyzed in the SL agent based modeling and simulation environment.

The implementation of this step is highly dependent on the type of mission scenario under consideration and the required level of detail of the outcome. This step can be skipped, and one can proceed directly with the DL mission level modeling and simulation, if any of the following conditions exist:

1. The down-selected families of concept are a number manageable by the computational and time resources available for analyzing them directly in detailed mission level modeling and simulation environment.
2. Computational and time resources are not an issue.

However, the implementation of the screening level modeling and simulation step not only becomes mandatory, but also renders the analysis in the DL environment redundant if following condition holds true:

1. The mission and/or map only require simulation of top level strategy or tactics and 2D level of detail is sufficient to quantify the mission performance of the MAST systems. This case can be referred to as ‘General’s View’ analysis. In essence, it implies that the level of detail required for gauging the success of MAST systems in a given mission is what a military general in his office would need; as in a map of the war zone and anticipated movement of the assets and enemies. The convoy assistance mission defined in previous chapter would fall under this category. The mission performance of MAST systems can be quantified at a reasonable level by looking at the mission from the ‘top-down’ in real time. The primary factors determining the mission success would involve understanding how paths are planned and hostiles are avoided. The 3D details provided by DL environment are not expected to provide any further useful insight.

For the purpose of the research presented in this dissertation, only Joppa Urban mission is analyzed using the screening level environment presented in this section. The results obtained are compared with the similar ones gathered from more in-depth analysis. Conclusions are drawn regarding the added information gleaned from further analyses. Since computational and time resources are deemed to be sufficient, ARL IBR mission is only analyzed using the DL analysis.

With the premise of the modeling and simulation for the screening level defined, the next step is to develop the tool. It is necessary that the selected environment meets the requirements and properties defined for the screening level modeling and simulation in the previous chapter. Several different modeling and simulation platforms are evaluated for the development of the screening level agent based modeling and simulation environment. These are summarized below:

- Netlogo [172]: Developed by Uri Wilensky and developed at the Center for Connected Learning (CCL) and Computer-Based Modeling, Northwestern University, it is a multi-agent programmable modeling environment. It is extensively used around the world and available free of cost. It is also open-source.
- FLAMES [173]: It is a framework for 'easy' and reconfigurable detailed modeling and simulations. It can model very complex environments with detailed specification of agents. However it has a very steep learning curve and not open source.
- Repast [174] : Repast is an open source agent based modeling and simulation environment. It is an object oriented modeler based on Java and enables scheduling of simulations in a hierarchical order. Although the learning curve is not as steep as for FLAMES, it still requires considerable effort and time to adapt it.

Since the core intent of choosing and implementing a modeling and simulation platform is to test the MLMS modules, the factors most heavily effecting the decision are: easy to learn and implement, simplicity, reasonable accuracy of results, and short run time for cases. Considering these, Netlogo is selected as the basis for the screening level environment. It is based on an object oriented language that is suitable for modeling and simulating representative behavior of agents, which enables analysis of the top level system metrics. Netlogo also has the capability to receive inputs and relay outputs to external modules.

The Screening level modeling and simulation environment, based on Netlogo, developed for this research features user-specified inputs for MoPs, swarm parameters, and MoEs, as mentioned previously. The inputs for these parameters are mission dependent and are sourced from QTA level of the framework. It utilizes agent-based modeling logic and enables simulations to investigate effectiveness of MAST systems for a given mission, while taking into consideration the effects of emergent and swarm behaviors. The mission scenarios are designed using GUI that is programmed to enable graphical drawing of elements such as walls, openings, placement of agents, etc [175]. Parameters are defined using input mechanisms such as slider bars and flip buttons. Various types of MAST platforms can be defined or selected including the types of sensors to be equipped. The sensor parameters are also parametrically variable. A screenshot of the developed screening level environment is shown in Figure 35.

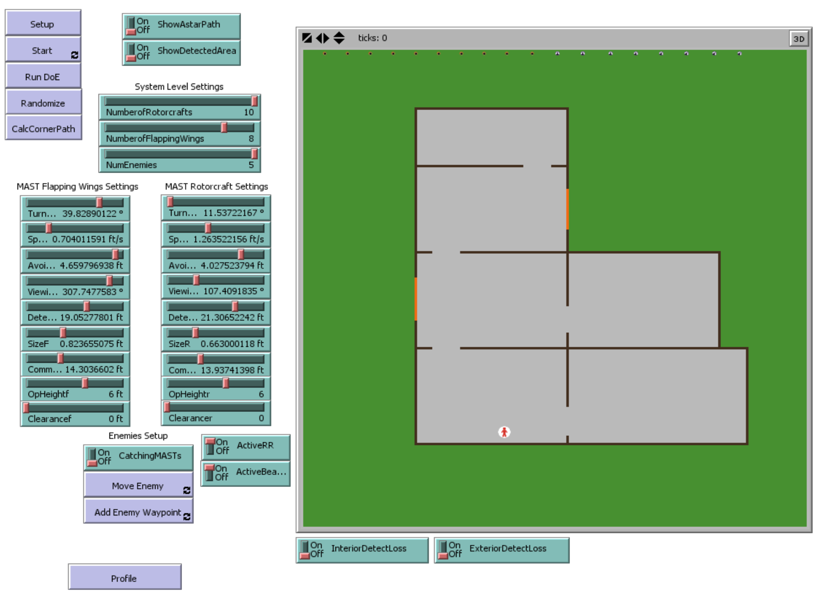


Figure 35: Screening Level Environment in NetLogo

The main focus, at this step in the process, is on analysis and investigation of the agents' behaviors within the mission. It is accomplished by developing the means of simulating robotic behavior at a reasonable level of accuracy. This relies on how an agent perceives and locates itself within the mission space and how it uses information obtained to make intelligent decisions for navigation of the space, which effectively defines its mission performance. The primary source of this logic are the algorithms being developed for MAST and other robotic applications. Furthermore, the interaction of MAST systems with enemies is also considered. The two possibilities of modeling this behavior that are developed in this research are: 1) If MAST system is within detection range of enemy, it is detected and both agents react according to the programmed logic. 2) Simply being in detection radius doesn't necessarily mean that MAST system will always be detected by an enemy. It depends on a probability of detection, which depends on technology attributes of the platform. It is variable throughout the mission, either increasing or decreasing depending on factors such as platform size, speed, operating height, etc. For instance, platforms smaller in size will have a lower probability of detection when compared to larger platforms. These factors are parametrically changeable based on an understanding of humans interactions, including object detection, within the environment.The coding for the simulations was jointly developed by the author and the members of 2010 Grand Challenge MAST team at ASDL, under the author's supervision as the technical supervisor. The coding has generated an autonomous navigation algorithms based on the potential field theory [159] to guide the agents to the objective and A* path planning algorithm. A screenshot of the developed environment with a notional map of a Joppa Urban building layout is shown in Figure 36.

The input parameters are controlled by green slider bars and on/off switches on the left-hand side. These parameters are in the form of MoPs for homogeneous integrated systems based on the down-selected technologies, from previous module - primarily quad-rotor and flapping platforms, with positioning and mapping capabilities. Specifically, following parameters are controlled:

- **System Level:**
    - Number of quad-rotors: total number quad-rotor based platform microsystems.
    - Number of flapping wings: total number flapping wing based platform microsystems.

- Number of enemies: total number of the human enemy units present within the mission map.

- **Vehicle Level:**
  - Speed of flapping wing, Speed of quad-rotor: constant/average speed of flapping-wing and quad-rotor microsystems respectively in m/s.
  - Close range sensor distance flapping wing, close range sensor distance quad-rotor: range for proximity sensor similar to LIDAR.
  - Viewing angle of flapping wing, Viewing angle of quad-rotor: angle for defining field of view. Defines capabilities of camera based sensor on-board vehicles.
  - Detection distance flapping, detection distance quad-rotor: Distance for detecting and recognizing obstacles and other features of the environment.

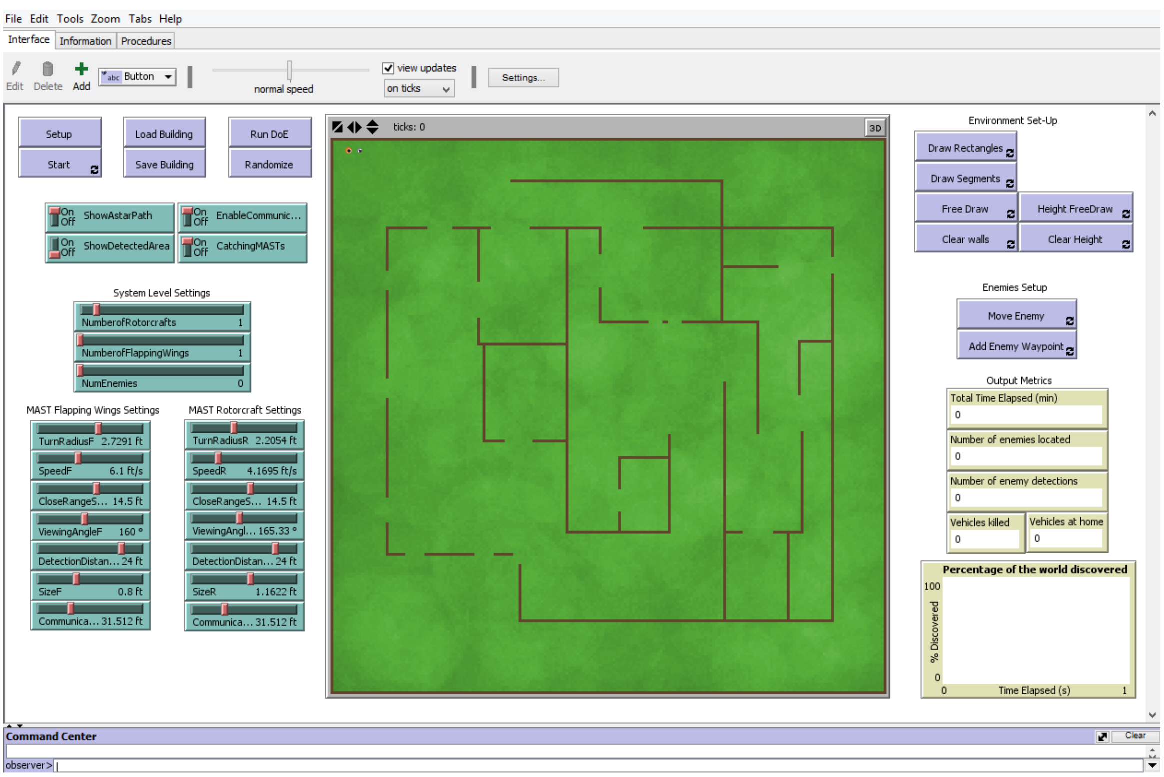


Figure 36: Screenshot of Screening level Environment

The white display boxes and plot charts on the lower right-hand side of the screen track outputs in terms of Mission MoEs. And finally, the blue boxes on the top right are tools for creating mission maps, including building layouts, in a graphical manner using the simulation visualization in the center of the screen. It is a top-down view of the mission in two dimensions, enabling system level analysis as intended. The basic overview of the environment, the assumptions, and the details of modeling and simulation logic are explained in the following subsections.

5.3.1. Vehicle Characteristics

Based on the results obtained from M-IRMA, only the top performing platforms of flapping-wing and quad-rotor are modeled and simulated. The primary differences between the two vehicles are defined by their speed, turn radius, size, and the equipped sensor properties. Each vehicle is considered a point mass and all internal dynamics are neglected. In a given swarm, all modeled quad-rotor vehicles and flapping wing vehicles will have the same characteristics. This is justifiable by considering that it is much more practical, from manufacturing and logistics point of view, to have same units of each platform in a swarm.

5.3.2. Building Characteristics

The building structures and walls are defined by making patches [172] non-passable. This provides the ability to define a building by drawing a top view projection [172] of the map in a manner similar to that used for sketching building blue prints. The width of each wall is fixed as one patch. There is no differentiation between the definition of walls and obstacles such as closed doors or windows. However, open windows and other entry points are defined as openings or breaks in the walls. The size of the openings can be defined as required. Since only single floor buildings can be defined (i.e. limitation of two-dimensional modeling), second or higher floors are modeled as annexed to the side of the lower level.

5.3.3. Equipped Sensors

Each vehicle is equipped with a camera sensor and several distance detecting sensors that mimic the capabilities of a LIDAR. The distance detecting sensors are placed evenly around the extremities of a vehicle. The detection range for distance is defined using vehicle metrics and is same for all four. At any given time, only the closest wall is detected and there is no interference caused among sensors.

The camera sensor is used for detecting enemies and walls. Its detection cone is defined using the vehicle metrics. There is no uncertainty associated with camera based detection. Both camera and distance detecting sensors are limited by the line of sight and can't sense through walls. Finally, all sensors operate in 2D plane.

5.3.4. Navigation Logic

As stated earlier, the navigation logic is based on the potential theory where each vehicle moves in the direction to minimize its potential. At every tick [172] during the simulation, each vehicle can either go forward, left or right. The chosen direction depends on where the potential can be minimized. The turn angle is defined by the maximum turn rate of the vehicle with no in-between values. Moreover, the vehicles only fly at their maximum speed and are not capable of slowing down other than completely stopping.

There is no uncertainty associated with the detected walls, obstacles, and other vehicle positions. These are determined with absolute accuracy and stored as such. Moreover, the environmental effects, such as wind gusts, are not considered.

The potential is determined using the current position of the vehicle and its path history. The potential level decreases as the vehicle moves closer to the target. For these simulations, the target is defined as an arbitrary patch [172] in the middle of the building. It also decreases based on the number of unknown patches that can be explored if a vehicle moves in certain direction. The potential level increases as it gets closer to the walls and other vehicles. Therefore, vehicles tend to explore away from walls and other vehicles in order to minimize the potential. This also ensures that vehicles explore in the direction that will maximize the number of patches discovered. The vehicle history is kept for up to last 30 positions. If the vehicle is still exploring quite close to where it was 30 ticks ago, then it switches to a wall following mode. The intention of this logic is to prevent any vehicle from getting stuck in a room.

Once an enemy is encountered, the vehicles retreat to home or the start point. Path planning algorithm A* is employed by vehicles to take an optimal path, through already explored regions, back to the home base. Therefore, a vehicle will not go through unexplored area unless it has been communicated to it by another vehicle. Moreover, the vehicles do not actively try to avoid previously detected enemies.

5.3.5. Communications Logic

Vehicles are capable of communicating with each other. Each vehicle is able to communicate its list of patches, which it has determined to be either a wall or an open area, to the other vehicles in range. If one vehicle detects an enemy, it can communicate the retreat command to all other vehicles in range and the ones it meets along its retreat path. However, if the vehicle is destroyed by the enemy then it won't be able to warn others about the presence of the hostiles. The dynamics of the communication are discrete. Either the vehicles are able to communicate perfectly or not at all. There is no modeling of interferences or distortion of communication signal. The rules of communication between vehicles are:

- The factors influencing communication are distance, d, and number of obstacles, o, between two vehicles.
- If the vehicles communication distance is more than distance and the number of obstacles between them is less than 2, then the vehicles can communicate.
- If the number of obstacles is more than 2 (or any other desired number) or if the distance between vehicles is more than their communication distance then vehicles can't communicate.

- Finally, quad-rotors and flapping wing vehicles are likely to have different communication distances. For cross platform communication, the larger communication distance metric of the two is considered.

5.3.6. Enemy Logic

The Screening level environment is capable of modeling and simulating enemies. The enemy metrics include turn rate, speed, and detection distance. These values are fixed and can be changed before starting a simulation. The speed of enemies changes depending on whether they are on patrol or chasing a detected MAST system. However, the speed change is discrete with no acceleration associated with it. The enemy patrol path can be defined using the waypoints. If a MAST system is detected, then the enemy diverges from it patrol path to chase it. A vehicle is detected if it enters the enemy's field of view. Being detected is discrete as well and the vehicle is either detected or not. The vehicles are considered captured or destroyed if the distance between them and the pursuing enemy is less than the size of the enemy. The captured/destroyed vehicles immediately cease to move or communicate.

5.3.7. Output Metrics – MoEs

Several output metrics based on the MoEs, previously determined for the missions, are defined in order to evaluate the mission performance of MAST systems. Depending on whether the mission being simulated is benign or hostile, following output metrics are determined and stored:

- **Benign:**
    - **Total Time Elapsed**: The amount of time that has elapsed since the beginning of the mission. The final time stored at the end of each mission signifies the total mission time.
    - **Percentage of the World Discovered**: The percentage of the map explored/discovered. This is a collective metric for the whole swarm.

- **Hostile:** The output metrics for hostile missions include those of benign plus the ones defined below:
    - **Number of Enemies Located:** Defines the number of unique enemy soldiers detected by MAST systems.
    - **Number of Enemies Detected:** Defines the number of times enemy soldiers have been detected by MAST systems. The distinction between the two lies in uniqueness of the enemies detected. Same enemy can be detected by same or different vehicles.
    - **Vehicles Killed:** Number of vehicles killed or captured by enemies.
    - **Vehicles at Home:** Number of vehicles that are able to safely return to start point or home base after completing exploration or upon retreat command.

5.3.8. End Criteria

The simulation for each run ends if any of the following criteria is reached:

- 95% of the map is discovered.
- All vehicles either made it safely back home and/or are captured by enemies.
- Pre-defined mission time has been reached.

Once the end criterion is reached for a given run, all output metrics are stored in a comma separated value file, along with input metrics.

5.3.9. Experimental Runs Setup

With the screening level environment defined and developed, the modeling and simulation experiments are setup in a manner that would enable testing of the hypotheses for research questions defined in Chapter 3. The main goal of the experiments in this module is to gain knowledge about the swarm level performance of a notional vehicle that mimics capabilities of quad-rotor and flapping wing MAST systems, while deployed in Joppa Urban mission. The effect of the mission time and the enemies in the given map are also of interest. It is important to compare the mission performance as mission length changes and how the percentage of the map discovered is affected by inclusion of the enemies. For the purpose of this research, the screening level experiments are designed to provide validation cases for generating credibility in the model. These experiments are based on simpler scenarios with the modeled environment having more controlled elements than variable ones. This enables the expected results to be intuitive and thus provide verification of the developed model. The complex experiments are performed at the detailed level modeling and simulation step and will be discuss later in this chapter.

The simulations are setup in form of an automated DoE, coded within the Netlogo model itself. Since the agent based modeling and simulation is stochastic [157] in nature, due to the effects of the resulting emergent and swarm behavior, it requires each run to be repeated a certain number of times. In order to assess the number of repetitions that will be able to reasonably capture the stochasticity of the model, simulation runs with the same combination of inputs are executed various number of times as the zeroth set. Based on the results of the zeroth set, each run in all subsequent sets is repeated that specific number of times. Considering the above, following experimental sets are defined and carried out:

1. **0^{th} Set - Number of Repetitions**
    - **Purpose:** The purpose of this set was to determine the number of repetitions for each run to capture the model's stochasticity.
    - **Design:** A random DoE (i.e. Monte Carlo [176]) simulation with 360 unique runs. Each run is repeated up to 1000 times.
    - **Expected Results:** The output metric histograms will start to level off after certain number of repetitions and wouldn't change significantly with further increase in number of repetitions.

2. **1st Set - Benign Mission: Area Discovered vs. Mission Time and Number of Vehicles**
   - **Purpose:** The purpose is to evaluate the mission performance, in benign environment, of MAST systems on discovering the area with respect to the mission time.
   - **Design:** A Latin Hypercube [157] space filling DoE with 180 unique runs of benign mission environment. The maximum mission time is limited to 20 minutes. Each run is repeated a number of times based on the results from 0th set. Single and multiple vehicles are simulated.
   - **Expected Results:** The area discovered will increase as the mission time increases and the number of vehicles increases. The effect of increased number of vehicles will be more prominent for longer mission lengths.

3. **2nd Set - Benign Mission: Area Discovered vs. Communication Distance**
   - **Purpose:** The purpose is to evaluate mission performance of MAST systems on discovering the area with respect to the inter-vehicle communication distance.
   - **Design:** A Latin Hypercube [157] space filling DoE with 180 unique runs of benign mission environment. The maximum mission time is limited to 10 minutes. Each run is repeated a number of times based on the results from 0th set. Single and multiple vehicles are simulated.
   - **Expected Results:** The area discovered will increase as the communication distance increases. Similar effect will be observed with increasing the number of vehicles even if the communication distance remains the same.

4. **3rd Set - Relative Importance of Measures of Performance**

- **Purpose:** The purpose is to determine the relative importance of vehicle's MoPs for Joppa Urban mission scenario, when operated as part of a swarm.
- **Design:** A space filling DoE [157] with 360 unique runs of benign mission environment. The maximum mission time is set as 10. Each run is repeated a number of times based on the results from 0th set. Multiple vehicles are simulated.
- **Expected Results:** Several parameters such as vehicle size are expected to be much more important than others.

5. **4th Set - Hostile Mission**: **Area Discovered vs. Presence of Enemies**

- **Purpose:** The purpose is to evaluate mission performance of MAST systems on discovering area in a hostile environment that is patrolled by the enemies.
- **Design:** A Latin Hypercube [157] space filling DoE with 180 unique runs of benign mission environment. The maximum mission time is limited to 10 minutes. Each run is repeated a number of times based on the results from 0th set. Single and multiple vehicles are simulated with presence of 1 to 4 enemies.
- **Expected Results:** The area discovered will decreases as the number of enemies increase. The area discovered will initially increase as the number of vehicles increases but then will decrease because the probability of detection will consequently increase.

6. **5th Set - Hostile Mission**: **Effect of Platform Type**

- **Purpose:** The purpose is to determine whether the screening level analysis can differentiate between platform types and on what level of characteristics.
- **Design:** A space filling DoE [157] with 360 unique runs of benign mission environment. The maximum mission time is limited to 10 minutes. Each run is repeated a number of times based on the results from 0th set. Multiple vehicles are simulated.
- **Expected Results:** The platform type is only expected to be differentiated based on its capabilities (i.e. flying, crawling) and/or if the ranges of parameters are significantly different.

Only the major experimental sets are defined above. There are several other experiments conducted during the course of this research in form of sensitivity studies and their details are presented in relevant sections below. The previously defined experimental sets are simulated and the results from each set are obtained and analyzed. Discussion and conclusions are presented in the subsequent sections. The results are analyzed using SAS JMP statistical package [177]. Mean, scatter, and density plots are primarily utilized to understand the relations between the response and the input variables. The darker areas in density plots represent higher occurrences.

5.3.10. 0th Set – Number of Repetitions

In order to determine the number of repetitions required for reasonably capturing stochastic nature of the simulations, 360 unique cases are simulated with each one being repeated up to 100 times. The results are used to create a histogram and observe patterns to understand the following: at what number of repetitions does the results began to level off reasonably? The results are plotted, for the MoE of the percent of total world discovered, in form of two histograms and are shown in Figures 37 and 38. The first histogram shows repetitions of a single run, while second histogram shows repetitions of the entire DoE. The purpose of the first histogram is to demonstrate that variability of the model is reasonable in terms of the ranges of the output metric. As evident by the plots, the variations within the model are clustered around a narrow range of levels of the response variable. The second histogram can now be utilized to determine the required number of repetitions for sufficiently capturing the model's variability.

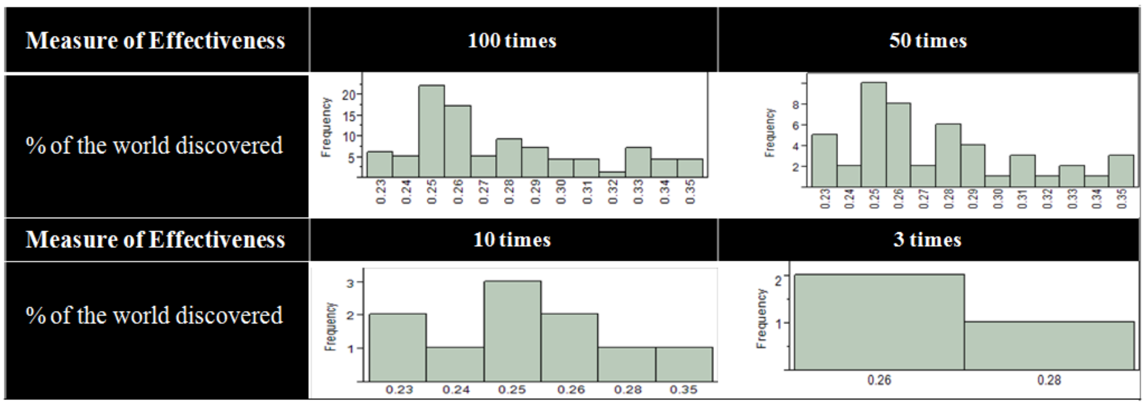


Figure 37: Variability of the Model - Screening Level Single Run Repetitions

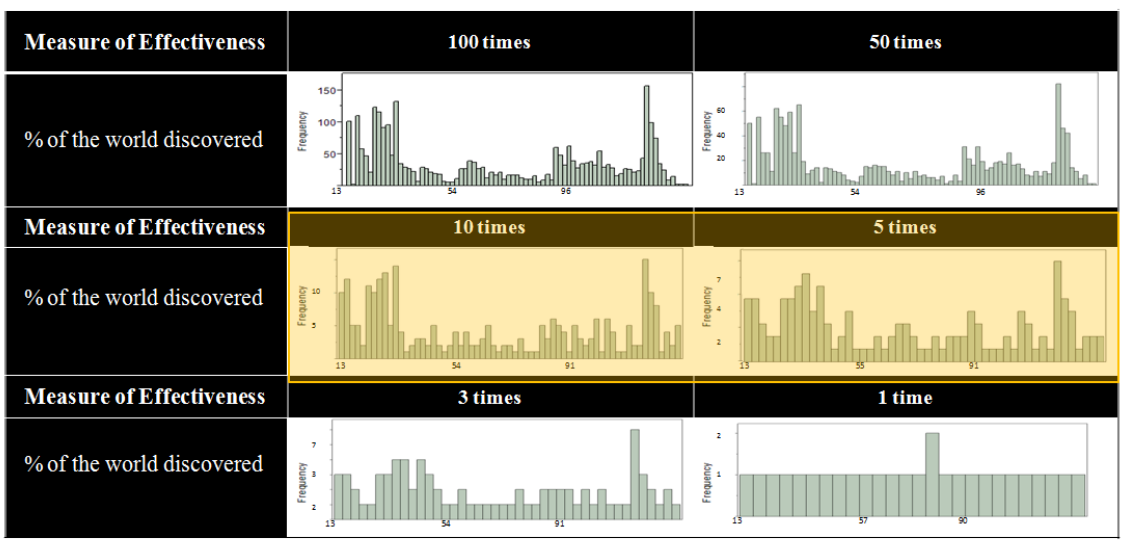


Figure 38: Variability of the Model - Screening Level 360 Runs

Considering the results, it is apparent that after five repetitions of each case, the results begin to give similar distributions as those obtained from higher number of repetitions. Repetitions lower than five show considerable variation in the distributions and signify that the model's stochasticity is not captured adequately. However with ten repetitions, there is almost no visible difference in the results when compared to those from fifty or even hundred repetitions. The slight differences are primarily due to the minor set of runs resulting in outliers. The extremely high number of repetitions is likely to result in such behavior. For all practical purposes, these differences can be ignored without affecting the conclusions to be made from the analysis. Therefore, five or ten repetitions of each case are assumed to capture the variability of the model at a reasonable level and each run in all of the subsequent experiments are repeated as such.

5.3.11. 1st Set – Benign Mission: Area Discovered vs. Mission Time

With the number of repetitions to be made for each run determined, the remaining sets of experiments are initiated, starting with the first set. The primary goal of this experimental set is to gain insight on how mission time affects the performance of a single notional vehicle, representing either a quad-rotor or a flapping wing depending on the parameters, in terms of total area discovered. The experimental design was setup as such to test various mission times ranging from 200 seconds to 1200 seconds. The experimental setup parameters are defined as following, while the design variables and their ranges are listed in Table 25:

- **Mission:** Joppa Urban
- **Conditions**: Perfect:
    - Collisions: No collisions. The vehicle(s) are able to avoid collisions with all objects 100% of the time.
    - Endurance: Unlimited
- **Primary Test Metric:** Total Area Discovered vs. Time
- **Communication:** There is no inter-vehicle communication but the area only needs to be explored collectively. Each vehicle automatically knows, in real time, the areas that have been explored by other vehicles.

- **No. of Vehicle(s):** 1
- **Platform Type:** notional vehicle; parameter ranges encompass both platforms
- **Enemies:** None
- **Mission Time:** 200s to 1200s
- **Vehicle(s) Start Location:** South West - Fixed

Table 25: Screening level Set 1 Experimental Design Parameters

Parameter	Minimum Value	Maximum Value
No. of Quad-rotors	0	6
No. of Rotorcrafts	0	6
Turn Radius (ft), Q	8	40
Turn Radius (ft), F	10	50
Speed (ft/s), Q	0.3	1.6
Speed (ft/s), F	0.1	1.3
Close Range Sensor Detection Distance (ft), Q	6	30
Close Range Sensor Detection Distance (ft), Q	6	30
Viewing Angle (deg), Q	30	360
Viewing Angle (deg), F	30	360
Camera Sensor Detection Distance (ft), Q	5	30
Camera Sensor Detection Distance (ft), F	5	30
Vehicle Size (m), Q	0.1	2
Vehicle Size (m), F	0.1	1
Mission Duration	1	20

* Q - quad-rotor; F - Flapping Wing

Understanding the time duration influence on % of total area discovered can be directly correlated to required endurance for MAST systems. Finding the optimal mission time to achieve the required level of MoE, under consideration, will provide technologies with proper endurance range requirement. The simulations results are shown in Figure 39. It depicts a plot with a mean curve of total area discovered by a single vehicle at different mission lengths. As expected from the perfect world conditions (i.e. no collisions) and unlimited endurance, the total area discovered increases as mission duration increases. No significant variation is observed between repetitions of any given run, which is primarily due to deployment of a single vehicle for accomplishing mission objectives. The primary source of stochastic variation in this research is interaction of vehicles with each other and the resulting emergent behavior. Hence, the exploration of the mission map by a single vehicle minimizes any occurrences of emergent behavior and leads to consistent results.

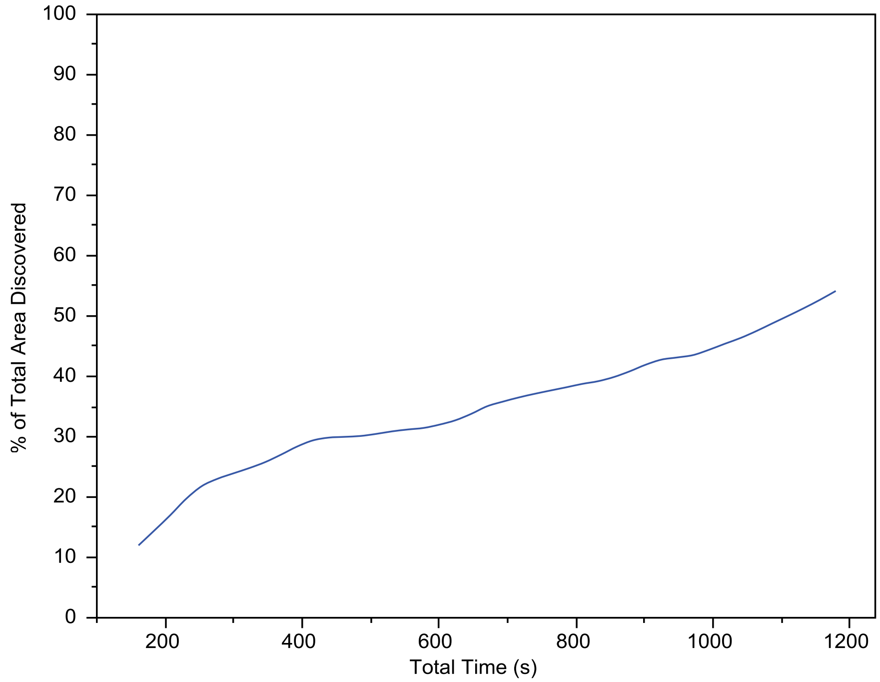


Figure 39: Total Area (Mean) Discovered vs. Mission Time

Analyzing the plot shown, several major conclusions can be drawn. The trend (i.e. mean value) is observed to follow a linear pattern with respect to the mission time. For mission time of less than 500s, it is very difficult for the vehicle to explore more than 50% of the area. For 900s or more of the mission time, over 75% of area is easily explored by a given vehicle. The sudden drop on area discovered at a mission time of less than 500s is attributed to the perceived discrete nature of the map. The urban mission presents an unknown area that consists of several different rooms and enclosed spaces. If the entrance to these places is found, then discovering the whole room or enclosed space becomes rather quick and easy. So given the time constraints, it is observed during experiments that entrances to the right half of the map, especially 'second' floor, are not found for shorter mission lengths. But close to 500s mark, most vehicles are able to find one of these entrances and thus create a sudden spike for total area discovered.

Finally, the slight variation, or shallow peaks and dips, throughout the trend line are attributed to agent based logic of the vehicles exploring the map. Depending on which direction is taken from the start point as well as at any given moment during simulation, the amount of area discovered for that mission is influenced. For instance, if a vehicle initially heads towards larger rooms (i.e. more terrain area) rather towards a cluster of smaller rooms (i.e. less terrain area) then the final outcome of the simulation run would be more area discovered for the former case. As mentioned previously, this can be considered as 'perceived' discrete nature of the mission map. It is justifiable for simulation conditions because the concept mimics how MAST system will likely operate in real life. Without having any prior knowledge of interior of the building, the vehicle would have to decide on the initial direction to take in a rather arbitrary manner. Moreover, this variation is observed to be higher for shorter missions and the dispersion decreases with increased mission time. This is due to the fact that increase mission time dampens the effect of initial direction of movement by providing more time to explore the other areas of the map. Considering these conclusions, the next step is to analyze the effect of increasing the number of vehicles for various fixed length missions. This is accomplished through a sensitivity study.

Sensitivity Study: Effect of Number of Vehicles

The purpose of this sensitivity study is to understand the effect on the mission performance for a given mission time as the number of vehicles exploring the area increases. Two extreme mission lengths are considered for this study, specifically 150 seconds (or 2.5 minutes) and 1200 seconds (20 minutes). This is to ensure that the aforementioned effect can be determined and analyzed regardless of any assumptions on the mission duration (i.e. only for short missions or only for long missions). From studying these two missions, the observed trend, if similar, can be safely interpolated for missions of length within the range.

For each of the selected mission time, a case representing mean performance from 1200s experimental runs is selected to be simulated for exploration ensemble consisting of 2-12 vehicles; each run is again repeated same number of times as it was for the runs in this experimental set. As for the original experimental set, the simulation conditions are deemed to be 'perfect' and there is influence of inter-vehicle communication. Nevertheless, vehicles are only required to explore the area collectively and always automatically know the areas that have been already explored by other vehicles within the swarm. The results are shown in plots in Figure 40.

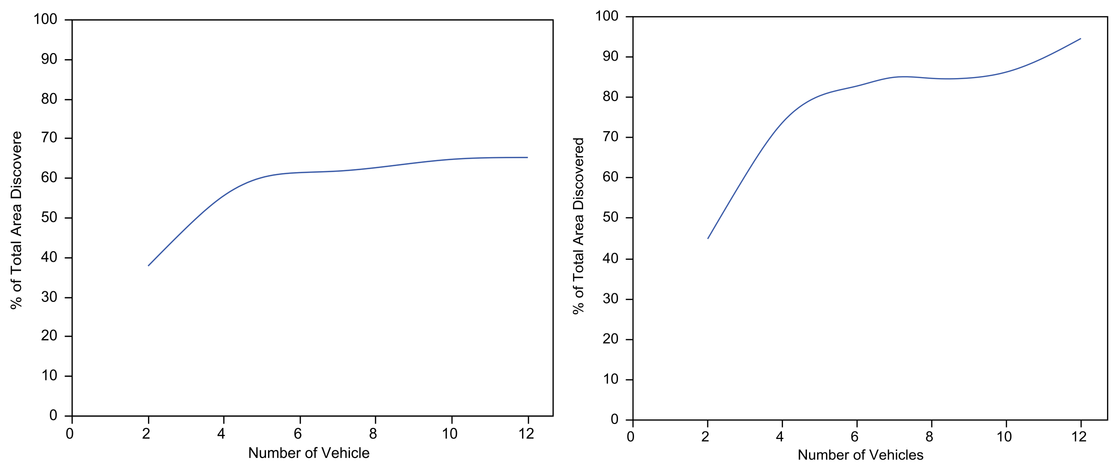


Figure 40: % Area Discovered (Mean) vs. No. of Vehicles - Fixed Mission Time a) 150 s; b) 1200 s

It can be observed from plots above that the percentage of the area discovered increases with increasing number of vehicles, collectively exploring the map, for a given mission time. The result is not surprising as given the perfect conditions of the simulated world; it is the effect of more participants accomplishing the same task. Naturally, the performance will improve with increasing number of participants. However, two important conclusions can be drawn from this sensitivity study. First, the trend is not linear. This is due to the fact that the map being explored consists of a number of rooms within the urban building and is of varying size with different entrances. So, it depends on the navigation and mapping logic of the vehicles on what areas are explored for any given run. Furthermore, increasing number of vehicles also lead to increased chance of emergent behavior as it becomes increasingly uncertain on the paths taken by each vehicle during exploration. The paths taken are dependent upon the areas already explored or are being explored by other vehicles. However, the uncertainty caused by the emergent behavior is reduced due to the perfect world assumptions.

The second conclusion to be drawn is about the occurrence of the point of diminishing mission performance returns with respect to the number of vehicles in the ensemble for the given mission times. It is apparent from the plots that this point is reached rather early for shorter mission time (i.e. for 150s cases). The curve starts to become asymptotic with 8 or more vehicles. This is due to the fact that there are only a finite number of possibilities for navigating the mission map given a starting location. With all the vehicles deployed at the same point, some of them will be required to navigate through already explored areas of the map to get to unexplored areas located further inside the building. However, if the mission time is short, these vehicles are not able to get to those unexplored areas before the mission ends. Hence, the asymptotic nature of the curve can be observed. Finally, this becomes less of an issue as the mission time is increased. Now, there is an ample time for vehicles to find the unexplored areas within the deep interior regions of the buildings before mission ends. So, the point of diminishing return is either delayed or depending on the mission, may not even be reached before mission completion.

Next, the mission performance metric of the area explored is analyzed with respect to the effect of communication distance among MAST systems.

5.3.12. 2nd Set – Benign Mission - Area Discovered vs. Communication Distance

The second set of experiments in the screening level environment is focused on determining the effect of inter-vehicle communication capability on area exploration mission performance of MAST systems. The conditions are quite similar to those of the previous experimental set and most of the design variables and ranges are carried over for this set. Therefore, Table 25 can be referred to for the details. The key difference is that the two vehicles explore the mission map and can communicate with each other based on the parametric setting of the communication distance. These difference and additional experimental settings are summarized below:

- **Mission:** Joppa Urban
- **Conditions**: Perfect with influence of communication distance:
  - Collisions: No collisions. The vehicle(s) are able to avoid collisions with all objects 100% of the time.
- **Primary Test Metric:** Total Area Discovered vs. Time
- **Communication:**
  - The communication capability is measure by communication distance. The tested range is 10m - 142m. Obstacles between two vehicles do not influence communication capability.
- **No. of Vehicle(s):** 2
- **Platform Type:** notional vehicle; parameter ranges encompass both platforms
- **Enemies:** None
- **Maximum Mission Time:** 600s
- **Vehicle(s) Start Location:** South West - Fixed

The inclusion of the communication distance metric is a slight deviation from perfect world assumptions. Although there are still no collisions and the vehicles have unlimited endurance (limited by mission length), they can only communicate, to exchange information about discovered walls and obstacles - influencing the potential field of each vehicle, with each other when within the communication distance. The purpose is to understand the importance of the communication capability and thus the communication equipment on the mission performance. The upper range for communication distance metric was determined by estimating the longest possible distance (i.e. diagonal) of the mission map. This provides a natural practical limit for the maximum possible communication range. According to the designed experiments, as presented previously, the cases are simulated and the results are analyzed below.

The results are presented in a mean curve plot depicted in Figure 41. The trend line shows the mean value of the area discovered for the range of communication distance metric.

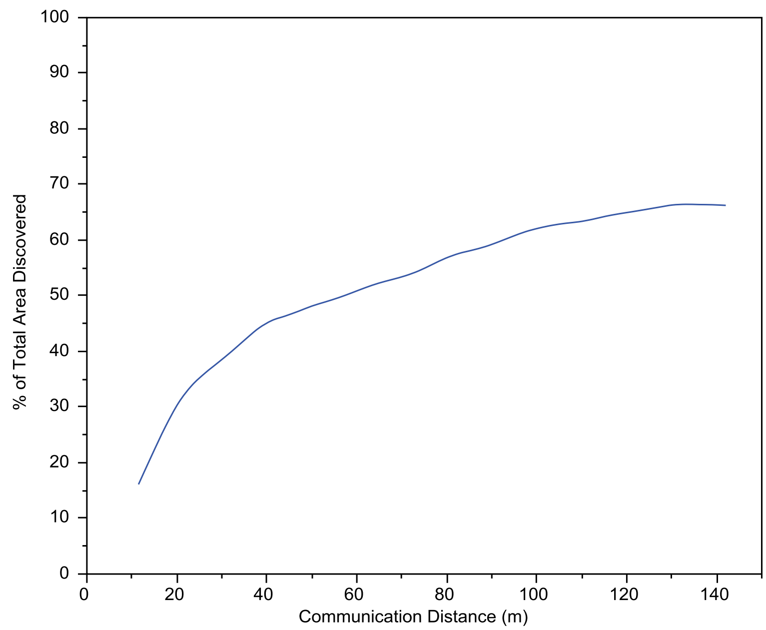


Figure 41: % of Total Area Discovered (Mean) vs. Communication Range

It can be observed that the area discovered increases quite proportionally as the communication range increases. It is not surprising to note this particular behavior of the results pattern. As the communication range increases, the vehicles are able to explore the map more efficiently by exchanging information of their exploration stats. Not only the location of walls and other obstacles are communicated to each other, but the navigation path of the vehicles is also improved by encouraging them to explore areas further away from each other. Essentially, it tells each vehicle to explore an area away from the one being explored by another vehicle. For Joppa Urban mission, communication range of 100m or more leads to over 80% area coverage, within 600 seconds, in several simulation cases.

The trend curve is not completely linear in nature, but it demonstrates that the mission improvement is somewhat proportional to the improvement in communication metric. The slight variations and dips along the way are attributable to the presence of the emergent behavior as two vehicles are exploring the map. Emergent behavior is likely to result in uncertainty. It is further confounded by the effective discrete nature of the mission map, which is caused by presence of various rooms at different locations within an unsymmetrical building. It can be speculated that if more cases, on order of thousands, are simulated, the curve will further smooth-out. However, it will be quite time and resource consuming and wouldn't provide any further useful insight to the problem.

Since only two vehicles are utilized for exploring the mission map in this experimental set, it is logical to study the effect of increasing number vehicles for a given communication range. This is the focus of the sensitivity study presented next.

Sensitivity Study: Effect of Number of Vehicles

The purpose of this sensitivity study is analyze the effect of increasing ensemble size, for a given communication range, on the mission performance for area exploration. In order to present results in a more relevant manner, the communication is directly correlated to the percent of map that it can cover, in terms of the maximum possible distance between two extreme locations. Therefore, communication range corresponding to 30%, 60% and 90% of mission map are the settings chosen to conduct the ensemble size sensitivity study. Cases representing average performance for these communication ranges are selected to serve as baseline vehicles composing the swarm. The results are shown in Figure 42, which depicts mean plots of the percentage of the area discovered by the ensembles of different sizes for the selected communication ranges.

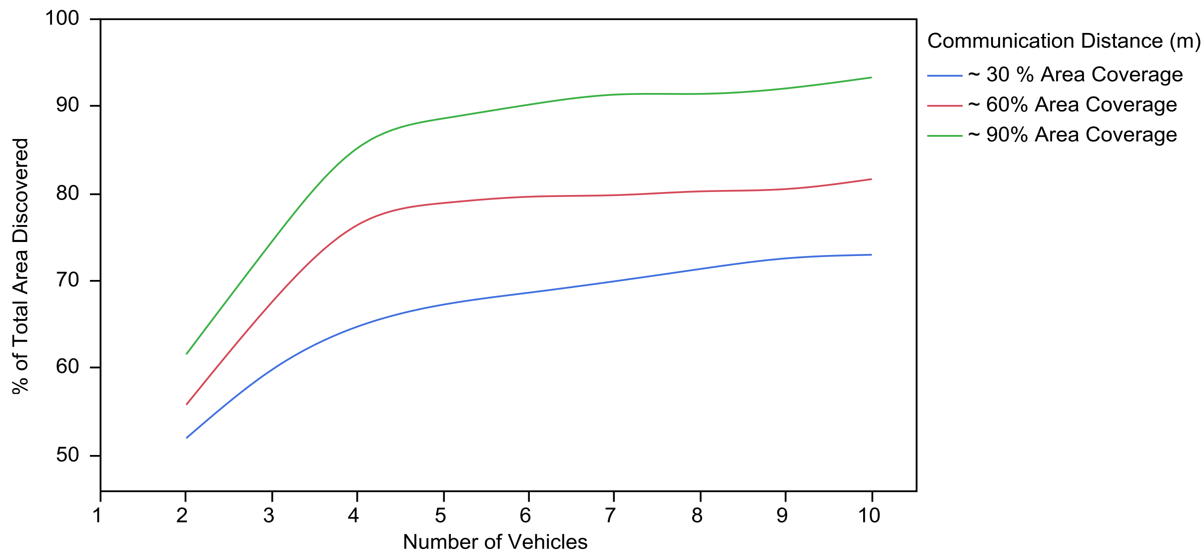


Figure 42: % Area Discovered (Mean) vs. No. of Vehicles - Communication Range

As apparent from the plot, the area discovered increases with increasing number of the vehicles for any given communication range. This is expected result, along with the previous ones, and serves to validate the models developed for the screening level modeling and simulation environment. Taking a closer look at the results, it is can be observed that the performance improvement effect is much more linear for low communication range than for high communication range. The curves for higher communication ranges tend to become asymptotic as the number of vehicles increase. The primary reason for this behavior is that for shorter communication range, presence of more vehicles improves the effective communication range for the ensemble as each vehicle is able to act like a relay point for other vehicles. For instance, if the distance between two vehicles is twice the communication range, then placing a third vehicle between them would result in all three communicating. And hence the performance improvement is much more drastic for short communication ranged ensembles. However, this effect is dampened as the range metric is increased. Now, the vehicles are able to communicate much more freely and the perceived benefit of vehicles acting as 'relays' diminishes.

This concludes the second experimental set of screening level modeling and simulation. The next set deals with determining the relative importance of Measures of Performance (MoPs).

5.3.13. 3rd Set - Relative Importance of Measures of Performance (MoPs)

This experimental set focuses on determining the most important MoPs affecting the percentage of the total area discovered. The analysis also takes into consideration the effect of mission duration on parameter influence. The simulation runs use the same setting as defined in Table 25, and the assumptions of perfect world, no collisions and unlimited endurance, also hold. Both notional flapping wing and quad-rotor vehicles are present at the same time with an ensemble. The ensemble size ranges from 2-12 vehicles. It is important to note that at this time, the consideration of whether or not the screening level analysis is capable of differentiating between the two platforms is not made. This issue will be addressed in the subsequent experimental sets. The mission length is fixed 10 minutes for the experiment and the obtained results are analyzed.

Pareto plot for is utilized to determine importance of design parameters. The plot is shown in Figure 43.

It is apparent that the most important parameters for MAST swarm in execution of the Joppa Urban mission are the number of vehicles, the speed, the turn radius and the detection distance. These parameters not only define the collective behavior of the vehicles as being advantages but also points to the importance of vehicle's agility. The agility of the vehicle is modeled by its speed and turn radius, defining how quickly it can move linearly and change its direction. Coupled with detection distance, the vehicle's capability to swiftly move across the terrain, while detecting the environment features, is captured. And not surprisingly, these are the most parameters influencing the amount of the area discovered for a given mission and maximum time. As explored in the previous experimental sets, increasing the number of vehicles results in positive effect on the mission performance and hence, is a very important SoM level parameter.

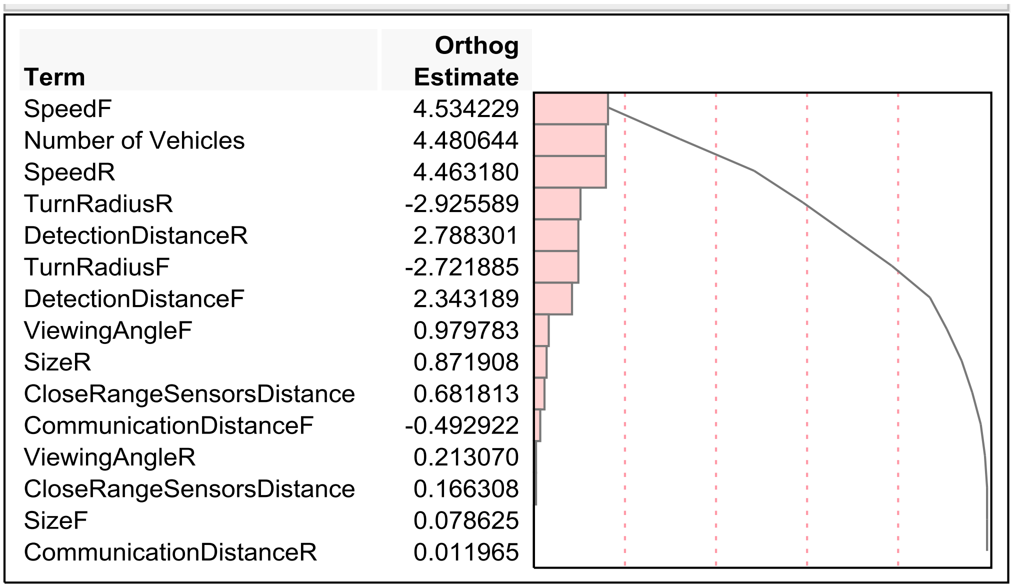


Figure 43: Pareto Plot - 10 Minutes Mission Length

Close range sensor distance is not shown as an important parameter as neither collisions nor object/enemy detection is modeled during the simulations of this experimental set. This serves as another validating result for the developed models. Further effects of MoPs on MoEs are analyzed and studied in-depth during the remaining experimental sets of the screening level and during the detailed level modeling and simulation experiments.

Now, it is time to add a new factor into the mission environments and consider its influence on the mission performance of MAST systems. Joppa Urban mission is made a hostile environment by introduction of patrolling enemies.

