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CHAPTER ONE

INTRODUCTION

1.1 Introduction

Interactive technology is focuses on direct human interaction with computer systems. Basically, the touch screen with multi touch features is simple interactive methodology that makes the gap between human and computer less than ever. The main concern in interactive input / output devices is to replace the conventional computer I/O devices by direct human commanding; like voice, touch, or body language. The interactive writing boards become a hot area of research in addition to its large scale of use in the market [1]. For example, around 1000 interactive board were sold in Jordan market during 2012 [2].

Interactive boards in modern technology replaces the conventional whiteboards with a lot of advantages; there is no ink, so, it's clean and green; the use of ink for whiteboards causes healthy effects in addition to many environmental effects. In addition, the interactive boards are smart in such a way it enables to use full computer features on class board. Figure (1.1) shows a sample interactive board that is capable to be used for writing using pen, or data show presentation, or even both in the same time. The interactive boards could be considered as large touch screens of a computer [1] [3].

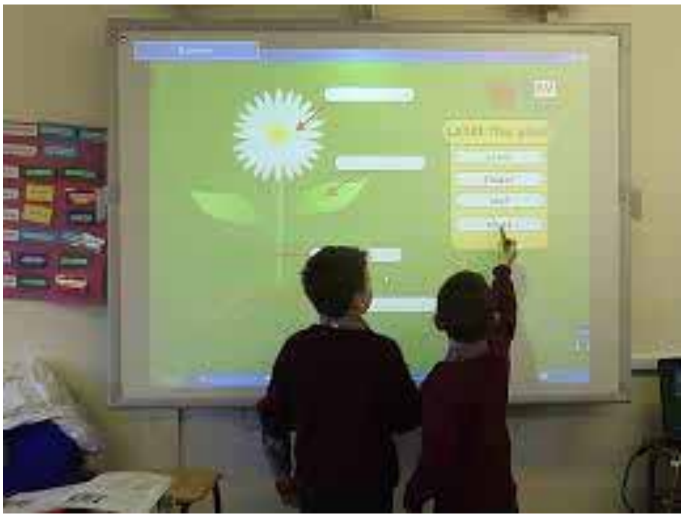

Fig. 1.1: An interactive board [4]

In general the whiteboards are divided into two categories; active and passive boards. The user is able to write using his / her finger or any pointing tool in the case of active boards, while in passive interactive boards, a dedicated pen is designed to write and to point on the board. The advantage of passive board over the active one is that, the passive board are very simple and don't has any electronic structure, thus, no maintenance needed, no calibration, and the output resolution is more controllable and could be relatively high [5].

The interactive boards are being used in education, class rooms, presentation and training rooms, studios, and other applications. Where the user are pointing directly to the board in order to write or perform a mouse event. In presentations, the instructor or presenter are moving inside the room, but when he / she needs to perform any action on the board he / she should return back near the board and directly click on it. Some actions that the user do frequently is not writing, but scroll, tick or click [1] [6].

The interactive boards nowadays implement many physical and engineering concepts to get the location of the pointer coordinates with respect to the board. Ultrasonic and resistive are older technologies; infrared and vision based are the mostly widely used technologies that falls under research at this time. This thesis presents a MEMS (Micro Electro Mechanical Systems) interactive pointing in 3D with respect to an interactive white board. This is basically the adaptation of MEMS sensors to measure the free space 3D location of mouse pointer absolutely. The MEMS motion sensor falls under emergent researches that suspected to make revolutions in the area of interactive boards and interactive technology [6].

In order to perform the mouse events in 3D space with high reliability, all of them will be used in this thesis; accelerometer, gyroscope, and magnetometer. The core unit of the proposed system is 9-axes MEMS motion sensing device. The concept of nine axes is that, there are different measurements with respect to either axis of motion or the measurement type itself. Three axes accelerometer enables to measure the translation of the target in 3D space, three axes gyroscope returns instantaneous angular rotation in 3D space, and the magnetic field of the Earth is capable to be measured using three axes magnetometer. Thus, the total is 9-axes motion sensing.

With respect to interactive boards, the writing pen could be represented as mouse pointer in either 2D or 3D. To calibrate the writing pen with PC software mouse pointer the 3D localization sensors should measure the 3D coordinate of the pen and calibrate it with the computer screen parameters, and interface it with the PC.