5.3.14. 4th Set – Hostile Mission: Area Discovered vs. Presence of Enemies

The format and methodology of the experiments for this set follow closely of the ones for the first set. The primary objective of experiments in this set is to understand the influence of enemy presence on the mission performance of a vehicle, in terms of the area coverage. The assumptions and settings are very similar to that of the first experimental set with the following key differences: One to four enemies are present and are patrolling by default; the maximum mission duration is limited to 10 minutes unless the vehicle is killed by an enemy. The design variable ranges are list in Table 25, while additional simulation parameters, specific to this experimental set, are summarized below:

- **Mission:** Joppa Urban
- **Conditions**: Perfect:
  - Collisions: No collisions. The vehicle(s) are able to avoid collisions with all objects 100% of the time.
  - Endurance: Unlimited
- **Primary Test Metric:** Total Area Discovered vs. Time
- **Communication:** There is no inter-vehicle communication but the area only needs to be explored collectively. Each vehicle automatically knows, in real time, the areas that have been explored by other vehicles. Re-treat command is not communicated and only the vehicle detected attempts to run away.
- **No. of Vehicle(s):** 1
- **Platform Type:** notional vehicle; parameter ranges encompass both platforms
- **Enemies:** 1-4; located inside and outside the building - fixed start locations
- **Maximum Mission Time:** 600s - if all vehicles die early, the mission ends.
- **Vehicle(s) Start Location:** South West - Fixed
- **Primary MoE:** % of total area discovered
- **Secondary MoEs:**
  - Number of enemies located
  - Number of enemies detected
  - Vehicles killed

The logic and the patrol rules of the enemies were laid out previously. The enemy start locations and the patrol paths are shown in Figure 44. Depending on the number of enemies present in a given mission, only certain enemies will appear during the simulation.

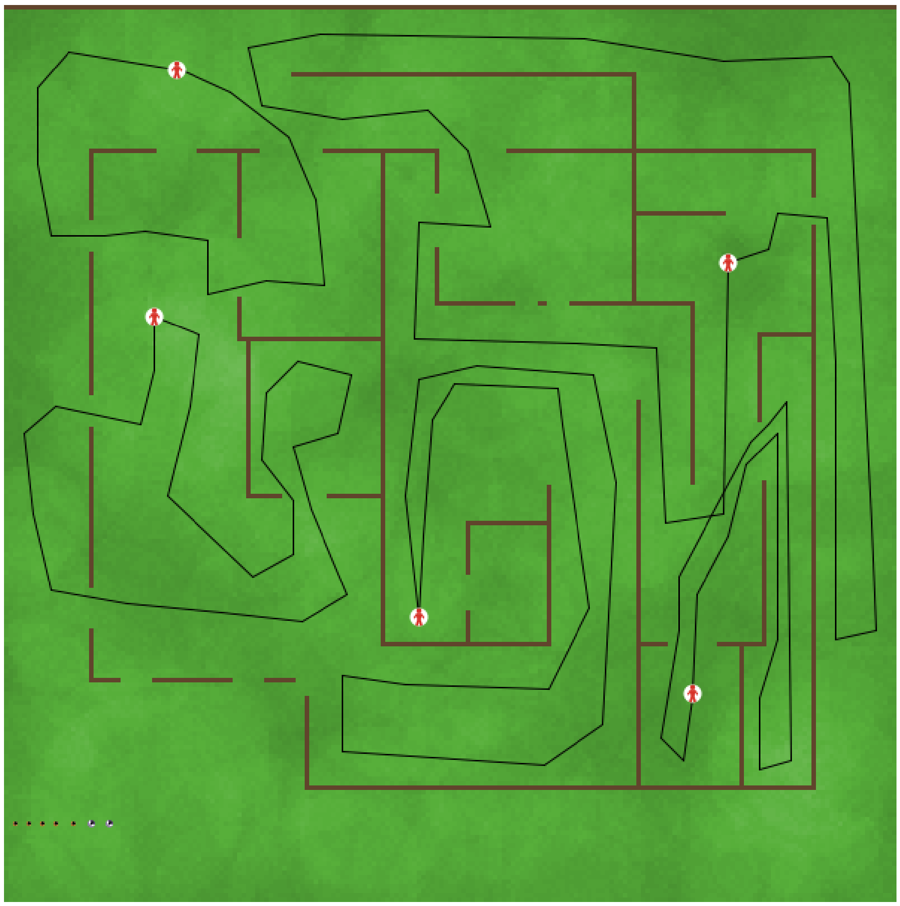


Figure 44: Joppa - Urban Enemy Start Locations and Patrol Paths

The presence of enemies is definitely a complete game changer for MAST systems, even in near perfect world conditions. The vehicle not only has to explore as much area as possible in given mission time but also needs to detect and avoid the enemies. If detected by enemies, the vehicle will attempt to return to the start position, while the enemy will attempt to chase and kill the vehicle. This issue is further aggravated when the number of enemies increases. Therefore, at this point, the intention is to gain insight into how the performance of a single vehicle, exploring unknown map, is affected as the number of enemies patrolling the mission map is increased.

The results of experiments are shown in Figure 45. The two plots show the same data in form of a mean curve and a bar chart, respectively.

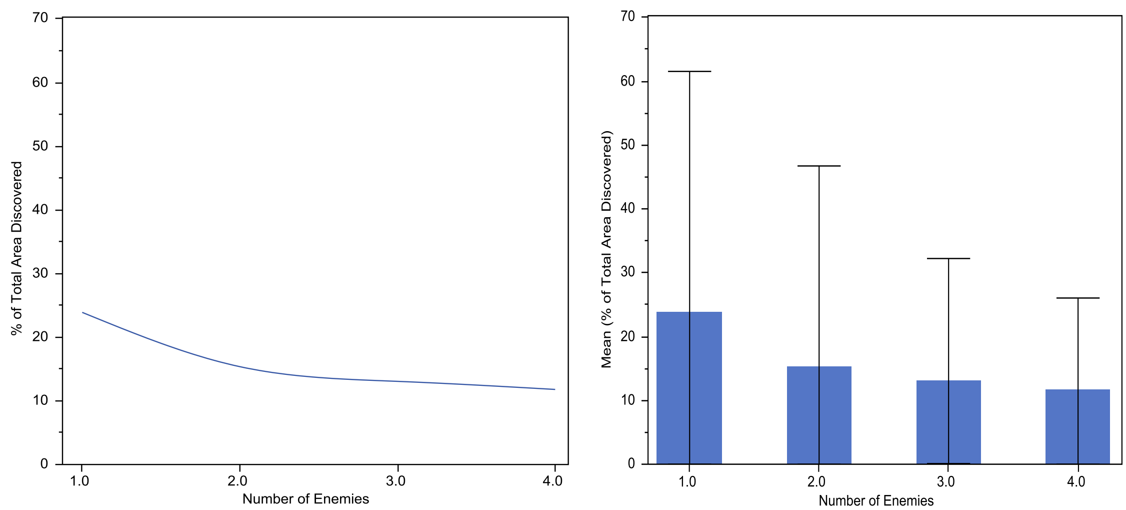


Figure 45: Area Discovered vs. No. of Enemies

As apparent from the plots above, there is a notable decrease in the area coverage with inclusion of the enemies. The effect is quite significant as the number of enemies increase to two or more. And the reason is that the start location of the enemies is fixed. The first enemy is located in the interior of the building and thus affords the exploring vehicle some liberty to discover a bit of area, mostly exterior, before being detected. However, as the number of enemies increase to two and three, this provision is diminished as enemies now start not only in the interior of the building but also on the outside and close to start location of the MAST vehicle. Going further, the effects of the enemies seem to dampen as they are increased further because the size of the map remains the same. So, three enemies are able to perform just as well as the inclusion of the fourth one. Nevertheless, there is a clear trend for decreased performance of the vehicle for discovering the unknown area. With four enemies present, the difference in performance is, on average, around 15% when compared to a mission with single enemy on patrol.

At this point, the logical question to ask is how the presence of the enemies will affect the performance of a MAST swarm of varying size. This question is addressed in the next sensitivity study.

Sensitivity Study: Effect of Number of Vehicles

The primary objective of this sensitivity study is to analyze the effect of enemy presence on the area explored mission performance as the size of MAST swarm changes. In the first experimental set of the screening level analysis, it was observed that increasing the number of vehicles resulted in improved area coverage for a given mission time. So, for a given mission time and number of enemies, the mission performance for swarm sizes of 1 to 10 vehicles is now studied.

The most important factor to consider for this study is the mechanics of vehicle detection by the enemies and the resulting response of the vehicle as an individual or a group. This effectively determines how 'stealth' behavior of the vehicles is defined. Since there is no inter-communication between the vehicles and the re-treat command for nearby vehicles is not effective, the stealth of each vehicle is measure individually. This means that only the detected vehicle will abort its mission and attempt to return to home base or start location. Other vehicles will continue to explore the mission map. So in essence, the collective stealth of the vehicle decreases with increasing number of enemies and vehicles.

The sensitivity studies are conducted for two enemy settings, specifically two and three enemies present, with maximum mission time fixed at 600 second. The results of the simulations are shown in Figure 46. Analyzing the plots above for presence of two and three enemies, the first observation to be made is regarding the similar shape of the trend line (mean) for both mission settings.

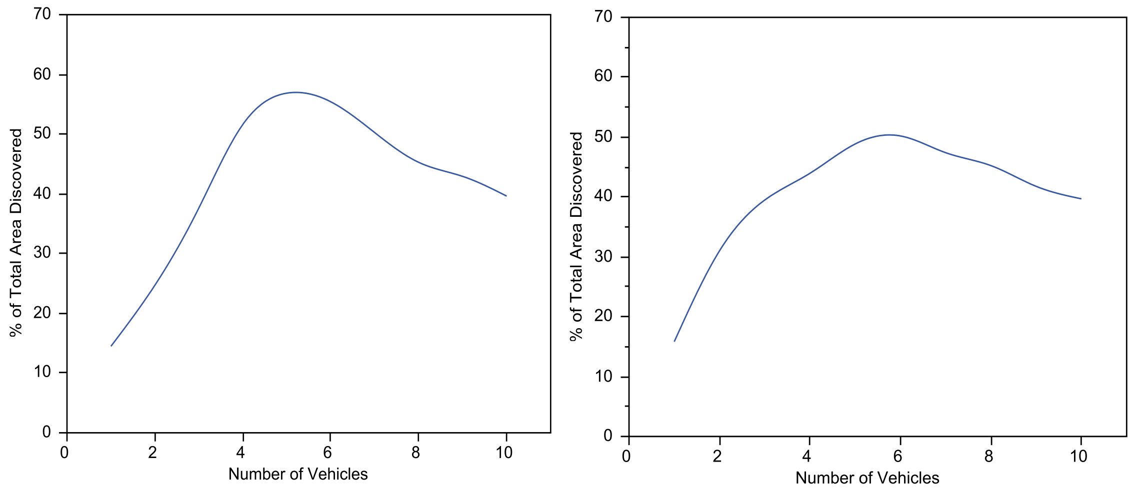


Figure 46: Area Discovered (Mean) vs. No. of Vehicles - Enemies Present: a) 2; b) 3

The mission performance of the swarm initially improves as the composing number of vehicles increase. However, it reaches its peak at around 4-6 vehicles and then the performance starts to decrease. The main reason behind this trend lies in the conflicting nature of the performance improvement afforded by increased number of vehicles and the resulting decrease in stealth. As more and more vehicles are added to the swarm, the probability of detection by the enemies also increases. Therefore, the peak performance is a compromise (or intersection) of the improvement afforded by increasing stealth and the increasing number of vehicles. And for Joppa Urban mission, it is between 4 to 6 vehicles, as apparent by the results.

The next conclusion to be drawn is based on the difference between the presences of either two or three enemies in the mission. As explained above, the trend is similar for both but only differs in magnitude. As expected, increased number of enemies decreases the mission performance of MAST SoMs across the board. On average, it seems that the area coverage decreases by around 5 to 10 percent.

Before moving on to next experimental set, a detour is taken to analyze a more complex version of Joppa Urban mission scenario by deviating considerably from 'perfect world assumptions' and simulating variations in more parameters at the same time. Although collisions are still not modeled, all other defined parameters are varied. It is important to keep in mind that the results from the extra follow-up experiment may not be intuitive due to increased influence of the emergent behavior.

Follow-up Sub-Experiment - Vehicles Return Home

The purpose of this follow-up experiment is to analyze the number of vehicles that are able to safely return home or to the start point, once an enemy is spotted. The context of analysis also includes the influence of the number of enemies present in the mission. Figure 47 shows the density plot of the number of vehicles that are able to return home versus the number of enemies and swarm size.

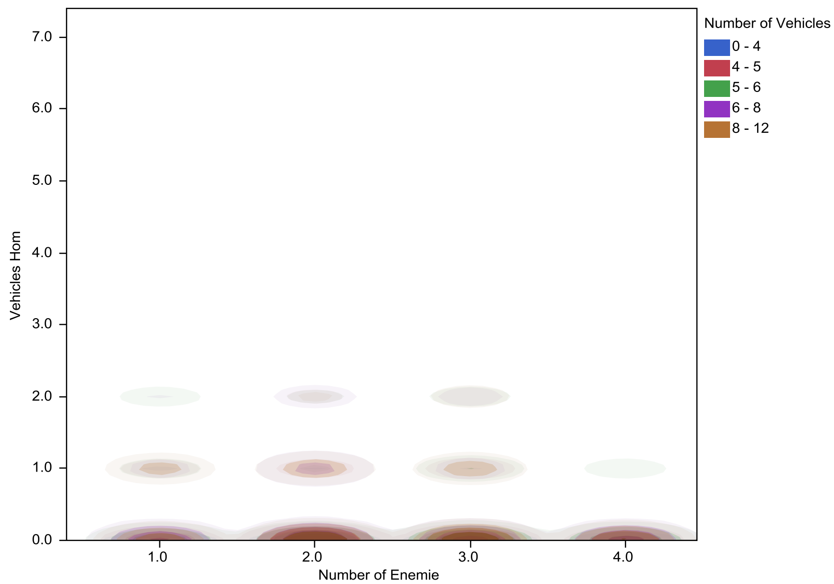


Figure 47: Vehicles Retuned Home vs. Number of Enemies

It seems that vehicles in bigger swarms are less likely to be able to make it back safely compared to those in smaller swarms for the same number of enemies. The reason for this, observed during the simulations, is not only that having bigger swarms increases the probability of detection but also that vehicles are more likely to hinder each other's retreat as they scramble to avoid getting captured.

This concludes the analysis of fourth set of the screening level experiments and presents a transition into understanding the effect of platform type on the mission performance.

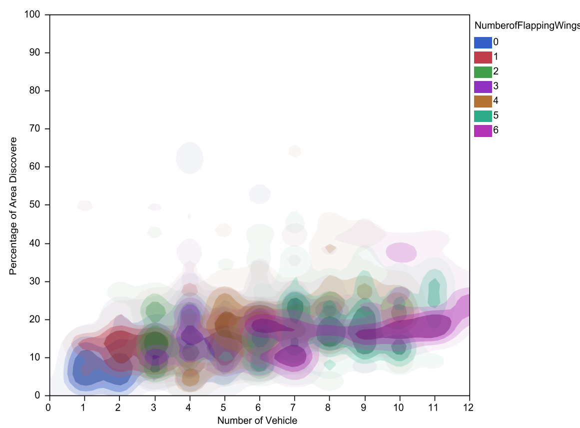
5.3.15. 5th Set - Effect of Platform Type

The final set of experiments at the screening level of modeling and simulation is intended to study how the type of platforms is differentiated during the simulations. In order to assess this effect, a more complex version of hostile Joppa Urban mission scenario is implemented. It deviates from the 'perfect' world assumptions in the following manner: 1) vehicles can cause hindrance for each, especially at entry points; 2) communication distance determines the sharing of the knowledge of the map; 3) detected vehicles send a re-treat command to other vehicles in range. The collisions are still not modeled and will be considered in the detail level modeling and simulation module. The simulations are setup as defined above and the obtained results are primarily analyzed using the density plots. With the presence of enemies, the goal is to understand if the outcome of the simulations differed based on the platform type of swarms. It is concluded above that the presence of hostiles in the mission results in drastic decrease in mission performance of the MAST systems.

In foresight, considering the similar capabilities and parameter ranges of both platforms, it can be hypothesized that there wouldn't be any difference in the outcome based on platforms. The screening level analysis is expected to treat them similarly and the DoE ensures that are results will be statistically similar.

Figure 48 show plots for the percentage of the total area discovered versus the number of vehicles and are overlaid with the number of flapping wings quad-rotors.

As predicted, analyzing the data shows no apparent difference, based on the platform type, on mission performance of the two platforms. Both platforms' mission performance follows the same generalized trend as discussed above. This conclusion fortifies the hypothesis that at the screening level, the simulation is only able to distinguish between platforms based on the functions they perform and ranges of their MoPs. For platforms that perform exactly the same functions and have overlapping MoP ranges, the screening level environment effectively treats them in a similar fashion and the mission performance only differs based on their individual technology attributes. Finally, the similar results also attest to statistical credibility of the simulations as mentioned above.



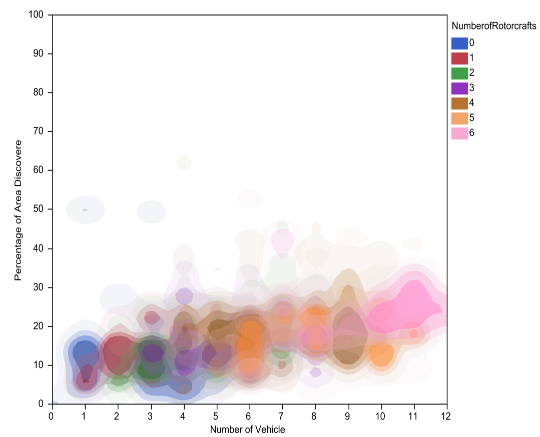


Figure 48: % of Total Area Discovered vs. No. of Vehicles - a) FW; b) Quad

Taking the analysis a step further, a closer look is taken at the composition of the swarm based on platform type and their specific numbers. A density plot for number of quad-rotors versus number of flapping wings is overlaid with the percentage of the total area discovered and is shown in Figure 49.

It can be observed that although the platform type isn't very influential on the percentage of the area discovered, improved performance is more densely present for equal number of both quad-rotors and flapping wings within the best performing range of swarm size, 4-7, for this particular set of experimental conditions. This is not a surprising result as both systems are capable of same capabilities (i.e. hover, forward flight) and their technology attributes ranges are quite close to each other. Hence at the screening level and 2D simulation, the resolution of analysis is not high enough to effectively distinguish between these two platforms.

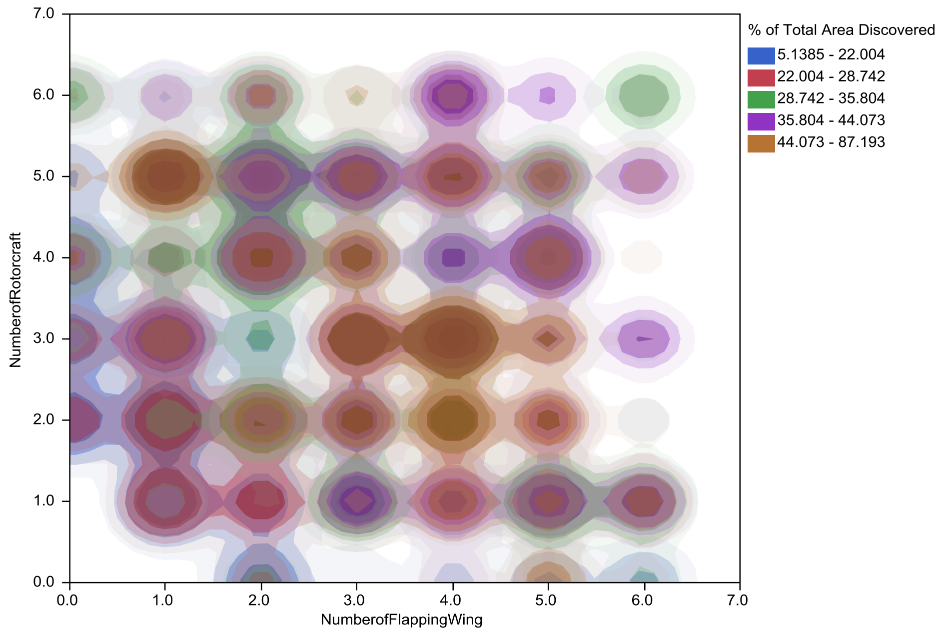


Figure 49: Swarm Composition - Screening level Joppa Urban

Nevertheless, the purpose of this level of analysis is to gain insight into very top SoM level MoPs, specifically swarm size, and the experiments in this set provide a quantified range for it. System and other lower level MoPs will be evaluated in the DL modeling and simulation environment later in the process.

These results and analyses conclude the fifth and final set of experiments performed in this step using the screening level modeling and simulation environment. A brief summary is presented below, paving the way for development and implementation of the remaining modules.

5.3.16.Summary - Screening level Results

A screening level modeling and simulation environment was developed based on Netlogo agent based modeling platform. The Joppa Urban mission was modeled, simulated and analyzed to perform controlled experiments for validating the underlying models and serving as a proof of concept for the presented methodology. Several assumptions for defining 'perfect' world were implemented to analyze the intuitive cases.

The obtained results were as expected. Furthermore, some complex follow-up experiments that significantly deviated from the 'perfect' world assumptions were carried out to determine the required MoPs values for mission success based on the primary MoE of the percentage of the area discovered. The results weren't expected to be intuitive and several fundamental quantitative insights were gained for the effect of the swarm size on the mission performance. Furthermore, the presence of enemies was also simulated and analyzed for its effect on the mission performance as compared to benign missions.

The experiments and results from this module are going to pave the way for further analysis of the Joppa Urban mission, along with the ARL IBR mission in the detailed mission level modeling and simulation environment. As the next level of analysis requires detailed modeling of MAST systems, sizing relations are invoked to generate a pool of feasible alternatives, based on different technology years or levels. The results output from the next step not only include the detailed level analyses but also consolidates the information obtained from all the previous modules. This enables simultaneous gap analysis, which leads to requirements redefinition.

5.4. Detailed Mission Level Modeling and Simulation, Sizing Relations and Gap Analysis

The next step in MAST mission effectiveness quantification and technology assessment framework is to analyze the down-selected platforms and technologies (i.e. from M-IRMA), while leveraging the insights gained on desirable ranges of MoPs that are more likely to result in better mission performance, for setting up the experiments. These filtered technologies and the MoPs are now going to be modeled and simulated for Joppa Urban and ARL IBR mission scenarios in a Detailed Level (DL) environment. Furthermore, sizing relations presented earlier are going to be utilized to generate a pool of technically feasible alternatives for current and future technology years. This coupling of modeling and simulation and sized alternatives ensures that the physically simulated vehicles, using agent-based logic, are not technically un-realistic for given technology years. It also enables the modeling and the simulation of vehicles built on scaled technology attributes, using k-factors, to conduct trade studies. The detailed mission level modeling and simulation environment is first selected and developed along with the sizing tools.

Finally, the gap analysis is conducted on the results obtained from the DL environment. Coupling of gap analysis with simulation results not only leads to the next step of requirements re-definition in this framework, but also aids in presenting the conclusions of the research in a coherent manner. The validation experiments for the DL environment will follow closely afterwards.

5.4.1. DLMLMS Environment Selection and Development

The requirements of the DL environment were laid out in the previous chapter, along with the primary inputs for modeling and simulation. A choice of environment can be now made based on the framework defined. For the purpose of this research, three modeling and simulation environments are explored and summarized in Table 26.

Table 26: DL Environment Options

Selection Criteria	USARSim [178]	Gazebo [179]	UberSim [180]
Fidelity of Environment	+	+	0
Fidelity of Physics Modeling	+	+	0
Ability to Add Robotic Control Interface	0	+	0
Expandability	+	+	0
Visual Aesthetic	+	0	0
Number of systems in same run	0	-	0
Acquisition Cost	+	+	0

Based on the selection criteria, USARSim is selected as the platform for the DL modeling and simulation environment. USARSim [181] stands for Unified System for Automation and Robot Simulation, originally developed by National Institute of Standards and Technology (NIST) and Carnegie Mellon to be a high-fidelity simulation tool for robotic systems and virtual environments. It is based on Unreal Tournament game engine [182] [183]. The core purpose of USARSim is be used as a research tool and it also used in RoboCup [184] and VMAC [185] competitions. The components are graphically shown in Figure 50 [23]. Combining UT2 (version of Unreal Tournament 2004) and USARSim provides a detailed mission level modeling and simulation environment for MAST quantification framework. The modeled environment shown in the aforementioned figure is based on city of Mogadishu features in ‘Black Hawk Down’ movie. The UT2 is an industry standard game engine that models a virtual world in which simulations can take place. Not only it is readily available, it also has a built in physics simulator that is reasonably accurate for vehicles. Moreover, it is designed to be practically modifiable to serve as a foundation for other games and simulations.

USARSim is serves as a bridge between external controller scripts or programs, which define a simulated vehicle’s behavior and the Unreal Tournament environment, built on Karma [186] physics engine, which simulates the vehicles and the mission maps. A graphical representation of the major components depicting information flow and interrelations is shown in Figure 51. The first step in setting up the simulation is to build the 3D virtual world, based on given mission scenario, in a fashion that is similar to graphical 3D modeling today. The tools and process for architecting the world will be described in a later section. Once it is created, the UT2 engine handles all rendering, physics and high level interactions such as collisions. The USARSim component establishes a connection (TCP/IP [187]) to UT2 rendered physical world to extract level data and telemetry from its otherwise proprietary protocol.

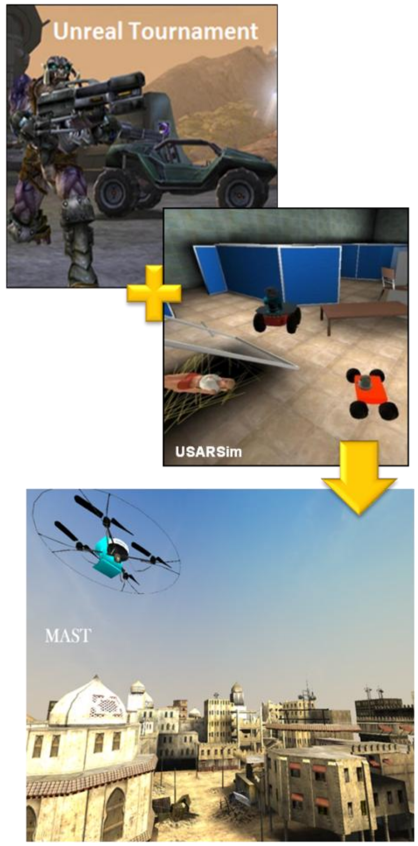


Figure 50: DL Environment [23]

UT2 also provides a library containing some standard models of robots (i.e. wheeled, aerial), sensors, and mission packages (i.e. pan tilts, grippers). A user can always develop customized robots, sensors and other components. The established connection also enables external controller scripts to obtain telemetry data and input high control commands to UT2, which results in simulation of the robot mimicking its behavior in the real world. The most important capability obtained through DL environment is that the controller acts in the same way as if it were a real robot instead of a virtual one. The external controller scripts define the behavioral and mission logic for integrated MAST systems. For instance, the vehicles can be programmed to use wall-following [188] or frontier-based exploration algorithms [189].

A user can also program other navigation and mapping algorithms such as Simultaneous Locating And Mapping (SLAM) and A*. The mission behavior can be defined using agent based logic, thus forming a hybrid simulation environment that combines physical world with agent based modeling logic. Moreover, these scripts can control several different vehicles at the same time in a single simulation, enabling detailed level modeling and analysis of emergent and swarm behavior.

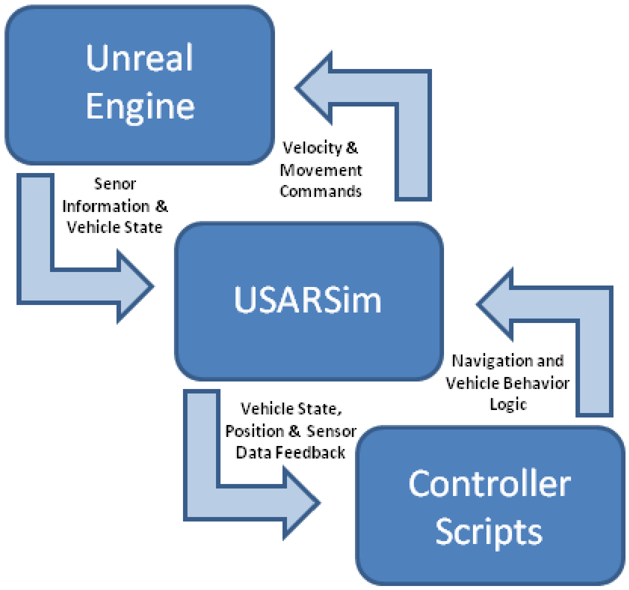


Figure 51: Detailed Level Environment Components and Information Flow

Therefore, the DL environment serves as a platform to test various autonomy and mission logic algorithms.

Navigation and Mapping Algorithm

For the purpose of this research, all external controller scripts are programmed using C++ and Python programming languages. Socket communication is used for connecting the vehicle logic scripts to USARSim. The programmed controllers, defining the behavioral and mission logic for integrated MAST systems, act in the same way as if it were a real robot instead of a virtual simulation. As mentioned above, the mission behavior is defined using agent based logic and parametrically variable vehicle MoPs.

For simulation of both Joppa Urban and ARL IBR missions, the navigation and the mapping behavior of the vehicles are defined in the following manner: the mission map is first discretized by defining spaces that are physically accessible in form of a network of nodes [190]. In essence, the task of mapping is partially done at the mission architecting level by denoting spaces that the MAST vehicles can physically explore. The node based discretization and assignment can draw an analogy similar to that of meshing for a CFD or FEM application. The objective is to ensure that the simulation space is discretized/covered at a desired or reasonable level of detail. As expected, the computational resources and time required for the simulations increase as the number of nodes increases. Figure 52 shows nodes and resulting physical space mesh for Joppa Urban mission.

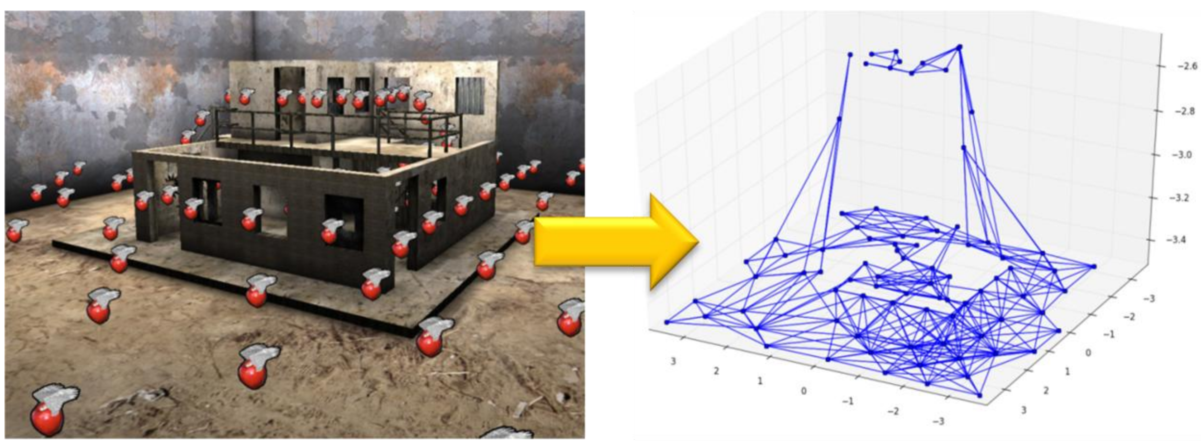


Figure 52: Joppa Urban - Nodes Placement and Physical Space Mesh

Depending on the availability of the computational and time resources, the mesh can be made as fine as desired. It is important to note that the navigation paths are not being defined at the moment and only the possible exploration space is defined. Therefore, the passable space is represented by nodes and clear Line of Sight (LOS) is represented by the edges connecting the nodes.

Once the physical space is discretized to the desired level, the vehicles are then programmed to detect and identify the passable space and use A* path planning algorithm [98] to explore the map. The obstacle avoidance and enemy detection is enabled through the use of equipped sensors such on-board LIDAR, video camera and other sensors.

The primary motivation for this method is two-fold. First, the intention of this research is not to develop a state of the art mapping and navigation algorithm. Extensive research is being currently conducted on the methods to improve navigation and mapping algorithms. The purpose of this environment is to provide a platform that would enable researchers to plug in their algorithms and virtually experiment with MAST vehicles. Second, this research aims to determine the technology levels in terms of MoPs that are more likely to result in successful mission completion. This requires modeling and simulation of not only future hardware but also future mapping and navigation algorithms. By utilizing the above mentioned mapping and navigation scheme for MAST vehicles, one can parametrically control its behavior and hence be able to simulate varying levels of autonomy based on current and expected future developments. Although this provision is not extensively explored during the research, it is strongly recommended as part of the future work.

For inter-vehicle communication, two similar yet slightly different kinds of schemes are utilized. The first one is termed as 'Informative', where vehicles only inform other vehicles, within range, about existence of unexplored areas or nodes. All vehicles are required to explore all of the nodes or required map area to complete the mission. The purpose of this scheme is to focus on the performance of each individual vehicle, while being a part of a swarm. In this case, the communication is essentially increasing the detection range of the vehicles. The second communication scheme is termed as 'Collaborative' and the vehicles explore the whole mission map collectively. This means that once an area or node has been discovered by a vehicle, all other vehicles in the range will assume it to be explored and move on to other unexplored areas of the map. This scheme focuses more on mission performance of the swarm as a whole rather than performance of individual vehicles as part of the group. Both schemes are implemented during simulations, for various experimental sets, to gain understanding in technology gap and mission requirements from both perspectives.

The scripts were coded by the author, Aaron Mosher and Pat Dees. They were later debugged and improved for communication (including the addition of two communication schemes) by the author and Arun Ramamurthy. These contributing members were part of the MAST Grand Challenge teams at ASDL and were technically supervised by the author [191].

With the framework of the DL modeling and simulation environment laid out, vehicle and mission logic controllers developed, the next step is to model the two mission scenarios of interest at the defined level.

Architecting Mission Environments

In order to run simulations, it is imperative that the mission scenarios are virtually built to represent the world in which MAST systems will operate. The advantage of building the DL environment on USARSim/UT2 platform is that it affords user a very practical method and process of architecting the mission maps. And it is relatively not very difficult to implement. The mission is built by developing a 3D cad model of the map using the arrangement and dimensions from mission blue prints and/or actual physical structures, if available. Unreal Tournament provides a graphical interface based 3D modeling environment known as 'Unreal Editor' for solid modeling of the missions. However, during the course of this research, a combination of Google SketchUp [192] and Unreal Ed is utilized to architect the missions. The reasoning behind implementing a third party software is that Google SketchUp is free and quite simple to use. Parametric 3D CAD models can be quickly generated to serve as the mission maps. This reduces development time and the generated models can be readily imported to the Unreal simulation environment, providing the backdrop for physics and agents to interact within.

Therefore, the baseline CAD models of both missions are generated using SketchUp and then textured in the Unreal Ed. The mapping nodes are also placed using Unreal Ed at this point. Figure 53 [129] and 54 depicts development process of Joppa Urban mission using actual blueprints [193] and the modeled building placed in the city of Mogadishu, respectively. The mission is geometrically modeled to keep it as close to the reality as possible, allowing simulation results to be of very high details. The modeled mission is capable of serving as a virtual experimentation platform for the mission maps and expected to provide results that closely approximate the trends from real life experiments. Similarly, an architected view of ARL IBR mission with placed nodes is shown in Figure 55. ARL IBR is architected using the details from the 'Black Hawk Down' movie and engineering judgment.

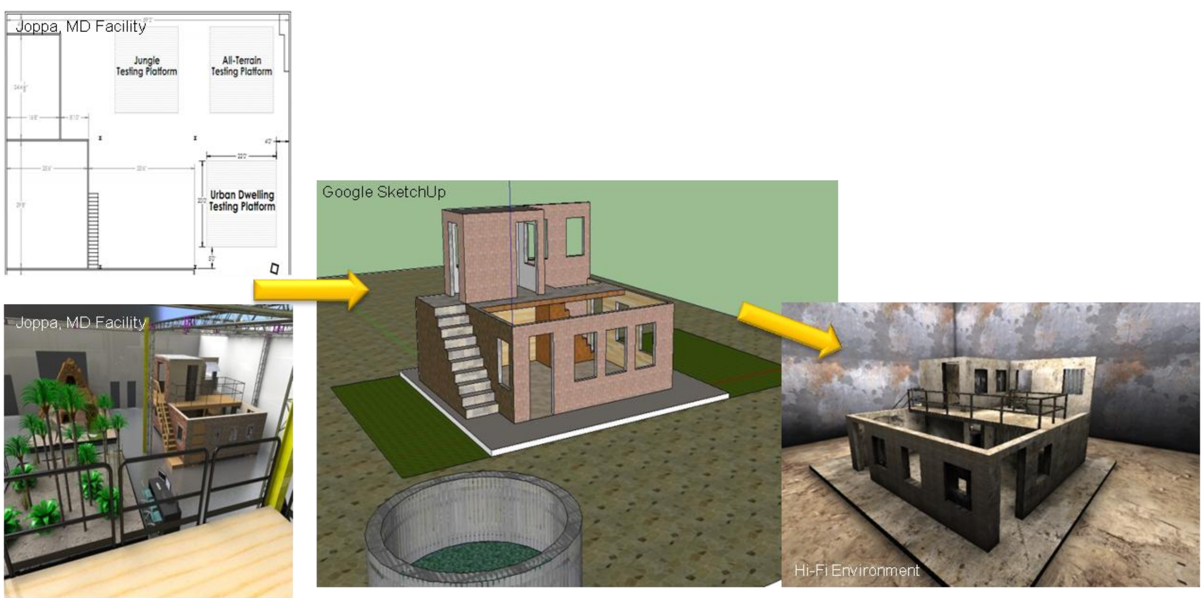


Figure 53: Architecting Environment [129]

The missions were modeled and architected by the author, with assistance from Pierre Valdez. The nodes were placed by the author, with assistance from Arun Ramamurthy. Again, these tasks were accomplished by the contributors, other than the author, as part of their Grand Challenge team tasks and were directly supervised by the author.

Figure 54: Joppa Building for Urban Mission

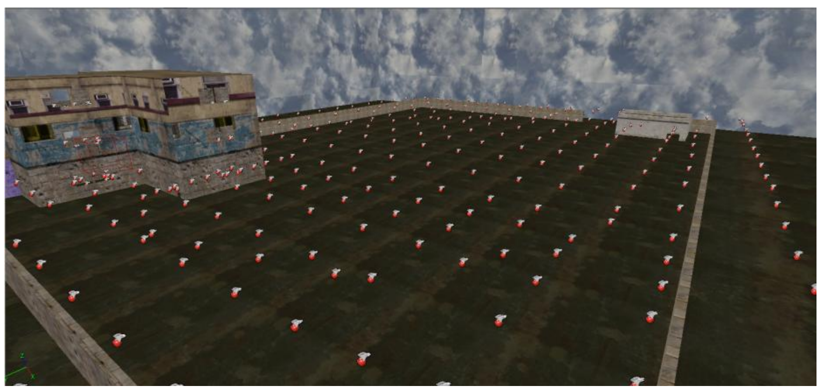


Figure 55: ARL IBR Mission Map and Nodes

With mission map defined and architected, the last piece of 3D modeling required before initiating the simulations is that of MAST platforms and technologies. For both Joppa Urban and ARL IBR missions, the down-selected platforms are quad-rotor and flapping wing aerial vehicle. Hence, the next step is to parametrically model these two platforms along with on-boards sensor, based on results from M-IRMA, in DL environment.

Vehicle and Enemy Modeling: Quad-rotor and Flapping Wing Aerial Vehicle

In a fashion similar to that of architecting missions, different technology platforms can be modeled and simulated in USARSim. In fact, there is already a library of various robotic platforms and sensors built into the package. Utilizing these libraries, both platforms are modeled to be equipped with Inertial Navigation System (INS) [194], a notional sensor mimicking LIDAR, Sonar, camera, and a communication unit. Both quad-rotor and flapping wing platform are modeled using the 'Airobot' vehicle, available in USARSim libraries, and is shown in Figure 56. The modeling of flapping wing platform was aided by members of Grand Challenge teams that were supervised by the author.

Finally, the enemies were modeled similar to quad-rotors but are only able to traverse through paths that are possible for humans. The enemies patrol at various locations within the map and upon detecting a MAST system (i.e. once a vehicle is within the enemy's detection distance), it will respond depending on the mission type, as following: 1) Stealth mission: the MAST system will die upon detection as it compromises the stealth aspect of the mission. Enemy will recognize the system and simulation will identify it as a kill. 2) Aggressive mission: the enemy will chase until it either captures the vehicle or loses sight of it. If the vehicle is captured, the simulation will identify it as a kill.

Figure 56: a. Modeled Quad-rotor Platform; b. Modeled Flapping Wing Platform

Before simulations can be initiated in the developed DL environment, a final detour needs to be taken to generate technically feasible alternatives. This requires implementation of the sizing relations, defined in the previous chapter, for quad-rotor and flapping vehicles, in order to provide a pool of feasible alternatives that can be modeled and tested for their performance in the desired mission scenarios. The next subsection discusses the implementation of these sizing relations and its integration with the DL modeling and simulation environment.

5.4.2. Implementation of Sizing Relations

The sizing relations need to be invoked for the down-selected pool of platforms and technologies to generate technically feasible alternatives for simulations in physics based virtual world provided by the DL environment. This is essential to understanding the available battery capacity of each vehicle and how long will it be able to operate during the mission. In order words, the endurance of a given vehicle is determined based on the available battery capacity and its battery consumption is determined by generating power curves using the sizing relations. The power consumption is directly related to the instantaneous velocity of each vehicle. The feasible alternatives can be generated based on a desired technology year. For current technologies, data obtained during the literature review is utilized for the sizing of the alternatives. For future technology years, k-factors are employed for weight and power of components to show the anticipated improvements and thus generate alternatives that will be technically feasible in future. Furthermore, the velocity profiles of each of the vehicles are also stored, in real time, within the DL environment, which can be later accessed and analyzed.

It is very important to note that not only this avoids the grave pitfall of simulating mission with an artificial time limit, but the velocity profile of each vehicle is essentially the mission profile for that specific alternative. By simulating multiple different alternatives, individually or as a swarm, in a mission scenario, the best alternatives or swarms capable of successfully completing the mission can be determined. The importance of this output cannot be overstated. The mission profile is required for the technologists to size and synthesize vehicles to meet the mission requirements. Until this point, it was not available or obtainable for any mission and for any MAST platform. The output from this module will be able to provide these mission profiles, for scenarios under consideration, of individual MAST vehicles as well as for the swarms that are either able to accomplish the mission or comes closest. By being able to model and simulate future technology alternatives, generated using sizing relations and k-factor, mission profiles of future concepts can also be obtained. These mission profiles will serve as requirements for the technologists to develop and synthesize vehicles in order to perform in the given mission at a level required for mission success. However, for the purpose of this research, velocity profiles will only be generated and saved during the course of the DL experiments, in this module, but will not be analyzed. As the objective of this module is to understand the requirements for the vehicles in terms of MoPs, which would enable determination of their desirable levels and perform technology gap analysis, the utilization of the mission profiles to synthesize vehicles is left as a suggested future and/or complementary task.

Now that the outputs and major insight to be gained from coupling of sizing relations with the DL modeling and simulation environment have been established, it's time to develop and implement a sizing framework based on the first sizing principles' for quad-rotors and flapping wing platforms. The theory behind the sizing relations has been presented in Chapter 4. The focus of this section is to provide details for the sizing process, content of the sensor packages to be equipped on vehicles, and the databases utilized for determining power and weight requirements of motors, rotors, structures, battery and sensors.

5.4.2.1.Sizing Process and Alternatives Generation

Using the sizing relations presented in the previous chapter, a simple framework consisting of codes for quad-rotor and flapping wing aerial vehicles is compiled to assist in generation of alternatives. The primary contributors in the coding, along with the author, were Pierre Valdez (for quad-rotor) and Arun Ramamurthy (for flapping wing).

As mentioned previously, these tasks were accomplished by the contributors, other than the author, as part of their Grand Challenge team tasks and were directly supervised by the author.

For each alternative to be generated, the process is initiated by specifying the properties of its structure, rotor (i.e. for quad-rotor), and payload. The vehicle can be equipped with the following payload:

- Sensors:
  - Inertial Measurement Unit (IMU)
  - LIDAR
  - Camera/Stereo Vision Camera
  - Processor
  - Sonar
- Communication unit:
  - Cisco Aironet
  - Air Live
  - Digi International Xbee TR
  - Futaba Receiver
  - KYL 500S RF
  - OpenPilot

The weight and power draw requirements are obtained through the literature review presented in Chapter 2 of this dissertation. The compiled databases are available in appendices. Specification databases along with determination of structural and rotor properties will be discussed in more detail shortly below.

Once the inputs are determined, they are passed into quad-rotor or flapping wing sizing codes, depending on the platform, to evaluate total thrust for the given configuration. Then, a design mass factor is applied to total thrust to evaluate the design mass of the vehicle. This is to ensure that there is some excess power available and the value of this factor is assumed to be between 0.1 - 1. Different alternatives have different design mass factor value and aids in understanding how it affects the mission performance. The next step is to utilize the databases of motors and battery specifications, discussed below, to evaluate power draw and power available for the alternative being generated. The battery capacity is determined based on the difference between TOGW and the sum of empty weight and payload weight. Using the battery database, a simple regression analysis enables determination of battery capacity required to power the system. At this point, power curves (using 4^{th} power polynomial regression) for the vehicle are generated and implemented in the simulation environment to dictate power consumption. The instantaneous power draw for a given vehicle velocity, at that moment in time, is used for calculating the remaining battery capacity. This is accomplished in real time within the DL simulation environment.

The mission continues either until the primary objective is accomplished or the vehicle runs out of the battery. Throughout this process, three iterative sizing loops are placed to ensure that the generated alternative is technically feasible. These check loops occur at vehicle total weight calculation, to ensure it is physically possible, motor sizing point, to ensure motor is sufficient to sustain flight, and the battery sizing module, making sure that the battery can power the motors and payload. The described process, scripts and the input parameters are schematically shown in Figure 57.

Before generating the alternatives and proceeding with the DL simulation runs, the motor, battery and sensor databases and method for determining rotor and structural properties is presented.

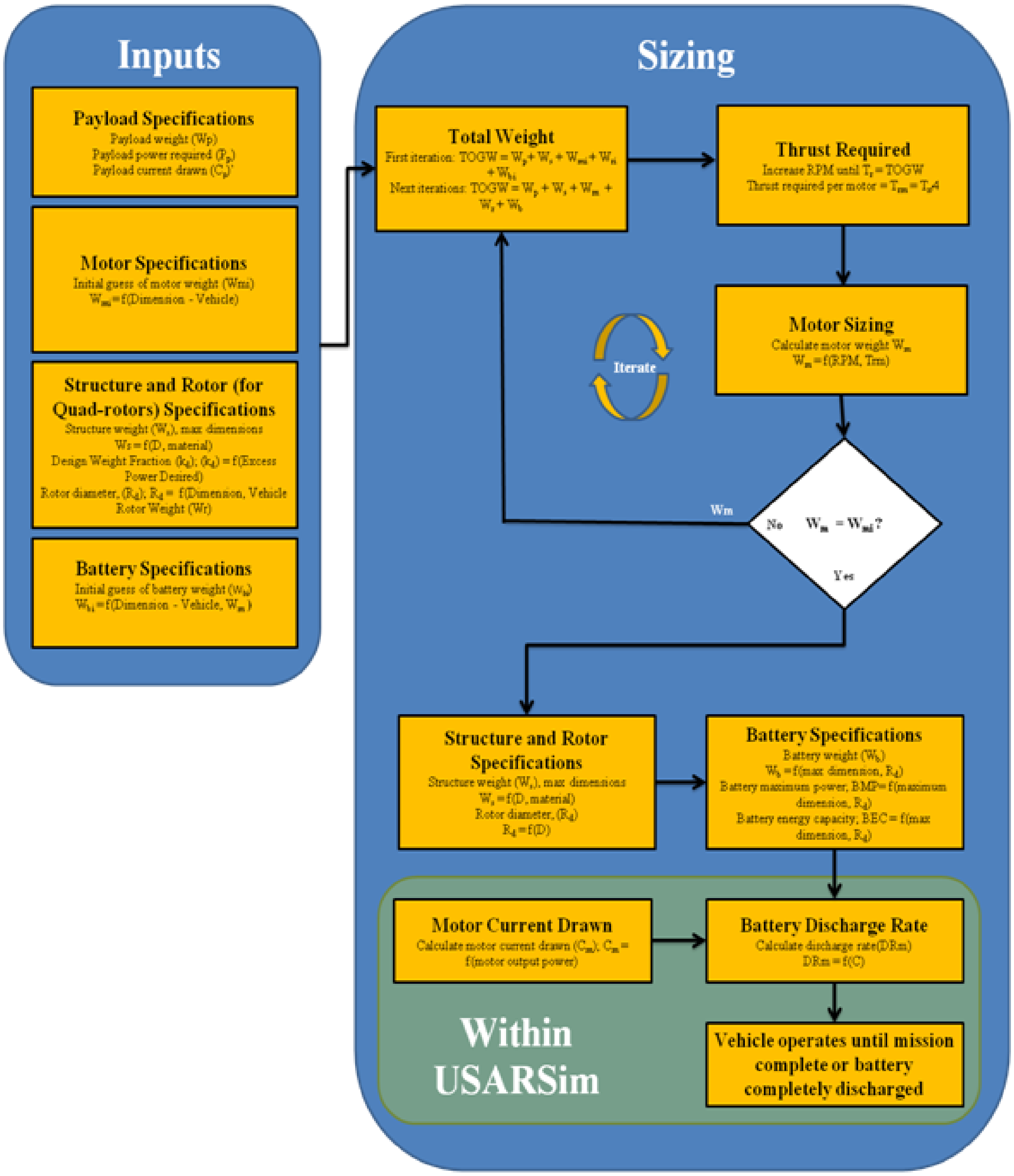


Figure 57: Sizing Process for Generating Alternatives

5.4.2.2.Sizing Databases

Over the years, several databases relevant to MAST systems have been compiled by the author and the Grand Challenges teams (2008-2013), most of which were technically supervised by the author. Extensive specifications for different sensors were provided in Chapter 2 during the literature review. Several additional databases were compiled by the author and the Grand Challenge team of 2012-2013. These databases are utilized to generate feasible alternatives. The ones specifically used are listed below.

- **Motors:** The database of motors used for the purpose of this research is available in Appendix D, along with source of specifications for each motor.
- **Batteries:** The database of batteries is compiled using the catalogues from Hobby King.com store. It is available in Appendix E.
- **Communication Units:** This database was primarily compiled by Sean Ford, under the supervision of the author, as part his Grand Challenge tasks and is available in Appendix FAPPENDIX F: DATABASE OF COMMUNICATION UNITS.
- **Rotors:** The database of rotors, relating diameter with weight, was obtained from APC Propellers online store. The rotor data was used to create a 3rd order polynomial regression plot and is shown in Figure 58.

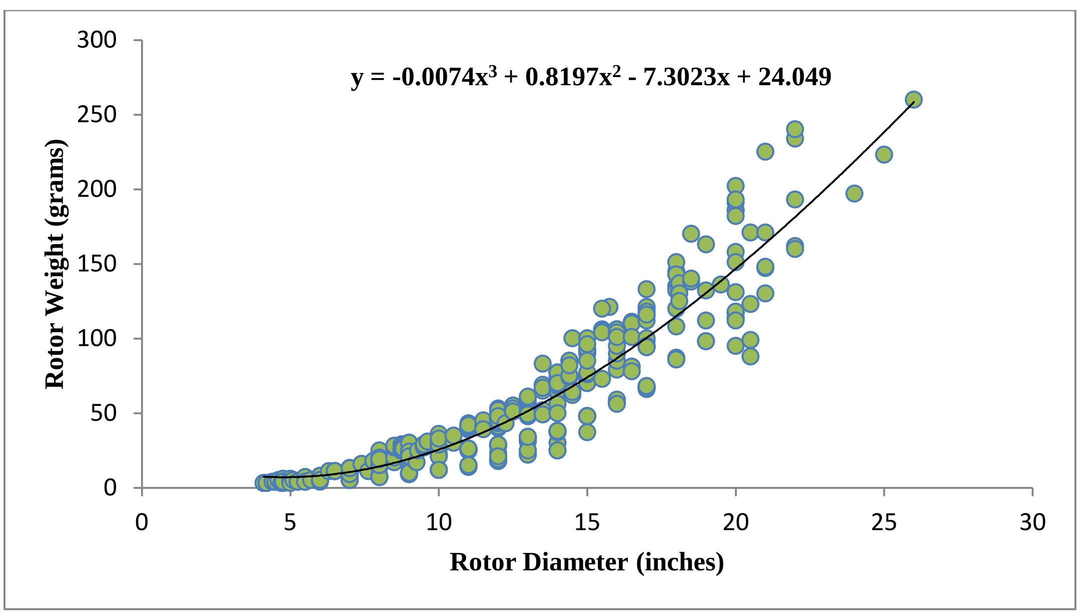


Figure 58: Rotor Weight vs. Rotor Diameter

5.4.2.3. Structural Properties

In order to size a candidate vehicle using the process defined above, structural weight needs to be estimated to calculate TOGW. For first principles' analysis, the structural weight is defined using the materials to be used and the estimated dimensions. Two similar methods were developed for quad-rotor and flapping wing platforms by the author, Pierre Valdez, and Arun Ramamurthy. Both methods estimate structural volume using a basic fuzzy shape of each of the platforms, with correlations obtained from some existing quad-rotors and flapping wing vehicles. Furthermore, the dimensions and volume of the vehicles are also correlated to the material using the same existing vehicles. This enables calculation of the structural weight for different materials and vehicle sizes. For quad-rotors, the vehicle sizes range from 0.05m to 2m and for flapping wing platforms, the sizes range from 0.015m to 0.6m.

The materials and their densities used in analysis and subsequent alternatives generation are shown in Table 27.

Table 27: Structural Materials and Densities

Material	**Density (kg/m^3)** [195], [196]
Aluminum	2700
Balsa (mid hardness)	150
Expanded polypropylene (EPP) – mid	130
Carbon Fiber	1750
Aero graphite	0.2

The details of the structural weight estimation method are provided in Appendix G. With this step undertaken, the candidate alternatives for both quad-rotor and flapping platforms are ready to be generated for the simulation in the DL environment.

5.4.2.4.Generating Alternatives

At this point, it is now possible to generate technically feasible alternatives consisting of current and future technologies. The sizing framework is utilized iteratively to randomly generate a number of different alternatives. Technology K-factors are used for modeling future technologies in terms of the following improvements:

- K-factor types:
    - Power consumption, K_p: Signifies improvement in power consumption (i.e. lower power consumed). It is applied to motors, sensors and communication units. It is also applied to battery capacity metric.
    - Weight, K_w: Signifies improvement in weight (i.e. lower weight at same performance). It is applied to structural weight (in terms of material density) and battery weight.
- K-factor range:
    - The improvement range represented by the k-factors used in this research is: 1, 1.5, 2, and 2.5. '1' signifies current technology level and subsequent numbers as that much improvement over it (i.e. '2' means that the attribute improves by two times of the current level).

Utilizing the above defined technology years, thousands of different alternatives for current and future technology years are generated along with their power curves to form the pool of candidates. These candidates are now going to be evaluated in the DL modeling and simulation environment through the Design of Experiments. All generated alternatives are equipped with LIDAR, IMU, Sonar, camera, and a communication unit (specifically Xbee [197]), as described previously.

5.4.3. Input and Output Metrics

Now that the pool of technically feasible candidate MAST systems is available, it is time to prepare for experimental runs in the DL simulation environment. The first step is to define the input and the output metrics that are relevant to mission MoEs and MoPs, which need to be tested for the analyses of the hypotheses in this research. These input parameters and the output metrics are defined in the following subsections.

Input Parameters

There are three main categories of the inputs, namely swarm level, vehicle level and enemy parameters, and are defined as following:

- **Swarm level:**
  - Number of Quads: Total number of quad-rotors in the swarm
  - Number of Flapping: Total number of flapping wings in the swarm
  - Number of Enemies: Total number of enemies present in the mission
- **Vehicle level – Quad-rotor/flapping wing – separate ones for both**
  - Quad/Flapping-RobotSize: Physical size of the vehicle.
  - Quad/Flapping -batcapacity: Battery capacity
  - Quad/Flapping -PC1: 4th order power curve coefficient - x^4
  - Quad/Flapping -PC2: 3rd order power curve coefficient - x^3
  - Quad/Flapping -PC3: 2nd power curve coefficient - x^2
  - Quad/Flapping -PC4: 1st order power curve coefficient - x
  - Quad/Flapping -HoverPower: Constant power curve coefficient
  - Quad/Flapping -PayloadPower: Payload power required
  - Quad/Flapping - MaterialDen: Material density
  - Quad/Flapping -k-factor-weight: K-factor for payload weight improvement (for future technologies)
  - Quad/Flapping -k-factor-power: K-factor for payload power draw improvement (for future technologies)
  - Quad/Flapping -MaxVelocity: Maximum forward velocity
  - Quad/Flapping -MaxRotVel: Maximum rotational velocity

- Quad/Flapping -ScanRange: Detection range for equipped LIDAR
- Quad/Flapping -PosGainK: Control gain constant - forward velocity
- Quad/Flapping -RotGainK: Control gain constant - rotational velocity
- Quad/Flapping -Ksafe: Gain constant for wall/obstacle detection
- Quad/Flapping -Kw: Gain factor for being attracted to open spaces
- Quad/Flapping -CaptureRadius: Capture distance/radius for nodes
- Quad/Flapping -VisitRadius: Additional/overlapping nodes recognition distance/radius
- Quad/Flapping -FriendlyRadius: Friendly recognition distance
- Quad/Flapping -DetectFriendlyChance: Probability of recognizing friendly within range
- Quad/Flapping -MinBattery: Operational battery life threshold
- Quad/Flapping -Finish_time: Maximum time limit for single mission simulation
- Quad/Flapping -Comm_timeout: Time delay between communication attempts

- **Enemy Parameters:**
  - Enemy-DetectEnemyRange: Detection distance for MAST systems to recognize enemies
  - Enemy-EnemyDetectsYouRange: Detection distance for enemies to recognize MAST systems.

Now that the input parameters have been defined, the next step is to set the ranges for them, which will be used in DoE to generate simulation cases for missions. These ranges are tabulated in Table 28. Depending on the technology year and the generated alternatives, some of these ranges may not be fully utilized.

Table 28: Experimental Parameter Ranges

	Parameter	Minimum Value	Maximum Value	Units
Swarm	Number of Quad-rotors	1	5	
	Number of Flapping Wings	1	5	
	Number of Enemies	1	2	
Vehicle	Quad -RobotSize	0.1, 0.2, 0.3, 0.5, 0.75, 1, 2		m
	Flapping -RobotSize	0.015, 0.03, 0.045, 0.15, 0.225, 0.45		m
	Quad/Flapping -batcapacity	120	480	W*h
	Quad/Flapping -PC1*	-	-	$W/(m/s)^4$
	Quad/Flapping -PC2*	-	-	$W/(m/s)^3$
	Quad/Flapping -PC3*	-	-	$W/(m/s)^2$
	Quad/Flapping -PC4*	-	-	W/(m/s)
	Quad/Flapping -HoverPower*	-	-	W
	Quad/Flapping -PayloadPower*	-	-	W
	Quad/Flapping - MaterialDen*	-	-	kg/m^3
	Quad/Flapping -k-factor-weight	1, 1.5, 2.0, 2.5		
	Quad/Flapping -k-factor-power	1, 1.5, 2.0, 2.5		
	Quad -MaxVelocity	0.3	1.5	m/s
	Flapping -MaxVelocity	0.3	1.3	m/s
	Quad/Flapping -MaxRotVel	12	20	m/s
	Quad/Flapping -ScanRange	1	9	m
	Quad/Flapping -PosGainK	0.3	1.5	-
	Quad/Flapping -RotGainK	0.3	1.5	-
	Quad/Flapping -Ksafe	0.1	0.8	-
	Quad/Flapping -Kw	0.1	0.8	-
	Quad/Flapping -CaptureRadius	0.1	0.45	m
	Quad/Flapping -VisitRadius	0.1	0.8	m
	Quad/Flapping -FriendlyRadius	0.3	1.5	m
	Quad/Flapping - DetectFriendlyChance	0.7	1	-
	Quad/Flapping -MinBattery	5	5	%
	Quad/Flapping -Finish_time	360	600	s
	Quad/Flapping -Comm_timeout	5	30	s
Enemy	Enemy- DetectEnemyRange	1	9	m
	Enemy- EnemyDetectsYouRange	1	20	m

Output Metrics

The output metrics of DL simulations are directly related to the generalized MAST mission MoEs, discussed in the previous chapter. Similar to the input parameters, the output metrics are categorized into two main levels, namely swarm and vehicle levels. The metrics are listed and described below:

- **Swarm Level:**
    - Number of vehicles: Total number of MAST systems in the simulation
    - Total killed by enemies: Total number of MAST systems killed by enemies
- **Vehicle Level - separate for both platforms:**
    - Total time (s): Total mission time of the best performing vehicle
    - Battery left (%): Battery remaining at end of mission
    - Vehicle type: Best performing vehicle type - Quad-rotor or flapping wing
    - Done: Boolean tag for the best performing vehicle for completing mission
    - Successful communications: Number of successful communication attempts by the best performing vehicle
    - Failed communications: Number of failed communication attempts by the best vehicle
    - Total nodes: Total number of nodes discovered by the best performing vehicle
    - Interior nodes: Number of interior nodes discovered by the best performing vehicle
    - Window nodes: Number of window nodes discovered by the best performing vehicle
    - Door nodes: Number of door nodes discovered by the best performing vehicle
    - Other nodes: Number of insignificant nodes discovered by the best performing vehicle
    - Enemy nodes: Number of enemy patrol path nodes discovered by the best performing vehicle

- Detected: Boolean tag for best performing vehicle for detection by enemy
- Death cause: Vehicle's cause of death
- Died: Boolean tag for his vehicle in swarm.
- Number of deaths: Total number of deaths in the swarm
- Total death by enemies: Number of vehicles killed by enemies

With definition of the input parameters, and their ranges, and the output metrics, for evaluating mission MoEs, complete, the next step is to setup the experimental sets through Design of Experiments.

5.4.4. Experimental Runs Setup - Detailed Mission Level Simulations

Following the process similar to the one used for the screening level experimental runs, several different set of experiments are now designed to test the hypotheses for the fundamental research questions, formulated in chapter 3. The primary goal of the detailed level simulations is not only to analyze the swarm performance of MAST vehicles, as was the case in the screening level analysis, but also to quantify the levels of MoPs, at vehicle level, that are necessary to successfully accomplish the given mission. By testing future and current technologies in the mission maps, the comparative levels of MoPs can be used for performing quantitative gap analysis.

Both Joppa Urban and ARL IBR mission are simulated in the developed DL environment. Moreover, each mission is simulated as benign and hostile. The benign missions not only served the purpose of simulating missions that are directly of interest to MAST consortium, but can also be considered as perfect stealth scenarios. The near perfect stealth assumption is likely to be achieved through scaling and camouflage. The simulations are setup in form of an automated DoEs that utilizes the pool of generated alternatives to account for vehicles' physically sized parameters and couples them with other input parameters, specifically those defining the agent based logic. Each case is generated (except for 8^{th} set) using a space-filling DoE and then a matching candidate is picked from the pool for that run. Although the swarm is composed of both quad-rotor and flapping wings, the vehicles belonging to same platform are identical in terms of their specifications. As was explained during the screening level runs, it is justifiable from practicality stance point in context of manufacturing and logistics issues.

The designed experiments are categorized in three major levels: 1). **Preliminary experiments** - determination of number of repetitions and parameter screening. 2). **Validation experiments** - simple scenarios with less variables modeled; the environment modeled has more controlled elements than variables and the results are expected to be intuitive. Conjectures on expected results are presented below. 3). **Complex experiments** - the experiments are setup to model as many variables as possible; the purpose is to simulate the vehicles' behavior in a manner that mimic an actual mission as close to reality as possible. The results are not expected to be intuitive and a higher degree of uncertainty, specifically due to the emergent behavior, is likely to be present. Hence, speculations about the expected results are not put forth. The complex experiment results are also used for defining the gap.

The last issue to be addressed, before running the simulations, is to determine the number of repetitions required for each case to sufficiently capture the stochastic nature of the experiments. The stochasticity results from the use of agent-base logic and the swarm dynamics leading to emergent behavior. The repetition number is the first thing to be determined, in the 0^{th} set. All experimental sets are formulated and described below:

Preliminary Experiments:

1. **0^{th} Set - Number of Repetitions**
    - **Purpose:** The purpose of this set is to determine the number of repetitions to capture stochasticity.

- **Design:** A random DoE (i.e. Monte Carlo [176]) simulation with 500 unique runs. Each run is repeated up to 10 times. Joppa Urban mission scenario is simulated.
- **Expected Results:** The output metric histograms will start to level off after a certain number of repetitions and wouldn't change significantly with further increase in the number of repetitions.

2. **1st Set: - Parameter Screening**
   - **Purpose:** The purpose of this set is to serve as parameter screening and to find the default values for less important input parameters.
   - **Design:** An optimal design of 500 cases of benign mission environment for Joppa Urban. The maximum mission time is limited to 10 minutes. Each run is repeated a number of times based on results from 0th set
   - **Expected Results:** Several parameters will be screened out as less influential and will be fixed to a determined default value for the remaining experiments.

<u>Validation Experiments:</u>

3. **2nd Set - Area Discovered vs. Vehicle Size**
   - **Purpose:** The purpose is to evaluate the mission performance, in benign environment, of a vehicle for discovering the area with respect to its size. The effect of mission time is explored as well. The environment models physical collisions based on mass, inertia, etc.
   - **Design:** A Latin Hypercube [157] space filling DoE with 125 unique runs of benign mission environment. The maximum mission time is limited to 10 minutes. Each run is repeated a number of times based on the results from 0th set. Single vehicle is simulated.

- **Expected Results:** The area discovered will increase as the vehicle size decreases. The smaller vehicles will be able to explore for longer period of time as they will be less likely to die due to collisions.

4. **3rd Set - Area Discovered vs. Endurance**
   - **Purpose:** The purpose is to determine the effect of a simulated battery capacity on the area explored by vehicles of different size.
   - **Design:** A Latin Hypercube [157] space filling DoE with 125 unique runs of benign mission environment. The maximum mission time is limited to 10 minutes. Each run is repeated a number of times based on the results from 0th set. Single vehicle is simulated.
   - **Expected Results:** The area discovered will increase as battery capacity increases. However, the increase in area discovered will be more prominent for smaller sized vehicles. Larger vehicles will be more prone to dying due to collisions and won't be able to utilize the full available battery capacity.

5. **4th Set - Area Discovered vs. Number of Vehicles**
   - **Purpose:** The purpose is to evaluate the effect of number of vehicles on the percentage of area discovered. The effect is also analyzed with respect to vehicle sizes and mission time.
   - **Design:** A Latin Hypercube [157] space filling DoE with 125 unique runs of benign mission environment. The maximum mission time is limited to 10 minutes. Each run is repeated a number of times based on the results from 0th set. Multiple vehicles are simulated.
   - **Expected Results:** Area discovered is expected to initially increase as number of vehicles increases and size decreases. However, increased

number of vehicles, after a certain point, will result in decreased performance due to increased inter-vehicle collisions.

6. **5th Set - Area Discovered vs. Communication Scheme**
    - **Purpose:** The purpose is to evaluate the effect of communication scheme (collaborative or individual) on the percentage of area discovered. The effect is also analyzed with respect to number of vehicles exploring the mission map.
    - **Design:** A space filling DoE [157] with 360 unique runs of benign mission environment. The maximum mission time is limited to 10 minutes. Each run is repeated a number of times based on the results from 0th set. Multiple vehicles are simulated.
    - **Expected Results:** Area discovered is expected to increase when vehicles employ collaborative communication scheme and explore the map collectively.

7. **6th Set - Area Discovered vs. Absolute Velocity Deviation**
    - **Purpose:** The purpose is to evaluate the effect of absolute velocity deviation of the vehicle on the percentage of area discovered.
    - **Design:** A space filling DoE [157] with 360 unique runs of benign mission environment. The maximum mission time is limited to 10 minutes. Each run is repeated a number of times based on the results from 0th set. Multiple vehicles are simulated.
    - **Expected Results:** Area discovered is expected to increase as vehicles' absolute velocity deviation decreases.

8. **7th Set - Killed by Enemies vs. Enemies' Detection Range**

- **Purpose:** The purpose is to understand the influence of enemies' detection range on the number of vehicles killed during mission.
- **Design:** A space filling DoE with 150 unique runs of both Joppa Urban and ARL IBR hostile (i.e. 2 enemies present) missions. Each run is repeated a number of times based on the results from 0th set. Multiple vehicles are simulated.
- **Expected Results:** More vehicles are expected to be lost with increasing enemies' detection range. The effect of vehicle size on detection may also be observed.

Complex Experiments:

9. **8th Set - Fixed Mission Length - Joppa Urban Benign:** An optimal design of 500 cases of benign mission environment for only Joppa Urban. The maximum mission time is limited to 10 minutes. Each run is repeated a number of times based on results from 0th set. The purpose is to evaluate mission performance without considering battery limitations. Moreover, the generated cases didn't require the utilization of the generated candidate pool.

10. **9th Set - Current Technology Sized Vehicles**: A space filling DoE with 360 unique runs of both Joppa Urban and ARL IBR benign missions. Each case is generated using randomly picked vehicles from the alternative pool based on current technologies only. The maximum simulation time is limited to 10 minutes but the actual endurance of each vehicle was based on its sized battery specifications. Each run is repeated a number of times based on results from 0th set. The purpose was to evaluate mission level performance of MAST systems built from current technology subsystems. Both informative and collaborative communication schemes are tested.

11. **10th Set - Future Technology Sized Vehicles**: A space filling DoE with 360 unique runs of both Joppa Urban and ARL IBR benign missions. Each case is generated using randomly picked vehicles from the alternative pool based on future technologies, based on k-factors. The maximum simulation time is limited to 10 minutes but the actual endurance of each vehicle was based on its sized battery specifications. Each run is repeated a number of times based on results from 0th set. The purpose is to evaluate mission level performance of MAST systems built from future technology subsystems. Both informative and collaborative communication schemes are tested.

12. **11th Set - Future Technologies Sized Vehicle - Hostile Mission**: A space filling DoE with 150 unique runs of both Joppa Urban and ARL IBR hostile (i.e. 2 enemies present) missions. The maximum simulation time is limited to 10 minutes but the actual endurance of each vehicle was based on its sized battery specifications. Each case is generated using randomly picked vehicles from the alternative pool based on the best performing vehicles, based on future technologies, from previous set. Each run is repeated a number of times based on results from 0th set. The purpose is to evaluate mission level performance of best performing MAST systems built from future technology subsystems in a hostile environment. The detection distance of enemies is fixed at 2m. Only collaborative communication schemes are tested. The difference between this set and the seventh set is that the enemy detection distance is fixed.

Over 15,000 cases are simulated and the results from each set are obtained and analyzed. The results from the first three sets are first discussed and presented in separate subsections. The results from the last three sets are simultaneously, for both missions, analyzed, discussed and presented in the subsequent sections. The categorization is based on output metrics. All results are analyzed using MS Excel and SAS JMP statistical package. Density and other types of plots are utilized to understand the relations between the MoPs and the output metrics. As was the case for the screening level results, the darker areas in density plots represent higher occurrences.

5.5. Mission Simulation Results and Gap Analysis

At this point in the research, every component of the framework (except validation) is developed and the results are obtained from all the prior modules in a consolidated fashion. The focus of this section is to quantify technological attributes necessary for achieving the required levels of the MoEs, as defined in the previous chapter, for Joppa Urban and ARL IBR missions. The output metrics, directly related to MoEs of interest, obtained from the simulation results for both missions are simultaneously analyzed to present a coherent comparison of the two missions. Comparing and contrasting results from various experimental conditions, such as current and future technologies, enables quantification of previously unknown findings. Gap analysis quantifies the difference in technology metrics or MoPs of current state of the art MAST systems and the required future state of those systems. Levels of MoPs dictated by future systems state are mandatory for achieving required levels of mission MoEs, in order to successfully complete a given mission scenario.

This section is divided into three major subsections, as explained above, for each type of experimental set. And within each set, the results are generally categorized based on the output and the input metrics of interest. Nevertheless, there are deviations from this general format for analyzing results of certain sets and are mentioned in respective sections. For complex experiments, Collaborative communication scheme is primarily implemented to understand the swarm performance while Informative communication scheme is used for analyzing the individual vehicle performance operating as part of a swarm. Nevertheless, all levels of both hierarchical categories are simulated using both of the communication schemes and the results from are analyzed to discover any discrepancies or interesting conclusions between the two implementations.

5.5.1. Preliminary Experiments

The purpose of preliminary experiments is to establish the number of repetitions required to capture the model's stochasticity and to conduct parameter screening of the input variables. Joppa Urban mission is used as the implementation scenario.

5.5.1.1. 0th Set – Number of Repetitions

The repetition number for each case is determined in a manner similar to that was employed for the screening level experiments. A random design of 500 unique cases is generated and executed for the Joppa Urban mission. Each case is repeated up to 10 times. The output metric of number of deaths is designated as the test metric for analyzing distributions of the response levels. The distributions are created and visualized using histograms and are shown in Figure 59.

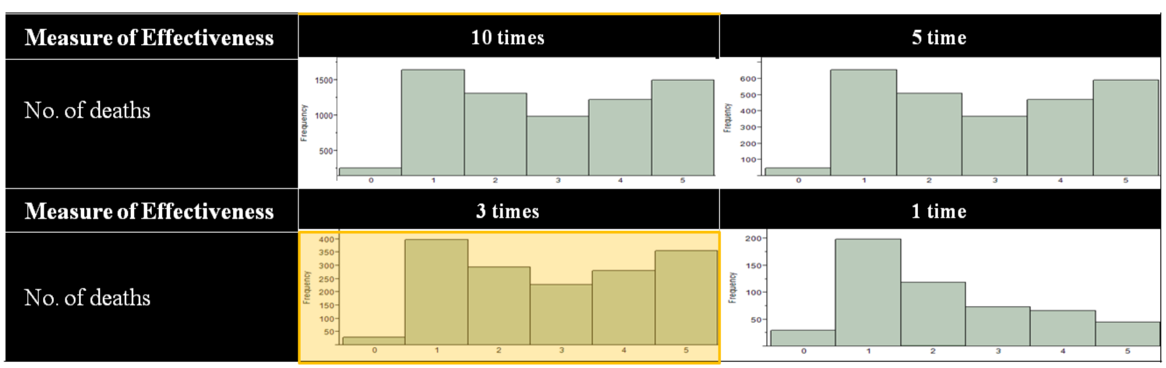


Figure 59: Variability of the Model - Detailed Level

Considering the results, it is apparent that even three repetitions of each case are able to capture the response level trends and thus, the stochasticity of this model reasonably. The difference in distributions between ten and five repetitions is almost non-existent and hence, five repetitions would be the recommended number. However, it can be observed that the difference in distributions of ten and three repetitions is primarily attributed to cases resulting in outliers. It is evident by considering the frequency of the levels that don't appear in histogram of three repetitions. Furthermore, the validation experiments, especially ones with single vehicles, are expected to vary even less because of lack of the inter-vehicle interactions. Therefore, considering the previous statement and the requirements of DL simulations, in terms of computational and time resources, it is decided that each case in subsequent experimental sets will only be repeated three times.

5.5.1.2. 1st Set - Parameter Screening

With the number of repetitions for each case decided, the next step is to perform a screening test on the input variables to determine the importance of each. It is necessary to screen-out input variables that are not very influential on the output metrics, which would minimize time and computational resources requirements for the simulations. This is mandatory considering the large number of the input variables defined above.

In order to accomplish parameter screening, an optimal design of 500 runs, with five repetitions each, is utilized for simulating the Joppa Urban mission scenario. Using standard least squares effects screening in JMP, Pareto plots are constructed to gauge the importance of each of the input variables. However, the mission success criteria is multi-attribute and hence, requires an Overall Evaluation Criterion (OEC) [136] to establish an evaluation base for judging the influence of the input variables on the output metrics. It is formulated as shown in equation 35. The focus of the OEC is to emphasis the most important MoEs of both missions under considerations. Specifically, the goal is to rank the SoMs and its comprising vehicles higher if they perform better in terms of the following metrics:

- **Number of deaths** - smaller is better
- **Discovering area: total and interior** - bigger is better

- **Time spent during mission** - smaller is better
- **Battery remaining** - should have almost no battery left once mission is accomplished (not considering the power required to return to base outside of mission area), this ensures most efficient design (i.e. not carrying any extra weight)
- **Swarm size** - smaller the better as not only the stealth factor improves, but also the swarm is logistically and economically desirable.

Equation 35: Overall Evaluation Criterion

$$OEC = \alpha\left(\frac{Total\ vehicles_{BL}}{No.of\ deaths}\right) + \beta\left(\frac{Interior\ discovered}{Interior\ area_{BL}}\right) + \gamma\left(\frac{Area\ discovered}{Total\ area_{BL}}\right) + \delta\left(\frac{Max\ mission\ time_{BL}}{Time\ elapsed}\right) + \epsilon\left(\frac{Total\ battery\ capacity_{BL}}{Battery\ remaining}\right) + \zeta(\frac{Max\ swarm\ size_{BL}}{Swarm\ size})$$

The values assigned for coefficients of the OEC are based on MoEs, as discussed in the previous chapter, and are listed in Table 29.

Table 29: OEC Coefficient Values

Coefficient	Value
α	1.5
β	2.5
γ	2
δ	2
ε	1.5
ζ	0.5

Utilizing the above OEC and effects screening, the results obtained are analyzed to conclude that the input variables, presented in Table 30, can be set to a constant default values for all subsequent experimental runs. The default values are determined by ranking and sorting the simulated cases using the OEC and engineering judgment.

Table 30: Screened-out Inputs and Default Values

Parameter	Minimum Value
Quad -MaxRotVel	0.4
Flapping - MaxRotVel	0.4
Quad/Flapping -ScanRange	5.5
Quad/Flapping -PosGainK	1.28
Quad/Flapping -RotGainK	0.34
Quad/Flapping -Ksafe	0.72
Quad/Flapping -Kw	0.33
Quad/Flapping -DetectFriendlyChance	1
Quad/Flapping -MinBattery	5
Quad/Flapping -Finish_time	600

With OEC formulated and screening test conducted, it is now time to initiate the next set of experiments using the reduced pool of the input variables.

5.5.2. Validation Experiments

The validation experiments presented in this section fulfills the primary objective of scientific experimentation step in a research process. The purpose is to conduct experiments on intuitive cases, which are to serve as the validation experiments for the methodology and the developed models. The experiments are set up to involve a number of controlled elements that allows the expected results to be intuitive. Notional quad-rotor platforms are simulated in the Joppa Urban mission. These experiments not only serves the purpose of building credibility in the underlying models and providing fundamental insight into the effects of the input metrics on the response parameters, but also pave the way for more complex experiments to be carried out.

Furthermore, the results from these experiments provide the Warfighter with trend charts to play decision making games, in terms of setting mission success constraints. These mission success constraints define the required levels of MoPs that need to be achieved in order to fulfill the mission needs.

5.5.2.1. 2^{nd} Set - Area Discovered vs. Vehicle Size

The first experimental set for validation cases considers the effect of vehicle size on the percentage of the total area explored. It was determined during the screening level analysis that the vehicle size is an important parameter, which strongly influences the amount of area discovered by the MAST systems. With the availability of detailed mission modeling and simulation environment, the physics of collision can now be simulated. Therefore, the environment will be set up to provide a 'near-perfect' world where collisions are possible. As explained previously, the collisions are modeled by the physics engine of Unreal Tournament that takes into account vehicle and obstacle parameters such as mass or inertia. For this set, only a single vehicle is simulated for the previously defined variables and their ranges. The experimental conditions are summarized below:

- **Conditions**: Near Perfect
    - Collisions: Modeled using the Karma physics engine
    - Endurance: Unlimited
    - Death: Vehicle can only die due to collisions
- **Primary Test Metric:** Total Area Discovered vs. Vehicle Size
- **No. of Vehicle(s):** 1
- **Platform Type:** Quad-rotor
- **Enemies:** None
- **Mission Time:** 600s

With the experimental conditions laid out, the simulations are executed and the collected data is analyzed. Understanding the influence of vehicle size on mission performance for the area coverage is essential in defining the required scaling factors for MAST technologies. The importance of scaling down size cannot be overstated in context of the MAST vision, and as such is a widely studied MoP throughout this research.

The results from experiments are shown in Figure 60, which the mean plot of the total area discovered by a given size of vehicle.

Studying the plot, it is apparent that the size strongly influences the amount of area discovered. The mean value of area explored varies over a range of about 25% as the size is increased from 0.1 m to 1.0m. Analyzing the data points shown in the plot, it is apparent that only the vehicles in size less than 0.5m are able to discover area over 50% in simulation cases, albeit only in some of the cases.

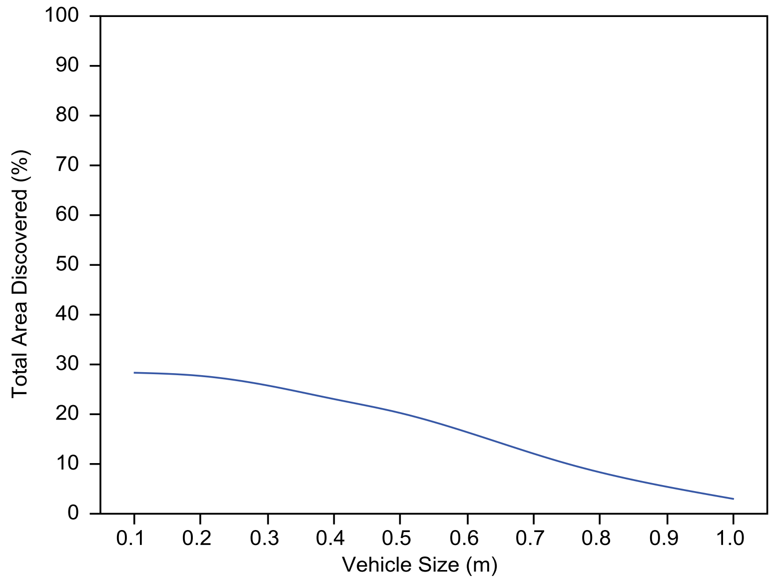


Figure 60: Area Discovered vs. Vehicle Size

The lacking performance of the vehicles larger than 0.5m is attributed to the difficult faced by these vehicles in gaining entry through access points such as doors and windows. It is understandable that since the clearance between the vehicle and the door/windows dimension would be extremely small or non-existence for these vehicles, the aforementioned difficulty in gaining entry will be become an issue. The reason for low mean value of the percentage of the area discovered is due to the fixed mission time of 600s. Nevertheless, several smaller sized vehicles were able to explore over 80% of the mission area within the allotted time. The general trend of the results conforms to intuition and provides a strong validation base for the created models.

Considering a more in-depth look at the data obtained from this experimental set, the relation between size and the amount of time a given vehicle is able to operate without dying is now analyzed. Although the maximum mission time is limited to 10 minutes, it does not prevent the vehicles from dying prematurely due to collisions. After all, the purpose of the detailed mission modeling and simulation is to analyze the influence of physical world aspects, which were not considered in the screening level analysis. Figure 61 depicts the mean plot of total area discovered versus duration of the vehicle operation for different sizes.

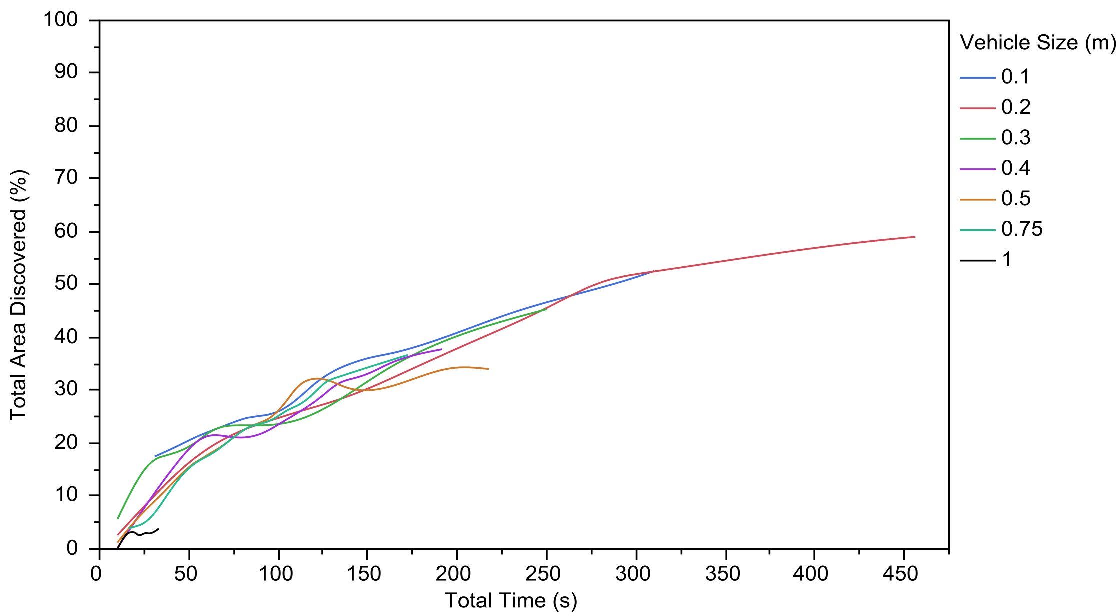


Figure 61: Total Area Discovered (Mean) vs. Total Time - Vehicle Size

The obtained results signify a direct relation between the operational time of the vehicle, its size, and the amount of the area discovered. Only smaller sized vehicles are able to fly longer and discover higher percentages of the area. The results demonstrate the higher probability of larger vehicles dying early and thus, being able to explore less amount of the total area. An extreme case here is demonstrated by vehicles of size 1.0m as they are quite prone to dying within the first minute of the mission, which is evident by the results' plot. This is caused by lack of their ability to gain entry into the building and the resulting collisions with the walls upon trying to squeeze through narrow doors or windows.

Finally, it is important to note that the variations and dips in the trends are caused by the vehicle deaths due to the collisions. Given agility and sensory parameters of a vehicle, the collision can occur when the vehicle is moving at a rate that is faster than its ability to detect an obstacle with sufficient lead time to be able to change its momentum. Furthermore, it also outlines the importance of navigational algorithm capabilities, which effectively dictates how intelligently a vehicle is able to explore the area and avoid the collisions.

The insight gained from this group of experimental sets can now serve as the motivation of analyzing the effect of vehicle endurance on the mission performance of MAST systems, specifically in terms of discovering the unknown area.

5.5.2.2. 3rd Set - Area Discovered vs. Endurance

The importance of the vehicle endurance for the mission performance was highlighted during the analysis of the previous experimental set's results. Hence, a closer look is taken on the endurance of vehicles operating in a 'near perfect' world, where the only deviating assumption is inclusion of physics based collisions. In order to assess and quantify the influence of endurance on the mission performance, this experimental set entails simulating a single quad-rotor platform based vehicle, for each DoE run. A notional battery capacity metric is designated to define the maximum endurance of a vehicle, ranging from 120 seconds to 1200 seconds. It is important to note that the vehicles can still die due to collisions before the battery is completely depleted. The experimental setup details are summarized below:

- **Conditions**: Near Perfect
    - Collisions: Modeled using physics engine

- Endurance: Battery Capacity - 120 second to 1200 seconds
- Death: Vehicle can die due to collisions

- **Primary Test Metric:** Total Area Discovered vs. Battery Capacity with respect to Vehicle Size
- **No. of Vehicle(s):** 1
- **Platform Type:** Quad-rotor
- **Enemies:** None

The simulations results are shown in Figure 62, depicting a series of mean area discovered plots for different levels of battery capacities with respect to vehicle size.

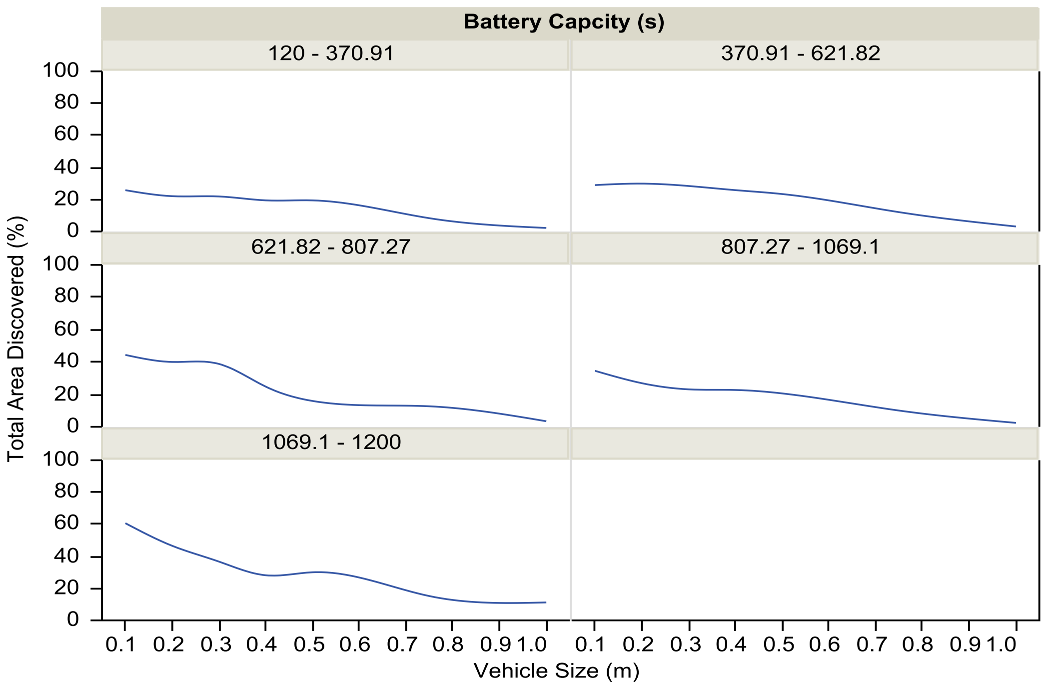


Figure 62: Area Discovered (Mean) vs. Battery Capacity - Vehicle Size

Considering the plots above, the trends are as predicted during the pre-experimental stage and provide further validation of the developed models. It is apparent from the plot curves that as battery capacity increases, the area discovered, regardless of possibility of collisions with obstacles, also increases. This is particularly significant for the vehicles 0.5m and smaller in size. For larger vehicles, the increased battery capacity is of little practical use as they are not able to gain entry into the building due to their sheer size. Furthermore, the larger vehicles are also more prone to dying before battery depletion. For smaller size vehicles, the area discovered increases from an approximate mean value of 30% to a mean value of 60%, as battery capacity is increased from 120 seconds to 1200 seconds.

As was the case with previous experimental set, the variations in the trend are caused by possibilities of collisions and presence of the emergent behavior during navigation. The path chosen by a vehicle of a given parameters is prone to slight variations depending on its interaction with the physical world.

Having established the importance of the vehicle size and the endurance for mission performance of single vehicles, it is now time to analyze the effect of introducing more vehicles to explore the map as an ensemble.

5.5.2.3. 4th Set - Area Discovered vs. Number of Vehicles

The purpose of this experimental set is to venture into detailed mission level modeling and simulation of multiple vehicles. The goal is to consider how mission performance is affected as the exploration is carried out by an ensemble rather than an individual vehicle. This metric was previously explored in screening level analysis and the results showed that in an environment based on 'perfect' world assumptions, the mission performance improves with increasing number of vehicles within the ensemble. So, now the 'perfect' world assumption is deviated by injecting elements of physics based world, primarily enabling collisions. The experimental setup details are similar to previous sets and are summarized below:

- **Conditions**: Near Perfect
    - Collisions: Modeled using physics engine
    - Endurance: 6 minutes
    - Death: Vehicle can die due to collisions

- **Primary Test Metric:** Total Area Discovered vs. Number of Vehicles
- **Mission Time:** 600s
- **No. of Vehicle(s):** 1 to 5
- **Platform Type:** Quad-rotor
- **Enemies:** None

Using the defined experimental setting, the simulations are imitated and the obtained results are analyzed. Figure 63 depicts the mean plot of total area discovered by ensembles composed of different number of vehicles operating as a group.

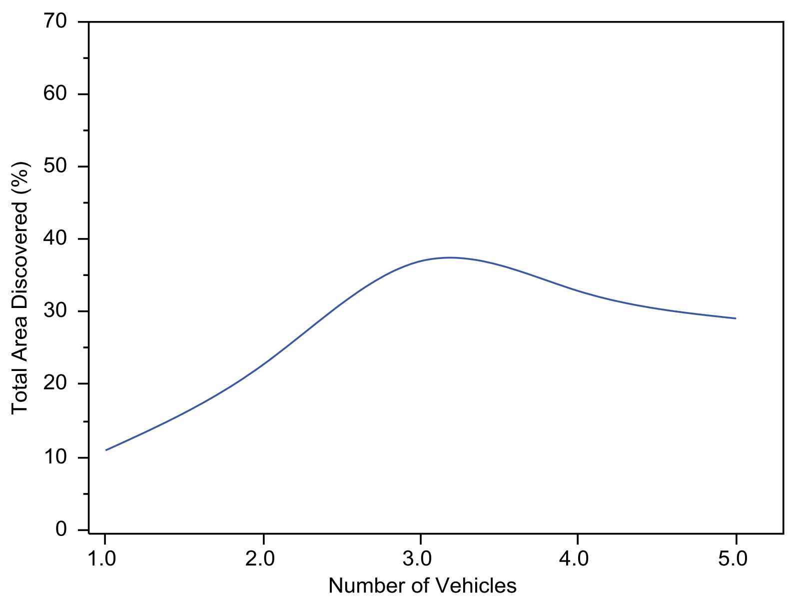


Figure 63: Area Discovered (Mean) vs. No. of Vehicles

As apparent from the plot, the total area discovered by group of vehicles initially increases as the group size is increased. It reaches a peak and then starts to decrease. This conclusion is somewhat in contrast with the one reached during the screening level analysis for similar experimental set results. Studying these experiments in detail reveals the reasoning behind this distinction. It is primarily due to the presence of physical world elements, specifically collisions. As number of vehicles in the group increases, the performance initially increases as more area can be explored collectively compared to an individual effort, for the same amount of time. However, the physical mission space is limited and the increased number of vehicles results increased probability of direct inter-vehicle collisions. These collisions result in vehicle loss and hence, effectively decrease the number of vehicles exploring the map. Furthermore, in-direct collisions are also increased as a result of evasive maneuvers performed by vehicles to avoid collisions with other vehicles. Therefore, indefinitely increasing the group size will not lead to indefinite increase in mission performance of area exploration, which was the case in screening level analysis.The importance of this result cannot be overstated as it places an upper limit, from performance stance point, on the number of vehicles to be deployed for Joppa Urban mission exploration. Making a mission map over-crowded with MAST vehicles is not necessarily conducive to improved mission performance.

Taking this analysis a step further, the total area discovered by a group of various sizes is analyzed in terms of the vehicle size. The purpose is to understand how different ensemble performance of MAST systems is affected by size of vehicles composing the group. For this analysis, each member of the group is same in size and hence, the swarms are homogenous in nature. Figure 64 shows the plot depicting mean values of the area discovered for groups consisting of different number of vehicles and the size of each member.

As obvious from the plot, there is an upward shift in mean curves as vehicle size decreases across the range of ensemble size. Not surprisingly, groups of vehicles composed of smaller sized vehicles are able to perform significantly better than those composed of larger vehicles. At peak performance, the difference can be approximated at around 30% improvement, as vehicle size is decreased from 1m to 0.4m. This also serves as a further validation of the previous results in this experimental set.

Before concluding this experimental set, one last metric is studied to understand the effect of vehicle endurance on performance of the group.

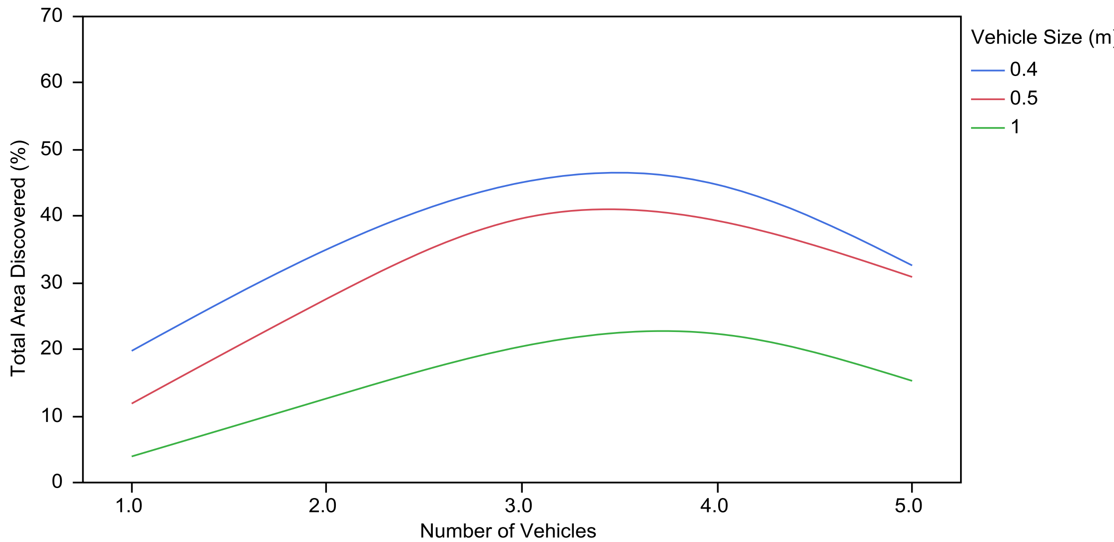


Figure 64: Area Discovered (Mean) vs. No. of Vehicles - Vehicle Size

The endurance ranges analyzed span from just over 3 seconds to over 300 seconds. The results are shown in Figure 65, as a series of plots depicting mission performance of different vehicle sizes of within different sized MAST ensembles and categorized using endurance range.

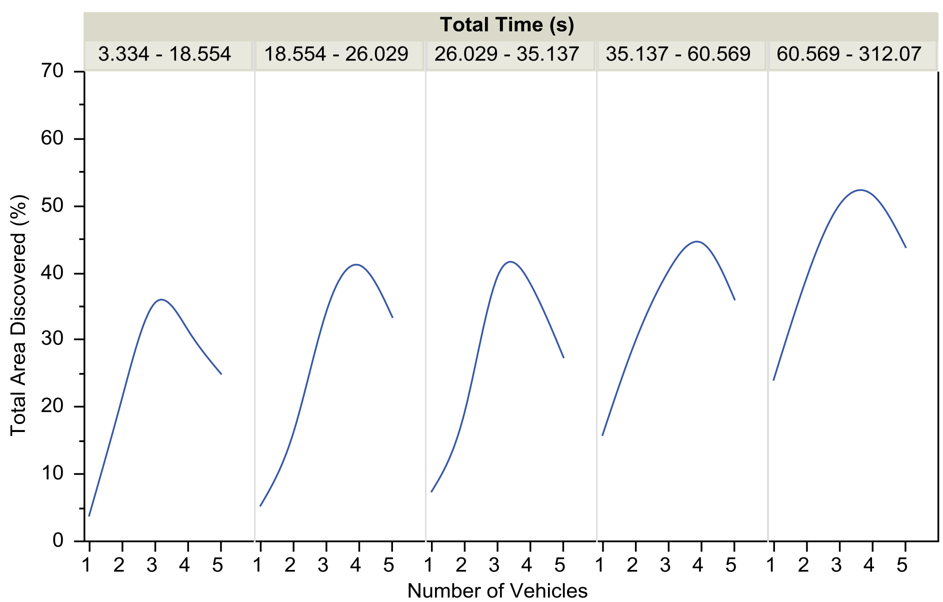


Figure 65: Area Discovered (Mean) vs. No. of Vehicles - Total Time

Again, the general trend is similar to the one found for the mission performance analysis of multiple vehicles exploring the map. For a given endurance range, the performance initially improves with increasing number of vehicles, reaches a peak and then starts to decline. The key take-away from this study is the clear trend of the upward shift of mean curves as endurance range is increased. The difference in the area coverage improvement can be approximated at 15% for as endurance is varied over a span of about 300 seconds.

This concludes the analysis of multi-vehicle deployment for area exploration of Joppa Urban mission map. The results obtained provided a solid foundation for validation of the developed environment and the models. Next, more involved vehicle level metrics such as the communication scheme and the velocity deviation are experimented with.

5.5.2.4. 5th Set - Area Discovered vs. Communication Scheme

The purpose of this experimental set is to present an analysis on the comparison of the two communication schemes, namely Informative and Collaborative, employed during the simulations, in context of the total area discovered. The details of experimental setup are similar to previous ones. Plots in Figure 66 demonstrate the effect of vehicles discovering the area collaboratively versus informatively. It is evident that in collaborative scheme, not only much more area is discovered but also the effect of collaboration and resulting emergent behavior causes the output metrics to vary significantly from run to run.