To measure the mouse motion in 3D space, this thesis presents relative and absolute motion detection, the relative done via six degree of freedom motion measurement by the use of accelerometer and gyroscope to measure the relative translation and rotation. The 3-axes magnetometer will be adopted in this thesis to measure the absolute referencing of the frame of reference, in addition to calibrating the interactive board.

Interactive board calibration is the process that used to determine the frame of the board or the area of display with respect to touch. This task is done by a procedure that displays a reference points on the screen and command the user to touch these points successively. The calibration program measure the relative geometry between the calibration points and set the border outline dimensions of the screen.

By concept, the motion measurement could be done with respect to different variables, where those are expressed as axes. The measurement axes could be physical motion axes in space or another physical axes that could be used as measuring variable that are capable to be manipulated to measure some motion properties[7].

The motion sensing principles that involved in this thesis are three types that would enable to measure the desired relative motion, proper speed, and other physical parameters in a relative space. The involved sensors are [7]:

- Accelerometer
- Gyroscope
- Magnetometer

The accelerometers are devices that specially designed to measure the linear translational motion of an object in terms of it linear acceleration. The gyroscopes are very meticulous devices are being designed in order to measure the angular motion in terms of angular speed. While the magnetometer measures the vector components of the Earth magnetic field [8].

From large mechanical device to an integrated circuits (IC), the motion sensors where adapted through decades. The nano-technology enables to build the accelerometer, gyroscope, magnetometer, and others in small chips. That part of the nano-technology is known as MEMS which regards to Micro (or Micro Machined) Electro Mechanical Systems [8].

The rise of MEMS technology makes a high contribution on those devices making them available in constrained embedded systems. Nowadays, gyroscope, accelerometer, and magnetometers become available in consumer electronics like mobile phone. The evolution of MEMS opens new research based on motion sensors in embedded systems [9].

1.2 Motivation

Interactive boards are big displays that transfer the computer screen on a large whiteboard via data show projector. The size of interactive board varies from few inches to hundreds of inches. As normal white boards, the presenter or instructor should be close to the board when writing on it, while he / she move inside the room during the lecture or meeting. The reason that force the instructor or presenter to be close to the board is that, the sensing devices that sense the pen or pointer location are two dimensional sensors. It's two dimensional sensors by the means of its scale, where the pointer should be close to the board to be sensed and it’s localized. Thus, the localization is done in two dimensional scopes (i.e. plane) only. This comes from the fact that, the most interactive white boards use sensors placed on the board itself. It could be mounted cameras on the board corners, IR detectors, ultrasonic receivers placed on predefined line on the board, or such.

When the presenter or instructor moves away from screen, many tasks he / she could do while moving away. There shouldn't be a need to get back to the board in order to do some simple and repetitive functions, like sliding. In traditional data show screens, a laser pointer is being used to point on the screen while the presenter is away. In addition, a pointer with control keys is being used with very simple functionality that is to control sliding forward and backward only.

When scrolling the presentation slides - for example - the user should be close to the board, while he / she almost need to stay away. This makes a need to invent a solution for the user; it should not be the traditional presentation wireless pointer. Conventional pointer are a wireless keys with laser pointer, it enables to slide on and back. The interactive technology should try to solve this problem [1] [3] [6].

To enable user input out of the plane, a three dimensional scope should be introduced. When moving inside an indoor area, free space input device should be used. Modern researches were involved in implementing three dimensional input devices for personal computer applications. The most modern and efficient researches will be discussed in chapter two. Those researches generally are specified for specific application with many limitations and constraints. This induce to keep going in that field to present novel researches in the field of interactive technology in general, and in the field of three dimensional interaction with interactive devices in different applications and generalized forms.

Another issue - rather than sliding-, the user needs to tick a checking box, or press a button while he moves around in the class room, ticking are shown in figure (1.2). This couldn't be achieved using the wireless pointer that is commonly used in slide show scrolling with laser pointing.

Fig. 1.2: ticking event [MS-Windows pictures]

KETAB Technologies Inc. is a Jordanian entrepreneur company working in interactive board's technology and educational supplies, while their market is Middle East. KETAB's market analysis strongly recommends starting researches to solve these problems. Hence, the interactive technology aims to make the computer system more life realistic, more reliable, and more friendly, such problems should be solved even though it do not considered as simple problem that could be implemented in classical way.

The companies that work in interactive technology like KETAB Technologies, and others, are continuously pushes the researchers to start researches in the advances of interactive technology. Those researches are either new solution of existed problems, or optimizations of current solutions. This thesis presents a novel research for interactive board technology interaction that is specialized in input device to make it more user satisfactory, generalized, and optimized.