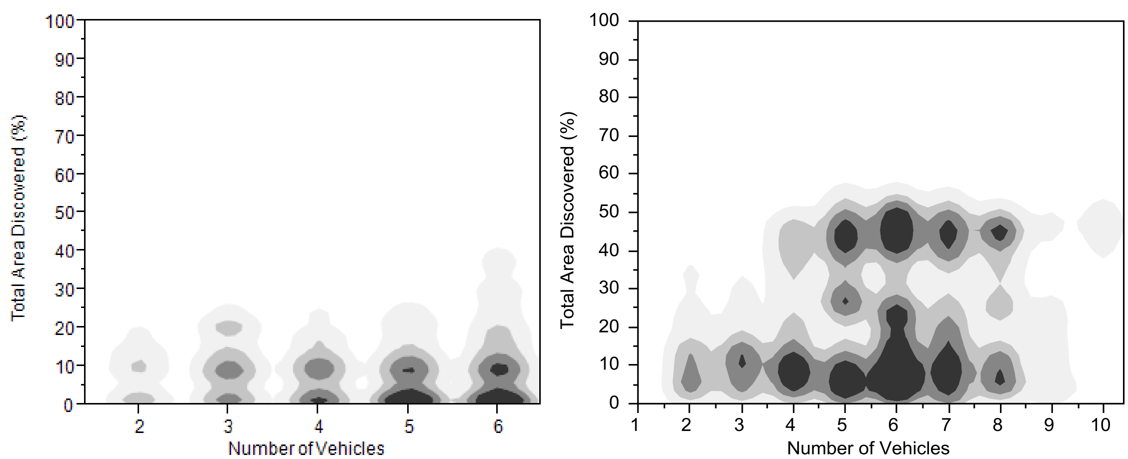


Figure 66: Total Area vs. Swarm Size JU Benign - Current Tech. - a) Informative; b) Collaborative

This leads to two important conclusions. First, swarm behavior and collaboration is quite beneficial for the MAST missions, as expected; hence, highlights the importance of implementing an effective communication scheme among the vehicles within the swarm. Second, collaborative exploration is more likely to lead to unpredictable emergent behavior, requiring extensive experimentation or simulations to be studied and quantify.

5.5.2.5.6th Set - Area Discovered vs. Absolute Velocity Deviation

In order to assess the effect of velocity changes on the mission performance of the vehicles, a derivative metric, absolute velocity deviation, is employed. Simply stating, it is the measure of the vehicle's deviation from its intended velocity. For experimental reasons, the intended velocity was considered to be vehicle's maximum velocity. The goal of the vehicle is to explore the mission map at its set velocity but obstacles cause the velocity to change from its default value. High absolute velocity deviation values would occur for cases during which vehicles frequently changed its traveling speed or direction, mostly due to senor specifications (i.e. low detection distance). The effect of this velocity change on mission performance in terms the area explored is the focus of this subsection.

First, the metric is derived by defining average velocity as shown in Equation 36.

Equation 36: Average Velocity

$$\overline{Vel} = \frac{Total\ Distance\ Traversed}{Total\ Time}$$

Then, absolute velocity deviation is defined as shown in Equation 37.

Equation 37: Absolute Velocity Deviation

$$Absolute\ Velocity\ Deviation = \sqrt{\left(\frac{Vel - \overline{Vel}}{Vel}\right)^2}$$

Finally, this metric was tracked during the simulations and the results for quad-rotor platforms, based upon current and future technologies, for Joppa Urban mission are shown in Figure 67

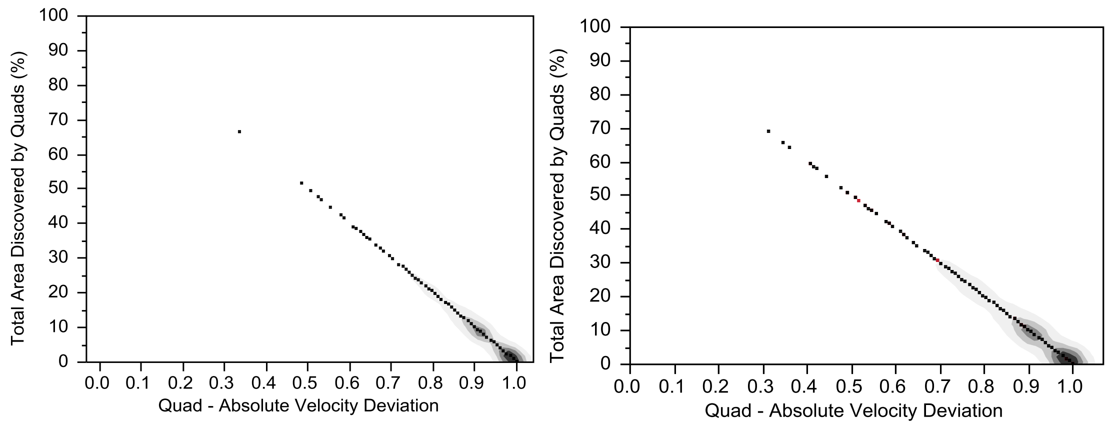


Figure 67: Total Area vs. Quad- Abs. Vel. Deviation JU Benign - a) Current Tech.; b) Future Tech.

As apparent from plots above, the percentage of the area explored increases with decreasing absolute velocity deviation. The trend is extremely linear for both current and future technology years. This leads to the conclusion that vehicles should be have enough detection range and sufficiently intelligent navigation algorithms to be capable of exploring terrain at same speed, ideally maximum, through the entire mission.

5.5.2.6.7th Set - Killed by Enemies vs. Enemies' Detection Range

It is now time to inject the hostile aspect of a scenario by introducing enemies within the Joppa Urban mission. Two enemies with a variable detection radius, ranging from 2m to 20m, are deployed to make the missions hostile. The simulations only consist of sized MAST systems built on future technologies. The key reason behind is that if a gap exists even with future systems, then the probability of current systems performing better is extremely low, if not zero. Figures 68and 69 show the plots of the simulation results for the total area discovered as a function of swarm size for hostile versions for the two missions. Another deviation from previous experimental sets' setup is that both Joppa Urban and ARL IBR missions are simulated.

For Joppa Urban mission, enemies capable of detecting within a radius of about 9m are able to spot vehicles as small as 0.1m in their longest dimension. At detection distance of around 15m, even vehicles 0.1m in size are detected. Of course, the probability of detecting vehicles above 0.2m in size remains much higher throughout the range.

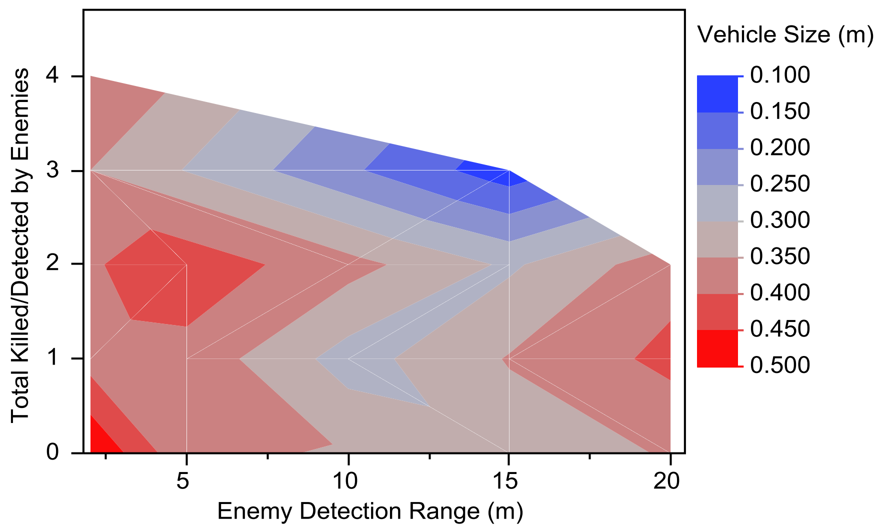


Figure 68: Killed vs. Enemy Detection Range and Vehicle Size - JU Hostile Mission- Future Tech.

The results are slightly different for ARL mission. It can be observed that the vehicles 0.2m or less more not likely to be detected by enemies regardless of their range. It is observed during simulations that there are two main reasons for this: 1. The much larger terrain afforded by ARL map aided vehicles in avoiding enemies and hiding from them. 2. Two enemies are not enough to effectively patrol the whole map.

The conclusion to be drawn from this set of experimental results is that the vehicles not only should be 0.2m or less in size but also should employ camouflage to rely on stealth and avoid detection. This is absolutely necessary for smaller mission maps such as Joppa Urban or one with greater number of enemies. Finally, it should be noted that only the visual detection is simulated during the experiments and further studies need to be conducted to analyze the constraints that maybe imposed by detection through other senses, such as auditory. This is recommended as possible future work.

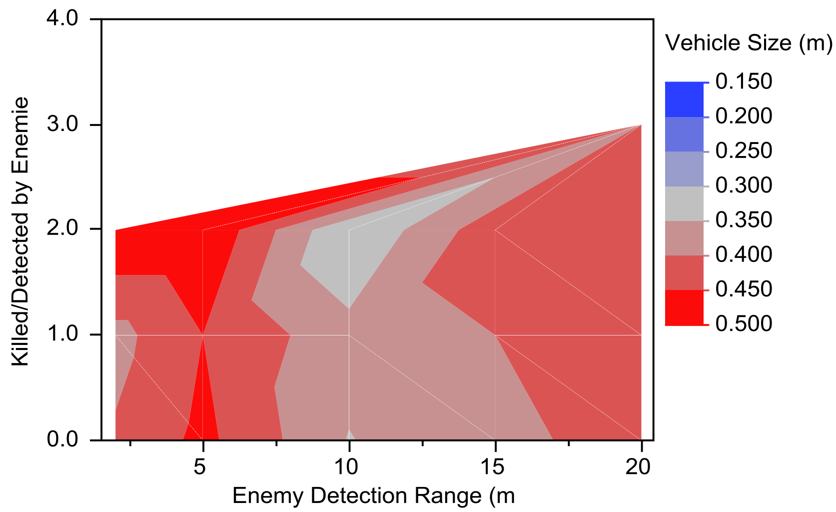


Figure 69: Detected/Killed vs. Enemy Detection Range and Vehicle Size - ARL Hostile Mission-Future Tech.

This not only concludes the analysis of this experimental set but also serves as a closure for the entire group of validation experiments. At this point, the results obtained from developed detail mission level modeling and simulations environment have been logically verified to be reasonable. This provides sufficiently credibility for developed tools and models to proceed with more complex experiments and subsequent gap analysis.

5.5.3. Complex Experiments

With validation experiments completed, it is now time to handle more complex mission situations that considerably deviate from 'near-perfect' or 'perfect' world conditions and are setup to mimic actual war zone, as much as possible. The results from these experiments are not expected to be always intuitive due to high, yet understandable, degree of uncertainty caused by emergent behavior and a large number of variables. The following experimental sets have been already defined before, and hence the analysis is initiated with the eighth set.

5.5.3.1.8th Set - Fixed Mission Length - Joppa Urban Benign

The primary focus of this set of experimental runs is to simulate MAST systems in Joppa Urban mission scenario without the presence of enemies [198]. The vehicles are assumed to be capable of 10 minutes of endurance without the constraints imposed by a given battery capacity. Therefore, the sized alternative pool is not going to be utilized for generating these runs. The experimental design is chosen as optimal with 500 cases, repeated 3 times each, of which 25% are random runs. The reason for running experiments in this set is to evaluate 'perfect stealth' scenarios and the influence of mission length on mission performance of MAST systems.

The primary MoPs (each one uniquely assigned for both quad-rotors and flapping wings) defined for evaluation of the mission are: Number of vehicles, size - longest dimension or diameter (m), maximum forward velocity (m/s), maximum rotational velocity (m/s), battery capacity (s), distance for exploring new areas (m), avoidance distance between two vehicles (m), and time duration between two communication attempts with other vehicles (s).

The results obtained from simulations are analyzed at two levels of hierarchy: swarm level and individual vehicle level. Starting with swarm level, the mission performance is measured in terms of percentages of total and interior area discovered for a given swarm size. The effect of vehicle size on area explored is also analyzed. As apparent in Figure 70, the increasing swarm size initially results in improved mission performance of exploring unknown area. The performance seems to peak with a swarm size of about 5-7 vehicles. For swarms bigger than 7, the area explored starts decreasing. The main reason, observed during experiments, is that the large swarms (7+ vehicles) tended to become less efficient as vehicles would bump into each other and cause collisions. Moreover, vehicles would be more likely to explore the same area as each other due to sheer number present in a relatively small map. It is important to note that similar conclusions were reached from analysis of screening level experimental runs, signifying a good match between two experimental setups and validating each other's results.

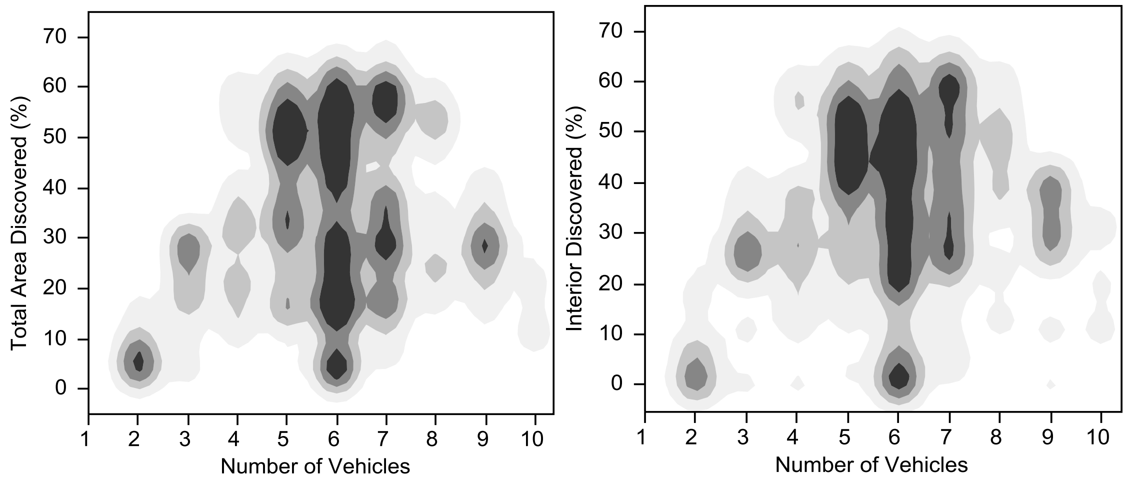


Figure 70: Total area explored vs. a) swarm size; b) Interior explored vs. swarm size.

The next set of metrics to be analyzed at swarm level is primary entry points into the urban building, represented by doors and windows. Analyzing the plots in Figure 71, it is evident that the vehicles large than 0.5m (diameter) were rarely able to access doors and windows. They were simply too big to go through and had to find other entry points such as open roof. The doors were modeled with a nominal width of 0.9m.

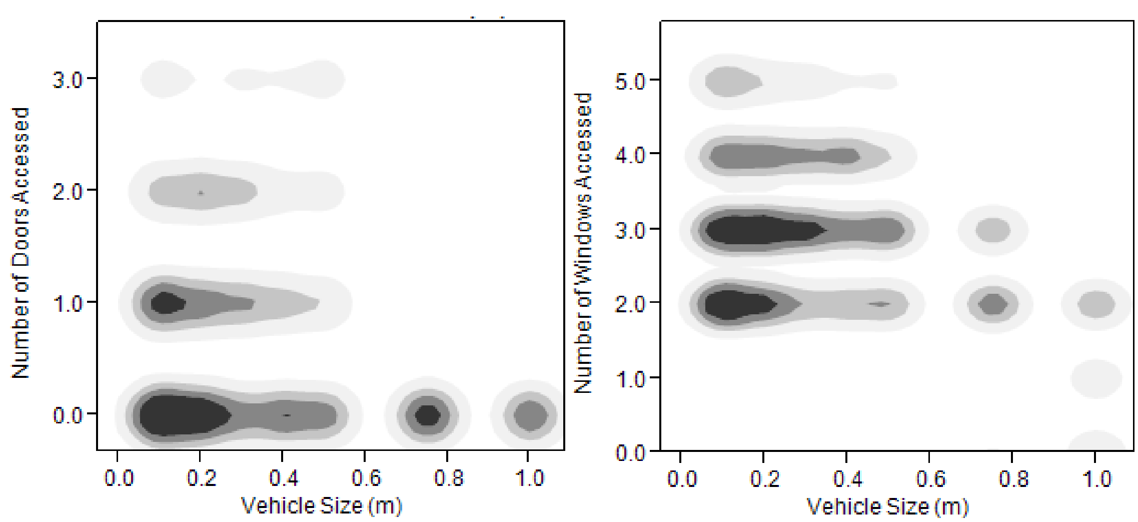


Figure 71: No. of doors accessed vs. a) vehicle size; b) No. of windows accessed vs. vehicle size.

This renders any vehicle larger than 0.9m useless in terms of accessing doors. It was observed during simulations that even vehicles size 0.75m had considerable difficulty in accessing doors, due to collision low tolerance margin at that width.

Next, individual vehicle level results are considered, starting with the effect of both flapping wings and quad-rotors vehicle sizes on their ability to discover exterior and interior areas. As depicted by the plots in Figures 72 and 73, the vehicles of size less than 0.5m are the only ones that are capable of discovering more than 40% of the area.

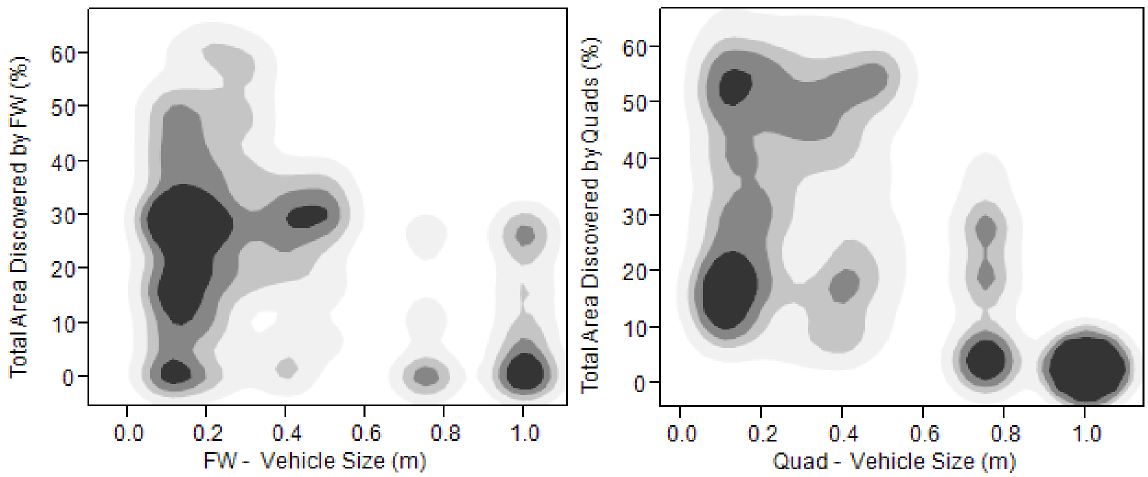


Figure 72: Total area explored as a function of a) FW size; b) Quad size

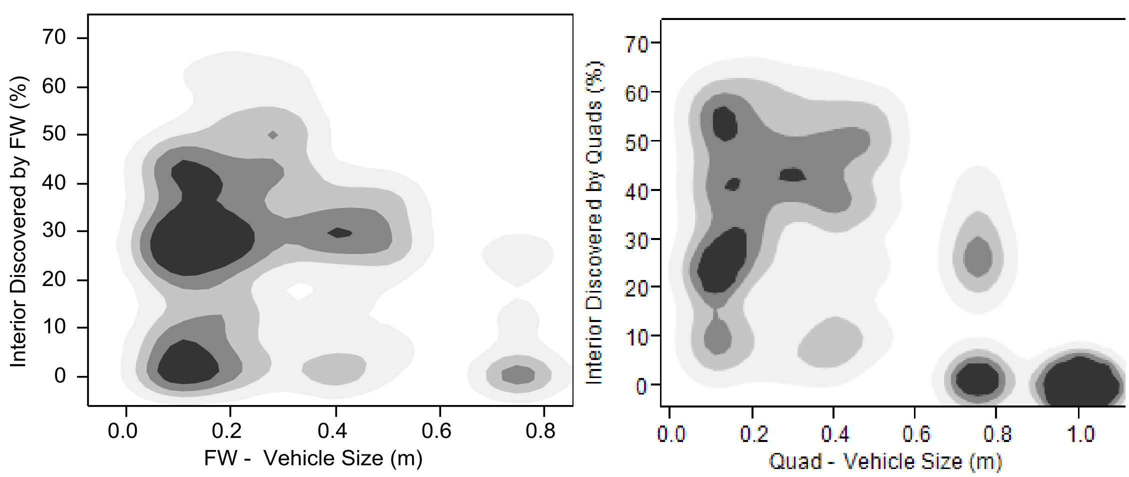


Figure 73: Interior area explored as a function of a) FW size; b) Quad size

The metric value is even lower for interior area explored and much more pronounced for larger vehicles, as they are more prone to face difficulty while entering the building and dying due to wall collisions.

The last metric that is analyzed in this experimental set is the cause of death for vehicle platforms with respect to their size. As shown in Figure 74, the larger vehicles are not only more likely to die due to collisions but are also more prone to getting stuck in smaller areas during exploration, which is not a surprising result. Larger vehicles would face considerable difficulty in maneuvering out of tight spots due to low tolerance margins.

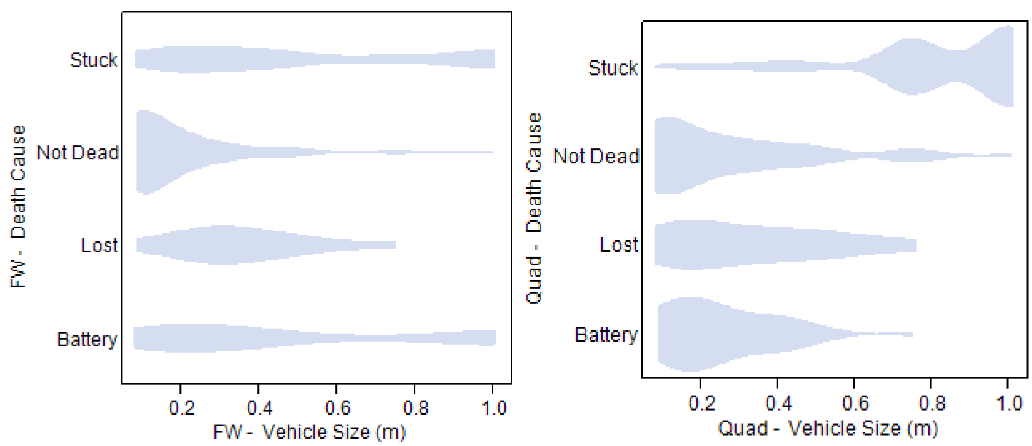


Figure 74: Death Cause as a function of a) FW size; b) Quad size

The tolerance margins are defined as the gap between vehicle and surrounding walls or obstacles in a given region of the map. On the other hand, smaller vehicles are more prone to dying due battery depletion (or in this case, reaching mission time limit). As these vehicles are able to avoid early death due to collisions, they are able to explore for extended period of time. Nevertheless, the mission time limit appears to be the main obstacle to achieving mission objectives for smaller sized vehicles.

Before proceeding to the next set of experimental runs, a quick summary of the results gleaned from this set, in terms of required MoPs levels, is presented here. The analyzed technology metrics are now stated in terms of the gap existing that prevents the MAST SoMs from achieving required levels of mission MoEs. In order to explore a benign, or under perfect stealth conditions, Urban mission environment at over 60% coverage rate, the vehicle size needs to be 0.3m or less. Furthermore, the simulated battery time of 10 minutes is not sufficient to complete the mission, falling short of discovering the required 80%+ of total area. These metrics are further analyzed, for sized systems, in the subsequent sets.

The remaining sets of experiments are carried out with the generalized settings, defined above, and in the manner similar to that of previous sets. Since the results obtained from the next four experimental sets of DL simulation are based on consolidation of the information and analyses of all prior modules in the framework, it is only logical to analyze them in conjunction with technology gap analysis.

5.5.1.1. Swarm Level

The metrics of interest at swarm level primarily relate to the ability of the MAST SoMs to explore the mission map in a collaborative and synergistic fashion, discover entry points into the building structures, and avoid detection and subsequent death by enemies. As mentioned previously, these output metrics are directly definable in terms of mission MoEs and, hence, requires same quantitative levels to be achieved for the mission under consideration to be deemed accomplished. Table 31 lists these output metrics, along with the related mission MoEs, and the levels required for mission success.

Table 31: Output Metrics, MoEs, Required Levels

Output Metric	**MoE**	**Joppa Urban**	**ARL IBR**
% Total Area Explored	Total Area Coverage	> 90%	> 90%
% Interior Area Explored	Interior Coverage	> 90%	> 90%
No. of Doors Accessed	Entry Points Identified	> 80%	> 80%
No. of Windows Accessed	Entry Points Identified	> 80%	> 80%
No. of Vehicles Detected/Killed by Enemies	Enemies Identified, Analyzed, Avoided	<10%	<10%

These responses are dependent on a number of MoPs that directly relate to specific vehicle parameters. The details of these relations were presented in chapter 4, and only the most important ones are listed here. These include swarm size, vehicle size, battery capacity, mission duration, and detection range of the enemies.

With MoEs and MoPs for swarm level experiments defined, it is now time to begin analyzing the results obtained from simulations runs, beginning with the effect of swarm size on area discovered.

Area Explored vs. Swarm Size

The first output metric to be considered is the percentage of the total and the interior mission areas explored in response to the number of vehicles comprising the swarm. The required coverage percentage, for both the total and the interior area, is 90% for both ARL IBR and Joppa Urban missions, as defined previously.

First, an analysis on mission performance of MAST SoMs, built using the current and the future technologies, in light of the total and the interior area discovered is presented. The simulation results for the total area discovered for Joppa Urban and ARL IBR missions by swarms consisting of the current and the future technologies' systems are shown in plots in Figure 75 and 76, respectively.

As evident by the plots of JU mission, the swarm tends to perform relatively better when the number of vehicles is within 3-6. The major reasons for this trend are that smaller groups are not afforded enough time to explore the mission map within the battery constraints and larger groups tend to become inefficient due to increased inter-vehicle collisions. For swarms of more than 6 vehicles, it is observed during simulations that vehicles are more likely to explore same areas as the other vehicles. This is the result of same start location and navigation guidance received from the leading vehicles to the lagging ones. Contemplating on this observation, it can be concluded that having distinct start locations for vehicles within the swarm may be a more efficient method of exploring mission maps, particularly for bigger swarms. However, it may not be always logistically practical to deploy MAST vehicles from different locations as it increases the chances of deploying soldiers being detected by the enemy. Other times, only one approach to the combat zone may be available. Considering these challenges and recognizing that the same start location defines a more constraining problem, it is justifiable to set identical start location for all MAST systems during simulations. If a swarm can accomplish the given mission from single start location, then it is safe to assume that the performance will only improve with implementation of multiple deployment locations.

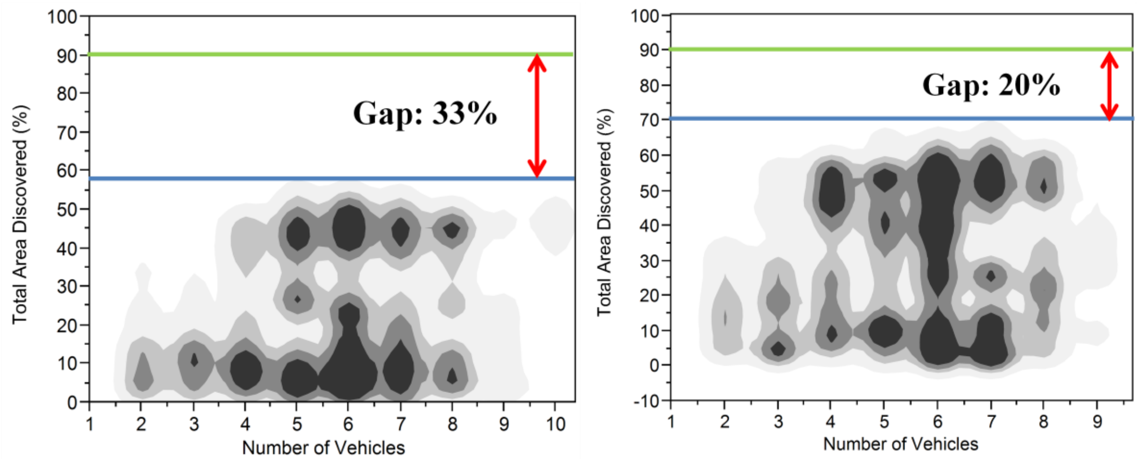


Figure 75: Total Area vs. Swarm Size JU Benign - a) Current Tech.; b) Future Tech.

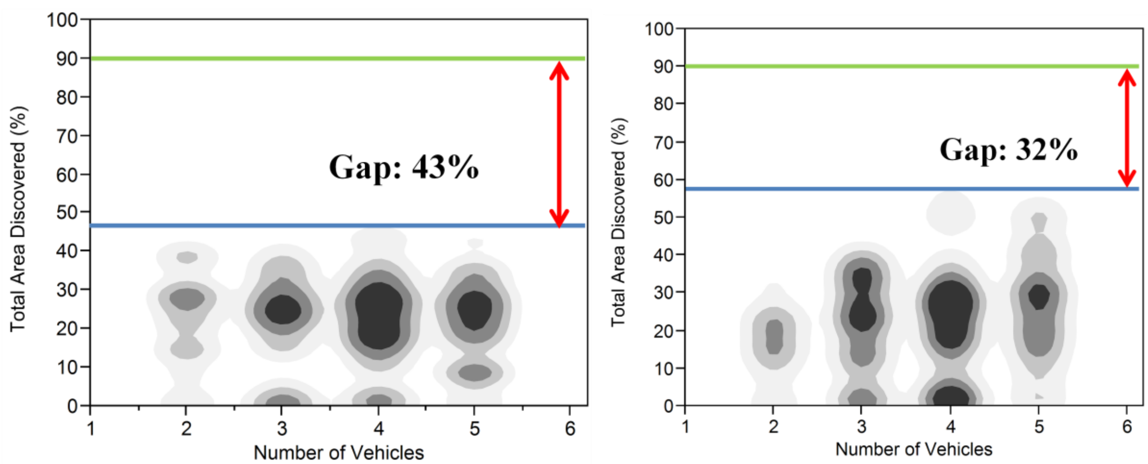


Figure 76: Total Area vs. Swarm Size ARL Benign - a) Current Tech; b) Future Tech.

These conclusions are summarized as following:

1. The smaller swarm size is ineffective mainly because they are not afforded enough time to explore the map comprehensively.
2. Smaller swarm size also results in increased chances of MAST systems getting lost as they are less likely to be in the communication range of others to get navigation guidance.
3. The larger swarm size is less effective mainly because the MAST systems would start getting in each other's way resulting in collisions and hinder exploration.
4. Larger swarm sizes are also observed to become less efficient due to their behavior of 'letting others explore' as there are too many of them in any given region of the map.

Another observation made during the experiments is that the vehicles within a larger swarm tended to wander away from the building. This was the result of following vehicles assuming that there is no area left to explore ahead as the other vehicles, ahead of them, are already exploring all possible paths from perspective of that specific location. This fortifies the conclusion that rather large swarms are not very efficient for mission maps that are similar to JU and ARL mission scenarios.

MAST systems, built using current technologies, performed poorly for both missions. They are only able to explore less than 60% and 50% of JU and ARL missions, respectively. Therefore, for the total area coverage, the resulting gap is quantified as 33% for JU mission and 43% for ARL mission. The reason for the increased gap present in performance for ARL mission is because of two reasons: 1) The area being explored is much larger. 2) The vehicles first need to find entry points into the compound, explore the courtyard, locate the two buildings, and then explore their interiors. This makes the mission map much more complex than the one present in JU mission. In contrast, the vehicles start very close to the building, which needs to be explored, in JU mission.

Next, the effect of presence of enemies in a mission on total area coverage is explored for both missions. Two enemies with a fixed detection radius of 2m are deployed to make the missions hostile. The simulations only consist of MAST systems built on future technologies. The key reason behind is that if a gap exists even with future systems, then the probability of current systems performing better is extremely low if not zero. Figure 77 shows the plots of the simulation results for the total area discovered as a function of swarm size for hostile versions of both missions.

As apparent from the plots, the gap increased by 25% for JU mission and 23% for ARL mission. This is rather substantial increase in gap when compared to benign versions of the same missions. The effect is more pronounced for JU because the building is much smaller and the two enemies are able to patrol it much more efficiently. In comparison, the ARL mission map is much larger and thus affords MAST systems greater opportunity to avoid and evade the two enemies present. These results highlight the pressing need to consider enemy presence for setting requirements to dictate the MAST systems design. It goes without saying that most missions relevant to Warfighter would fall under the category of hostile environments.

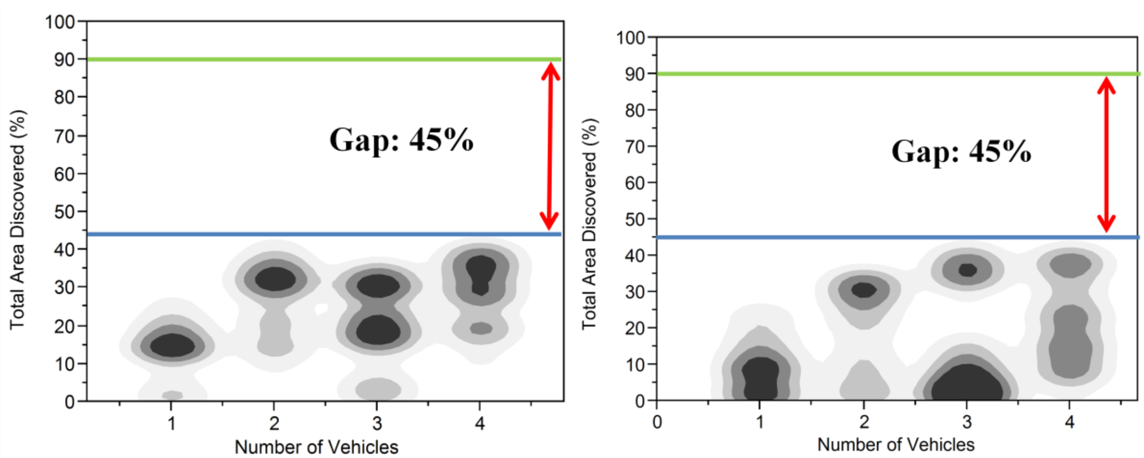


Figure 77: Total Area vs. Swarm Size - Hostile Missions - Future Tech. - a) JU; b) ARL

Now, the percent of the interior area explored is analyzed for a given swarm size in a manner similar to that used for the total area coverage. First, the results of interior discovered in benign mission environments, for the current and the future technologies, are shown in plots in Figures 78 and 79, respectively.

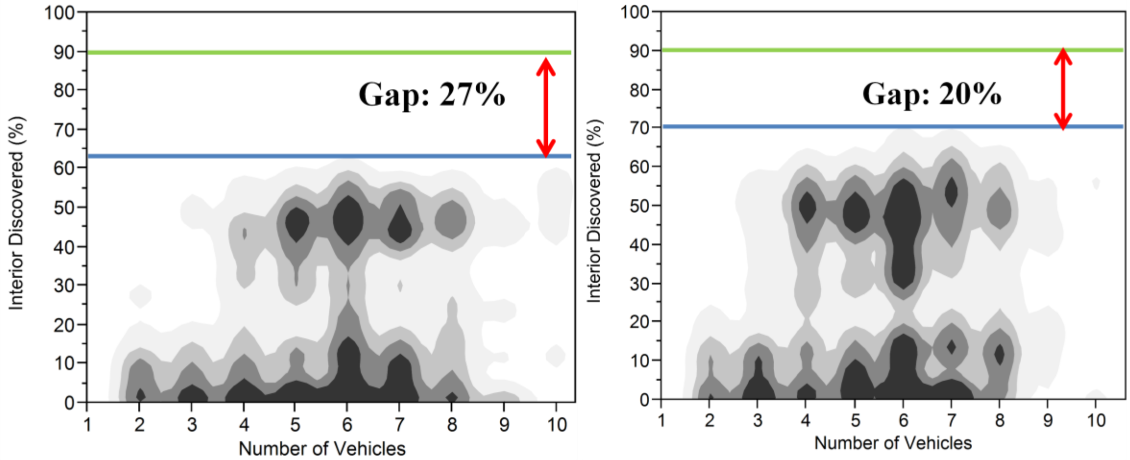


Figure 78: Interior Area vs. Swarm JU Benign - a) Current Tech.; b) Future Tech.

Although the technology gap for discovering interior in Joppa mission is similar to that for discovering total area, the mission performance in ARL map is abyssal for both future and current technologies. The gap is on order of 80% for performance in ARL mission. The major reason for such poor performance is not that the swarm size needs to be bigger or smaller but other factors such as navigational capabilities and finding entry points are at play here. Some of these factors will be analyzed subsequently.

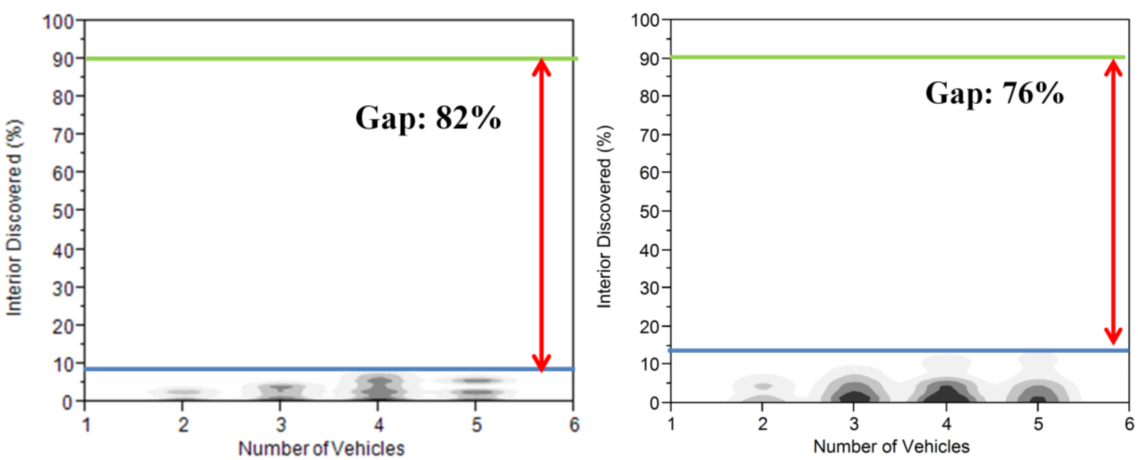


Figure 79: Interior Area vs. Swarm Size JU Benign ARL - a) Current Tech.; b) Future Tech.

The next step is to add the enemies in the missions and analyze the effect of discovering the interior areas on swarms. Again, two enemies with fixed detection radius of 2m are simulated in the experiments. The resulting plots are only for future technologies simulations in both missions and are shown in Figure 80.

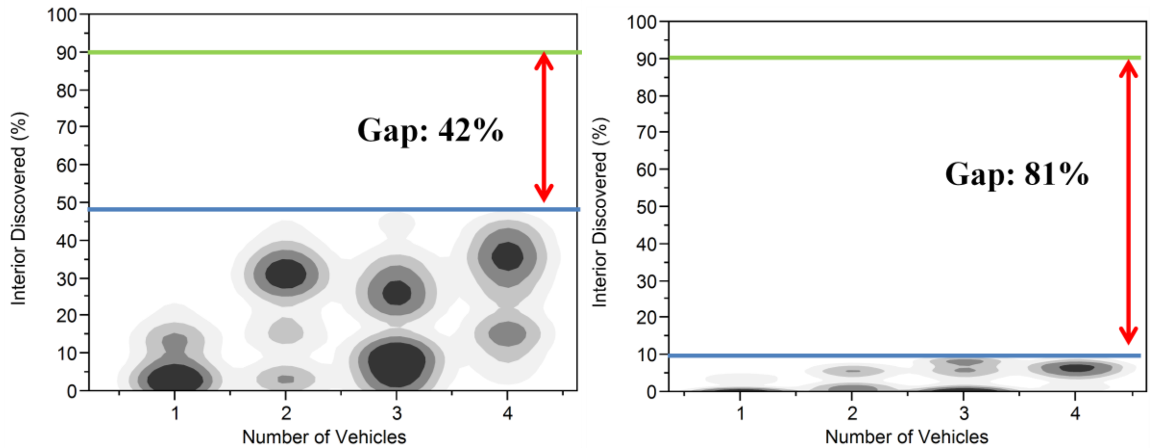


Figure 80: Interior Area vs. Swarm Size - Hostile Missions - Future Tech. - a) JU; b) ARL

As expected, the gap increased for both missions with a more pronounced effect on Joppa Urban map. The reasons are same as the ones mentioned for the total area explored under hostile conditions above. The resulting gap increased by 22% for Joppa mission and 5% for ARL IBR mission.

Considering the results obtained for area coverage as a function of swarm size, it can be concluded that for Joppa Urban and ARL IBR missions, swarm size of 3-5 vehicles is sufficient. Any further increase in size is only likely to result in decreased performance. However, even with 3-5 vehicles, built from the future technologies, present in the swarm, a rather large gap exists for achieving the required levels of the MoEs under consideration. Therefore, the next step is to analyze these MoEs in context different sizes of vehicles composing the swarm.

Area Explored vs. Vehicle Size

The next step is to analyze the percentage of the total and the interior mission area explored in response to the size of the vehicles within the swarm. As previously, the required coverage percentage, for both the total and the interior area, is 90% for both missions. Following the process similar to that implemented for previous output metric-input variable analysis, the mission performance in terms of the total and the interior area discovered by MAST SoMs, for current and future technologies, is conducted. The simulation results for total area discovered for Joppa Urban and ARL IBR missions by swarms consisting of various sized vehicles, built from current and future technologies, are plotted in Figures 81 and 82.

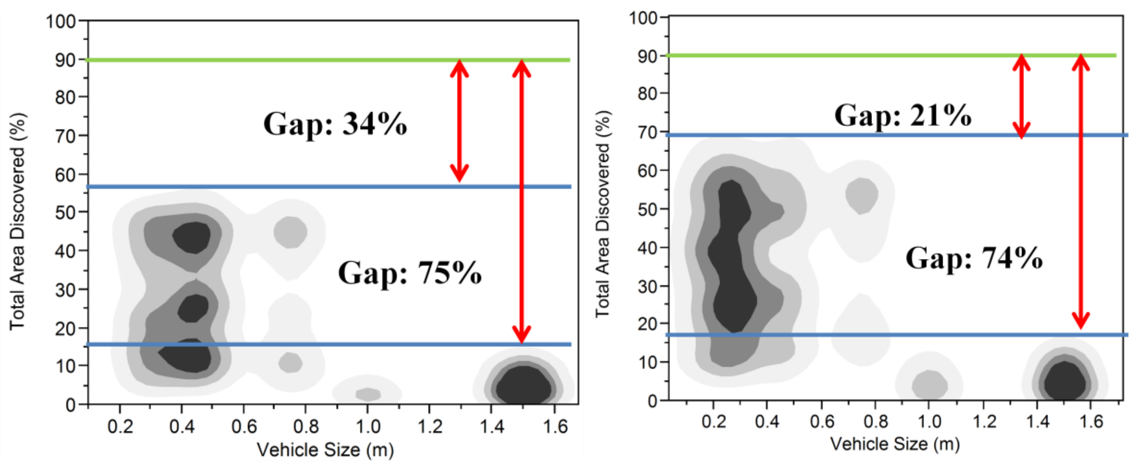


Figure 81: Total Area vs. Swarm Size JU Benign - a) Current Tech.; b) Future Tech.

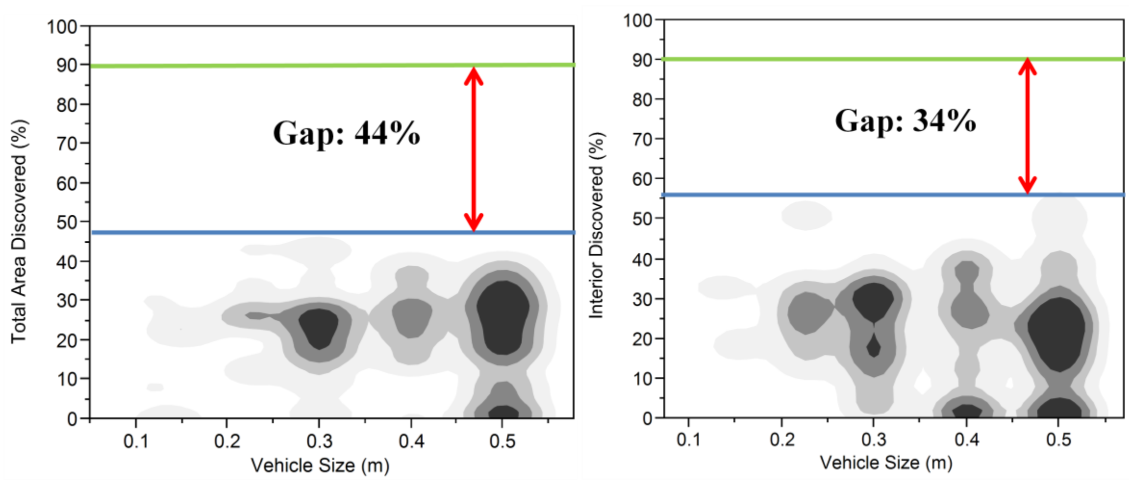


Figure 82: Total Area vs. Swarm Size ARL Benign - a) Current Tech.; b) Future Tech.

The plots above signify the importance of the composing vehicles' size (i.e. characteristic dimension) for the swarm's ability to explore areas. Anything above 0.5m is practically useless for exploration of JU mission. The gap for vehicles over one meter in size is close to 75% and this doesn't change even with the infusion of the future technologies. The best relative results are obtained at 0.3m or smaller vehicles. Considering this, only vehicles of 0.5m or less are simulated for ARL mission. The lack of smaller sized vehicles discovering more area is due to the fact that only very few small size vehicles are present in the candidate pool for systems built using the current technologies. The gap trends are similar for both missions, but the magnitude is much higher for the ARL mission. That is primarily due to the mission being more complex and influenced heavily by the exploration logic and navigation capabilities. Nevertheless, even with the future technologies infused onto the MAST systems, the gap ranges between 20-35% from meeting the 90% explored area requirement.

Next, the effect of making the mission hostile on the total area discovered is considered. Figure 83 shows the plots of the simulation results for the total area discovered as a function of vehicle size for both of the missions.

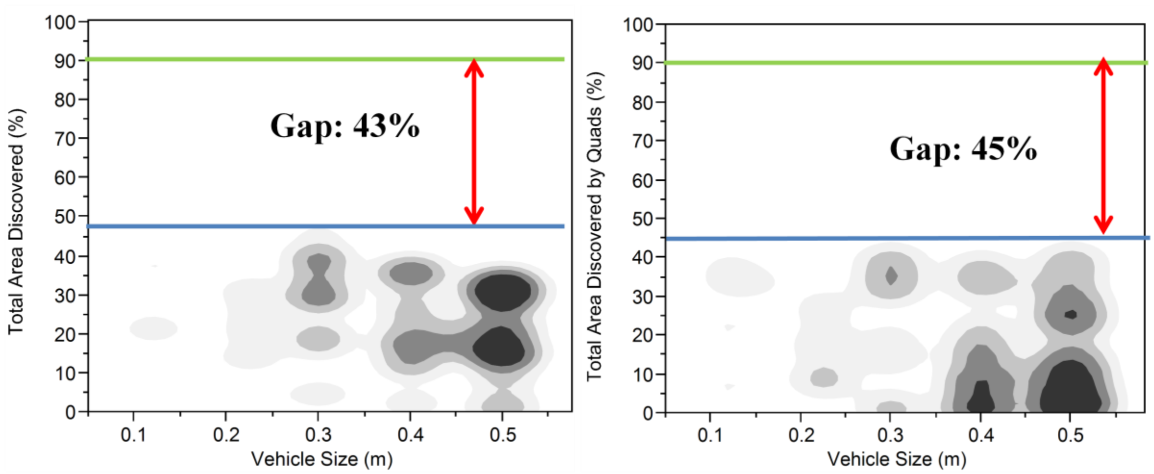


Figure 83: Total Area vs. Vehicle Size - Hostile Missions - Future Tech. - a) JU; b) ARL

As previously, two enemies with a fixed detection radius of 2m are deployed in the mission and only the swarms based on future technologies are simulated. The main reason for this decision is that if a gap exists even with the future systems, then it will certainly exist for the current systems as well.

The gap visibly increased for both missions as expected. For Joppa Urban, the gap increased by 22% and for ARL IBR, it increased by 11%. Again, the effect of enemies is more pronounced on JU mission as it is much smaller and easier for enemies to patrol. The gap increased by 25% for JU mission and 23% for ARL mission.

The focus will now shift to interior area explored and its dependence on vehicle size. Starting with benign missions, the plots in Figures 84 and 85 depict the simulation results for interior area coverage as a function of vehicle size.

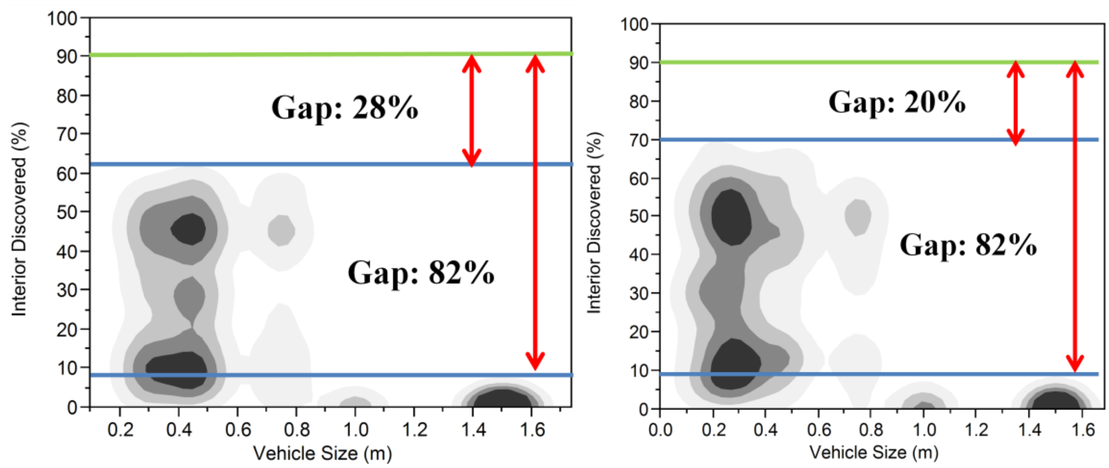


Figure 84: Interior Area vs. Vehicle Size JU Benign- a) Current Tech.; b) Future Tech.

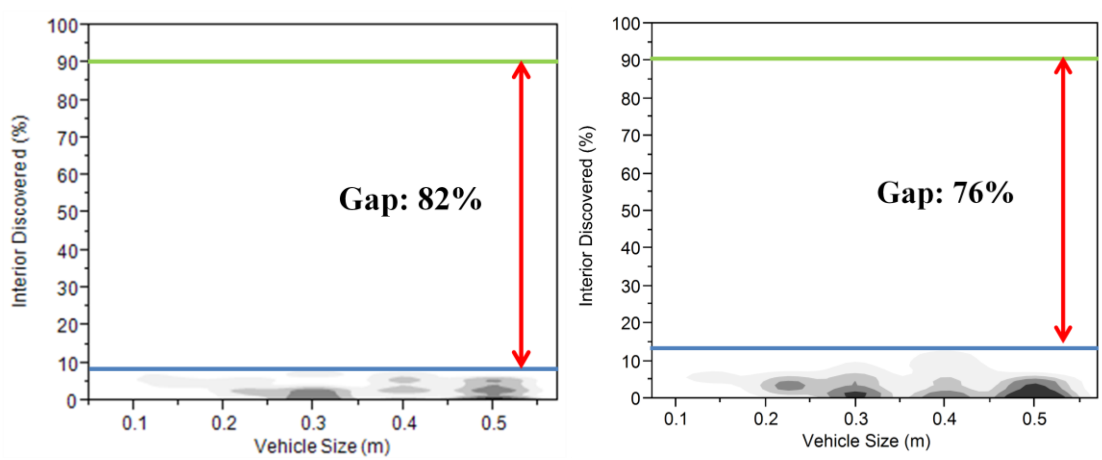


Figure 85: Interior Area vs. Vehicle Size ARL Benign - a) Current Tech.; b) Future Tech.

Not surprisingly, the trends are quite similar to those for total area explored as a function of vehicle size. As observed before, the complexity of ARL mission makes it extremely difficult for vehicles of any size to properly explore the interior of the buildings within the map. The vehicles run out of the battery before being able to discover the buildings. This can be primarily attributed to the navigation algorithms and the need to make them more intelligent and efficient for exploration of complex environments. This is expected to become clearer as more metrics are analyzed. The gaps for ARL mission are on the order of around 80% for both current and future technologies.

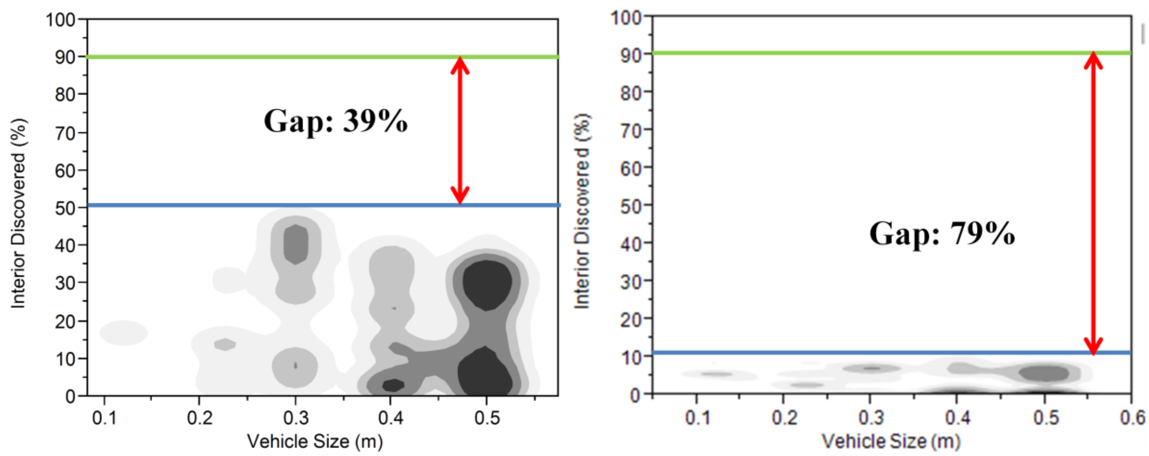


Figure 86: Interior Area vs. Vehicle Size - Hostile Missions - Future Tech. - a) JU; b) ARL

Finally, the influence of enemies in context of vehicle size is explored. As before, two enemies with fixed detection radius of 2m are simulated. MAST systems built only using the future technologies are deployed in the experiments. Figure 86 shows the resulting plots. The presence of enemies increased the gap by 11% for the JU mission and 3% for the ARL mission. The small increase in the gap for ARL isn't due to stellar performance of the vehicles, but due to the fact that the performance in benign missions is poor to begin with. Furthermore, the size and complexity of the mission also dampens the influence of enemies, especially if only two are present in such a large area. At this point, it is justifiable to conclude that vehicles need to be 0.3m or less to be able to perform the missions at reasonable level. The maximum size that a vehicle can have is 0.5m. Above that, the performance is unacceptable by all accounts.

Total Area Explored vs. Battery Capacity

The next MoP to be analyzed for its influence on the total area explored is the battery capacity. Not only it defines the endurance of the vehicles within the mission environment but also places an upper limit on the possible mission duration. Such limitations are essential to be considered during mission planning phases to ensure that vehicles will be able to accomplish the tasks without running out of the battery power.

Figures 87 and 88 depict battery capacity plots for current and future technologies both JU and ARL IBR missions.

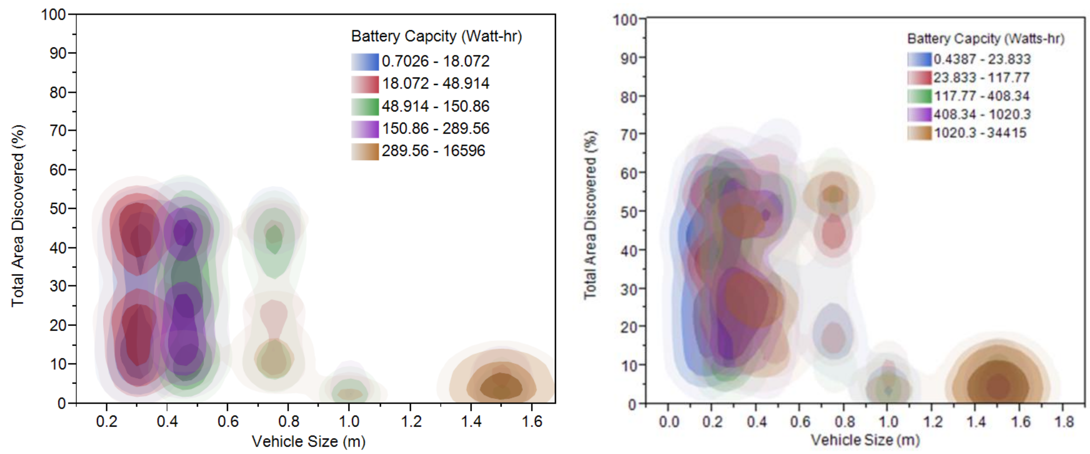


Figure 87: Battery Capacity JU - a) Current Tech.; b) Future Tech.

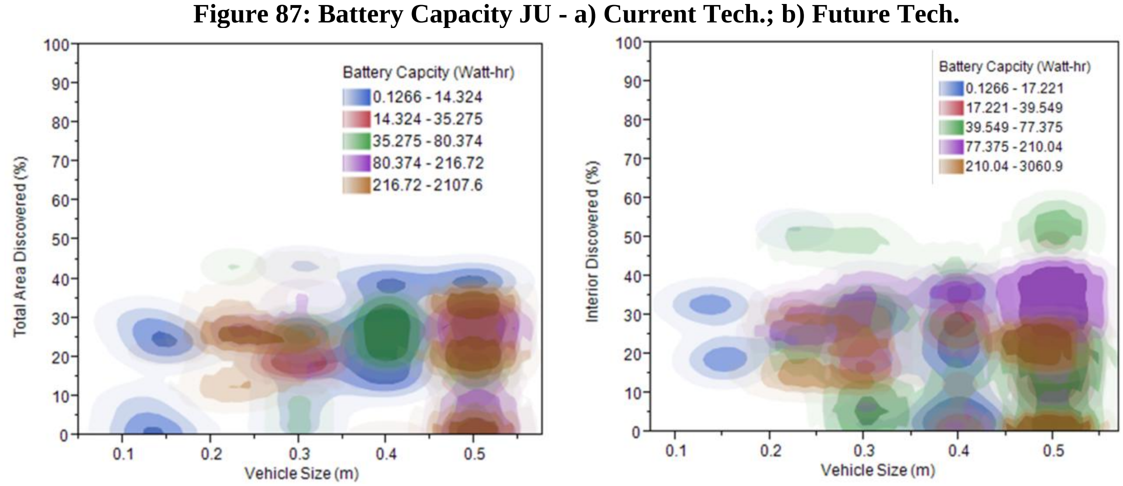


Figure 88: Battery Capacity ARL - a) Current Tech.; b) Future Tech.

The battery capacity is related to the size of the vehicle in terms of dimensions, hence, its capacity and the depletion rate, depending on vehicle power required, is selected during sizing stage. Therefore, in order to correctly gauge the battery capacity's effect on the total area discovered, it is important to analyze the results in context of vehicle size. This is accomplished by overlaying the battery capacity on the plots of the total area discovered vs. vehicle size.

Considering the above plots, it is evident that the highest capacity batteries are not necessarily equipped on the top performing vehicles. Following conclusions are drawn from the results.

- For JU mission with current technology based systems, vehicles with battery capacity between 18 Watt-hr and 290 Watt-hr are able to explore the most amount of area. It may appear, at first that batteries with higher capacities seem to perform quite poorly during the mission. But the fact of the matter is that the batteries with higher capacities are too big and heavy to be carried by vehicles 0.5m or smaller in size. The only vehicles that are able to carry these high capacity batteries are mostly 1.0m or larger in size and primarily performed poorly due to their large dimensions.
- It becomes evident, when considering the results of JU mission with future technologies infused, that not only the available battery capacity has increased two-fold but it can also be equipped on smaller vehicles. The reason is that with improvements in power requirements and weight, smaller vehicles are now able to carry higher capacity batteries and hence higher battery capacity can now be correlated with increased area explored. Nevertheless, it seems that the best performing systems were equipped with mid to high battery capacities, specifically 117 Watt-hr - 1020 Watt-hr. In order words, a compromise between increased battery capacity and resulting increase in weight leads to better performance.

- For ARL mission with current technology based systems, conclusions similar to those for JU can be drawn. Higher capacity batteries are too bulky to be equipped on smaller vehicles and hence lead to poor mission performance. It is primarily due to the virtue of increased vehicle size to accommodate the battery. The ideal range in this case is between 35 Watt-hr to 80 Watt-hr.
- For ARL mission simulated with the improvements afforded by k-factors, smaller vehicles are now able to be paired with higher capacity batteries. Similar observations are made for JU mission. However, the difference is that the best performing systems are not as greatly influenced by being able to fly longer. The reason is that the complexity of the mission map presents a non-linear relationship with vehicle endurance. In order words, the vehicles not only need higher endurance but also need to be able to navigate more intelligently. Nevertheless, the best battery capacity range for this scenario is 39 - 80 Watt-hr, which is similar to that for ARL IBR mission, executed by systems built from current technologies.

Doors Accessed vs. Vehicle Size

Detecting entry points and utilizing them are necessary for MAST systems to successfully accomplish the mission. The first type of entry point utilization to be analyzed is a door. The goal of the MAST systems is to locate entry points in form of a door and use them to access the building structure. Opening of the doors or an accessing mechanism are not simulated. The vehicles are assumed to be able to access the doors, once located, without any hindrance depending on its navigational logic.

Figures 89 and 90 show the number of doors that are access by MAST systems, based on current and future technologies, of different sizes for benign versions of both JU and ARL IBR missions.

In order to assess the performance of the MAST systems in terms of discovering and accessing doors, it is necessary to define the total number of doors present in the missions. The total doors present are:

- Joppa Urban mission: 2
- ARL IBR mission: 4

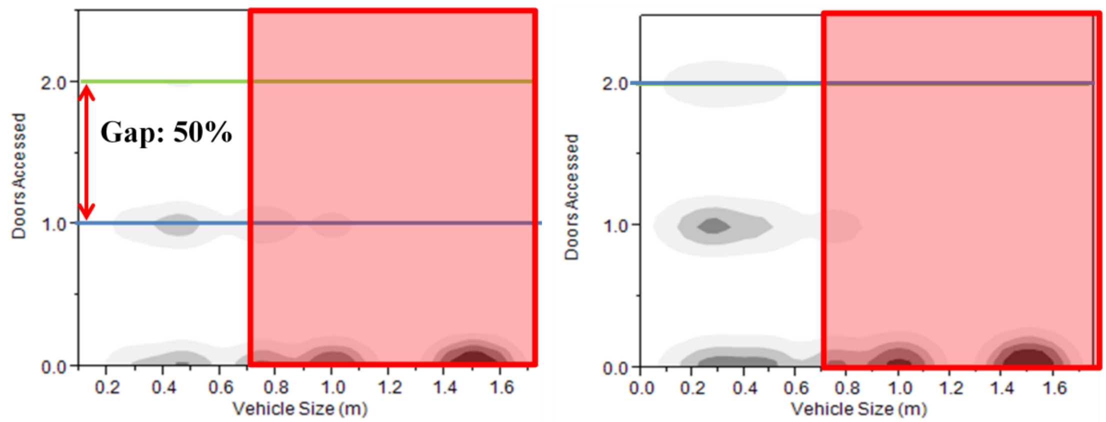


Figure 89: Doors Accessed JU - a) Current Tech.; b). Future Tech.

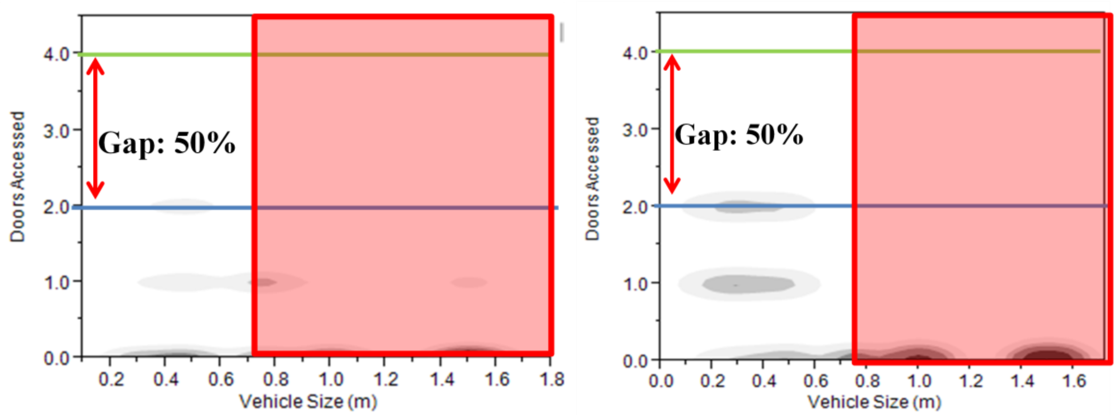


Figure 90: Doors Accessed ARL - a) Current Tech.; b) Future Tech.

As evident by the plots, the vehicles larger than 0.75m, in their characteristic dimension, are not able access any of the doors, even if they are detected. The reason for this is simply that they are too big or wide to go through them. This holds true regardless of the technology year under consideration. Hence, the right rides of the plots are shaded red to show technically non-feasible regions.

For systems based on current technologies, a gap of 50% exists for both JU and ARL missions. Only half the number of doors are discovered and accessed. However, with infusion of future technologies, a small percentage of MAST systems are able to find and access both doors in JU mission. These systems were almost always less than 0.5m in their characteristic dimension, demonstrating the need for vehicle to be in that range. For ARL mission with future technologies considered, more of the smaller sized vehicles are able to discover and access doors but a discrete gap still remained at 50%. The reasons are again the complexity and dimensions of the mission, impeding the smaller size vehicles to explore sufficiently without getting lost.

Nevertheless, the conclusion that the characteristic dimension of the vehicles needs to be less than 0.5m holds true. This requirement sets hard limitation on size of the MAST systems. And the capabilities of the navigational and feature detection algorithms can't be understated.

Windows Accessed vs. Vehicle Size

The next type of entry point to be assessed is a window. Tactically speaking, MAST systems are more likely to gain entry into a building through windows. It is not only stealthier but also more likely to not require deployment of opening mechanisms. The main goal of this analysis is to determine if there needs to be a more stringent requirement on vehicle size than the one imposed by accessing doors.

Figure 91 demonstrate the performance of MAST systems, based on current and future technologies, for JU mission in context of discovering and accessing windows. The total number of windows present in the mission are modeled to be three.

Considering the plots, it is observed that a minor percentage of the MAST systems, based on current technology, are able to discover and access all three of the windows. However, only with the infusion of the future technologies are a respectable number of vehicles able to find and access all three windows. Conservatively speaking, the technically infeasible zone, in terms of vehicle size, starts at 0.75m in characteristic dimension.

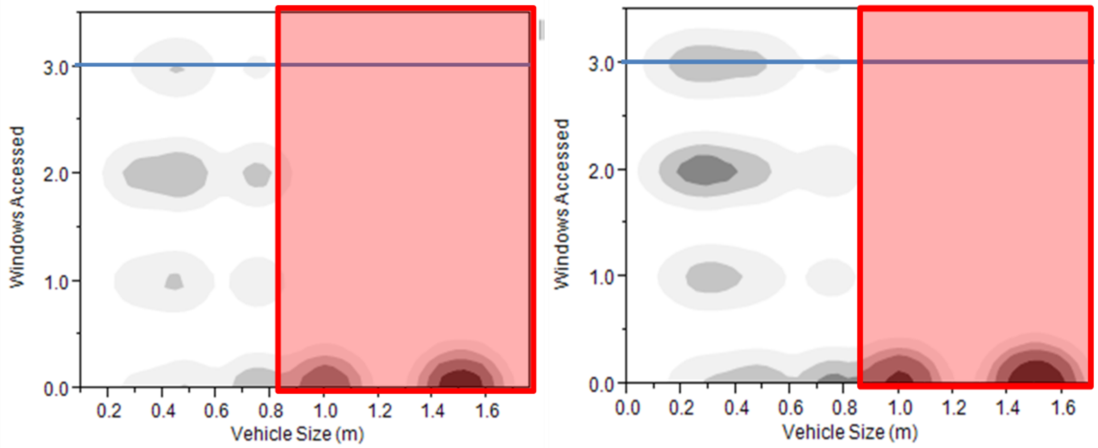


Figure 91: Windows Accessed JU - a) Current Tech.; b) Future Tech.

Although there isn't a metric gap visible within the plots, it is important to note that vehicles larger than 0.5m were extremely unlikely to access any windows. Therefore, the requirement for vehicles to be less 0.5m remains as the upper limit on dimensions.

Area Explored vs. Mission Duration

The effect of battery capacity, or rather useable endurance limit of the vehicles, on the percentage of area discovered has been explored above. It is only logical to consider the mission time limit on the performance of MAST systems. It is in the similar category as that of battery capacity, yet a very different metric quite in terms of the information it provides. While battery capacity directly affects the endurance of a MAST vehicle and is a technical specification, mission time limit is based on logistics of the mission planning. The mission time limit is defined as the maximum time allotted for MAST systems to accomplish their objectives regardless of their technical capabilities. For instance, in a mission with time limit of 10 minutes, a vehicle capable of 20 minutes of flight will need to achieve its objectives within 10 minutes instead of 20. This metric is of interest to the Warfighter directly, for mission planning, and to the technologists indirectly, for tweaking metrics other than endurance to meet time limitations.

Figure 92 shows the effect of the mission time on total area discovered for Joppa Urban mission by vehicles built using current and future technologies.

The mission time can be directly correlated with increased area discovered, which is not a surprising result by itself. However, the effect is more much pronounced for future technologies. The reason behind is that these vehicles are able to explore for longer due to the increased endurance afforded by the improved battery capacities. The vehicles built on current technologies are more prone to dying early due to the battery running out and/or collisions with walls and other vehicles in the vicinity. Comparatively, future technologies are no longer dying due to battery depletion. It is important to note how only a handful of current technology vehicles are able to utilize the full mission time of 600 seconds.

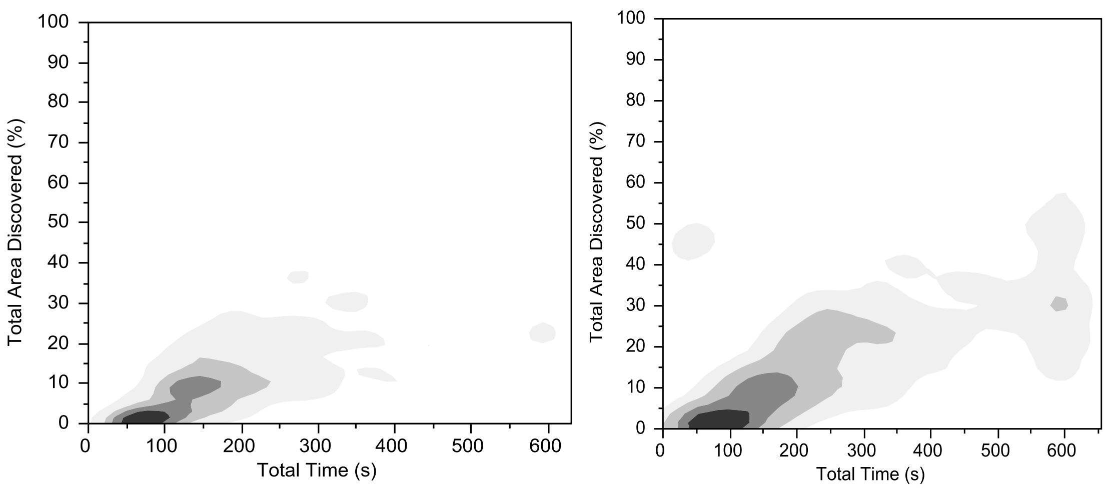


Figure 92: Mission Duration JU - a) Current Tech.; b) Future Tech.

In contrast, quite a higher number of the future technology vehicles are utilizing full 600 seconds of the given mission time. In fact, the 600 second mission time becomes the limiting factor for area exploration. Nevertheless, the major conclusion from this analysis is that at least 10 minutes are required for MAST vehicles to explore Joppa Urban mission. And it is close to 10 minute mark that the direct correlation starts to get distorted. It signifies that further increase in mission time may not result in increased performance, if other MoPs remain the same.

Deaths vs. Swarm Size and Vehicle Size

Previously, it has been noted that large swarms are more likely to suffer from decreased performance due to inter-vehicle collisions and decreased exploration efficiency. This problem was further confounded with large sized vehicles. So, it would be interesting to analyze the number of deaths in reference to swarm and vehicle sizes.

Figures 93 and 94 show the number of a vehicles, built from current technologies, dying based on a given swarm size and composing vehicles' sizes for JU and ARL IBR missions, respectively.

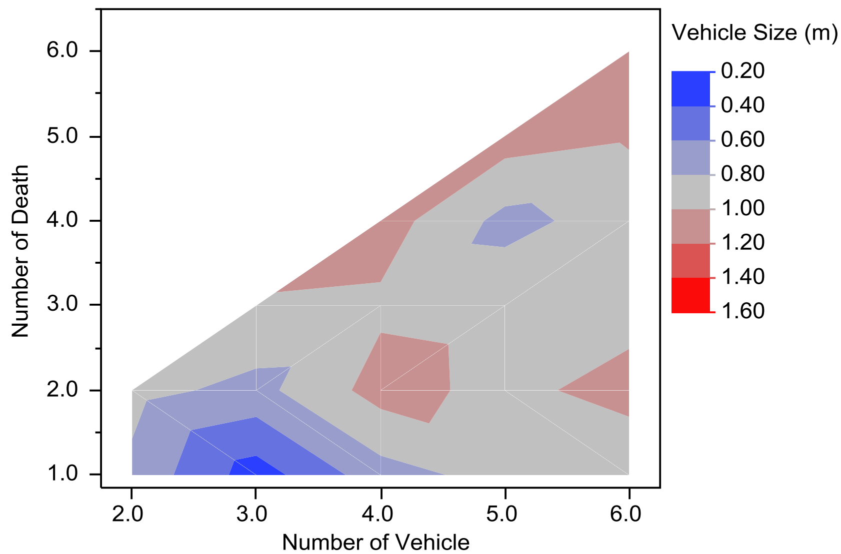


Figure 93: Deaths vs. Swarm and Vehicle Size JU - Current Tech.

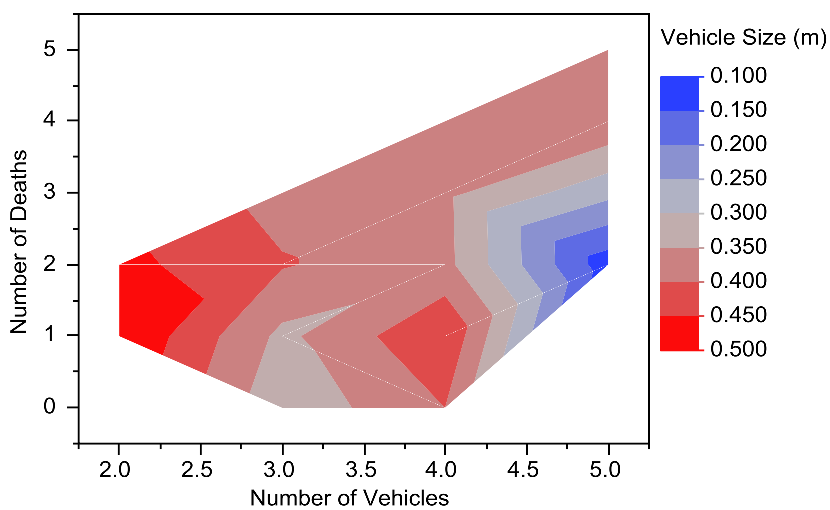


Figure 94: Deaths vs. Swarm and Vehicle Size ARL - Current Tech.

For current technology year, as swarm size increases, vehicles larger than 0.25 are more likely to die in both missions. Increased swarm size increases the likelihood of vehicles colliding with each other or with walls, while trying to avoid other vehicles. The cause of death isn't distinguished in the plots presented in this subsection. However, the missions analyzed are of benign nature, so it is justifiable to conclude that one of the reasons of vehicles' death in larger swarms is due to inter-vehicle collisions. It was further validated by observations of simulation trials. Depending on the agility of the vehicles, collisions occur even in cases when sensory ranges are high enough to detect other vehicles nearby. The issue is that the inertia of the vehicle is larger than avoidance capabilities of vehicle afforded by it's the maneuvering abilities. Hence, the collisions would result and increase the number of deaths within the swarm.

Moving on, future technologies are infused and the results from experiments are shown in Figures 95 and 96 for JU and ARL IBR missions, respectively.

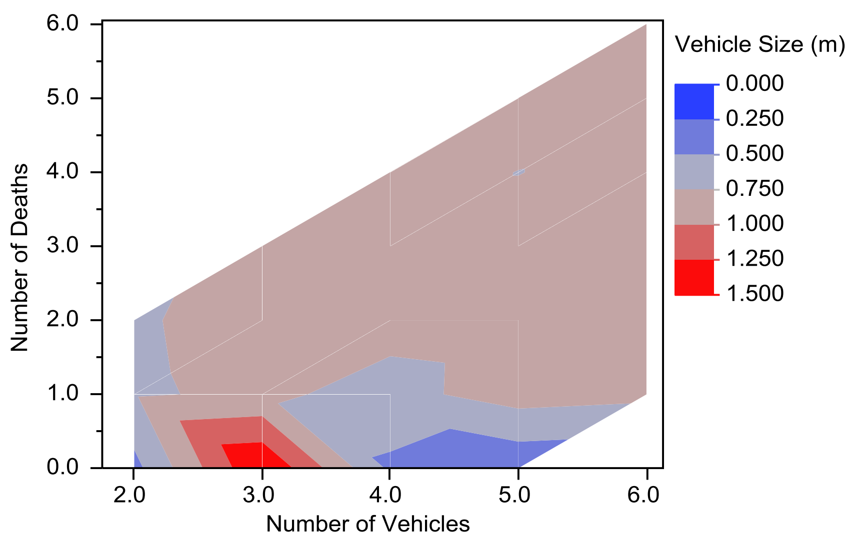


Figure 95: Deaths vs. Swarm and Vehicle Size JU - Future Tech.

With future technologies infused, it can be observed that vehicles smaller than 0.25m in characteristic dimension become almost immune to swarm size and are able to explore without dying.

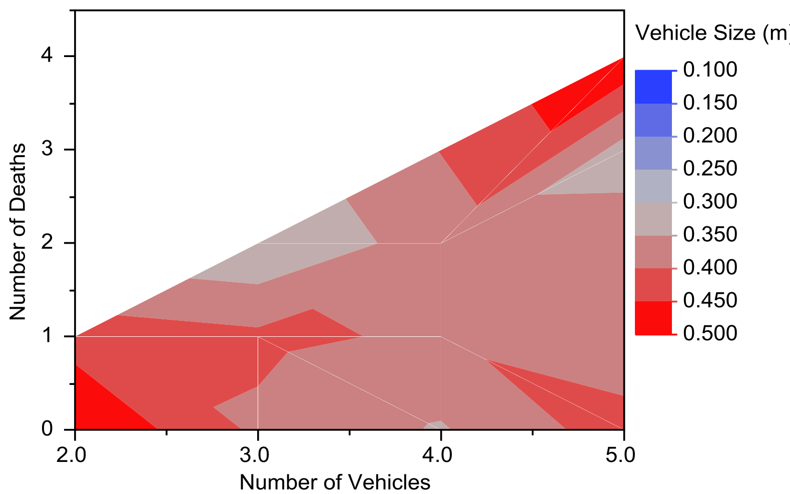


Figure 96: Deaths vs. Swarm and Vehicle Size ARL - Future Tech.

This means that their smaller size dampens the effect of collision hindrance and greatly reduces the inter-vehicle collisions. Nevertheless, further improvement in mission performance requires significant advances in vehicle intelligence level afforded navigational and obstacle avoidance algorithms.

<u>Detected/Killed by Enemies vs. Swarm and Vehicle Size</u>

The dynamics of any mission are expected to change drastically if there is a presence of enemies. In hostile mission, MAST systems are not only required to achieve the objective of exploring unknown terrain but are also required to detect and avoid enemy patrols. The mission becomes considerably more difficult and the constraints on MoPs are expected to become even more stringent. The effect of hostiles on area explored was previously assessed. It's now time to understand the relation between presence of enemies and death of MAST systems in context of swarm and vehicle size. Density plots with color overlays (for third variable) are primarily utilized for analysis. For this set of experiments, the number of enemies present is two and their detection radius is fixed at 2m range. Starting with Figure 97, the results for detections by enemy are shown.

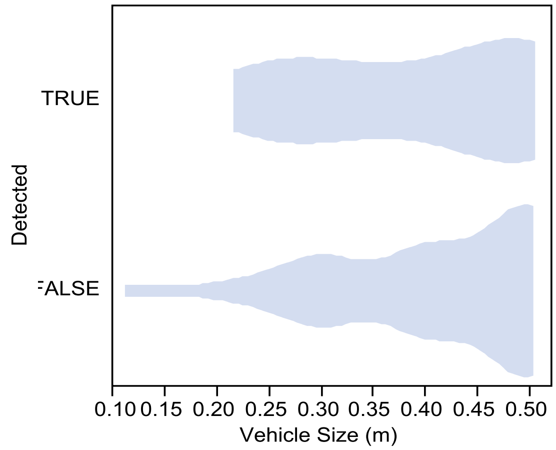


Figure 97: Detected vs. Vehicle Size JU Hostile Mission- Future Tech.

It is apparent that vehicles larger than 0.2m in characteristic dimension are always detected by enemies. Only smaller vehicles have a slight chance of escaping detection. As mentioned before. only vehicles composed of future technologies are simulated in hostile missions. It is justified by the assumption that the constraints determined for future technology also form the feasibility limit for current technologies.

Next, the cause of death in context of vehicle size is explored for both Joppa Urban and ARL IBR missions. These results for death cause are shows in Figures 98 and 99 for hostile Joppa Urban and ARL IBR mission, respectively.

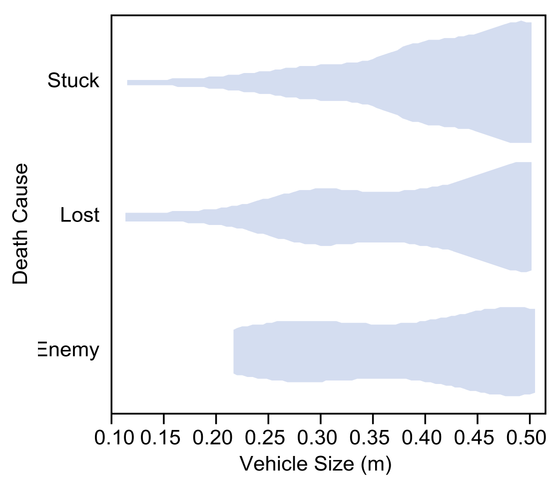


Figure 98: Death Cause vs. Vehicle Size JU Hostile Mission- Future Tech.

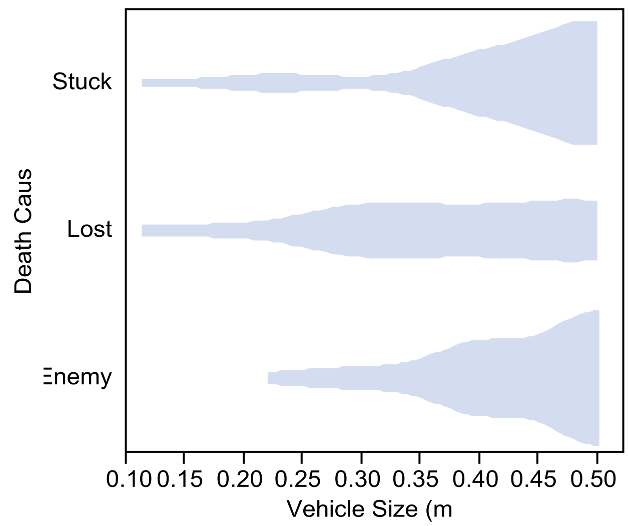


Figure 99: Death Cause vs. Vehicle Size ARL Hostile Mission- Future Tech.

Again, vehicles above 0.2m in size are able to be detected by enemies in both missions. However, the detection rate is less for ARL mission. It is simply because of the area being much larger than the JU mission map. It can be also observed that larger vehicles are also more likely to die by getting stuck in small areas of the map.

Next, a closer look is taken into deaths by enemies by relating the vehicle size to the number of vehicles killed by enemies. Figures 100 and 101 show the chance of vehicle being detected by enemy, based on its size. For both missions, it is apparent, that only vehicles smaller than 0.2m are able to escape detection by enemies.

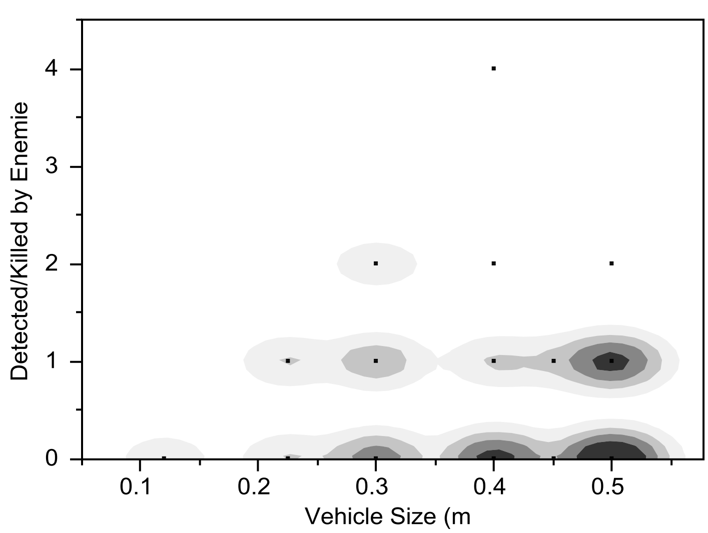


Figure 100: Detected/Killed vs. Vehicle Size JU Hostile Mission- Future Tech.

Considering the analysis of this subsection, it can be concluded that the vehicles need to be less than 0.2m in their characteristics dimension to avoid detection by enemies with detection range of 2m.

It is important to note that 2m detection radius is rather low, in real world terms, for human enemies. At this point, it is important to recall the effect of enemy detection range on mission performance of vehicles that was presented during the analysis of validation experiments. This aspect will be re-visited from vehicle level stance point later in this chapter.

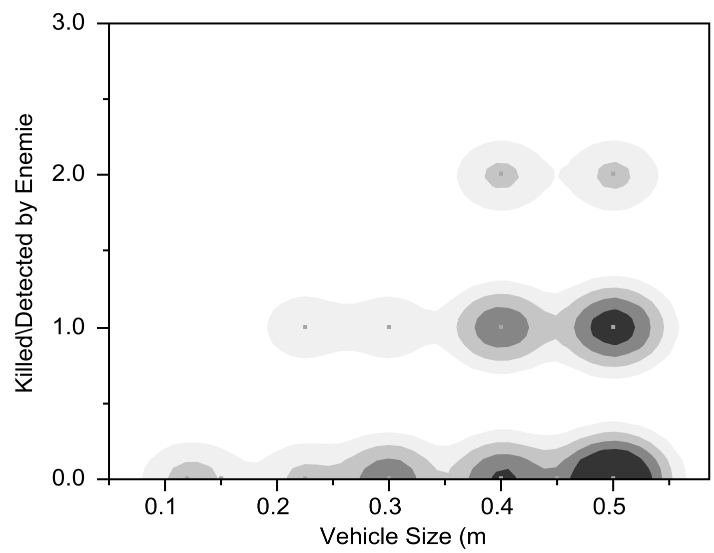


Figure 101: Detected/Killed vs. Vehicle Size ARL Hostile Mission- Future Tech.

As alluded above, the focus of analysis will now be shifted from swarm level to vehicle level.

5.5.1.2.Vehicle Level

With mission performance studied at swarm level, it is now time to go a level lower and analyze individual vehicles, operating as part of swarm, and their capability to perform missions. Analysis in this section follows the same format as that used for swarm level studies. Density plots are used extensively to understand the effect of MoPs on responses. It is important to note that although the mission performance of individual vehicles is under scrutiny here, the simulations are still conducted for the whole swarm. Both flapping wing and quad-rotor platforms are analyzed. The major difference between swarm level and this level is that the simulations employed 'Informative' communication scheme and only the best performing vehicle in each swarm for each run is considered. Table 32 lists the output metrics, under consideration, along with the relevant mission MoEs and their required levels to consider a mission accomplished. These apply to both Joppa Urban and ARL IBR missions.

Table 32: Output Metrics, MoEs, Required Levels

Output Metric	MoE	Joppa Urban	ARL IBR
% Total Area Explored	Total Area Coverage	> 90%	> 90%
% Interior Area Explored	Interior Coverage	> 90%	> 90%
No. of Doors Accessed	Entry Points Identified	> 80%	> 80%
No. of Windows Accessed	Entry Points Identified	> 80%	> 80%
No. of Vehicles Detected/Killed by Enemies	Enemies Identified, Analyzed, Avoided	<10%	<10%

The MoPs for evaluating these metrics include vehicle size, battery capacity and detection radius of the enemy.

Area Explored vs. Vehicle Size

The first metric to be considered at the vehicle level are the total and interior areas explored, in context of vehicle sizes, for Joppa Urban and ARL IBR missions. Both current and future technologies in benign mission environment are considered. The hostile missions for these metrics were already studied at swarm level.

The premise for assessment standard is that each individual vehicle shall be capable of individually meeting the required level of the metric. It can be considered conservative but it is a safer assumption. Therefore, in order for a swarm to be successful, each of its members shall be capable of achieving the primary mission objectives.

Starting with the total area explored for JU mission, a huge gap exists for both flapping wing and quad-rotor platforms built using current year technologies. With infusion of future technologies, this gap is reduced by around half for both platforms. Specifically, gap for flapping platforms is reduced from 68% to 30%, while quad-rotors' gap reduces from 59% to 35%. The results are shown in Figure 102 and 103 for current and future technologies, respectively.

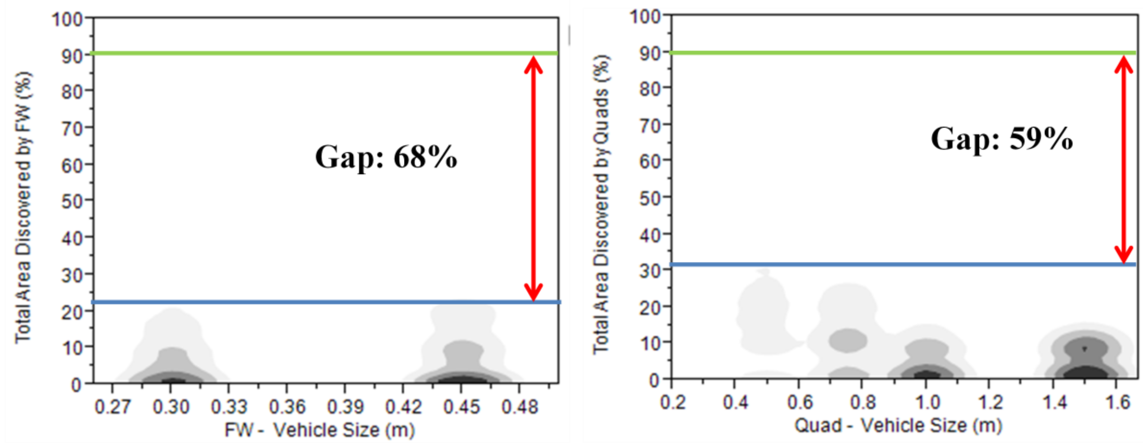


Figure 102: Total Area vs. Vehicle Size JU - Benign, Current Tech. - a) FW; b) Quad

Flapping wing vehicles are observed to improve relatively more than quad-rotor platforms as future technologies are infused. Nevertheless, vehicles larger than 0.5m in their characteristic dimension perform very poorly for any technology year. Again, the constraining requirement to be drawn from here is the absolute maximum size of the vehicles. Based on the results, it needs to be less than 0.5m.

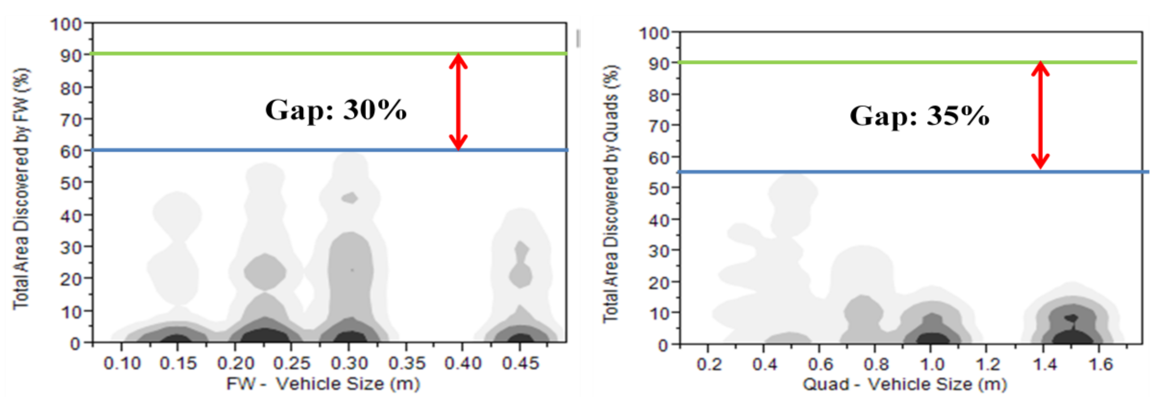


Figure 103: Total Area vs. Vehicle Size JU - Benign, Future Tech. - a) FW; b) Quad

Next, the results from benign ARL mission are shown in Figure 104 for current technologies and in Figure 105 for future technologies.

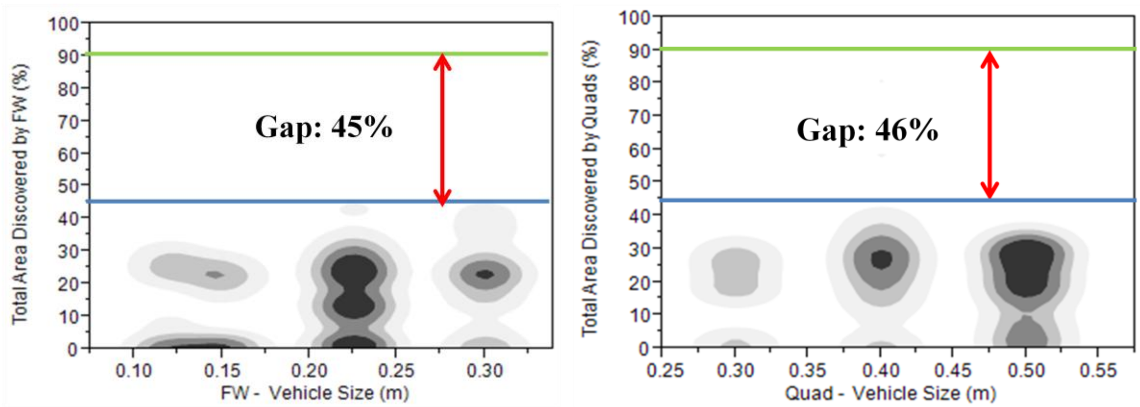


Figure 104: Total Area vs. Vehicle Size - ARL - Benign, Current Tech. - a) FW; b) Quad

Both platforms tend to perform slightly better than for JU mission in exploring total area. The primary reason for improved performance is the presence of greater exterior area, which is generally easier to explore than interior area, compared to Joppa Urban mission. Therefore, it is important to note that the improved performance in ARL IBR doesn't necessarily signify improved mission accomplishment.

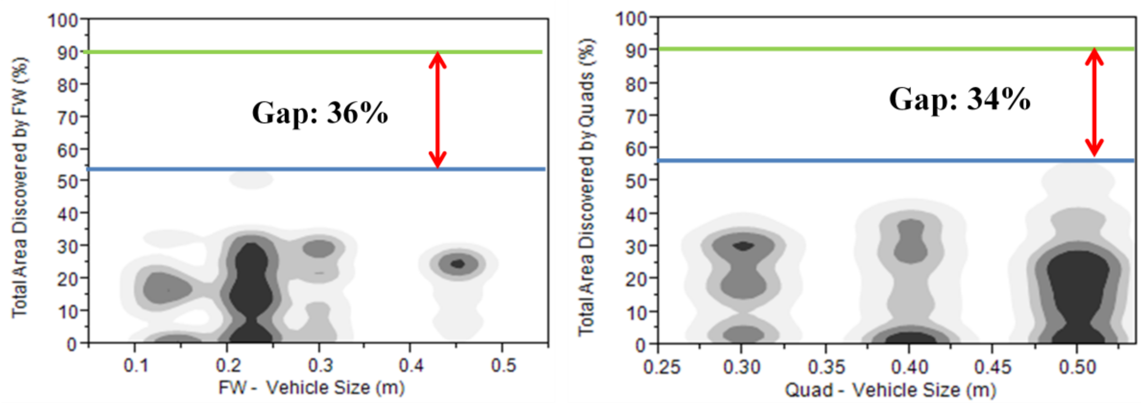


Figure 105: Total Area vs. Vehicle Size ARL - Benign, Future Tech. - a) FW; b) Quad

To put things into perspective, this aspect is studied in terms of interior area discovered below. Nevertheless, the gap is reduced from 45% to 36% for flapping wing vehicles and from 46% to 34% for quad-rotor platforms with infusion of future technologies. Smaller flapping wing vehicles, size on order of 0.2m or less, are more likely to perform better than the larger ones.

Figures 106 and 107 depict the current and future technologies based MAST systems' simulation results of exploring interior area of Joppa Urban missions.

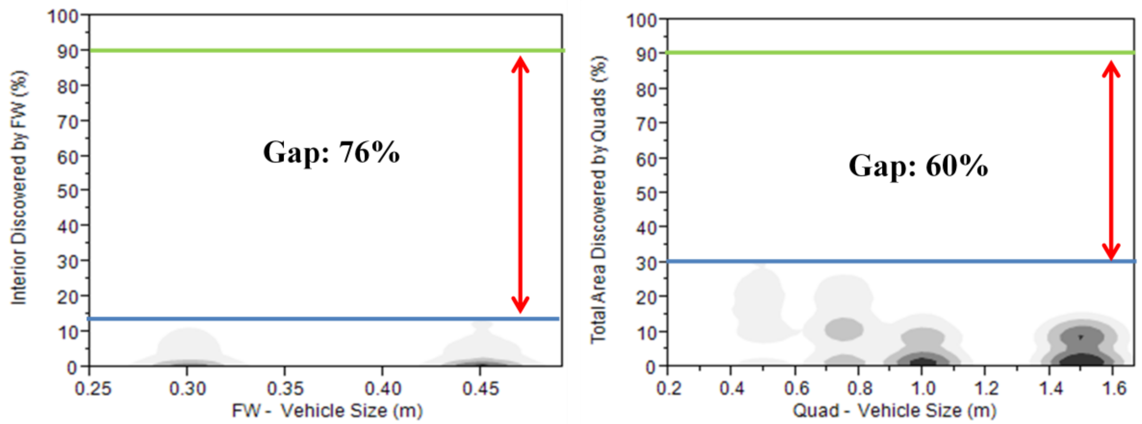


Figure 106: Interior Area vs. Vehicle Size JU - Benign, Current Tech. - a) FW; b) Quad

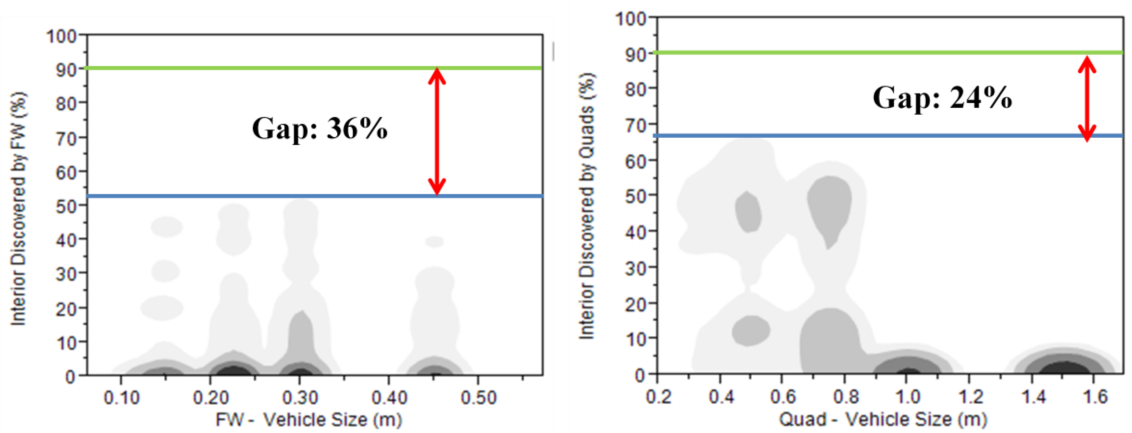


Figure 107: Interior Area vs. Vehicle Size JU - Benign, Future Tech. - a) FW; b) Quad

The current year technologies' performance of both platforms is extremely poor in terms of discovering interior year. A gap of over 70% for flapping wing platforms and 60% for quad-rotors exists, which is far from meeting the 90% interior area explored objective. However, there is a drastic improvement with addition of new technologies, easily slashing the gap by over 50% for both platforms. Similar to total area explored

MoE, the infeasible region, for exploring interior area in context of vehicle size requirements, starts from 0.5m or larger sizes.

Next, interior discovered for ARL mission is analyzed and is shown in Figures 108 and 109 for current and future technologies, respectively.

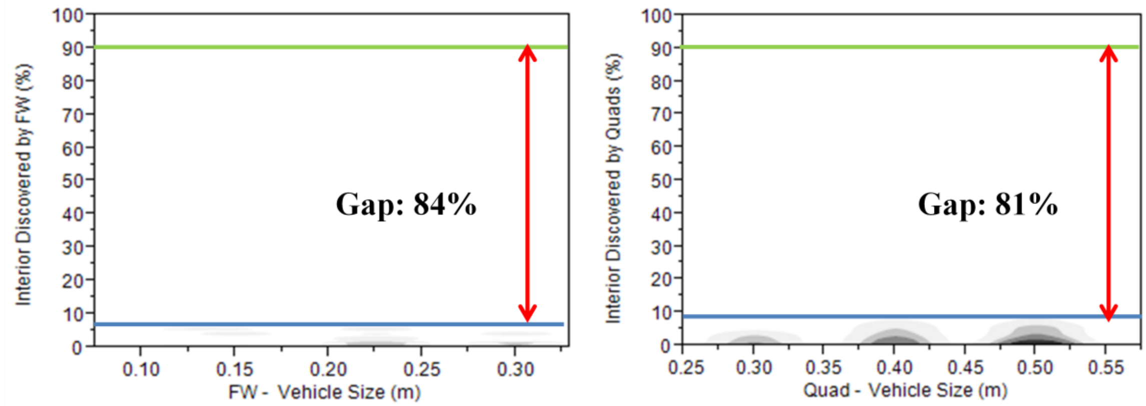


Figure 108: Interior Area vs. Vehicle Size ARL - Benign, Current Tech. - a) FW; b) Quad

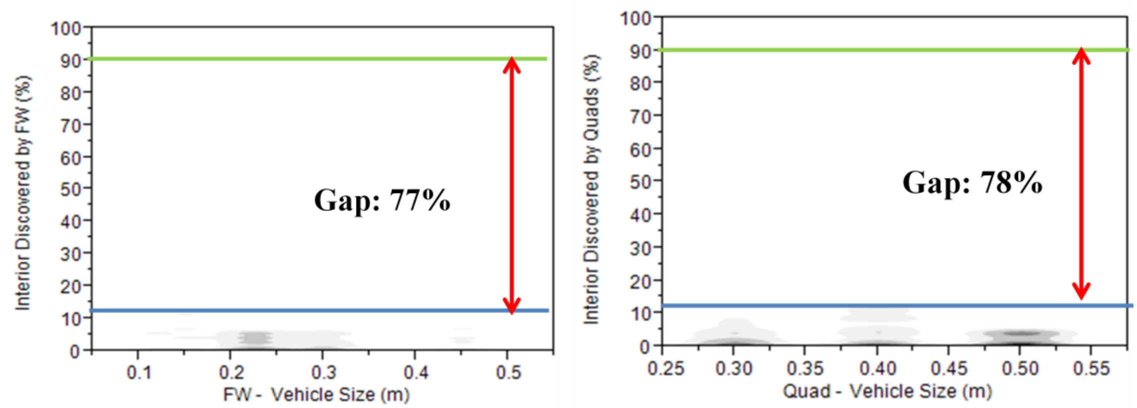


Figure 109: Interior Area vs. Vehicle Size ARL - Benign, Future Tech. - a) FW; b) Quad

As speculated above, both platforms tend to performance much worse in ARL mission than in JU mission. Even with infusion of new technologies, the interior area explored MoE is far from being achieved, with gaps ranging around 80%. As alluded above, the perceived better performance of total area discovered for ARL IBR mission compared to JU mission is actually misleading. The MAST systems spend most of the time on the exterior regions of the map in ARL IBR mission map and barely discover the interior, which is more important from intelligence gathering and mapping objectives.

Therefore, it is safe to conclude that MAST systems, overall, perform better in JU mission.

Furthermore, it is apparent that advances in scaling are not the only requirements for accomplishing complicated missions maps such as the one presented by ARL IBR. It is observed during simulations that although vehicles need to be less than 0.5m in size to have a chance of meeting MoE requirements, they also need to be much more intelligent in terms of navigation and exploration logic. Nevertheless, the primary conclusion from this set of results in that the vehicle size requirement is less than 0.5m in characteristic dimension.

Before proceeding with analysis of the next metric, the effect of vehicle size, in context of swarm size, is studied for hostile versions of Joppa Urban mission. It is important to remember that the results are experiments executed using 'Informative' communication scheme and hence, focus on the individual performance of the vehicles, based on future technologies, as part of the swarm. The simulation results for total area explored as function of swarm and vehicle sizes are shown Figures 110 and 111.

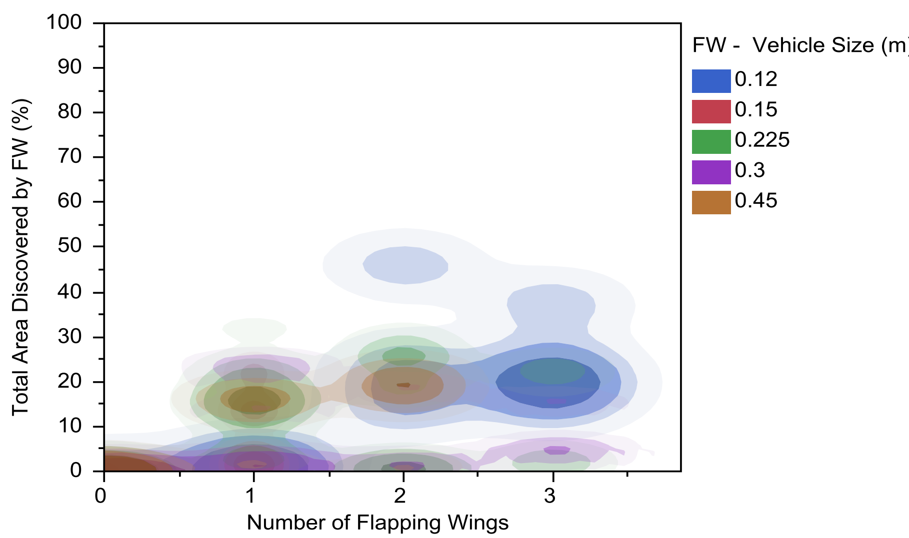


Figure 110: Total Area vs. FW - No. of Vehicles and Sizes - JU Hostile, Future Tech.

Considering the plots, it can be observed that for both platforms, the smallest sized vehicles perform better with increasing swarm size. This enabled the increasing number of vehicles occupying the same mission map to avoid collisions and dampen the effect of exploration hindrance by the virtue of their smaller size footprint. However, for missions with only a single vehicle deployed, larger sized ones are able to perform better. The reason is that they have more endurance and are able to explore for longer, which is essential when benefits of swarm or collaborative behavior are not present and the whole map needs to be explored as an individual.

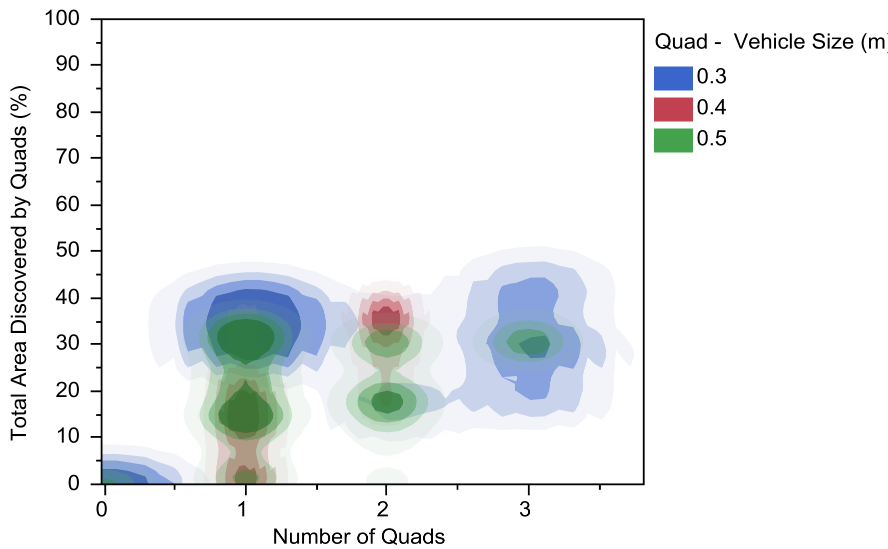


Figure 111: Total Area vs. Quad - No. of Vehicles and Sizes - JU Hostile, Future Tech.

Next, the effect of structural material of the vehicles is analyzed on mission performance for total area explored MoE.

Area Explored vs. Structural Material

The feasible alternative pool was generated based on the structural material of the platforms and hence its effect on area discovered is an important metric to be studies. The experiments are conducted for Joppa Urban mission and benign environment for MAST systems built using both current and future technologies. Current technology simulations utilized alternatives sized based on current material densities, while alternatives in future technology simulations are based on k-factor improvements of the current material densities. The results for current technology years are shown in Figure 112 for flapping wing platform vehicles.

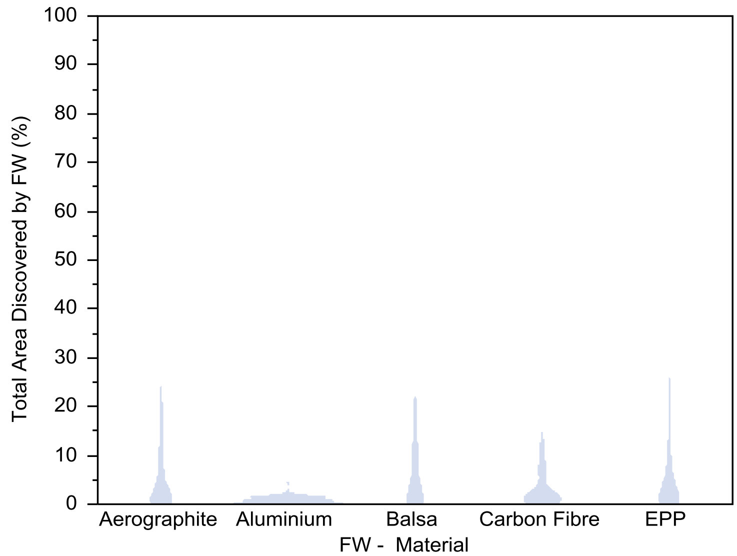


Figure 112: Total Area Discovered vs. FW - Material JU Benign Mission- Current Tech.

It can be observed from the plot that the extremely light weight materials such as aero-graphite, balsa and EPP perform much better than heavier ones like aluminum and balsa. A difference of up to 20% in total area discovered can be observed by vehicles built from relatively less dense and denser materials. The relative magnitude of the effect of the material density can be studied by comparing the current technologies based MAST systems results with those of future technologies based vehicles. The results for future technologies infusion are shown in Figure 113 for flapping wing platform vehicles.

Three important conclusions can be drawn from analyzing the results of future technologies infusion. First, there is drastic improvement in MoE of total area discovered by building platforms from less dense material. It improves over 30% in comparison to performance by of vehicles built from currently available materials. Second, the benefits gained from employing these future materials, much lighter than current ones, seem to reach the limit of diminishing results. This shows that other metrics and navigational algorithms must be improved to increase the performance level. Third, by only considering the material density, the k-factor application for simulating future technologies blurs the line between effects of various materials as they become similar with improving weight of the material. Hence, as expected, all of the materials reach the same performance level, stagnating at the limit of diminishing returns obtained from density improvement. This conclusion also presents a validation to the underlying sizing models.

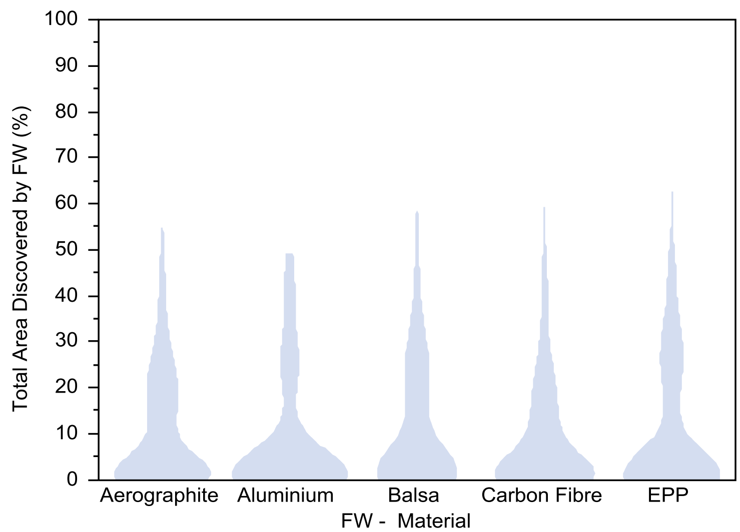


Figure 113: Total Area Discovered vs. FW - Material JU Benign Mission- Future Tech.

Moving on, the next metric to be analyzed is the cause of death for the vehicles and how it related to their characteristic dimension.

Death Cause vs. Vehicle Size

Simulations are executed for both hostile and benign version of the Joppa Urban mission. Since the focus of analysis is vehicle level, performance of quad-rotor platforms, built upon current and future technologies, are studied for benign mission. For hostile mission, only quad-rotors infused with future technologies are considered.

The results for death cause in benign mission are shown in Figure 114. The possible death causes documented include vehicles getting stuck in enclosed spaces, wandering away from mission boundaries, or dying of battery depletion. Studying the plots, several logical conclusions can be drawn. The trends observed are heavily dependent on the size factor of the vehicles. For current technology year MAST systems, smaller sized vehicles are most likely to die due to battery depletion, while larger ones are more prone to collisions and getting stuck in smaller spaces.

The results are not surprising as the battery packs carried by smaller sized vehicles are of considerably lower capacities. That is simply due to the fact that high capacity batteries would be heavier and hence not carry-able by smaller vehicles. So, it is reasonable to notice that these vehicles almost always die due to battery depletion. A very small percentage of these vehicles are killed by getting stuck in complex areas of the map, which is primarily due to values of agility and sensory parameters. On the other hand, larger vehicles are able to carry battery of higher capacities and thus avoid battery depletion within the mission time constraints. However, the larger dimensions of these vehicles result in increasing their chances of getting stuck. Finally, the chance of death from getting lost is more or less same for most vehicle sizes as it is directly related to navigational abilities of the MAST systems. The extremely small size vehicles are observed to die due to battery depletion well before getting lost and hence the result of no significant number of deaths from getting lost is observed.

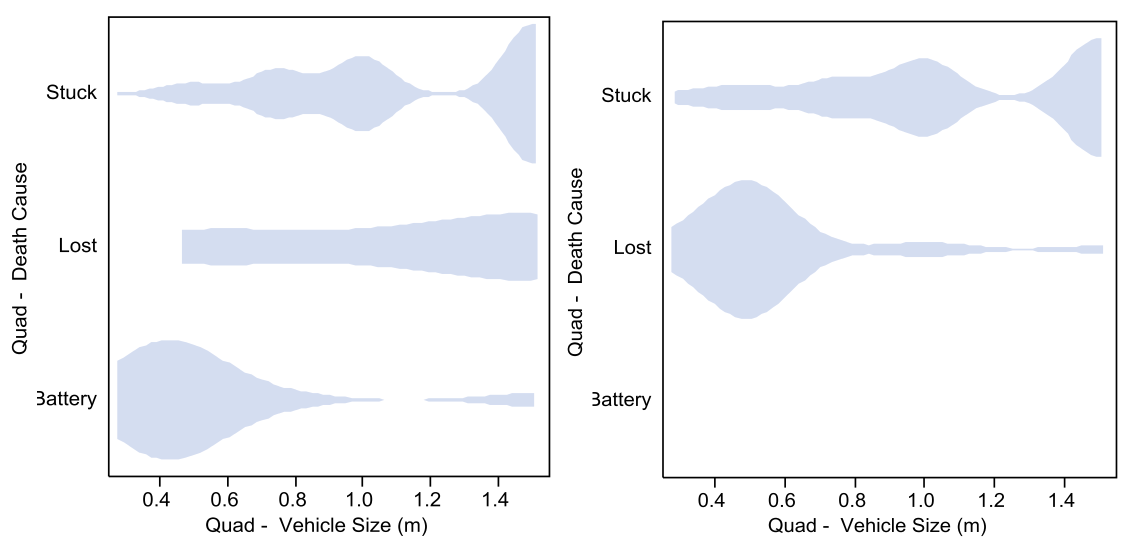


Figure 114: Death Cause vs. Quad - Size - JU Benign - a) Current Tech.; b) Future Tech.

With infusion of future technologies, death due to battery depletion is no longer an issue. However, with increased endurance, the smaller vehicles are more likely to wander away from mission area. This is a result of more exploration time afford, increasing chances of getting lost, and from inherent lower sensory range due smaller size platform. Furthermore, these systems are also observed to be more prone to be not able to find their way back to mission area if they start to head away. On the other hand, larger vehicles, again, are plagued by getting stuck in smaller areas within the building structure. It appears that infusion of future technologies, in terms of size and power improvements, is not able to offset the disadvantage of being large in size.

Next, the effect of enemy presence is explored by simulating hostile version of Joppa Urban mission. The results are shown in Figure 115.

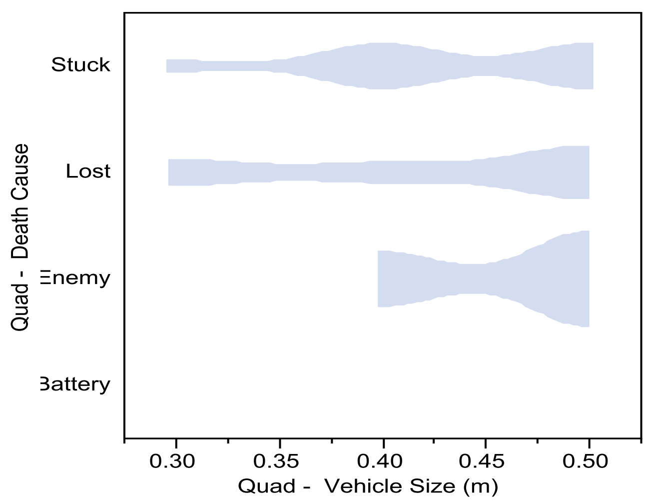


Figure 115: Death Cause vs. Quad - Size - JU Hostile - Future Tech.

The trends for death causes are greatly influenced by presence of enemies. The lack of death due to battery depletion is because of infusion of future technological capabilities, as was observed for benign missions. However, not only vehicles are now killed by enemies directly, they are also more likely lose their navigational path, wander away from the mission area, or navigated to smaller and more complex mission spaces as a result of evasive maneuvers performed to avoid enemies. Therefore, enemies are not only responsible for directly killing the vehicles but are also causing an increase in the number of deaths indirectly. This underscores the importance of smaller dimensions of the vehicle, increased sensory ranges, and more intelligent navigational algorithms.

Finally, it is apparent that vehicles smaller than 0.4m in size are the only ones not detected by the enemies and thus sets the requirement of vehicle dimension. However, it important to be reminded that the enemies' detection range was only 2m radius. The effect of range will be explored next to refine the size requirements in hostile environments.

Detected/Killed by Enemies vs. Vehicle Size

A broad conclusion was drawn from previous section regarding size of the vehicle and chance of detection by enemies in a hostile mission environment. In this experimental set, a closer look is taken at these metrics by focusing on vehicle platforms. Simulation results for hostile versions of both Joppa Urban and ARL IBR missions are conducted to study the effect of size on detection probability of flapping wing and quad-rotor platforms. The enemy detection radius is fixed at 2m. The simulation results for both platforms for Joppa Urban mission are shown Figure 116.

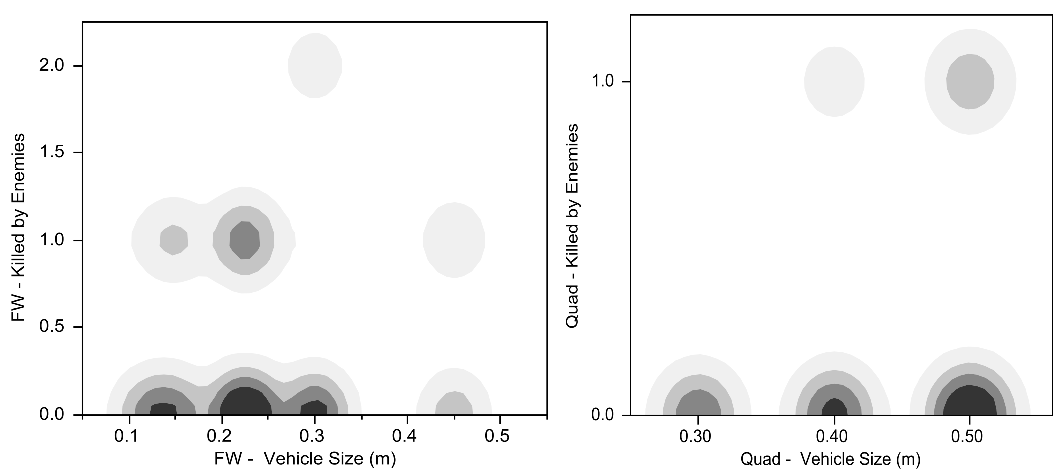


Figure 116: Killed By Enemies vs. Vehicle Size - JU Hostile - Future Tech. - a) FW; b) Quad

Studying the plots, it is apparent that vehicles smaller than 0.5m are less likely to be detected by enemies. Vehicles sized 0.1m perform drastically better than other sizes. For quad-rotor platforms, there are almost no casualties from enemies. It is important to recognize that the detection range of 2m for enemies is on par with the lower end of scan range of vehicles. This means that MAST systems, with scan range higher than 2m, are able to detect enemies before they are detected. In theory, if these vehicles are agile enough to quickly change their direction upon detection of an enemy, they would be able to avoid getting killed by enemies at all times. However, detecting enemies first doesn't ensure that the agility of the vehicles is at the level to ensure that they can maneuver in a manner that will enable them to avoid getting detected. And hence, only very agile vehicles with higher scan range are able to survive hostile environment.

Next, the results for ARL IBR mission are shown in Figure 117. The plots demonstrate similar trends but at different magnitudes of vehicle casualties by enemies.

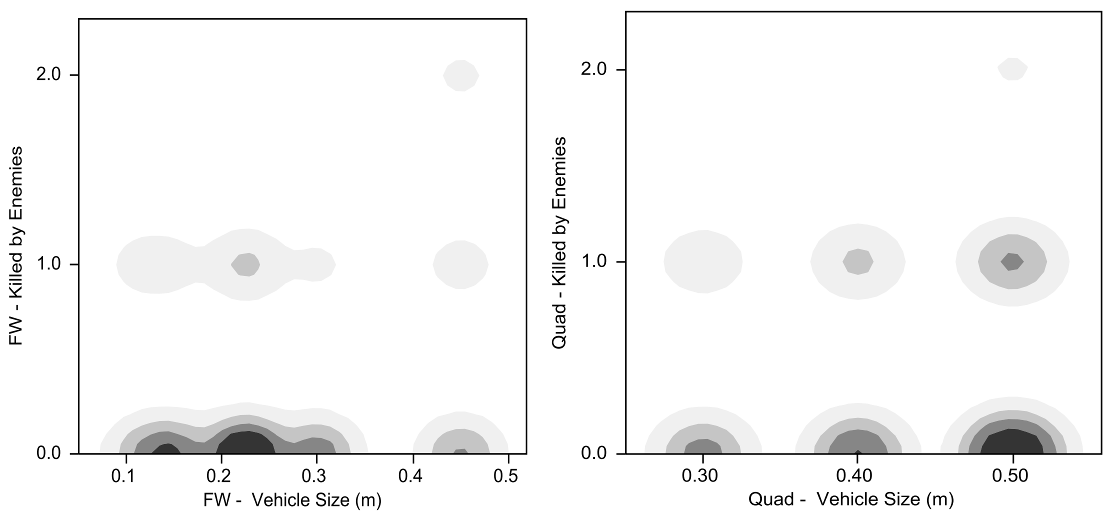


Figure 117: Killed By Enemies vs. Vehicle Size - ARL Hostile - Future Tech. - a) FW; b) Quad

Although lower number of vehicles were killed by enemies in ARL IBR mission, compared to Joppa Urban mission, vehicles sized 0.1m were also detected and killed. It seems that the larger mission area afforded by ARL IBR results in both advantages and disadvantages. It is beneficial for MAST systems as now the enemies have to patrol and guard a larger area, which results in more area/spots for vehicles to hide and/or escape detection. However, the presence of courtyard also makes it difficult for vehicles to avoid enemies in the open area. Overall, this mission map increases the performance requirements for MAST systems.

For both missions, the generalized conclusion is that, in total lack of camouflage, vehicles should be made as small as 0.1m or less in size. The importance of improving stealth through camouflage is also underscored by recognizing the short detection range of enemies. Furthermore, the agility of vehicles is closely tied with scan range and avoidance maneuvers to evade detection and death by enemies. This analysis complemented by studying the effect of enemy detection radius on vehicle detection, which is the focus of the next section.

Killed by Enemies vs. Enemy Detection Radius

This set of experiments is intended to complement the ones for vehicle detection by enemies with fixed detection range of 2m. Similar to the experimental set performed for the swarm level, the detection radius of enemies is varied between the ranges of 2m to 20m. However, the focus of the analysis is at vehicle level. The results for Joppa Urban mission are shown in Figures 118 and 119 for flapping wing and quad-rotor platforms, respectively.

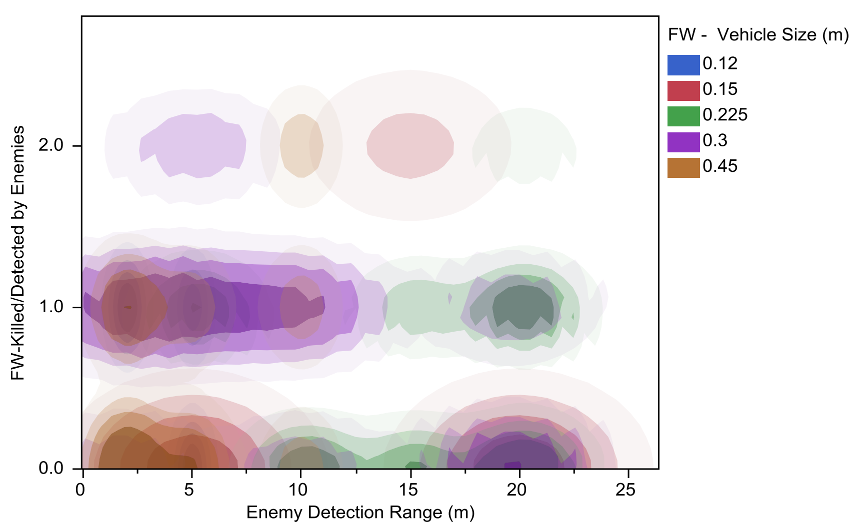


Figure 118: FW Detected/Killed vs. Enemy Detection Range - JU Hostile Mission- Future Tech.

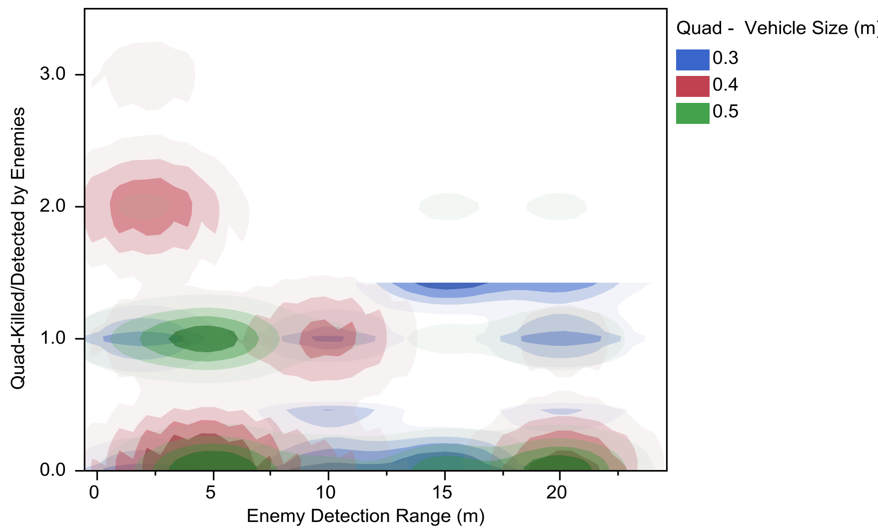


Figure 119: Quad Detected/Killed vs. Enemy Detection Range - JU Hostile Mission- Future Tech.

Similar assumptions of lack of vehicle camouflage and detection by enemies once within range are applied. Simulations are conducted for both platforms and both missions. As observable from the plots, enemies with detection radius of 10m or more are able to detect and kill vehicles of all sizes. However, flapping wing platforms are observed to have higher probability of avoiding detecting compared to quad-rotor platforms, especially at smaller sizes. The vehicles of size 0.3m or less for quad-rotor platform and 0.225m or less for flapping wing platform have the greatest chance of survival from hostiles across the spectrum. At detection range of less than 7.5m, the chances of detecting vehicles smaller than 0.4m for quad-rotors and 0.225m for flapping wing are quite slim. These smaller sized vehicles are not only able to escape the limited detection range of the enemies but are also able to detect the enemies earlier and hence, change navigational course. It can be directly related to the scan range attribute of MAST systems that ranges from 1m to 9m. Once the enemy detection range exceed 9m, it becomes almost impossible for the vehicles to avoid enemies without detection, which is evident by vehicles getting killed by enemies regardless of the size.

Next, Figures 120 and 121 depict results for ARL IBR mission for quad-rotor and flapping wing platforms, respectively. Similar to the trend observed during analysis of hostile experimental set for ARL IBR mission, the vehicles, of all sizes, were less likely to be detected and killed by enemies, when compared to Joppa Urban mission scenario.

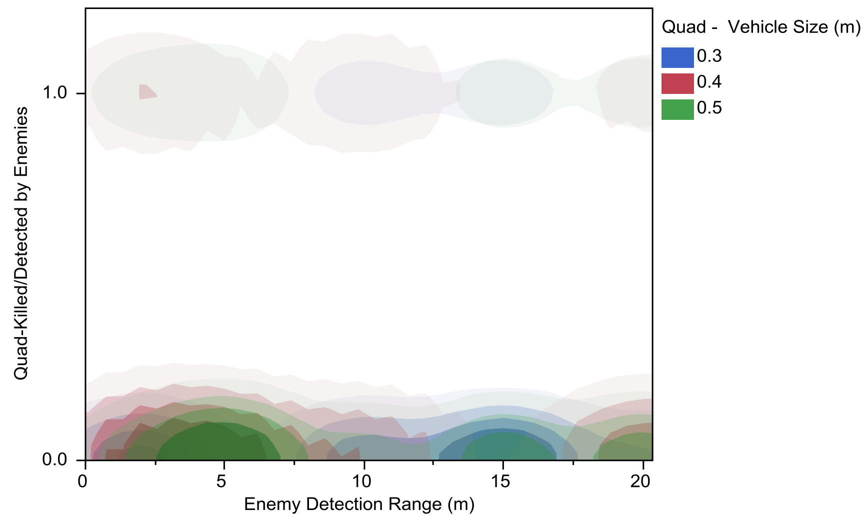


Figure 120: Quad Detected/Killed vs. Enemy Detection Range - ARL Hostile Mission- Future Tech.

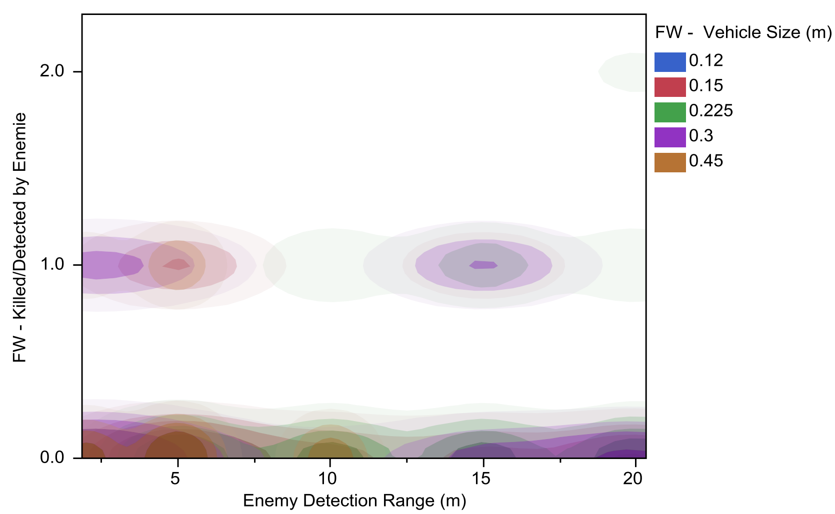


Figure 121: FW Detected/Killed vs. Enemy Detection Range - ARL Hostile Mission- Future Tech.

Again, it is attributed to low number of enemy patrolling a relatively larger mission map. However, the size trends for comparative survival ratio of vehicles, in reference to death by enemies, are similar to Joppa Urban mission. Vehicles smaller than 0.4m for quad-rotor platforms and 0.225m for flapping wing platforms have the highest chances of survival. Therefore, it is desirable for vehicles to be smaller than 0.2m in their characteristic dimension. Enemies with a detection radius of less than 10m levels the playing field for MAST systems, as now the scan range of the vehicles is on par with enemies detection range. Hence, either the enemy members' have detection radius of less than 10m, which is unlikely, or the vehicles have scan range more than 10m. The latter is can be achieved for future technology fusion and by lowering effective detection range of enemies though camouflage. Although these simulations only considered visual detection issues, the results can be applied to other sensory forms of detections. Nevertheless, relevant MoP values will be different and thus further studies need to be performed to quantify them. This is recommended as part of the future work.

In conclusion, the take away lesson from hostile missions and resulting casualties is that the size of vehicles must be small, camouflage must be employed, and the scan range of the vehicles must be greater than the anticipated detection range of the hostiles.

This section also concludes the presentation and analysis of sizing analysis, DL simulation, and gap analysis results. An interim summary is presented below before proceeding with the next module of the framework.

5.5.2. Summary - DL/Sizing Results and Gap Analysis

This section presented in-depth analysis of the experimental results from DL modeling and simulation, sizing, and gap analysis modules. The analyses served two objectives for the research. 1) Developed methods, models, and tools were validated through results obtained from intuitive experimental; 2) Results from complex experiments provided new discoveries for and insights into non-intuitive aspects of mission effectiveness quantification and technology assessment. The results were in form of output from DL environment, consolidating knowledge and information gained from all of the previous modules, enabling quantification of the technology gap for various metrics. Benign and hostile versions of both Joppa Urban and ARL IBR missions were used for conducting experiments. The primary goal was to analyze the mission performance of different MAST SoMs in order to determine the required levels of MoPs for mission success. MoPs for the unfulfilled MoEs were quantified using gap analysis. Finally, the insights gleaned from these experiments and results will be utilized for requirements definition in a section below. However, a quick detour will be taken before that to present the development of methodology and implementation for experimental validation of DL modeling and simulation environment.

5.6. Experimental Validation of DL: Quad-rotor

In order to facilitate validation of DL modeling and simulation environment, an experimental autonomous prototype quad-rotor was developed by the author, with the help of Patrick Dees and Tim Dyer. The purpose of the prototype, aside from the validation platform for DL environment, is to also to serve as a test bed for evaluation of various autonomy algorithms and tactics. It is capable of autonomous flight, which includes automatic take-off, altitude hold, and operational level obstacle avoidance. Robotic Operating System (ROS) [199] and HectorSlam (aided by Young-Ki Lee) [200] have been implemented onto the quad-rotor operating system to enable mapping capabilities. It is primed for plugging in any compatible navigation algorithm to utilize the mapping capabilities, enabling full autonomous mission operation. The current configuration of the quad-rotor is shown in Figure 122.

The quad-rotor, one meter in diameter, is based on a commercially available platform known as ArduCopter [201]. It utilizes the ArduPilot Mega (APM) board to provide stability, with the help from an IMU and an ATMega microcontroller. However, the platform has been almost re-built from ground up to meet the requirements of validation for the research presented. Most of the structural components have been redesigned and manufactured, using laser cutter, from scratch to accommodate added controller board and sensors.

It is equipped with a sonar - for altitude hold, a Hokuyo [202] ranging LIDAR sensor - for obstacle avoidance, navigation and mapping, and a wireless communication device - for communicating with ground station.

Figure 122: Quad-rotor Prototype

To achieve autonomous flight capabilities, a secondary board was added to the vehicle, which required restructuring of the air frame as mentioned above. The board, known as the PandaBoard [203], is outfitted with an OMAP4 [204] processor (the successor to the GumStix's OMAP3 [205]). The PandaBoard can take laser ranging data from the LIDAR and IMU data from ArduCopter's stability system, the APM, to perform navigation. Another major component needed for autonomous flight is a communication link between the PandaBoard and the ArduCopter's APM. The APM's firmware was modified to transmit IMU data and system diagnostic data to the PandaBoard over a serial data link. The APM was also modified to allow it to accept guidance commands (forward, backwards, left, right, etc.) from PandaBoard over the same serial link. Software has been developed for the PandaBoard to gather the IMU and diagnostic data from the APM, while simultaneously sending guidance commands.

Development of DL environment and the experimental platform provides a unique opportunity for simultaneously performing identical real and virtual world experiments. A test case is shown in Figure 123, where the experimental quad-rotor is being flown in a hallway of the Weber building at Georgia Tech and simultaneously, a simulation is being run on a machine simulating same hallway and quad-rotor. Both virtual and experimental vehicles are equipped with same sensors and utilized same algorithms.

The idea here is to present a methodology for virtual 'wind tunnel' testing of autonomous vehicles. By extensive validation of the virtual environment and subsequent tweaking of its simulation parameters, it is possible to gain enough confidence in the environment for utilizing it as a substitute for real-world testing.

Figure 123: DL Validation Set Up

As a canonical demonstration for the purpose of this research, few simple experiments are performed to validate the DL environment's simulation of the endurance of the quad-rotor at different speeds.

The experimental setup consisted of the quad-rotor with the following vehicle and test settings:

- **Location:** Tethered
- **Test Equipment Specs:**

  - ArduPilot Mega (APM) board
  - PandaBoard [186], outfitted with an OMAP4
  - Hokuyo [185] LIDAR
  - 3S (11.1V) 5000mah battery
- **Experiment Repetitions:** 2
- **Test Velocities**: Hover, 0.5m/s, 1.0m/s, 1.5m/s
- **Response Parameters:**
  - Endurance

The goal of experiment is to compare the endurance of the real and the virtual world quad-rotors (same specifications) at different speeds. For DL environment, the quad-rotor is simulated with fixed desired forward velocity flying in a square pattern until battery depletion.

For experimental setup, the quad-rotor was tethered to a spot and is allowed to hover at different throttle levels. The throttle levels are correlated to a forward velocity by flying it forward in a straight line (at constant levels of throttle and forward command) and determining the velocity by measuring distance covered over time. In this manner, the throttle and forward command positions re correlated to specific forward velocities. Then three experiments are conducted with determined throttle and forward command levels (fixed) on the tethered quad-rotor. The experiments continue until battery depletion and the final time is noted as endurance. The plotted comparison results are shown in Figure 124.

Considering the results plot, there is a reasonable agreement between two simulations. The discrepancy comes from a number of factors including the crude method of determining throttle and forward command positions, in reference to forward velocity, and the tethered nature of the experimental runs. Further experiments of similar nature are required for in-depth validation and/or tweaking of DL environment and is left as recommended future work.

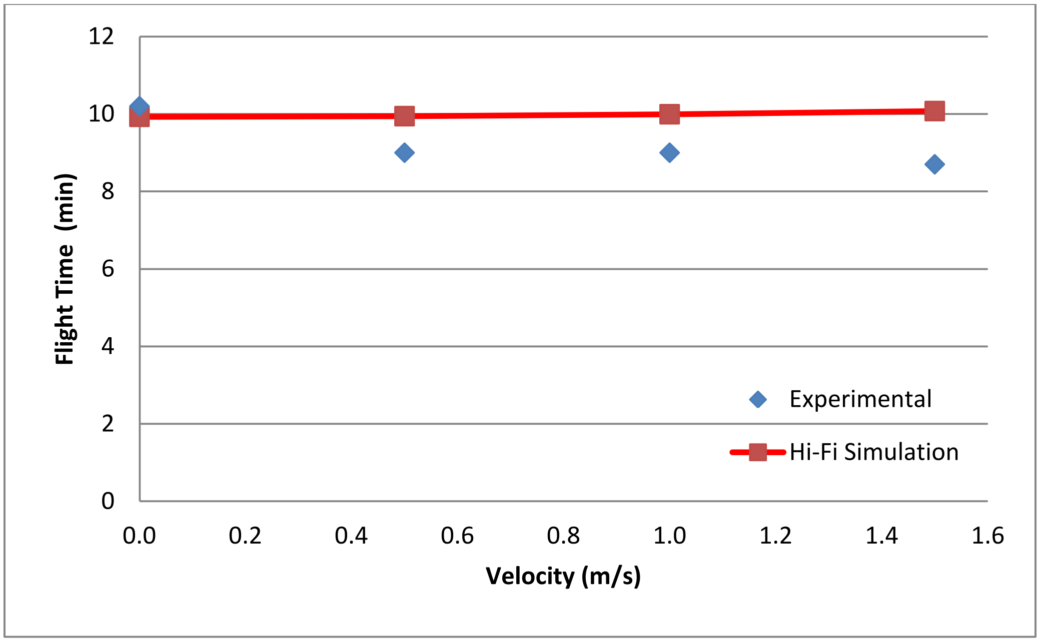


Figure 124: Quad Endurance - Experimental vs. Simulation

The purpose of this module was to present a methodology for validation of simulation environment and to demonstrate it applicability using a simple canonical problem. Both of these objectives are deemed accomplished based on the experiments and results presented in this section.

5.7. Requirements Re-definitions

The very final step in this framework is to utilize the data obtained and consolidated from all the previous modules, experimental sets, and quantitative gap analysis to re-define the mission based requirements for MAST system. This module is not intended to capture the all of the insights gained and discoveries discussed but only to summarize the most important ones in an articulate manner.

Before proceeding with enumeration of the requirements, it is worth mentioning that one of the smallest quad-rotors, currently being researched at UPenn, has a representative size of about 0.5m [206]. Even at this size, based on the results, the percentage of area discovered and entry points accessed in simulations of Joppa Urban and ARL IBR missions are substantially low. Generally speaking, the size needs to be 2 to 3 times smaller than that to result in reasonable level of mission performance for the given constraints. On the other hand, constraints can be relaxed to enable systems characterized by lower levels of MoPs to provide acceptable level of mission performance.

The requirements derived from the results and the discoveries presented in this dissertation are listed below; stating current state of the art and required future state.

Requirement 1: Swarm Size

- **Current state of the art**
  - Only one vehicle (e.g. Packbot) can be carried by a soldier due to size and weight.
- **Future - Required state:**
  - One soldier should be able to carry 4 - 7 MAST vehicles. The size and weight needs to be reasonable for that many to be carried.

Requirement 2: Vehicle Size

- **Current - state of the art:**
  - Quad-rotor – Smallest size available: about 50 cm diameter.
- **Future - Required state:**
  - Quad-rotor – Required size: 20 cm or less in diameter.
  - Flapping Wing – Required size: 20 cm or less in diameter.

Requirement 3: Absolute Velocity Deviation

- **Required state:**
  - The absolute velocity deviation should be as close to zero as possible. This is to be achieved by increased sensors ranges and intelligent navigation and mapping algorithms

Requirement 4: Visual Stealth Factor

- **Future - Required state:**
    - For enemy detection radius of 2m: The characteristic dimension of vehicle should be 0.2m or less.
    - For enemy detection radius of 7m: Visual camouflage is required.

Requirement 5: Battery Capacity

- **Future - Required state:**
    - Joppa Urban: 117 - 1020 Watt-hr capacity battery, small and light enough to be practical for vehicles of size 0.2m or less.
    - ARL IBR: 77 - 210 Watt-hr capacity battery, small and light enough to be practical for vehicles of size 0.2m or less.

Requirement 6: Mission Time

- **Current - Tested:**
    - Joppa Urban: 10 minutes
    - ARL IBR: 10 minutes
- **Future - Required state:**
    - Joppa Urban: 10 minutes is sufficient
    - ARL IBR: More than 10 minutes is required.

The above stated requirements are based on the results obtained and analyzed throughout this chapter. They merely scratch the surface of the discoveries made and the insight gained through the course of this chapter. Therefore, it is strongly recommended to utilize the previous chapters for in-depth analyses.

This concludes the requirements re-definitions for the Joppa Urban and ARL IBR missions and hence, the module.

5.8. Chapter Summary

This chapter documented the development of the MAST mission effectiveness quantification and technology assessment framework's modules and implementation of test scenarios to address the core research questions driving the investigation presented in this dissertation. Joppa Urban and ARL IBR missions were selected to serve as canonical problem scenarios for analysis that not only enabled the evaluation of the missions but also demonstrated the practicality of framework's application. The obtained results validated the developed methodology through output of intuitive results for well-defined and controlled experiments. These served the purpose of validating the implementation tools/codes and the underlying models. Furthermore, results from more complex experimental cases, analyzing higher number of design variables, provided novel discoveries for mission based assessment of MAST vehicles that couldn't have been obtained otherwise. The results from these experiments presented a scientific approach to understanding the problem at hand that closely mimics the reality of urban warfare intelligence gathering mission for MAST systems and novel and invaluable insight for addressing it.

The application of M-IRMA was carried out using the output of mission analysis and operational architecture to down-select alternatives families of concepts from an astronomically large concept space. These down-selected technologies were then modeled, simulated, and evaluated using Screening Level modeling and simulation environment, which was also developed along the process. Insights gained from screening level analysis were used to define the experimental setup of detailed level simulations. Sizing relations were used for generating technically feasible alternatives, for current and future technology years, which were then modeled and simulated in Detailed Level modeling and simulation environment. The results obtained from a large number of experimental sets were studied in-depth to address the required levels of MoPs for various levels of desired MoEs. Technology gap, for current and future technology years, was quantified through gap analysis. In order to provide a method for validating modeling and simulation environments, an experimental validation approach was constructed that entailed development of a physical quad-rotor test platform. The approach provided a methodology to correlate results from physical and virtual experiments. Furthermore, it presents a method to enable virtual 'wind tunnel' provision within the framework. Simple experiments were conducted to show basic validity of simulations in the DL environment. Finally, the consolidated results were summarized in form of the requirements definition for the two missions that were analyzed.

The next chapter presents a conclusion to the research documented in this thesis, reviews the hypothesis put forth in the beginning, and analyzes how the developed framework is able to answer each of the fundamental research questions that drove this investigation.

CHAPTER VI

CONCLUDING REMARKS

The research documented in this dissertation was driven by the motivation presented in the first chapter and followed the plan laid out, based on hypothesis formulated, to answer the research questions put forth in the third chapter. The background research and literature review was conducted to explore the observations that led to core research issues to be addressed. The methodology and framework was conceived, developed and then implemented on two relevant mission scenarios, namely Joppa Urban and ARL IBR. The results obtained were analyzed to come across findings and discoveries previously unknown in context of MAST problem. This chapter seeks to close the loop for the research presented by reviewing the hypotheses in context of the core research questions addressed.

6.1. Reviewing Hypotheses: Research Questions and Objectives Addressed

The fundamental research questions are now re-visited to evaluate the hypotheses and present the capabilities gained by development of each module of the framework.

<u>Research Questions Addressed: 1 and 2</u>

> *How to explore and evaluate the enormous combinatorial space consisting of integrated systems, technologies, and scenarios?*
>
> *Can various MAST technologies be evaluated rapidly for mission specific scenarios?*

Hypothesis 1:

If missions can be quantified in a systematic manner in terms of operational functions then combinations of technologies can be mapped to them and rapidly evaluated by means a mathematical scoring scheme.

This hypothesis was proven correct by development and implementation of Mission Definition, Operational Architecture and M-IRMA modules. These modules enabled the capabilities to define mission parameters, MoEs, MoPs, and determination of operational functions through operational architecture. The M-IRMA methodology provided a mathematical methodology to generate and evaluate billions of different alternative families of concept in practical timeframe.

Research Questions Addressed: 3 and 4

How can integration effects of various platforms be modeled, and how are the resulting emergent behaviors identified within the microsystem ensemble?

Hypothesis 2:

If missions and multiple MAST systems (current and future) can be modeled and simulated in a virtual world without the existence of physical based technology specific models then integration effects and emergent behavior can be identified and analyzed.

The methodology developed for screening and detailed level simulation modules provides substantial support for the second hypothesis. The implementation of these modules enabled the capabilities to model and simulate, in 2D and 3D, various MAST technologies and platforms for specific mission scenario. It also enabled the modeling and simulation of ensemble behavior, using ABM logic, for heterogeneous systems in a physics based virtual world, aiding in evaluation of emergent behavior and resulting synergy. Fidelity level is variable to enable control over computation time and desired resolution level. Moreover, implementation and testing of navigation and control algorithms can be undertaken by the developed cyber physical framework.

Research Question Addressed: 5

> *How can modeling and simulation environments for System of Microsystems be validated to ensure that the accuracy is reasonable?*

Hypothesis 3:

> *If virtual simulation missions can be physically simulated in real world then the comparison of outcome can either validate virtual world or guide its calibration.*

This hypothesis was only tested in a preliminary manner by conducting simple endurance based validation experiments. The results show support for the hypothesis but further in-depth studies are required, which are left for future work. The experimental quad-rotor platform presents a great resource testing of various algorithms and validation of modeling and simulation environment.

Research Questions Address: 6

> *How can technical feasibility of the microsystems in modeling and simulation environment be evaluated based on current state of the art technologies?*

Hypothesis 4:

> *If simplified sizing relations for power and mass can be developed for different platforms and technologies then model and simulated integrated systems can be sized and checked for technical feasibility.*

Although the hypothesis was proven correct by use of sizing relations, it was determined that a more practical way to addressing Research Question 6 was to couple the sizing relations with DL environment. The capability gained was still, as hypothesized, the mapping of vehicle parameters to mission MoEs through MoPs.

However, the output from sizing relations module was used as an input to the DL environment in form of a generated pool of technically feasible alternative MAST system, based on current and future technology years.

Research Question Addressed: 7

How can technology gap be quantified, while considering all aspects of a mission scenario including swarm and emergent behavior, and lead to re-definition of requirements for MAST systems?

Hypothesis 5:

Once requirements disconnect is bridged through implementation of previous modules then mission based requirements can be defined and compared with current state of the art to quantify technology gap.

The gap analysis module not only provided quantitative measures of technology gap, based on consolidated results of all other modules, but also enabled definition of requirements in terms of MoPs and vehicle characteristics. Therefore, the hypothesis was found to be supported.

Having established that the formulated hypotheses were able to answer all of the research questions in a satisfactory manner, it is time to take a closer look at how the research objectives and key motivation were addressed. The underlying reason for conducting this research was to understand the requirements disconnect between the Warfighter and the technologist and to develop a methodology to bridge this gap. The research objectives were to quantify the mission effectiveness of MAST system operating in a swarm and provide assessment of their relevant MoPs in context of mission MoEs. It was desired that the assessment methodology provides a way to not only evaluate MAST systems composed of current state of the art technologies but to also enable users to be able to analyze systems based on future technologies. Essentially, the capability being sought here is the ability to test non-existing systems, operating as part of a swarm, in a mission scenario. This would not only enable technologists to gauge the performance of various MAST technologies in an actual test scenario but also provide the Warfighter with ability to define technology requirements necessary for accomplishment of any modeled mission scenario. Therefore, by formulating and implementing a multidisciplinary framework that considers information from all hierarchical levels, in terms of systems and systems of systems, to methodically develop traceable quantitative relations between top level mission parameters and bottom level technological attributes, the objectives and motivation of mission effectiveness quantification and assessment of MAST SoMs are fulfilled. The development methodology and results document in this dissertation provides sufficient evidence to serve as attestation of achieving all of the research objectives.

6.2. Contributions, Recommendations and Lessons Learned

The major contributions presented in this dissertation include the formulation of methodology to quantify mission effectiveness and assess MAST systems, development of various modeling and simulation tools, creating a framework to enable practical information flow, and the implementation of cyber-physical provision for experimental data mining, farming and validation. Some specific contributions are summarized below:

- A methodology to systematically assess the effect of existing, new and emerging technologies on specified mission scenarios, taking into account mission level objectives and operational architecture.
- A framework for assessment current and future technologies in context of mission scenarios, tactics and requirements without the luxury of having existing sizing and synthesis codes or complete physics based models at disposal. It enables the

capability to optimize heterogeneous swarms of MAST vehicles for modeled mission scenario.

- An automated version of IRMA that utilizes multi-layer mappings, expert knowledge and scoring scheme to sweep through an astronomically large concept space in a practical manner.
- Modeling and simulation modules that provide the capabilities to model and simulate mission scenarios with current and future MAST technologies and future technology capabilities of existing technologies. Representative technological capabilities that may be available and/or required in future can also be evaluated.
- A framework for hardware-in-the-loop experimentation and validation. It also enables virtual 'wind-tunnel' testing for mission scenarios.
- Sizing module that provides the capability to generate technically feasible alternatives for current and future technology years.
- A methodology for quantifying technology gap, if it exists, and dictating updated requirements to close the gap.

Although the presented framework provides a state-of-the-art methodology to assess swarms of autonomous systems for mission scenarios, there is still quite a lot of potential for improvements in terms of fidelity and computational time. The take-away lessons from this research are that there is no alternative to physical experimental and improving the efficiency of coded module is extremely important for practicality. For instance, the M-IRMA run times were slashed ten-fold by simply saving output data in a "comma separated value" file instead of "Excel" spreadsheet file. Therefore, the major recommendations are that not only coding efficiency be improved but also extensive data mining, through experimental means, should be undertaken to further improve the fidelity of this framework. However, these physical experiments must be designed based on the results obtained from an iteration of this framework and subsequently use the data to improve the results. Hence, the fidelity level will improve as the iterations of the framework march forward in time.

6.3. Closing Remarks

In the end, the research conducted and presented in this dissertation provides an important methodology and framework for quantifying MAST technologies and creating a bridge between the Warfighter and the technologist. The ability to evaluate and quantify existing and future subsystem technologies from mission perspective is not only essential for realization of MAST vision but also provide a decision making platform. As progress through research was made, several MAST vehicles were conceptually designed, in terms of vehicle specifications that were likely to represent near optimized solutions. Nevertheless, the most important contribution of this research is the developed methodology and framework itself.

Furthermore, this framework is not intended to be only limited to MAST applications but has been developed with generalization in mind, which enables it to be implemented for other systems of systems problems. For instance, this framework can be readily applied for marine based ensemble of autonomous vehicles. If future technologies that currently do not exist are part of the equation, then the presented methodology can be considered as a strong contender for assessing these heterogeneous solutions and quantifying their mission effectiveness.

APPENDIX A: MAST OPERATIONAL ACTIVITIES

- **Provide MAST C2**
  - Provide MAST Component Control
    - Provide Individual Manual Control
      - Determine Connection Needs
      - Disseminate Breach Request
      - Disseminate Distraction Request
      - Disseminate Jamming Request
      - Disseminate MAST_FRAGO [Commanded Position]
      - Generate Breach Request
      - Generate Distraction Request
      - Generate Jamming Request
      - Generate MAST_FRAGO [Commanded Position]
      - Plot Path to Desired Position
      - Receive/Retrieve Current Physical location
      - Receive/Retrieve MAST System Interconnections
      - Receive/Retrieve MAST_FRAGO [Individual Command]
      - View Current Physical location
      - View MAST System Interconnections
      - View MAST_FRAGO [Individual Command]
    - Provide Autonomous Control
      - Balance Scanning Needs
      - Determine Best Location For Breach
      - Determine if Distraction Needed
      - Disseminate Breach Request
      - Disseminate Distraction Request
      - Disseminate Jamming Request
      - Disseminate MAST_FRAGO [Commanded Position]
      - Generate Breach Request
      - Generate Distraction Request
      - Generate Jamming Request
      - Generate MAST_FRAGO [Commanded Position]
      - Receive/Retrieve Current Physical location
      - Receive/Retrieve Damage Assessment Sweep Pattern
      - Receive/Retrieve Entry Request
      - Receive/Retrieve Environment
      - Receive/Retrieve Forces Sweep Pattern
      - Receive/Retrieve MAST System Interconnections
      - Receive/Retrieve MAST_SITMAP [Terrain]
      - Receive/Retrieve MAST_SPOTREP [Human Location]
      - Receive/Retrieve Surveillance Positioning
      - Receive/Retrieve Trafficability Sweep Pattern
      - Reconcile Sweep Patterns
      - Updated Surveillance
      - View Current Physical location
      - View Damage Assessment Sweep Pattern
      - View Entry Request
      - View Environment [for Hostile RF Signals]
      - View Forces Sweep Pattern
      - View MAST System Interconnections
      - View MAST_SITMAP [Terrain]
      - View MAST_SPOTREP [Human Location]
      - View Surveillance Positioning

        - View Trafficability Sweep Pattern
- Operate MAST Network
    - Provide Routing
        - Disseminate MAST System Interconnections
        - Generate MAST System Interconnections
        - Receive/Retrieve Hardware Communications Request
        - Receive/Retrieve Routing Table
        - View Hardware Communications Request
        - View Routing Table
    - Provide Network Management
        - Develop Dynamic Routing Tables
            - Disseminate Routing Table
            - Generate Routing Table
            - Receive/Retrieve Vertex Map
            - View Vertex Map
        - Determine Location of MAST Nodes
            - Disseminate Vertex Map
            - Generate Vertex Map
            - Receive/Retrieve Achieved Physical Location
            - Receive/Retrieve Environment
            - Receive/Retrieve Hardware Communications Request
            - View Achieved Physical Location
            - View Environment
            - View Hardware Communications Request
    - Provide Communications Links within MAST Network
        - Disseminate Hardware Communications Link
        - Generate Hardware Communications Request
        - Receive/Retrieve Achieved Physical Location
        - Receive/Retrieve Hardware Communications Request
        - View Achieved Physical Location
        - View Hardware Communications Request
    - Link MAST System to Operational Command
        - Disseminate Hardware Communications Link
        - Disseminate Relay Extended Communications
        - Generate Extended Communications
        - Generate Hardware Communications Request
        - Receive/Retrieve Achieved Physical Location
        - Receive/Retrieve Extend Comms Command
        - Receive/Retrieve MAST System Interconnections
        - Relay Hardware Communications Request
        - View Achieved Physical Location
        - View Extend Comms Command
        - View MAST System Interconnections
- Manage Tactical Information
    - Service Sense Data Request
        - Disseminate Raw Sense Data
        - Generate Raw Sense Data
        - Receive/Retrieve Environment
        - Receive/Retrieve MAST System Interconnections
        - Receive/Retrieve MAST_FRAGO [Return Sense Data]
        - View Environment
        - View MAST System Interconnections
        - View MAST_FRAGO [Return Sense Data]

- Construct Terrain Map
  - Disseminate MAST_SITMAP [Terrain]
  - Generate MAST_SITMAP [Terrain]
  - Receive/Retrieve Terrain Data Package
  - View Terrain Data Package
- Collect Relevant Information
  - Update Known Tag Locations
    - Disseminate Tag Location
    - Generate Tag Location
    - Receive/Retrieve Tag Location
    - Receive/Retrieve Tag track
    - View Tag location
    - View Tag track
  - Filter and Aggregate Intelligence Products
    - Disseminate Terrain Data Package
    - Generate Terrain Data Package
    - Receive/Retrieve Interiors Map
    - Receive/Retrieve MAST System Interconnections
    - Receive/Retrieve MAST_ROUTEREP
    - View Interiors Map
    - View MAST System Interconnections
    - View MAST_ROUTEREP
  - Assess Accuracy Timeliness, Usability, Completeness, and Precision of Information
    - Assess Information
    - Disseminate MAST_FRAGO [Reconnaissance update]
    - Disseminate MAST_FRAGO [Surveillance Update]
    - Generate MAST_FRAGO [Reconnaissance update]
    - Generate MAST_FRAGO [Surveillance Update]
    - Receive/Retrieve Tag Location
    - Receive/Retrieve Terrain Data Package
    - View Tag Location
    - View Terrain Data Package

- **Position MAST**
  - Occupy Hide Site
    - Determine Possible Hide Site Locations
    - Disseminate Achieved Physical Location
    - Generate Achieved Physical Location
    - Generated Planned Path
    - Receive/Retrieve Current Physical location
    - View Environment
    - View Extend Comms Command
    - View MAST_FRAGO [Commanded Position]
    - View Surveillance Map
  - Maneuver Openly
    - Determine Overt Movement
    - Disseminate Achieved Physical Location
    - Generate Achieved Physical Location
    - Generated Planned Path
    - Receive/Retrieve Current Physical location
    - Receive/Retrieve Environment
    - Receive/Retrieve Extend Comms Command
    - Receive/Retrieve MAST_FRAGO [Commanded Position]
    - Receive/Retrieve MAST_SITMAP [Terrain]
    - View Current Physical location
    - View Environment
    - View Extend Comms Command

            - View MAST_FRAGO [Commanded Position]
            - View Surveillance Map
        - Maneuver Covertly
            - Determine Covert Movement Plan
            - Disseminate Achieved Physical Location
            - Generate Achieved Physical Location
            - Generated Planned Path
            - Receive/Retrieve Current Physical location
            - Receive/Retrieve Environment
            - Receive/Retrieve Extend Comms Command
            - Receive/Retrieve MAST_FRAGO [Commanded Position]
            - Receive/Retrieve MAST_SITMAP [Terrain]
            - View Current Physical location
            - View Environment
            - View Extend Comms Command
            - View MAST_FRAGO [Commanded Position]
            - View Surveillance Map
        - Conduct Evasive Maneuvers
            - Determine Physical Location of Conflict
            - Disseminate Achieved Physical Location
            - Generate Achieved Physical Location
            - Generated Planned Path
            - Receive/Retrieve Current Physical location
            - Receive/Retrieve Environment
            - Receive/Retrieve Extend Comms Command
            - Receive/Retrieve MAST_FRAGO [Commanded Position]
            - Receive/Retrieve MAST_SITMAP [Terrain]
            - View Current Physical location
            - View Environment
            - View Extend Comms Command
            - View MAST_FRAGO [Commanded Position]
            - View Surveillance Map
    - **Perform MAST Surveillance**
        - Provide Tagging, Tracking, and Locating
            - Track Tag
                - Disseminate Tag track
                - Generate Tag track
                - Identify existing targets
                - Receive/Retrieve Achieved Physical Location
                - Receive/Retrieve Environment
                - Receive/Retrieve MAST_ASTSTATREP [Tag applied, status]
                - View Achieved Physical Location
                - View Environment
                - View MAST_ASTSTATREP [Tag applied, status]
            - Provide Beacon
                - Disseminate MAST_FM.BEALOC
                - Generate MAST_FM.BEALOC
                - Locate Target
                - Receive/Retrieve MAST_OPORD [Conduct Surveillance / Recon]
                - View MAST_OPORD [Conduct Surveillance / Recon]
            - Locate Tag
                - Disseminate Tag location
                - Generate Tag sweep pattern

- Identify existing tags
- Receive/Retrieve Achieved Physical Location
- Receive/Retrieve Environment
- Receive/Retrieve MAST_ASTSTATREP [Tag applied, status]
- Receive/Retrieve MAST_SPOTREP [Human Location]
- Receive/Retrieve MAST_SPOTREP [Vehicle Location]
- View Achieved Physical Location
- View Environment
- View MAST_ASTSTATREP [Tag applied, status]
- View MAST_SPOTREP [Human Location]
- View MAST_SPOTREP [Vehicle Location]

– Identify Target

- Classify Target (determine if target is in the OPORD)
- Disseminate Tagging Decision
- Generate Tagging Decision
- Receive/Retrieve Environment
- Receive/Retrieve MAST_OPORD [Conduct Surveillance / Recon]
- Receive/Retrieve MAST_SURRECONREP
- View Environment
- View MAST_OPORD [Conduct Surveillance / Recon]
- View MAST_SURRECONREP

– Apply Tag

- Deploy Tag
- Disseminate MAST_ASTSTATREP [Tag applied, status]
- Generate MAST_ASTSTATREP [Tag applied, status]
- Receive/Retrieve MAST_OPORD [Conduct Surveillance / Recon]
- Receive/Retrieve MAST_SITMAP [Terrain]
- Receive/Retrieve MAST_SPOTREP [Human Location]
- Receive/Retrieve MAST_SPOTREP [Vehicle Location]
- Receive/Retrieve Tagging Solution
- View MAST_OPORD [Conduct Surveillance / Recon]
- View MAST_SPOTREP [Human Location]
- View MAST_SPOTREP [Vehicle Location]
- View SITMAP Terrain
- View Tagging Solution

- Establish Perimeter

– Observe Entry/Exit of Region of Interest

- Disseminate MAST_SPOTREP [Human Location]
- Disseminate MAST_SPOTREP [Vehicle Location]
- Generate MAST_SPOTREP [Human Location]
- Generate MAST_SPOTREP [Vehicle Location]
- Identify Tags
- Receive/Retrieve Environment
- Receive/Retrieve Surveillance Positioning
- View Environment
- View Surveillance Positioning

– Develop MAST Disposition Recommendation

- Determine Potential Surveillance location
- Disseminate Surveillance Positioning
- Generate Surveillance Positioning
- Receive/Retrieve Achieved Physical Location
- Receive/Retrieve MAST_FRAGO [Surveillance Update]
- Receive/Retrieve MAST_OPORD [Conduct Surveillance / Recon]
- Receive/Retrieve MAST_SITMAP [Terrain]
- Receive/Retrieve MAST_SURRECONREP
- View Achieved Physical Location

- View MAST_FRAGO [Surveillance Update]
- View MAST_OPORD [Conduct Surveillance / Recon]
- View MAST_SURRECONREP
- View SITMAP Terrain

– **Provide MAST Reconnaissance**

- Plan Reconnaissance
  - Disseminate Damage Assessment Goals
  - Disseminate Force Evaluation Goals
  - Disseminate Mapping Goals
  - Generate Damage Assessment Goals
  - Generate Force Evaluation Goals
  - Generate Mapping Goals
  - Initiate and Generate Overall Recon Plan Report
  - Receive/Retrieve MAST_FRAGO [Reconnaissance update]
  - Receive/Retrieve MAST_OPORD [Conduct Surveillance / Recon]
  - Receive/Retrieve MAST_SURRECONREP
  - View MAST_FRAGO [Reconnaissance update]
  - View MAST_OPORD
  - View MAST_SURRECONREP
- Find and Report All Forces in the Area
  - Plan Search
    - Analyze Force Evaluation Goals
    - Disseminate Forces Sweep Pattern
    - Generate Forces Sweep Pattern
    - Receive/Retrieve Force Evaluation Goals
  - Detect Vehicles
    - Sample Local Environment for Vehicles
        - Disseminate Vehicle Readings
        - Generate Vehicle Readings
        - Receive/Retrieve Environment
        - Receive/Retrieve Force Evaluation Goals
        - Use Environment Data
        - View Force Evaluation Goals
      - » Process Vehicle Detection Readings
        - Disseminate Vehicle Test Results
        - Generate Vehicle Test Results
        - Receive/Retrieve Vehicle Readings
      - » Determine Vehicle Presence
        - Disseminate MAST_SPOTREP [Vehicle Location]
        - Generate MAST_SPOTREP [Vehicle Location]
        - Receive/Retrieve Vehicle Test Results
  - Detect Humans
      - » Sample Local Environment for Humans
        - Disseminate Human Readings
        - Generate Human Readings
        - Receive/Retrieve Environment
        - Receive/Retrieve Force Evaluation Goals
        - Use Environment Data
        - View Force Evaluation Goals
      - » Process Humans Detection Readings

            - Disseminate Human Test Results
            - Generate Human Test Results
            - Receive/Retrieve Human Readings
        - » Determine Humans Presence
            - Disseminate MAST_SPOTREP [Human Location]
            - Generate MAST_SPOTREP [Human Location]
            - Receive/Retrieve Human Test Results
    - – Capture Sense Data Around Vehicles
        - Disseminate MAST_RFI [ID by Operator]
        - Generate MAST_RFI [ID by Operator]
        - Receive/Retrieve Environment
        - Receive/Retrieve MAST_SPOTREP [Vehicle Location]
        - Use Environment Data
        - View MAST_SPOTREP [Vehicle Location]
    - – Capture Sense Data Around Humans
        - Analyze MAST_SPOTREP [Human Location]
        - Disseminate MAST_RFI [ID by Operator]
        - Generate MAST_RFI [ID by Operator]
        - Receive/Retrieve Environment
        - Receive/Retrieve MAST_SPOTREP [Human Location]
        - Use Environment Data
- Determine Trafficabiliy of the Zone
    - – Map Zone
        - Apply Trafficability Sweep Pattern
        - Disseminate Interiors Map
        - Generate Interiors Map
        - Receive/Retrieve Environment
        - Receive/Retrieve Trafficability Sweep Pattern
        - Use Environment Data
    - – Identify Obstacles/Cover
        - Sample Terrain Data
            - Apply Trafficability Sweep Pattern
            - Disseminate Consolidated Terrain Data
            - Generate Consolidated Terrain Data
            - Receive/Retrieve Environment
            - Receive/Retrieve Trafficability Sweep Pattern
            - Use Environment Data
        - Profile Local Terrain and Classify
            - Disseminate Cover type and location
            - Disseminate Obstacle Type and Location
            - Generate Cover type and location
            - Generate Obstacle Type and Location
            - Generate/Process Combined Terrain and Environment Data
            - Receive/Retrieve Consolidated Terrain Data
            - View Consolidated Terrain Data
    - – Generate Zone Sweep Pattern
        - Apply Achieved Physical Location
        - Disseminate Trafficability Sweep Pattern
        - Generate Trafficability Sweep Pattern
        - Receive/Retrieve Achieved Physical Location
        - Receive/Retrieve Mapping Goals
        - View Mapping Goals
    - – Detect CBRN

- Sample CBRN Environment
    - Apply Trafficability Sweep Pattern
    - Disseminate CBRN Readings
    - Generate CBRN Readings
    - Receive/Retrieve Environment
    - Receive/Retrieve Trafficability Sweep Pattern
    - Use Environment Data
  » Process CBRN Readings
    - Disseminate CBRN Test Results
    - Generate CBRN Test Results
    - Receive/Retrieve CBRN Readings
- Diagnose CBRN
    - Disseminate MAST_SPOTREP [NBC]
    - Generate MAST_SPOTREP [NBC]
    - Receive/Retrieve CBRN Test Results

– Detect Bobby Traps

- Sample Local Environment
    - Apply Trafficability Sweep Pattern
    - Disseminate Booby Trap Readings
    - Generate Booby Trap Readings
    - Receive/Retrieve Environment
    - Receive/Retrieve Trafficability Sweep Pattern
    - Use Environment Data
- Process Readings for Signs of Booby Traps
    - Disseminate Booby Trap Test Results
    - Generate Booby Trap Test Results
    - Receive/Retrieve Booby Trap Readings
- Diagnose Bobby Trap Proximity
    - Disseminate MAST_MINOBREP
    - Generate MAST_MINOBREP
    - Receive/Retrieve Booby Trap Test Results

– Analyze Traversable Route

- Apply Mapping Goals
- Compile Obstacle and Cover Details
- Disseminate MAST_ROUTEREP
- Generate MAST_ROUTEREP
- Receive/Retrieve Cover type and location
- Receive/Retrieve Interiors Map
- Receive/Retrieve Mapping Goals
- Receive/Retrieve MAST_MINOBREP
- Receive/Retrieve MAST_SPOTREP [NBC]
- Receive/Retrieve Obstacle Type and Location
- View Cover type and location
- View Interiors Map
- View MAST_MINOBREP
- View MAST_SPOTREP [NBC]
- View Obstacle Type and Location

• Assess Local Damage

– Plan Damage Assessment

- Apply Achieved Physical Location
- Apply Damage Assessment Goals
- Disseminate Damage Assessment Sweep Pattern
- Generate Damage Assessment Sweep Pattern
- Receive/Retrieve Achieved Physical Location
- Receive/Retrieve Damage Assessment Goals

– Observe Local Damage

        - Analyze MAST_RFI [ID by Operator]
        - Analyze MAST_SPOTREP [Human Location]
        - Apply Damage Assessment Goals
        - Disseminate MAST_BDAREP
        - Generate MAST_BDAREP
        - Receive/Retrieve Damage Assessment Goals
        - Receive/Retrieve MAST_RFI [ID by Operator]
        - Receive/Retrieve MAST_SPOTREP [Human Location]
      - Find Humans
        - Sample Local Environment for Humans in Rubble
          - Apply Damage Assessment Sweep Pattern
          - Disseminate Human Readings
          - Generate Human Readings
          - Receive/Retrieve Damage Assessment Sweep Pattern
          - Receive/Retrieve Environment
          - Use Environment Data
        - Process Readings from Confined Space
          - Disseminate Human Test Results
          - Generate Human Test Results
          - Receive/Retrieve Human Readings
        - Determine Human Presence
          - Disseminate MAST_SPOTREP [Human Location]
          - Generate MAST_SPOTREP [Human Location]
          - Receive/Retrieve Human Test Results
      - Find Equipment Signatures
        - Sample Local Environment for Equipment
          - Apply Damage Assessment Sweep Pattern
          - Disseminate Equipment Detection
          - Generate Equipment Detection
          - Receive/Retrieve Damage Assessment Sweep Pattern
          - Receive/Retrieve Environment
          - Use Environment Data
        - Process equipment Detection Readings
          - Disseminate Equipment Test Results
          - Generate Equipment Test Results
          - Receive/Retrieve Equipment Detection
  - **Deploy/Recover MAST System**
    - Infiltrate Building
      - Enter from Infrastructure
        - Analyze for Infrastructure Entrance
        - Disseminate Entry Request
        - Generate Entry Request
        - Receive/Retrieve Entrance Plan
        - Receive/Retrieve Extend Comms Command
        - View Entrance Plan
        - View Extend Comms Command
      - Enter from Air
        - Analyze for Air Entrance
        - Disseminate Entry Request
        - Generate Entry Request
        - Receive/Retrieve Entrance Plan
        - Receive/Retrieve Extend Comms Command
        - View Entrance Plan
        - View Extend Comms Command
          »

- Enter by Ground
  - Analyze for Ground Entrance
  - Disseminate Entry Request
  - Generate Entry Request
  - Receive/Retrieve Entrance Plan
  - Receive/Retrieve Extend Comms Command
  - View Entrance Plan
  - View Extend Comms Command
- Determine Point of Entrance
  - Probe Area with Swarm Intelligence
    - Disseminate Entrance Plan
    - Generate Entrance Plan
    - Receive/Retrieve Environment
    - Receive/Retrieve MAST_OPORD [Deploy to Mission]
    - Receive/Retrieve MAST_ROUTEREP
    - View Environment
    - View MAST_OPORD [Deploy to Mission]
    - View MAST_ROUTEREP
  - Probe Are with Sense Data
    - Disseminate Entrance Plan
    - Generate Entrance Plan
    - Receive/Retrieve Environment
    - Receive/Retrieve MAST_OPORD [Deploy to Mission]
    - View Environment
    - View MAST_OPORD [Deploy to Mission]

- Develop Search Direction to Deployment Area
  - Disseminate MAST_FRAGO [Commanded Position]
  - Generate MAST_FRAGO [Commanded Position]
  - Generate Search Pattern to Deployment Area
  - Receive/Retrieve MAST_OPORD [Deploy to Mission]
  - Receive/Retrieve True Initial Location
  - View MAST_OPORD [Deploy to Mission]
  - View True Initial Location
- Determine Path to return Area
  - Disseminate MAST_FRAGO [Commanded Position]
  - Generate MAST_FRAGO [Commanded Position]
  - Generate Search Pattern to Deployment Area
  - Receive/Retrieve MAST_OPORD [Deploy to Mission]
  - Receive/Retrieve True Initial Location
  - View MAST_OPORD [Deploy to Mission]
  - View True Initial Location
- Deactivate MAST
  - Disseminate MAST_CLOSEREP
  - Generate MAST_CLOSEREP
  - Receive/Retrieve MAST_OPORD [Return from Mission]
  - View MAST_OPORD [Return from Mission]
- Activate MAST
  - Disseminate Current Physical location
  - Generate Current Physical location
  - Perform System Warm Up/Check
  - Receive/Retrieve MAST_OPORD [Deploy to Mission]
  - Receive/Retrieve True Initial Location
  - View MAST_OPORD [Deploy to Mission]
  - View True Initial Location

- **Affect Environment with MAST**

- Weaken Gates
    - Disseminate MAST_SPOTREP [Door weakened]
    - Generate MAST_SPOTREP [Door weakened]
    - Initiate Count Down to Action
    - Receive/Retrieve Breach Request
    - View Breach Request
- Jam Nearby Electronics
    - Disseminate Jamming Signal
    - Generate Jamming Signal
    - Receive/Retrieve Jamming Request
    - View Jamming Request
- Create Distraction
    - Disseminate Distraction
    - Generate Distraction
    - Initiate Count Down to Action
    - Receive/Retrieve Distraction Request
    - View Distraction Request

APPENDIX B: FUNCTIONAL WEIGHTINGS - JOPPA URBAN

Function	Weighting	Function	Weighting	Function	Weighting
Receive/Retrieve	1	Generate Extended Communication	2	Generate Vehicle Readings	0
View/ Apply	9	Generate Hardware Communication Request	8	Generate Consolidated Terrain Data	9
Perform System Warm up/Check	5	Identify existing tags	2	Generate Raw Sense Data	2
Generate current physical location	2	Generate Tag sweep pattern	3	Generate Tag Track	2
Relay / Disseminate	9	Determine Covert movement plan	10	Generate Distraction request	0
Compile obstacle and cover details	8	Determine Overt movement plan	10	Determine best location for breach	1
Generate MAST ROUTEREP	9	Generate Interiors map	10	Generate Breach request	1
Deploy Tag	4	Survey area of Interest	0	Generate Jamming request	0
Generate ASTSTETREP	9	Generate MAST_BDAREP	1	Determine Connection needs	4
Assess information	10	Determine Possible Hide site Locations	3	Generate Trafficability Sweep Pattern	4
Generate MAST_FRAGO	6	Generate Damage Assessment Sweep Pattern	0	Classify Target	8
Use Environment Data	2	Generate Force Evaluation Goals	6	Generate Tagging Decision	8
Analyze MAST_SPOTREP	5	Generate Mapping Goals	0	Generate Jamming Signal	8
Analyze MAST RFI	6	Generate Damage Assessment Goals	10	Generate Tag location	6
Generate MAST_RFI	6	Initiate and Generate Overall Recon Plan Report	0	Update Surveillance	5
Determine Physical location of conflict	0	Analyze Force Evaluation Goals	0	Reconcile Sweep patterns	6
Generate Planned Path	2	Generate Force Sweep Pattern	6	Balance Scanning needs	10
Generate achieved physical location	4	Generate Entrance Plan	7	Determine if distraction needed	0
Generate MAST_SITMAP	0	Gather and Organize swarm data	8	Plot Path to Desired Position	8
Create Distraction	0	Generate CBRN Test Results	2	Generate Terrain Data Package	0
Generate MAST_CLOSEREP	7	Generate Equipment Test Results	0	Generate Human readings	0
Generate MAST SPOT_REP	5	Generate Human Test Results	8	Generate Equipment Detection	0
Generate vertex map	6	Generate Booby Trap Test Results	0	Analyze for Infrastructure entrance	7
Generate Path Plan to Return area	8	Generate Vehicle Test Results	0		
Generate Routing Table	5	Generate/Process Combined Terrain and Environmental Data	2		
Determine Potential Surveillance location	3	Generate Obstacle Type and Location	1		
Generate Surveillance position	3	Generate Cover Type and Location	7		
Generate Search Pattern to deployment area	7	Locate Target	2		
Generate MAST_MINOBREP	0	Generate MAST FM.BEALOC	5		
Analyze for Ground Entrance	10	Provide MAST System Interconnections	1		
Generate Entry Request	7	Generate CBRN Test readings	1		
Analyze for Air Entrance	7	Generate Booby Trap Readings	2		

APPENDIX C: FUNCTIONAL WEIGHTINGS – ARL - IBR

Function	Weighting	Function	Weighting	Function	Weighting
Receive/Retrieve	1	Generate Extended Communication	2	Generate Vehicle Readings	0
View/ Apply	9	Generate Hardware Communication Request	8	Generate Consolidated Terrain Data	9
Perform System Warm up/Check	5	Identify existing tags	2	Generate Raw Sense Data	2
Generate current physical location	2	Generate Tag sweep pattern	3	Generate Tag Track	2
Relay / Disseminate	9	Determine Covert movement plan	10	Generate Distraction request	0
Compile obstacle and cover details	8	Determine Overt movement plan	10	Determine best location for breach	1
Generate MAST ROUTEREP	9	Generate Interiors map	10	Generate Breach request	1
Deploy Tag	4	Survey area of Interest	0	Generate Jamming request	0
Generate ASTSTETREP	9	Generate MAST_BDAREP	1	Determine Connection needs	5
Assess information	10	Determine Possible Hide site Locations	3	Generate Trafficability Sweep Pattern	5
Generate MAST_FRAGO	8	Generate Damage Assessment Sweep Pattern	0	Classify Target	8
Use Environment Data	2	Generate Force Evaluation Goals	6	Generate Tagging Decision	8
Analyze MAST_SPOTREP	5	Generate Mapping Goals	7	Generate Jamming Signal	8
Analyze MAST RFI	10	Generate Damage Assessment Goals	10	Generate Tag location	6
Generate MAST_RFI	10	Initiate and Generate Overall Recon Plan Report	0	Update Surveillance	5
Determine Physical location of conflict	3	Analyze Force Evaluation Goals	0	Reconcile Sweep patterns	6
Generate Planned Path	2	Generate Force Sweep Pattern	6	Balance Scanning needs	10
Generate achieved physical location	4	Generate Entrance Plan	7	Determine if distraction needed	0
Generate MAST_SITMAP	0	Gather and Organize swarm data	8	Plot Path to Desired Position	8
Create Distraction	0	Generate CBRN Test Results	2	Generate Terrain Data Package	0
Generate MAST_CLOSEREP	7	Generate Equipment Test Results	0	Generate Human readings	0
Generate MAST SPOT_REP	5	Generate Human Test Results	8	Generate Equipment Detection	0
Generate vertex map	6	Generate Booby Trap Test Results	0	Analyze for Infrastructure entrance	7
Generate Path Plan to Return area	8	Generate Vehicle Test Results	0		
Generate Routing Table	5	Generate/Process Combined Terrain and Environmental Data	2		
Determine Potential Surveillance location	3	Generate Obstacle Type and Location	1		
Generate Surveillance position	3	Generate Cover Type and Location	7		
Generate Search Pattern to deployment area	7	Locate Target	2		
Generate MAST_MINOBREP	0	Generate MAST FM.BEALOC	5		
Analyze for Ground Entrance	10	Provide MAST System Interconnections	5		
Generate Entry Request	7	Generate CBRN Test readings	0		
Analyze for Air Entrance	7	Generate Booby Trap Readings	0		

APPENDIX D: DATABASE OF MOTORS

TYPE	SOURCE	MOTOR NAME	WEIGHT	VOLTAGE	NO LOAD CURRENT	NO LOAD SPEED	STALL CURRENT	STALL TORQUE	MAX EFFICIENCY
UNITS			grams	Volts	milli-Amperes	rev per minute	milli-Amperes	milli-Newton-meters	%
IRON CORE	PRECISION MICRODRIVE	112-001	8	2.4	120	16000	1250.00	1.55	50.452
IRON CORE	PRECISION MICRODRIVE	112-002	13	2.4	225	17000	3000.00	3.3	50.280
IRON CORE	PRECISION MICRODRIVE	120-002	22.4	1.5	100	6000	1000.00	2	48.355
IRON CORE	PRECISION MICRODRIVE	124-001	21.2	5.9	25	7200	480.00	2.9	51.176
IRON CORE	PRECISION MICRODRIVE	124-002	13.5	2	60	4800	440.00	1.23	37.471
IRON CORE	PRECISION MICRODRIVE	132-100	39.3	4.5	18	2800	460.00	4.4	43.436
IRON CORE	PRECISION MICRODRIVE	136-201	160	6	820	11600	20200.00	86	59.704
CORELESS VIBRATOR	PRECISION MICRODRIVE	103-100	0.3	3	32	50000	78.00	0.028	23.279
CORELESS VIBRATOR	PRECISION MICRODRIVE	106-001	1.4	1.3	24	24000	340.00	0.14	49.691
CORELESS VIBRATOR	PRECISION MICRODRIVE	104-001	0.5	3	16	50000	68.00	0.03	34.912
CORELESS VIBRATOR	PRECISION MICRODRIVE	104-003	0.8	3	13	28500	90.00	0.04	23.214
CORELESS VIBRATOR	PRECISION MICRODRIVE	106-002	1.3	3	17	23000	180.00	0.2	52.193
CORELESS VIBRATOR	PRECISION MICRODRIVE	107-001	2.4	1.5	20	9500	170.00	0.25	54.073
CORELESS VIBRATOR	PRECISION MICRODRIVE	108-103	3.7	3	44	18000	600.00	0.93	60.305
CORELESS VIBRATOR	PRECISION MICRODRIVE	108-104	3.7	3	44	18000	600.00	0.93	60.305
CORELESS VIBRATOR	PRECISION MICRODRIVE	108-105	2.5	3	46	18000	450.00	0.72	57.721
CORELESS VIBRATOR	PRECISION MICRODRIVE	110-003	4.9	1.3	45	9500	380.00	0.37	41.240
BRUSHLESS FLAT	MICROMO	1202-004BH	1.1	4	28	41740	246.20	0.222	55.103
BRUSHLESS FLAT	MICROMO	1202-006BH	1.1	6	15	37600	83.45	0.124	48.084
BRUSHLESS FLAT	MICROMO	1509-006B	6.9	6	17.4	14700	266.75	0.97	59.196
BRUSHLESS FLAT	MICROMO	1509-012B	6.9	12	8.7	14700	126.04	0.92	58.719
BRUSHLESS FLAT	MICROMO	2610-006B	20.1	6	12	6200	858.03	7.73	77.939
BRUSHLESS FLAT	MICROMO	2610-012B	20.1	12	6	6200	422.40	7.68	78.520
BRUSHLESS MICRO	MICROMO	0308-B	0.31	3	29	60500	83.04	0.024	24.114
BRUSHLESS MICRO	MICROMO	0515-B	1.5	6	62	37800	353.46	0.43	39.869
BRUSHLESS DC	TELCOINTERCON	DM1422-03	18	3	6	780	12.19	0.3	23.143
BRUSHLESS DC	TELCOINTERCON	DM1422-08	18	8	10	4200	70.89	1.13	46.313
BRUSHLESS DC	TELCOINTERCON	DM1632-05	26	5	50	5000	445.22	3.82	50.405
BRUSHLESS DC	TELCOINTERCON	DM1632-12-000	26	12	50	6840	156.69	1.99	30.955
BRUSHLESS DC	TELCOINTERCON	DM1632-12-002	26	12	80	14340	1108.72	8.26	57.929
BRUSHLESS DC	TELCOINTERCON	DM1632-12-005	26	12	120	24840	2544.22	11.22	64.520
BRUSHLESS DC	TELCOINTERCON	DM1632-12-011	26	12	200	31760	6123.21	21.37	69.382

BRUSHLESS DC	TELCOINTERCON	DM1632-14-002	26	24	90	14400	323.69	4.03	33.535
BRUSHLESS DC	MAXONMOTORUSA	RE606-386782	2	4.5	16.1	18500	217.13	0.469	57.445
BRUSHLESS DC	MAXONMOTORUSA	RE606-349189	2	1.5	42.6	18500	581.94	0.419	57.604
BRUSHLESS DC	MAXONMOTORUSA	RE606-386780	2	1.5	48	18500	623.61	0.449	56.977
BRUSHLESS DC	MAXONMOTORUSA	DC10010-1	10	3	37.8	12100	2038.79	4.73	75.909
BRUSHLESS DC	MAXONMOTORUSA	DC10010-2	10	9	12.3	11900	680.34	4.81	76.058
BRUSHLESS DC	MAXONMOTORUSA	EC606-250101	3	12	19	34400	147.24	0.427	47.122
BRUSHLESS DC	MAXONMOTORUSA	EC606-310599	3	6	53.1	45100	479.65	0.542	50.076
BRUSHLESS DC	MAXONMOTORUSA	RE606-386781	2	3	24.2	18500	336.81	0.485	57.831
BRUSHLESS DC	MAXONMOTORUSA	RE606-349190	2	3	21.3	18600	336.81	0.485	59.694
BRUSHLESS DC	MAXONMOTORUSA	RE606-349191	2	4.5	14.2	18600	217.13	0.469	59.290
BRUSHLESS DC	MAXONMOTORUSA	RE606-386783	2	6	12.1	18400	161.46	0.465	57.002
BRUSHLESS DC	MAXONMOTORUSA	RE606-349192	2	6	10.7	18600	161.46	0.465	59.128
BRUSHLESS DC	MAXONMOTORUSA	EC808-384409	6	6	69.2	35900	1980.52	3.05	68.485
BRUSHLESS DC	MAXONMOTORUSA	EC808-384411	6	24	22.1	42700	754.32	3.93	70.756
BRUSHLESS DC	MAXONMOTORUSA	EC808-384407	6	12	46	43800	1541.50	3.9	70.303
BRUSHLESS DC	MAXONMOTORUSA	EC808-384408	6	24	22.1	42700	754.32	3.93	70.756
BRUSHLESS DC	MAXONMOTORUSA	EC808-384406	6	6	69.2	35900	1980.52	3.05	68.485
BRUSHLESS DC	MAXONMOTORUSA	EC808-384410	6	12	46	43800	1541.50	3.9	70.303
BRUSHLESS DC	MAXONMOTORUSA	RE808-347725	4	6	7.3	13300	206.51	0.857	68.248
BRUSHLESS DC	MAXONMOTORUSA	RE808-347727	4	12	4.44	15600	130.10	0.925	68.949
BRUSHLESS DC	MAXONMOTORUSA	RE808-347728	4	7.2	6.66	14300	187.04	0.866	68.147
BRUSHLESS DC	MAXONMOTORUSA	RE808-347723	4	2.4	19.2	13900	581.76	0.925	69.059
BRUSHLESS DC	MAXONMOTORUSA	RE808-347724	4	4.2	11.2	14200	340.15	0.932	69.496
BRUSHLESS DC	MAXONMOTORUSA	RE808-347726	4	9	5.35	14400	165.86	0.957	69.478
BRUSHLESS DC	MAXONMOTORUSA	DC10010-3	10	1.5	70.4	11600	3893.44	4.75	76.761
BRUSHLESS DC	MAXONMOTORUSA	DC10010-4	10	12	9.04	11200	204.00	2.04	66.698
BRUSHLESS DC	MAXONMOTORUSA	DC10010-5	10	6	18.9	12100	933.05	4.32	74.924
BRUSHLESS DC	MAXONMOTORUSA	DC10010-6	10	4.5	26.3	11900	627.12	2.22	67.536
BRUSHLESS DC	MAXONMOTORUSA	DC10010-7	10	9	13.1	11900	680.34	4.81	75.489
BRUSHLESS DC	MAXONMOTORUSA	DC10010-8	10	3	40.4	12100	892.24	2.07	66.614
BRUSHLESS DC	MAXONMOTORUSA	RE10010-118390	7	9	4.44	10700	123.48	0.957	68.177
BRUSHLESS DC	MAXONMOTORUSA	RE10010-118396	10	6	11.1	12400	660.09	3.01	77.321
BRUSHLESS DC	MAXONMOTORUSA	RE10010-118398	10	9	7.27	12200	443.17	3.08	77.522
BRUSHLESS DC	MAXONMOTORUSA	RE10010-256092	7	7.2	8.01	10500	150.32	0.944	63.298
BRUSHLESS DC	MAXONMOTORUSA	RE10010-118394	10	4.5	15.5	12800	921.21	3.04	77.009
BRUSHLESS DC	MAXONMOTORUSA	RE10010-118399	10	9	6.42	11100	370.90	2.83	76.944
BRUSHLESS DC	MAXONMOTORUSA	EC10010-315170	13	6	169	49200	10434.78	12	77.710

BRUSHLESS DC	MAXONMOTORUSA	EC10010-315171	13	9	124	52400	8074.53	13	77.708
BRUSHLESS DC	MAXONMOTORUSA	EC10010-315176	13	12	95.2	53200	6462.26	13.7	78.263
BRUSHLESS DC	MAXONMOTORUSA	RE10010-118383	7	3	13	11100	374.53	1	73.499
BRUSHLESS DC	MAXONMOTORUSA	RE10010-118384	7	3.6	10.4	9930	284.13	0.949	67.977
BRUSHLESS DC	MAXONMOTORUSA	RE10010-118386	7	6	8.07	13000	292.74	1.25	71.256
BRUSHLESS DC	MAXONMOTORUSA	RE10010-256088	7	4.5	13.9	11200	297.00	1.09	64.647
BRUSHLESS DC	MAXONMOTORUSA	RE10010-256091	7	7.2	8.86	11600	197.18	1.12	65.236
BRUSHLESS DC	MAXONMOTORUSA	RE10010-256093	7	9	6.51	10600	123.48	0.957	63.211
BRUSHLESS DC	MAXONMOTORUSA	RE10010-118393	10	3	18.5	10700	961.83	2.52	75.471
BRUSHLESS DC	MAXONMOTORUSA	RE10010-118395	10	4.5	12.1	10600	619.05	2.47	75.757
BRUSHLESS DC	MAXONMOTORUSA	RE10010-118397	10	6	8.33	9880	457.89	2.61	76.311
BRUSHLESS DC	MAXONMOTORUSA	RE10010-256099	10	4.5	15.1	12800	921.21	3.04	77.246
BRUSHLESS DC	MAXONMOTORUSA	RE10010-256100	10	4.5	11.8	10600	619.05	2.47	75.991
BRUSHLESS DC	MAXONMOTORUSA	RE10010-256103	10	9	7.06	12200	443.17	3.08	77.783
BRUSHLESS DC	MAXONMOTORUSA	RE10010-256104	10	10	6.45	12300	411.53	3.14	77.626
BRUSHLESS DC	MAXONMOTORUSA	RE10010-118388	10	7.2	6.04	11400	197.18	1.12	68.208
BRUSHLESS DC	MAXONMOTORUSA	RE10010-256096	10	2.4	21.7	10400	1152.78	2.49	75.793
BRUSHLESS DC	MAXONMOTORUSA	EC10010-315174	13	6	169	49200	1321.74	1.52	53.581
BRUSHLESS DC	MAXONMOTORUSA	EC10010-315172	13	12	95.2	53200	6462.26	13.7	78.263
BRUSHLESS DC	MAXONMOTORUSA	EC10010-315177	13	18	70.8	57100	5252.53	15.6	79.195
BRUSHLESS DC	MAXONMOTORUSA	RE10010-118387	7	6	7.04	11400	231.56	1.13	70.399
BRUSHLESS DC	MAXONMOTORUSA	RE10010-118389	7	7.2	5.46	10600	150.32	0.944	68.302
BRUSHLESS DC	MAXONMOTORUSA	RE10010-118391	7	12	3.59	11600	105.76	1.01	68.924
BRUSHLESS DC	MAXONMOTORUSA	RE10010-118392	7	2.4	16.1	13000	431.78	0.924	85.275
BRUSHLESS DC	MAXONMOTORUSA	RE10010-118385	7	4.5	9.34	11300	297.00	1.09	69.624
BRUSHLESS DC	MAXONMOTORUSA	RE10010-256085	7	2.4	23.4	10200	431.78	0.924	62.664
BRUSHLESS DC	MAXONMOTORUSA	RE10010-256089	7	6	11.8	12900	292.74	1.25	66.667
BRUSHLESS DC	MAXONMOTORUSA	RE10010-256101	7	6	10.8	12400	328.95	1.5	70.731
BRUSHLESS DC	MAXONMOTORUSA	RE10010-256086	7	3	18.8	10300	374.53	1	64.070
BRUSHLESS DC	MAXONMOTORUSA	RE10010-256087	7	3.6	14.9	9840	284.13	0.949	63.286
BRUSHLESS DC	MAXONMOTORUSA	RE10010-118400	7	12	5.67	12500	361.11	3.25	77.528
BRUSHLESS DC	MAXONMOTORUSA	EC10010-315175	13	9	124	52400	8074.53	13	77.708
BRUSHLESS DC	MAXONMOTORUSA	RE10010-256090	7	6	10.5	11300	232.03	1.13	65.301
BRUSHLESS DC	MAXONMOTORUSA	RE10010-256094	7	12	5.37	11500	105.76	1.01	63.830
BRUSHLESS DC	MAXONMOTORUSA	RE10010-118392	10	3	23.9	13000	694.44	1.5	69.728
BRUSHLESS DC	MAXONMOTORUSA	RE10010-256097	10	2.4	17	8560	770.99	2.02	74.186
BRUSHLESS DC	MAXONMOTORUSA	RE10010-256102	10	7.2	8.55	11900	549.12	3.13	77.980
BRUSHLESS DC	MAXONMOTORUSA	RE10010-256105	10	12	5.5	12500	360.00	3.24	77.762

BRUSHLESS DC	MAXONMOTORUSA	EC10010-315173	13	18	70.8	57100	5252.53	15.6	79.195
BRUSHLESS DC	MAXONMOTORUSA	AM12012-200937	11	3	21.1	13900	786.07	1.58	72.000
BRUSHLESS DC	MAXONMOTORUSA	AM12012-200938	12	3	34.5	13700	786.07	1.58	65.706
BRUSHLESS DC	MAXONMOTORUSA	AM12012-265374	11	4.5	11.5	11900	439.09	1.55	72.416
BRUSHLESS DC	MAXONMOTORUSA	AM12012-265376	11	9	5.87	12100	219.65	1.52	71.972
BRUSHLESS DC	MAXONMOTORUSA	AM12012-265393	12	15	6.88	13500	1057.38	1.29	9.843
BRUSHLESS DC	MAXONMOTORUSA	AM12012-265377	11	12	4.5	12300	167.77	1.52	71.803
BRUSHLESS DC	MAXONMOTORUSA	AM12012-265389	12	4.5	18.8	11700	439.09	1.55	65.981
BRUSHLESS DC	MAXONMOTORUSA	AM12012-265390	12	6	15.5	12600	373.85	1.63	66.182
BRUSHLESS DC	MAXONMOTORUSA	AM12012-265378	12	12	7.83	12100	167.77	1.52	64.687
BRUSHLESS DC	MAXONMOTORUSA	AM12012-265392	11	15	4.2	13800	129.00	1.29	69.139
BRUSHLESS DC	MAXONMOTORUSA	EC13013-371405	34	24	87.5	71200	18437.50	59	86.990
BRUSHLESS DC	MAXONMOTORUSA	RE13013-118462	21	3	50.8	12200	4415.58	10.2	80.223
BRUSHLESS DC	MAXONMOTORUSA	RE13013-118475	21	24	5.82	11500	450.25	8.87	79.698
BRUSHLESS DC	MAXONMOTORUSA	RE13013-118506	21	1.5	43.8	6570	2893.02	6.22	78.187
BRUSHLESS DC	MAXONMOTORUSA	RE13013-118515	21	6	11.5	6810	663.85	5.49	76.742
BRUSHLESS DC	MAXONMOTORUSA	RE13013-118535	15	20	29.7	13300	250.39	3.18	48.929
BRUSHLESS DC	MAXONMOTORUSA	EC13013-384216	44	24	129	79400	49305.56	142	90.296
BRUSHLESS DC	MAXONMOTORUSA	EC13013-384185	44	48	64.3	79400	25868.06	149	90.508
BRUSHLESS DC	MAXONMOTORUSA	EC13013-370540	34	48	53.5	82900	11363.64	62.5	87.089
BRUSHLESS DC	MAXONMOTORUSA	EC14013.6-339251	8	6	152	21200	1500.00	3.54	50.243
BRUSHLESS DC	MAXONMOTORUSA	EC14013.6-339252	8	12	52.6	20100	764.82	3.87	55.700
BRUSHLESS DC	MAXONMOTORUSA	EC14013.6-236679	8	18	32.2	21000	474.58	3.36	54.435
BRUSHLESS DC	MAXONMOTORUSA	EC14013.6-339253	8	24	28.8	21200	374.60	3.54	53.574
BRUSHLESS DC	MAXONMOTORUSA	AM16016-110042	21	3	38.1	12300	1969.43	4.51	75.776
BRUSHLESS DC	MAXONMOTORUSA	AM16016-110044	21	9	12.7	12300	700.58	4.82	76.478
BRUSHLESS DC	MAXONMOTORUSA	RE16016-320178	21	18	3.35	7940	225.82	4.81	78.181
BRUSHLESS DC	MAXONMOTORUSA	EC16016-283835	52	24	39.9	11900	1176.47	22	69.236
BRUSHLESS DC	MAXONMOTORUSA	RE16016-118715	40	12	45.9	13900	4229.35	34.3	80.676
BRUSHLESS DC	MAXONMOTORUSA	RE16016-118724	40	48	3.63	5320	144.22	12.1	72.524
BRUSHLESS DC	MAXONMOTORUSA	AM16016-352853	21	3	117	11700	1969.43	4.51	60.454
BRUSHLESS DC	MAXONMOTORUSA	AM16016-231379	21	9	12.7	12300	700.58	4.82	76.478
BRUSHLESS DC	MAXONMOTORUSA	AM16016-110051	22	1.2	73.9	8560	2923.66	3.83	72.840
BRUSHLESS DC	MAXONMOTORUSA	AM16016-110068	21	18	25.9	10900	310.42	4.47	54.970
BRUSHLESS DC	MAXONMOTORUSA	RE10016-320179	21	24	2.44	7760	76.29	2.22	70.903
BRUSHLESS DC	MAXONMOTORUSA	RE16016-118723	40	48	7.66	10100	540.18	24.2	78.807
BRUSHLESS DC	MAXONMOTORUSA	EC16016-393216	58	12	372	40600	51428.57	144	84.256
BRUSHLESS DC	MAXONMOTORUSA	EC16016-396928	58	32	175	47500	32863.85	210	86.268

BRUSHLESS DC	MAXONMOTORUSA	EC16016-405795	58	48	110	45600	20520.52	205	86.279
BRUSHLESS DC	MAXONMOTORUSA	RE16016-118681	38	3.2	18.6	6270	3140.50	15.2	85.623
BRUSHLESS DC	MAXONMOTORUSA	EC16016-320818	32	9	96.3	12800	900.16	5.59	52.512
BRUSHLESS DC	MAXONMOTORUSA	EC16016-283833	52	9	107	11900	2820.51	19.8	68.092
BRUSHLESS DC	MAXONMOTORUSA	RE17017-216007	26	48	8.56	10100	79.77	3.51	55.005
BRUSHLESS DC	MAXONMOTORUSA	RE17017-214896	26	4.5	21	9650	2963.80	13.1	84.432
BRUSHLESS DC	MAXONMOTORUSA	RE17017-214899	26	21	5.81	11300	909.60	16.1	85.508
BRUSHLESS DC	MAXONMOTORUSA	RE17017-215985	26	30	3.47	10200	517.99	14.4	84.541
BRUSHLESS DC	MAXONMOTORUSA	RE17017-215992	27	12	6.45	6920	205.52	3.35	71.035
BRUSHLESS DC	MAXONMOTORUSA	RE17017-215999	26	4.8	93.4	10900	3178.48	13	70.864
BRUSHLESS DC	MAXONMOTORUSA	RE17017-214895	26	3	40.7	11300	7312.25	18.5	86.417
BRUSHLESS DC	MAXONMOTORUSA	RE17017-215997	27	36	2.48	7720	196.14	8.63	79.843
BRUSHLESS DC	MAXONMOTORUSA	AM19019-110084	33	6	18.6	7790	1019.39	7.36	76.187
BRUSHLESS DC	MAXONMOTORUSA	AM19019-110088	33	18	8.25	9300	450.83	8.16	75.980
BRUSHLESS DC	MAXONMOTORUSA	AM19019-249986	33	9	51.9	8840	908.40	8.33	61.439
BRUSHLESS DC	MAXONMOTORUSA	AM19019-110094	34	6	16.6	6090	642.31	5.89	72.335
BRUSHLESS DC	MAXONMOTORUSA	AM19019-240035	34	2.4	288	11700	2670.45	4.7	50.910
BRUSHLESS DC	MAXONMOTORUSA	AM19019-344596	34	12	44.6	9930	834.86	9.1	62.311
BRUSHLESS DC	MAXONMOTORUSA	AM19019-240133	33	2.4	288	11700	2670.45	4.7	50.910
BRUSHLESS DC	MAXONMOTORUSA	EC20020-351101	15	24	12.5	9450	309.57	7.12	65.746
BRUSHLESS DC	MAXONMOTORUSA	EC20020-351098	15	6	48	9130	899.66	5.29	61.826
BRUSHLESS DC	MAXONMOTORUSA	EC20020-339255	15	6	48	9130	899.66	5.29	61.826
BRUSHLESS DC	MAXONMOTORUSA	EC20020-351100	15	12	25.6	9540	501.77	5.67	62.599
BRUSHLESS DC	MAXONMOTORUSA	EC20020-241916	15	9	34.8	9760	957.14	8.04	67.285
BRUSHLESS DC	MAXONMOTORUSA	EC20020-339258	15	24	12.5	9450	309.57	7.12	65.746
BRUSHLESS DC	MAXONMOTORUSA	EC20020-339257	15	12	25.6	9540	501.77	5.67	62.599
BRUSHLESS DC SERVOMOTOR	MICROMO	0620-006B	2.5	6	62	46500	646.05	0.73	53.449
BRUSHLESS DC SERVOMOTOR	MICROMO	0620-012B	2.5	12	20	35600	196.08	0.57	51.880
BRUSHLESS DC SERVOMOTOR	MICROMO	1226-006B	13	6	88	20100	2811.29	7.19	64.773
BRUSHLESS DC SERVOMOTOR	MICROMO	1226-012B	13	12	74	27200	2247.24	9.21	69.690
BRUSHLESS DC SERVOMOTOR	MICROMO	1628-012B	31	12	98	28650	2849.00	11	68.677
BRUSHLESS DC SERVOMOTOR	MICROMO	1628-024B	31	24	52	29900	1620.00	12	69.504
BRUSHLESS DC SERVOMOTOR	MICROMO	2036-012B	50	12	102	17600	3476.00	22	70.841
BRUSHLESS DC SERVOMOTOR	MICROMO	2036-024B	50	24	53	18000	1701.00	21	70.049
BRUSHLESS DC SERVOMOTOR	MICROMO	2036-036B	50	36	40	19500	1276.00	22	70.589
BRUSHLESS DC	MICROMO	2036-048B	50	48	25	17400	780.00	20	70.020

SERVOMOTOR									
BRUSHLESS DC SERVOMOTOR	MICROMO	2057-012B	95	12	210	21900	21809.00	113	82.114
BRUSHLESS DC SERVOMOTOR	MICROMO	2057-024B	95	24	147	26500	16848.00	144	82.640
BRUSHLESS DC SERVOMOTOR	MICROMO	2444-024B	100	24	184	23000	11322.00	111	77.394
BRUSHLESS DC SERVOMOTOR	MICROMO	2444-048B	100	48	88	22500	5750.00	115	77.747
BRUSHLESS DC SERVOMOTOR	MICROMO	3056-012B	190	12	168	8790	7410.00	95	74.287
BRUSHLESS DC SERVOMOTOR	MICROMO	3056-024B	190	24	75	8200	3626.00	98	73.898
BRUSHLESS DC SERVOMOTOR	MICROMO	3056-036B	190	36	56	8840	2574.00	99	75.105
BRUSHLESS DC SERVOMOTOR	MICROMO	3056-048B	190	48	42	8740	1900.00	100	76.056
BRUSHLESS DC SERVOMOTOR	MICROMO	3564-012B	310	12	206	7850	20079.00	291	81.858
BRUSHLESS DC SERVOMOTOR	MICROMO	3564-024B	310	24	189	11300	18550.00	371	81.357
BRUSHLESS DC SERVOMOTOR	MICROMO	3564-036B	310	36	131	11550	12886.00	379	81.543
BRUSHLESS DC SERVOMOTOR	MICROMO	3564-048B	310	48	109	12200	10827.00	401	81.420
BRUSHLESS DC SERVOMOTOR	MICROMO	4490-024B	750	24	554	9550	101052.00	2406	86.002
BRUSHLESS DC SERVOMOTOR	MICROMO	4490-036B	750	36	432	10450	81747.00	2637	85.206
BRUSHLESS DC SERVOMOTOR	MICROMO	4490-048B	750	48	354	11000	66192.00	2758	86.820
BRUSHLESS DC SERVOMOTOR	MICROMO	4490-024BS	750	24	217	5450	34920.00	1455	85.125
BRUSHLESS DC SERVOMOTOR	MICROMO	4490-036BS	750	36	160	5790	26928.00	1584	85.399
BRUSHLESS DC SERVOMOTOR	MICROMO	4490-048BS	750	48	129	6060	21957.00	1689	87.734

APPENDIX E: DATABASE OF BATTERIES

PRODUCT/PRODUCER NAME	ENERGY DENSITY	VOLTAGE	DISCHARGE	WEIGHT	DIMENSION		
					Z	X	Y
UNITS	mAh	V (x 3.7)	C	g	mm	mm	mm
Turnigy nano-tech	850	3	45	73	55	25	31
Zippy Compact	850	3	25	64	59	20	31
Zippy Compact	850	3	35	73	58	30	24
Turnigy nano-tech	950	3	25	69	72	25	20
Turnigy nano-tech	1000	3	25	79	77	35	17
Turnigy	1000	3	30	93	73	35	19
Turnigy nano-tech	1000	3	45	97	74	19	35
Zippy Flightmax	1000	3	25	90	73	36	18
Turnigy nano-tech	1000	3	25	94	78	36	19
Zippy Compact	1000	3	25	82	76	15	34
Zippy K-Flightmax	1000	3	25	95	110	32	18
Zippy Compact	1000	3	35	92	76	35	17
Turnigy	1000	3	20	87	79.5	36.5	17
Rhino	1050	3	20	100	73	35	18
Rhino	1050	3	30	96	70	34	17
Zippy	50	1	20	1.8	19	14	5
Zippy	70	1	20	2	18	14	6
Turnigy nano-tech	80	1	15	2	30	7	7
Turnigy nano-tech	90	1	15	3	36	6	6
Zippy	100	1	20	3	30	15	4
Turnigy nano-tech	160	1	25	4.7	46	6	10.5
Turnigy nano-tech	160	1	25	4.5	39	12	8
Turnigy nano-tech	180	1	15	4	38	8	8
Turnigy nano-tech	180	1	25	11.5	33.5	10	21
Turnigy nano-tech	200	1	15	5	52	7	7
HK 188/189	220	1	0	6	31	20	7
Zippy Lightmax	240	1	30	9.9	63	26	3
Zippy	240	1	20	6	24	19	5
Turnigy nano-tech	260	1	35	8	32	20	7
Turnigy nano-tech	260	1	35	14	33	20	13.5
Turnigy nano-tech	270	1	15	6	56	8	8
Turnigy nano-tech	300	1	35	8	43	17	6
Zippy lightmax	100	1	20	5.1	32	20	3.3

NE-B918	129	1	10	3.7	35	12	16
Turnigy nano-tech	130	1	15	4	39	7	7
Turnigy nano-tech	130	1	25	4	39	7	10.5
Turnigy nano-tech	130	1	25	4	40	7	11
Turnigy nano-tech	130	1	25	3.8	39	12	7
Zippy	138	1	20	6.6	37	26	3.2
Nine Eagles High-Cap	155	1	10	4.2	46	12	6
Turnigy	160	1	30	4.3	37	12	6
Turnigy nano-tech	160	1	25	4.3	39	7	11
Turnigy nano-tech	160	1	25	4.8	46.5	6	10
Turnigy nano-tech	300	1	35	7.6	48.5	7.1	19
Turnigy nano-tech	300	1	45	9	43	17	6
Turnigy nano-tech	300	1	45	8	44	6	17
Zippy-K Flightmax	315	1	20	13	52	23	7
Zippy lightmax	350	1	30	12.3	63	26	3.7
Zippy	350	1	20	8.7	36	21	7
Turnigy nano-tech	350	1	15	10	75	8	8
Turnigy nano-tech	350	1	65	15	52	30	5
Zippy lightmax	400	1	30	13.2	63	26	4
Zippy	400	1	20	9.8	39	23	7
Zippy	450	1	20	11	49	31	5
Turnigy nano-tech	600	1	35	15.8	79	7	19
Zippy	600	1	20	14.8	50	30	5
Turnigy nano-tech	650	1	15	13	41	13	13
Zippy	740	1	20	20.4	64	35	5
Turnigy nano-tech	750	1	35	18	43	24	9
Zippy	850	1	20	20.2	50	31	7
Turnigy nano-tech	900	1	15	18	58	12	12
Turnigy nano-tech	950	1	25	25	68	7	25
Turnigy nano-tech	1000	1	15	20	70	12	12
Turnigy	1000	1	20	25.5	63	64	6
Turnigy nano-tech	1200	1	15	23	58	15	15
Turnigy	2200	1	20	55	97	34	8
Turnigy	2200	1	40	58	99	34	8
Turnigy nano-tech	260	2	35	16	33	20	13.5
Turnigy nano-tech	300	2	35	16	44	18	12
Turnigy nano-tech	300	2	35	17	44	12	17
Turnigy	300	2	45	19	45	17	12
Zippy compact	350	2	25	25	58	30	8
Turnigy nano-tech	350	2	65	34	54	30	10
Zippy Flightmax	350	2	20	21	40	20	15

Rhino	360	2	20	22.5	43	15	21
Turnigy nano-tech	370	2	25	27	63	32	9
Turnigy nano-tech	450	2	65	26	48	29	11
Turnigy nano-tech	460	2	25	33	65	29	11
Rhino	460	2	20	28.5	52	30	8
Zippy compact	500	2	35	32	58	30	10
Zippy compact	500	2	25	29	56	9	30
Turnigy	500	2	20	36	55	30	10
Zippy Flightmax	500	2	15	31	56	31	10
Zippy Flightmax	500	2	20	30	55	31	10
Rhino	610	2	20	35	52	10	30
Rhino	750	2	20	45	67	4	35
Zippy K-Flightmax	780	2	20	49	94	24	13
Turnigy nano-tech	800	2	20	50	77	25	14
B-Grade	800	2	20	52	67	60	16
Zippy Flightmax	800	2	20	49	55	31	15
Zippy Flightmax	800	2	15	43	54	30	14
Turnigy	800	2	30	62	56	30	17
Turnigy	800	2	35	63	58	30	17
Turnigy	800	2	40	64	57	30	17
Turnigy	800	2	20	48	55	28	14
Turnigy nano-tech	850	2	25	49	60	31	16
Zippy Compact	850	2	25	44	56	14	30
Zippy Compact	850	2	35	50	58	30	16
Zippy K-Flightmax	920	2	25	58	109	32	10
Turnigy nano-tech	950	2	25	46	71	25	14
Turnigy nano-tech	1000	2	25	60	71	35	12
Turnigy	1000	2	20	62	70	35	13
Turnigy	1000	2	30	64	75	34	12
Zippy compact	1000	2	25	58	75	10	34
Zippy Flightmax	1000	2	20	60	75	35	12
Zippy K-Flightmax	1000	2	25	70	106	32	12
Zippy Flightmax	1000	2	15	59	71	35	11
Rhino	1050	2	20	71	70	35	11
Rhino	1050	2	30	73	68	36	12
Rhino	1050	2	40	75	72	39	12
Turnigy nano-tech	1200	2	15	64	127	12	20
Turnigy	1200	2	15	68.1	125	12	20
Zippy K-Flightmax	1200	2	25	70	109	31	12
Rhino	1250	2	30	81	91	34	12
Rhino	1250	2	20	82	88	34	11

Turnigy nano-tech	1300	2	25	79	168	12	18
Turnigy	1300	2	20	82	70	35	15
Zippy Compact	1300	2	25	71	74	13	34
Zippy Flightmax	1300	2	20	76	72	36	13
Turnigy	1300	2	20	84	93	30	14
Turnigy nano-tech	1300	2	20	67	71	34	14
Zippy Flightmax	1300	2	15	71	74	37	13
Turnigy nano-tech	1300	2	25	86	85	34	16
Turnigy nano-tech	1300	2	25	80	166	14	18
Zippy K-Flightmax	1350	2	20	77	71	34	16
Polyquest	1350	2	8	70	75	36	15
Turnigy nano-tech	1400	2	15	76	126	13	22
Turnigy nano-tech	1400	2	15	79	125	14	21
Turnigy	1500	2	25	88	80	34	18
Turnigy nano-tech	1500	2	35	91	85	35	14
Turnigy nano-tech	1500	2	25	86	87	33	15
Turnigy nano-tech	1500	2	20	75	87	34	13
Rhino	1550	2	20	97.7	92	33	14
Rhino	1550	2	37	99	104	34	14
Turnigy	1600	2	20	102	69	46	16
Turnigy	3300	1	20	78.9	129	43	7
Turnigy	5000	1	20	114	128	42	10
turnigy	5000	1	40	130	128	50	9
Turnigy nano-tech	5000	1	50	148	93.2	47	18.5
Turnigy nano-tech	5600	1	65	152	93.2	47	18.5
Turnigy	5800	1	25	143	136	50	10
Zippy Flightmax	5800	1	60	177	92	46	19
Turnigy nano-tech A-Spec	6000	1	65	139	93	47	18
Zippy Flightmax	6200	1	30	179	92	46	19
Turnigy nano-tech	120	2	25	8.5	33	7.5	20
Turnigy	138	2	10	7.2	35	12	12
Turnigy nano-tech	180	2	25	13	35	20	10
Zippy K-Flightmax	1600	2	20	90	75	40	18
Turnigy	1600	2	20	80	88	28	17
Turnigy	1600	2	20	97	106	32	13
Zippy Flightmax	1600	2	20	90	103	34	12
Polyquest	1600	2	8	80	78	36	18
Polyquest	1600	2	18	85	72.5	34.5	17.5
Turnigy	1600	2	30	102	105	35	14
Turnigy nano-tech	1600	2	25	103	118	32	15
Turnigy	1700	2	20	82	100	26.5	20

Rhino	1750	2	25	109	95	35	18
Rhino	1750	2	20	110	94	33	14
Turnigy nano-tech	1800	2	20	100	103	18	34
Turnigy nano-tech	1800	2	25	100	103	13	35
Turnigy nano-tech	1800	2	25	113	115	35	15
Turnigy	1800	2	30	115	108	38	15
turnigy	1800	2	40	117	116	34	14
turnigy	1800	2	20	108	106	34	13
Zippy Compact	1800	2	25	93	106	12	34
Zippy K-Flightmax	1800	2	20	110	112	33	17
Zippy Flightmax	1800	2	20	108	100	36	14
Turnigy nano-tech	1800	2	25	103	100	14	35
Turnigy nano-tech	1800	2	20	103	99	14	35
Turnigy nano-tech	1800	2	65	124	104	35	16
Zippy Flightmax	1800	2	40	116	103	35	15
Turnigy nano-tech	2000	2	15	109	125	10	21
Turnigy nano-tech	2000	2	15	106	127	19	21
Turnigy nano-tech	2000	2	20	98	87	34	17
Zippy Flightmax	2000	2	45	136	102	36	16
Polyquest	2050	2	35	120	106	35.5	18
Zippy Flightmax	2100	2	8	94	59	35	27
Polyquest	2100	2	8	104	117	31	16
Rhino	2150	2	37	129	121	35	16
Rhino	2150	2	30	129	111	40	16
Rhino	2150	2	20	132	123	34	14
Turnigy nano-tech	2200	2	40	119.6	87	19	34
Turnigy nano-tech	2200	2	25	133	112	35	18
Zippy Compact	2200	2	25	113	104	14	35
Turnigy	2200	2	25	138	114	33	17
Zippy Flightmax	2200	2	40	143	105	35	18
Zippy Compact	2200	2	35	125	111	35	15
Zippy Flightmax	2200	2	45	148	101	37	18
Zippy Flightmax	2200	2	20	133	104	34	17
Turnigy	2200	2	30	135	105	34	16
Turnigy	2200	2	20	130	105	33	16
Turnigy	2200	2	40	140	114	34	19
Turnigy nano-tech	2250	2	65	142	103	35	19
Rhino	2350	2	20	144	153	44	12
Rhino	2350	2	25	144	143	44	11
Zippy Flightmax	2450	2	30	155	137	45	12
Turnigy	2450	2	30	153	135	42	11

Turnigy nano-tech	2650	2	45	155	134	43	11
Zippy Flightmax	2650	2	45	175	134	45	13
Zippy Flightmax	2650	2	40	166	137	45	12
Turnigy	2650	2	30	176	136	43	12
Turnigy nano-tech	2650	2	25	151	147	44	11
Turnigy	2650	2	40	180	139	43	13
Zippy Compact	2700	2	25	138	136	10	44
Zippy Compact	2700	2	35	151	137	44	11
Turnigy nano-tech	2700	2	65	177	133	43	14
Turnigy nano-tech	3000	2	20	146	88	34	25
Turnigy nano-tech	3000	2	25	165	147	57	16
Zippy compact	3700	2	35	211	145	43	14
Rhino	3700	2	20	223	152	45	15
Rhino	3700	2	25	225	160	44	15
Polyquest	3700	2	30	232	137	46.5	24
Turnigy	3800	2	25	235	136	45	22
Turnigy nano-tech	3850	2	65	242	133	43	19
Zippy Flightmax	4000	2	30	256	137	47	25
Turnigy	4000	2	2	133	71	50	19
Zippy Compact	4000	2	25	197	145	14	43
Zippy Flightmax	4000	2	20	238	137	46	25
Turnigy nano-tech	4000	2	40	227.2	135	20	43
Zippy Flightmax	4000	2	40	239	145	50	14
Zippy Flightmax	4000	2	25	235	138	47	23
Zippy Flightmax	4000	2	45	252	142	52	15
Zippy Flightmax	4000	2	30	255	137	51	24
Turnigy nano-tech	4000	2	35	234	152	49	14
Turnigy nano-tech	4000	2	25	233	172	49	14
Turnigy	4000	2	30	245	143	50	15
Turnigy nano-tech	4000	2	45	254	152	48	15
Turnigy	4000	2	40	259	152	49	16
Turnigy	4000	2	30	254	135	45	21
Turnigy nano-tech	4200	2	40	230	138	47	23
Turnigy nano-tech A-Spec	4200	2	65	195	95	46	25
Turnigy nano-tech Shorty	4200	2	65	189.9	96	46.4	25
Turnigy nano-tech	4400	2	65	278	151	48	17
Zippy Compact	4500	2	35	249	161	45	15
Zippy Flightmax	4500	2	30	260	143	50	16
Turnigy nano-tech	4500	2	25	255	167	49	16
Zippy Flightmax	4500	2	45	275	142	50	17

Turnigy nano-tech	4500	2	35	260	152	49	15
Turnigy nano-tech	4500	2	45	273	154	49	16
Turnigy	4500	2	30	278	154	49	16
Polyquest	4550	2	30	258	165	47	18
Turnigy nano-tech	4850	2	50	290	138	47	25
Rhino	4900	2	20	270	170	44	17
Polyquest	4950	2	20	260	166	44	15
Turnigy nano-tech	5000	2	25	279	173	49	16
Zippy Flightmax	5000	2	20	264	137	46	25
Zippy Flightmax	5000	2	30	301	138	47	25
Zippy	5000	2	20	250	144	51	17
Turnigy	5000	2	40	308	147	49	18
Zippy Flightmax	5000	2	20	279	137	46	25
Turnigy	5000	2	20	282	148	49	16
Zippy Compact	5000	2	25	237	162	14	46
Zippy Flightmax	5000	2	30	278	137	47	24
Zippy Flightmax	5000	2	40	290	145	50	17
Zippy Flightmax	5000	2	45	308	143	52	19
Turnigy	5000	2	20	276	135	45	22
Turnigy nano-tech	5000	2	45	279	152	49	17
Turnigy	5000	2	30	304	137.5	46	25
Turnigy nano-tech	5000	2	35	286	150	49	17
Turnigy nano-tech	5000	2	30	285	70	47	50
Turnigy	5000	2	30	301	143	50	19
Turnigy nano-tech	5000	2	65	304	151	48	19
Turnigy	5000	2	50	339	139	46	26
Turnigy	5000	2	40	326	137.5	46	25
Polyquest	5050	2	35	279	145	47	25
Polyquest	5050	2	35	295	137	46.5	24
Turnigy nano-tech	5100	2	65	290	69	47	50
Zippy Flightmax	5200	2	30	314	137	46	25
Turnigy	5200	2	30	336	137	46	25
Turnigy nano-tech	5300	2	30	271	138	46	25
Turnigy nano-tech	5300	2	50	295	138	47	25
Polyquest	5300	2	25	291	137	46.5	24
Turnigy	5300	2	25	325	138	46	25
Polyquest	5400	2	18	288	137	46.5	24
Zippy Flightmax	5400	2	35	306	138	46	25
Zippy Flightmax	5400	2	50	308	138	46	25
Polyquest	5500	2	20	261	167	43.5	19
Turnigy nano-tech	5600	2	50	294	138.5	47	25

Turnigy nano-tech A-Spec	5600	2	65	290	69	46	50
Zippy Flightmax	5700	2	25	340	69	49	62
Zippy Flightmax	5700	2	50	324	138	46	25
Turnigy nano-tech	5800	2	30	296	138	46	25
Turnigy nano-tech	5800	2	40	307.5	135	24	43
Zippy Compact	5800	2	25	273	159	16	45
Zippy Flightmax	5800	2	30	289	140	50	19
Turnigy	5800	2	25	336	150	49	19
Zippy Flightmax	5900	2	60	320	138	46	25
Turnigy nano-tech	6000	2	65	313	138	46	25
Turnigy nano-tech	6000	2	25	333	155	49	20
Turnigy	6000	2	25	371	132	45	29
Zippy Flightmax	6000	2	50	334	138	46	25
Zippy Flightmax	6000	2	35	338	138	46	25
Turnigy	6000	2	25	415	143	50	34
Polyquest	6100	2	20	292	163	45	20
Turnigy nano-tech A-Spec	6200	2	65	296	138	47	25
Turnigy nano-tech	6600	2	65	290	138	46	25
Turnigy nano-tech A-Spec	6600	2	65	274	150	43	19.5
Turnigy nano-tech	7600	2	40	377.3	154	27	45
Zippy Flightmax	8000	2	30	415	166	69	15
Turnigy nano-tech	10000	2	40	499	137	41	43
Turnigy nano-tech	12800	2	40	614	154	42	45
Turnigy nano-tech	180	3	25	19	35	20	15
Zippy Compact	350	3	25	38	58	30	11
Turnigy nano-tech	350	3	65	46	56	30	14
Rhino	360	3	20	32.4	42	20	23
Zippy Flightmax	3000	2	40	185	135	45	14
Turnigy	3000	2	30	189	147	45	14
Turnigy	3000	2	40	198	136	42	15
Polyquest	3200	2	18	195	137	46.5	24
Zippy Compact	3300	2	35	193	146	13	43
Turnigy nano-tech	3300	2	35	191	132	43	15
Turnigy nano-tech	3300	2	25	183	145	44	14
Turnigy nano-tech	3300	2	45	209	133	44	16
Turnigy	3300	2	30	204	134	43	15
Turnigy nano-tech	3300	2	65	220	132	43	17
Turnigy	3600	2	30	214	137	43	15
Zippy Compact	3700	2	25	193	146	44	13

Turnigy nano-tech	370	3	25	39	60	31	13
Turnigy nano-tech	460	3	25	45	67	30	15
Rhino	460	3	30	41.4	53	12	31
Zippy Compact	500	3	25	42	56	13	30
Zippy compact	500	3	35	47	58	30	15
Zippy Flightmax	500	3	20	43	53.5	30	16
Zippy Flightmax	500	3	15	45	55	31	11
Turnigy	500	3	20	51	57	30	14
Rhino	610	3	20	50.9	55	31	16
Rhino	750	3	20	66	68	12	35
Turnigy	800	3	20	75	57	29	23
Zippy Flightmax	800	3	20	78	54	30	23.5
Turnigy	800	3	40	88	60	30	25
Turnigy	800	3	35	85	58	30	25
Turnigy	800	3	40	90	60	30	25
Turnigy nano-tech	850	3	25	69	63	32	25
Rhino	1050	3	50	103	69	34	18
Turnigy nano-tech	1200	3	15	94	128	17	20
Turnigy nano-tech	1200	3	15	99	125	6	21
Rhino	1250	3	30	113	99	34	17
Rhino	1250	3	30	116	90	35	18
Turnigy nano-tech	1300	3	25	119	70	34	22
Turnigy nano-tech	1300	3	45	119	72	23	35
Turnigy	1300	3	25	116	71	34	24
Turnigy	1300	3	20	115	81	36	21
Turnigy nano-tech	1300	3	25	122	167	6.5	18
Zippy Compact	1300	3	25	101	76	19	35
Zippy Flightmax	1300	3	20	118	71	35	21
Zippy K-Flightmax	1300	3	20	108	72	35	23
Turnigy	1300	3	30	123	73	34	23
Turnigy nano-tech	1300	3	25	113	168	18	18
Rhino	1350	3	35	126	77	35	21
Rhino	1350	3	30	124	86	36	24
Turnigy nano-tech	1400	3	40	118.7	87	19	34
Turnigy nano-tech	1400	3	15	110	127	20	21
Turnigy nano-tech	1400	3	15	115	128	21	20
Turnigy	1450	3	1	95	93	40	14
Zippy Flightmax	1500	3	20	138	100	34	18
Turnigy	1500	3	20	146	107	35	19
Turnigy	1500	3	25	132	80	34	25
Turnigy nano-tech	1500	3	25	124	87	34	21

Zippy Compact	1500	3	35	138	108	35	18
Zippy Compact	1500	3	25	113	106	14	35
Turnigy nano-tech	1500	3	35	129	88	34	21
Rhino	1550	3	30	136	91	33	21
Rhino	1550	3	20	129	91	34	20
Rhino	1550	3	25	137	95	35	22
Turnigy nano-tech	1600	3	25	143	120	34	18
Turnigy nano-tech	1600	3	25	143	120	34	18
Turnigy	1600	3	30	143	109	35	20
Turnigy	1600	3	20	137	106	35	19
Zippy K-Flightmax	1600	3	20	125	77	40	27
Zippy Flightmax	1600	3	20	122	102	35	17
Rhino	1750	3	30	155	93	33	22
Rhino	1750	3	25	158	95	35	25
Turnigy nano-tech	1800	3	25	161	115	35	21
Zippy	1800	3	20	153	102	36	20
Turnigy	1800	3	20	153	110	34	21
Zippy Compact	1800	3	35	155	108	34	20
Turnigy nano-tech	1800	3	20	148	105	20	35
Turnigy nano-tech	1800	3	65	180	103	35	25
Zippy Compact	1800	3	25	134	106	17	34
Zippy K-Flightmax	1800	3	20	168	115	35	25
Polyquest	1800	3	25	142	111	35	24
Turnigy nano-tech	1800	3	20	150	103	21	35
Turnigy	1800	3	30	152	106	35	21
Rhino	1850	3	40	177	111	34	20
Turnigy nano-tech	2000	3	15	155	126	21	29
Zippy Flightmax	2100	3	35	197	113	34	25
Rhino	2150	3	20	186	113	35	25
Rhino	2150	3	25	185	113	33	23
Rhino	2150	3	30	184	113	33	23
Turnigy	2200	3	30	197	104	34	24
Turnigy	2200	3	20	185	103	33	24
Turnigy nano-tech	2200	3	35	199	115	35	27
Turnigy nano-tech	2200	3	25	187	106	35	24
Zippy Flightmax	2200	3	20	180	102	37	24
Turnigy	2200	3	40	204	104	27	35
Zippy Flightmax	2200	3	25	173	104	36	25
Turnigy nano-tech	2200	3	45	201	112	36	26
Zippy compact	2200	3	25	163	107	21	34
Zippy Flightmax	2200	3	30	190	108	36	26

Turnigy	2200	3	25	188	105	33	24
Turnigy nano-tech	2200	3	35	199	113	34	25
Zippy Flightmax	2200	3	40	207	107	35	25
Turnigy nano-tech	2200	3	65	200	103	33	27
B-Grade	2200	3	30	195	105	35	26
Zippy Flightmax	2200	3	25	176	135	32	21
B-Grade	2200	3	20	190	105	35	25
Turnigy 9XR	2200	3	1.5	139	100	33	19
Zippy Compact	2200	3	35	181	114	34	21
Turnigy nano-tech	2250	3	65	207	104	35	27
Zippy Flightmax	2500	3	4	146	100	28	23
Turnigy nano-tech	2500	3	5	147	95	30	24
Turnigy nano-tech	2500	3	5	155	106	50	14
Zippy K-Flightmax	2500	3	20	195	113	35	33
Rhino	2620	3	3	160	102	30	26
Turnigy nano-tech	2650	3	25	215	148	44	18
Turnigy	2650	3	1	157	98	30	27
Turnigy nano-tech	2650	3	35	220	134	44	17
Turnigy	2650	3	30	247	140	44	19
B-Grade	2650	3	30	250	140	43	19
Zippy Compact	2700	3	25	203	137	15	44
Turnigy nano-tech	3000	3	25	231	150	43	17
Zippy Flightmax	3000	3	20	239	137	45	18
Turnigy nano-tech	3300	3	25	263	146	43	20
Turnigy nano-tech	3300	3	35	270	133	44	21
Turnigy nano-tech	3300	3	40	263.8	135	21	44
Turnigy nano-tech	3300	3	45	317	146	44	24
Turnigy nano-tech	3300	3	65	311	133	44	24
Turnigy nano-tech	6000	4	25	623	175	49	38
Zippy	8000	4	30	845	166	69	35
Turnigy nano-tech	5000	5	25	643	160	50	41
Turnigy	5000	5	20	666	149	48	42
Turnigy nano-tech	8000	5	25	924	194	45	47
Turnigy nano-tech A-Spec	2650	6	65	465	135	44	38
Turnigy nano-tech	2650	6	35	417	146	44	33
Turnigy	3000	6	20	487	137	42	36
Turnigy nano-tech	3300	6	35	522	136	44	43
Turnigy nano-tech	3300	6	25	489	145	53	37
Turnigy nano-tech A-Spec	4000	6	65	689	155	48	44
Turnigy nano-tech	5000	6	25	769	163	49	48

Zippy Flightmax	5000	6	25	772	143	50	51
Turnigy	5000	6	30	805	145	50	50
Turnigy nano-tech	5000	6	35	786	154	50	49
Turnigy nano-tech	5000	6	45	813	157	49	50
Turnigy	5000	6	20	793	152	50	51
Zippy Flightmax	5000	6	20	754	145	52	50
Turnigy nano-tech	5000	6	65	844	153	49	55
Turnigy nano-tech	6000	6	25	908	167	49	55
Zippy Compact	5800	7	25	913	160	46	57
Turnigy	3300	3	30	297	137	43	22
Turnigy nano-tech	4000	3	25	333	173	49	20
Turnigy nano-tech	4000	3	40	321	136	25	43
Turnigy nano-tech	4000	3	35	335	152	49	21
Zippy Flightmax	4000	3	20	306	146	51	22
turnigy	4000	3	30	347	144	50	22
Turnigy	4000	3	20	337	151	50	21
Turnigy nano-tech	4500	3	25	361	169	49	23
Turnigy	5000	3	20	412	145	49	26
Turnigy nano-tech	5000	3	35	409	150	49	26
Turnigy	5000	3	40	836	150	49	52
Turnigy nano-tech	5000	3	65	442	152	49	28
Turnigy nano-tech	5000	3	40	404.2	154	27	44
Zippy Compact	5000	3	25	354	162	21	46
Turnigy nano-tech	5000	3	45	425	150	48	27
Turnigy	5000	3	25	412	146	50	25
Turnigy nano-tech	6000	3	25	481	172	48	28
Zippy Flightmax	500	4	20	469	143	51	33
Turnigy nano-tech	850	4	45	99	56	31	33
Turnigy nano-tech	850	4	25	94	56	30	31
Turnigy	1000	4	30	121	75	34	24
Turnigy nano-tech	1000	4	45	124	73	25	35
Zippy Compact	1000	4	25	105	76	20	35
Turnigy	1300	4	30	157	78	34	32
Zippy Compact	1600	4	25	152	108	34	20
Zippy compact	1800	4	35	205	108	34	29
Turnigy	1800	4	25	207	117	36	28
Turnigy nano-tech	2200	4	25	239	119	35	32
Turnigy nano-tech	2200	4	35	253	117	36	35
Zippy compact	2200	4	25	210	107	28	34
Turnigy nano-tech	2200	4	45	257	109	35	33
Zippy Flightmax	2200	4	40	250	105	35	30

Turnigy	2200	4	35	257	113	34	33
Turnigy nano-tech	2250	4	65	268	103	35	36
Zippy Compact	2450	4	35	265	114	34	32
Turnigy nano-tech	2650	4	25	275	145	44	22
Turnigy nano-tech	2650	4	35	291	145	45	22
Turnigy nano-tech	2700	4	65	332	134	44	27
Zippy compact	2700	4	25	265	137	44	20
turnigy	3000	4	20	337	138	44	27
Zippy Flightmax	3000	4	20	313	139	46	25
Turnigy nano-tech	3000	4	25	299	150	45	24
Turnigy nano-tech	3300	4	25	337	147	44	26
Turnigy nano-tech	3300	4	35	361	145	45	26
turnigy	3300	4	30	385	137	43	30
Turnigy nano-tech	4000	4	25	433	173	48	26
Turnigy nano-tech	4000	4	35	427	155	49	27
Turnigy nano-tech	4000	4	45	485	168	49	29
Turnigy nano-tech	4500	4	25	467	173	49	29
Turnigy	5000	4	20	528	139	45	44
Turnigy nano-tech	5000	4	35	531	154	50	33
Turnigy nano-tech	5000	4	45	585	166	50	37
turnigy	5000	4	20	536	148	49	33

APPENDIX F: DATABASE OF COMMUNICATION UNITS

Unit	Freq Min (GHz)	Freq Max (GHz)	Receive Sensitivity (dBm)	rate [Mbps]	Transmit Power (dBm)	Weight (g)	current max (mA)	Min voltage DC	Max voltage DC	Max Power
Xbee Wi-Fi	2.4	2.5	-97	2	15	8	260	3.1	3.6	936
Xbee-PRO ZB	2.4	2.4	-102	0.2500	18	8	205	3	3.4	697
Xbee-PRO 900 HP	0.902	0.928	-110	0.2000	24	8	215	2.1	3.6	774
Xbee-PRO 900	0.9	0.9	-100	0.1560	17	3	210	3	3.6	756
Xbee DigiMesh 2.4	2.4	2.4	-92	0.2500	0	8	50	2.8	3.4	170
Xbee-PRO DigiMesh 2.4	2.4	2.4	-100	0.2500	18	8	340	2.8	3.4	1156
HY-RT56 - 433 (receiver and transmitter separate)	0.43392	0.43392	-108	0.0100	10	2.4	3	1.8	3.6	10.8
HYRM64	0.433	0.433	-110	0.00120	10	0.9	2.6	1.8	3.6	9.36
HYRM69S2	0.29	1.02	-120	0.00120	13	0.9	16	1.8	3.6	57.6
HYRM22B	0.43392	0.43392	-121	0.2560	20	0.8	18.5	1.8	3.6	66.6
Wixel CC 2511F32	2.4	2.4835	-103	0.3500	1	3.2	30	3	3.6	108
500S RF module	0.4	0.47	-123	1.2000	17	20	40	3	5	200
Xtend RF module	0.902	0.928	-110	0.1152	30	18	730	2.8	5	3650
Xbee-PRO DigiMesh 900	0.9	0.9	-100	0.1560	17	8	210	2.8	3.4	714
Xbee-PRO XSC (S3)	0.902	0.928	-106	0.0100	20	8	265	2.1	3.6	954
Xbee-PRO XSC (S3B)	0.902	0.928	-109	0.0200	24	8	215	2.1	3.6	774
Xbee 802.15.4	2.4	2.4	-92	0.2500	0	3	35	2.8	3.4	119
Xbee-PRO 802.15.4	2.4	2.4	-100	0.2500	18	3	215	2.8	3.4	731
Xbee ZB SMT	2.4	2.4	-100	0.2500	5	4	59	2.1	3.6	212.4
Xbee-PRO ZB SMT	2.4	2.4	-102	0.2500	18	4	114	2.7	3.6	410.4
HYRM69HS2	0.29	1.02	-120	0.0012	20	0.9	16	1.8	3.6	57.6
HYRT50	0.24	0.96	-121	0.2560	20	0.7	85	0.9	3.6	306

APPENDIX G: QUAD-ROTOR AND FLAPPING WING PLATFORMS STRUCTURAL WEIGHT ESTIMATION

<u>Quad-rotor platforms:</u>

Other Contributor: Pierre Valdez, Graduate Research Assistant, ASDL, GT

Schematic Dimensions:

- Frame:

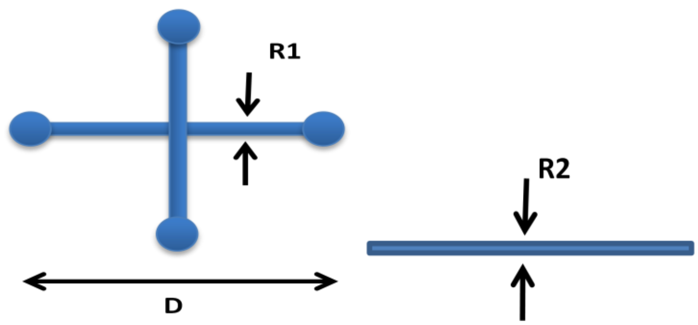


Figure 125: Quad-rotor – a. Top View; b. Side View

- Sensors/Payload:

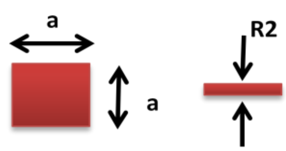


Figure 126: Sensors/Payload - a. Top View; b. Side view

- Complete:

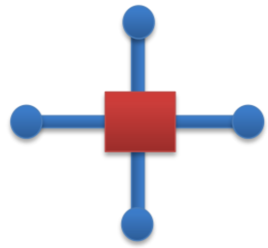


Figure 127: Complete Platform - Top View

From above dimension designations, the volume will be:

Equation 38: Quad-rotor Platform Volume

$$\boldsymbol{V = 2 * D * R1 * R2 + a * a * R2}$$

Relationships were obtained for R1/D, R2/D using the following existing quad-rotors' specifications of different materials:

- ASDL Quad (in-house built) – Aluminum
- GTAR Quad 'Pelican' – Carbon Fiber [207]

Then relationships were obtained for a/D, using GTAR Quad 'Pelican'. With relationships determined, the structural volume can be estimated for quad-rotors of diameters between 0.05m to 2.0m. Finally, the weight can be obtained using respective material's density values, as shown in Figure 128.

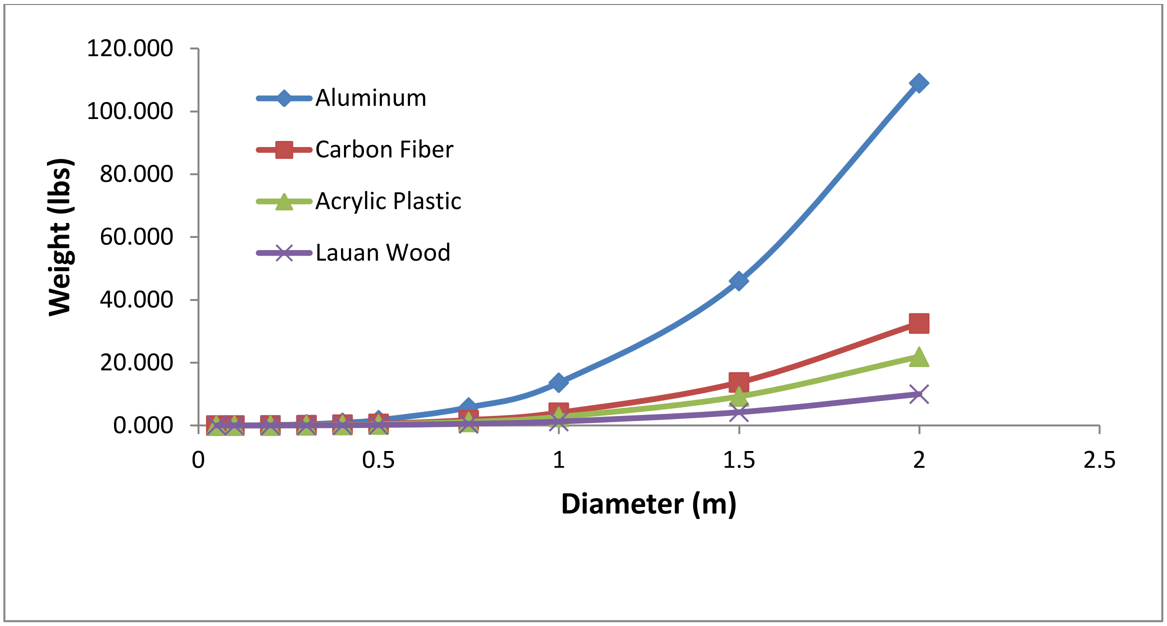


Figure 128: Quad-rotor Platforms - Structural Weight Estimation

Flapping platforms:

Other Contributor: Arun Ramamurthy, Graduate Research Assistant, ASDL, GT

Schematic Dimensions:

- Frame – based on ASDL flapping wing platform:

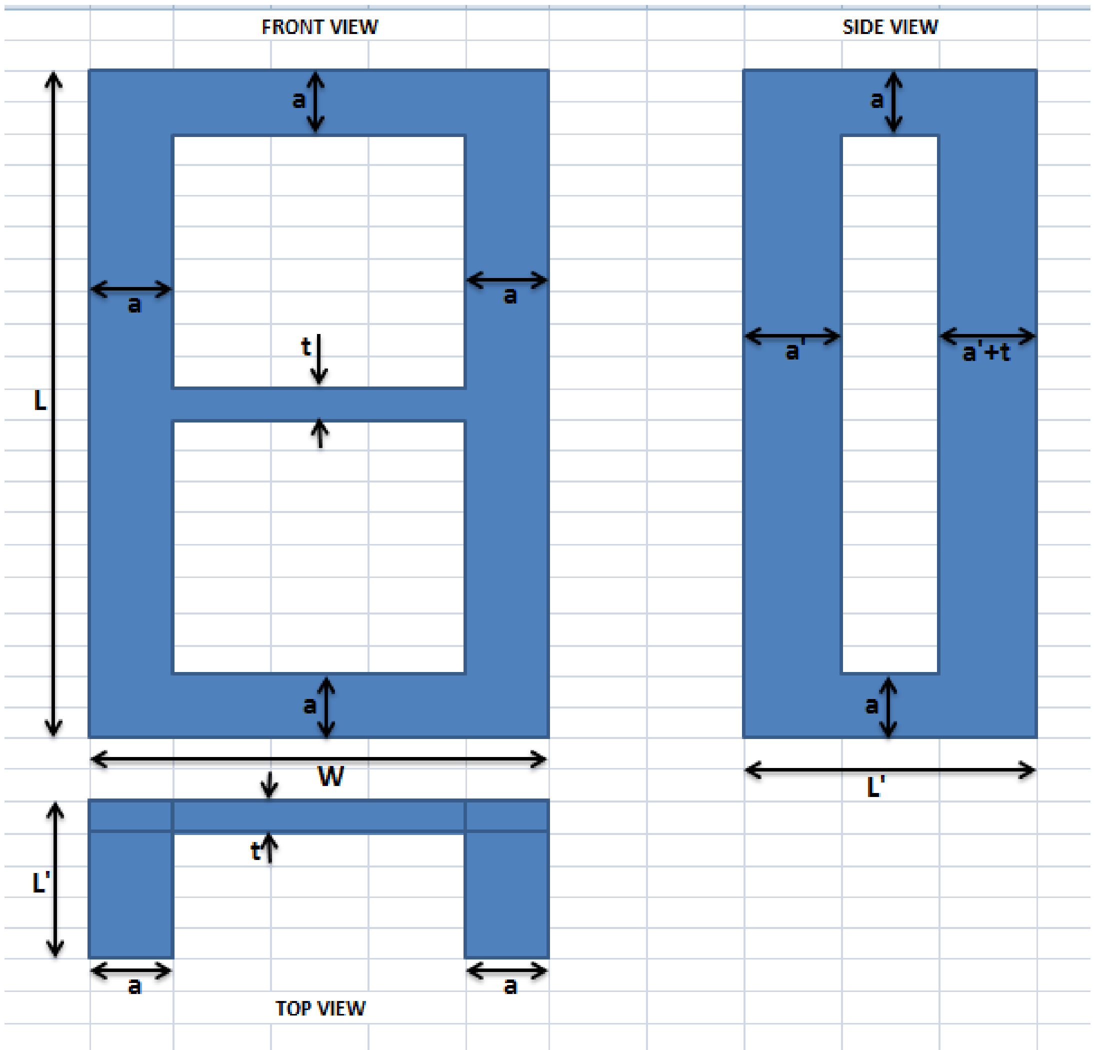


Figure 129: Flapping–Wing – Top, Front, Side Views

From the above dimension designations, relationships were obtained for a, a', and t using the dimensions of ASDL flapping. The relationships are assumed to hold for different materials. Using these relationships, volume can now be determined for flapping wing vehicles of different wingspans ranging between 0.015m to 0.6m. Finally, the weight can be obtained by using respective material density values.

The values are plotted in Figure 130.

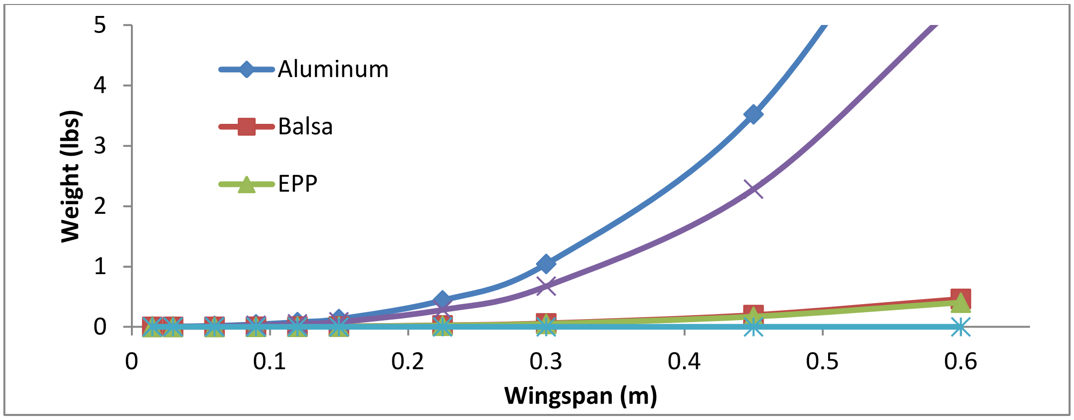


Figure 130: Flapping Wing Platforms - Structural Weight Estimation

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VITA

Zohaib Tariq Mian was born in Lahore, Pakistan to Tariq Ismail and Saira Tariq on November 13, 1985. He grew up in several different cities in Pakistan and Middle East, making him a traveler and a cosmopolitan person from the beginning. He graduated as a class Valedictorian from ISG-Dammam High School in 2004 and enrolled in Department of Aerospace Engineering in Middle East Technical University in Ankara, Turkey. Being an avid practitioner of mixed martial arts, Zohaib joined the university's karate competition team - ODTU Karate, and actively participated in martial arts competitions. In his senior year, he led a team of about 20 students for design, build and fly competition. In 2008, he graduated with Bachelor of Science degree in aerospace engineering, along with a minor in production engineering.

Upon graduation, Zohaib continued his globetrotting lifestyle and enrolled at Georgia Tech as a graduate research assistant and student at Aerospace Systems Design Laboratory. His primary research focused on development of micro unmanned and autonomous vehicles, and led him to opportunities such as his stint at Army Research Laboratory to design a pressurized structure unmanned aerial vehicle.

Zohaib's other professional interests include motorsports and race car engineering, where he enjoys applying aerospace grade knowledge to enhancing the performance of road vehicles.

Zohaib looks forward to an exciting career of working in the realm of high performance machines and aims to establish his own technology firm. He is also hopes to contribute to furthering education and technology in his native land of Pakistan.