The researches that concerns interactive technology in either two dimensions or three dimensions is not consider the modern motion sensors. The rise of MEMS based relative motion sensing will definitely assists in advances of space motion measurements in interactive technology in either output or input devices.

1.3 Problem Statement

The motivation of this research was started from the needs and problems of the current interactive screens, boards, and technology tools. The main events that the user needs to perform while he / she is locating away from the screen are:

- Ticking
- Scrolling
- Clicking
- Sliding
- Pointing

The creative solution of such problems needs three dimensional mouse events without mouse hovering. While the user entertains with the interactive board normal pen close to the board, he / she needs to make that pen realistic in 3D while moving away from the board. To implement such system, measurement of motion in 3D space should be contributed in reliable and efficient methodology resulting of a meaningful sensing or measurement that can be processed to localize the location of user's hand in order to move the mouse cursor into board coordinate that is relative to the user's hand, assuming that the user catches a device in his / her hand. Calibration of the board with respect to the contributed device is necessary.

While some researches try to solve the 3D mouse issues, the methodologies of those researches were concerns an ultrasonic triangulation, infrared triangulation, and multi-vision systems in most.

In fact, the resolution of such device is critical issue, in addition to size, and cost. The most practically applied researches on 3D mouse, uses conventional techniques that have many constraints and many disadvantages. The most known 3D air bat - SMK Link Electronics - are based on ultrasonic triangulation principle. But as it is scientifically known, the resolution of ultrasound triangulation is not proper for such technology usage, it has very bad resolution while working in standard common display area (i.e. 48" - 99"), further of working in large display size (i.e. more than 99" diagonal).In addition, the ultrasound transmitters / receivers are highly affected able by any ultrasound source that speaking around and power angry with respect to embedded systems scale [10].

The common three dimensional mice, are commonly known as bats, wands or flying mice, and those are almost three degree of freedom and uses either ultrasound triangulation (like SMK Link Electronics gyration mouse) or infrared (IR) range estimation (like Wii tracking mouse). The IR range estimation air mice have the same disadvantages of the ultrasonic mice, in addition to its higher cost and the affectability by high wavelength lighting [6] [10].

Another problem in such devices is that, the orientation of the device couldn't be accurate, the ultrasonic device transmits the sound in all directions and if it positioned in opposite direction of the board, it may be detected by the receivers due to reflections. This problem is common in IR devices, since, it is very noticeable in TV remote control devices (when the battery of the remote controller is good, the TV will receive the control key even though the remote controller are pointed out of the TV with 90^o degree, or even more). The orientation of the mouse device is important and the PC shouldn't recognize a mouse event unless the devices are pointing on the board or screen [6] [10].

The vision systems are very costly, and needs very heavy processing power, in addition to its large size with respect to consumer electronics scale, while this size could be avoided using other emerging technologies.

Also, the degree of freedom could be one problem of air gyration 3D input devices. Three degrees of freedom could measure the movement of the pointer in x-y coordinates, only 3DOF. The novel research that considers 3D input device should handles 6DOF. The question will be that, what is the need of 6DOF. The 6DOF is consists of three translational degrees of freedom, and three rotational degrees of freedom. The translational DOF's localizes the movement of the pointer where the rotational DOF's detects the orientation of the pointer; in addition, it is needed for substitutions of translational motion drift errors.

So, this thesis aims to contribute a 3D air gyration device that generates mouse events in 3D space with high resolution cursor localization and accurate orientation detection. The motion detection in 3D space is assumed to be 6DoF via MEMS motion detection device.

The MEMS motion sensors ensure high reliability design in terms of cost, performance, size, power, accuracy, and tolerance.

1.4 Contribution and Objectives

The last two sections, "Motivation” and "Problem Statement”, presents the market needs and the recommendations plus problems that lead to start this research. So, the objectives of this research are the following:

1) To study, design, and implement MEMS motion sensors in order to measure the 6DoF motion of an air flying device. This flying device represents an input device for personal computer to simulate the performance of conventional mouse.
2) To implement a significant resolution algorithm that process the MEMS motion sensors and localize the mouse pointer position. The MEMS output is a relative physical variables data that represents proper linear acceleration, proper angular speed, and the magnetic field measurement.

3) To develop and implement orientation measurement algorithm via MEMS motion sensors.
4) To develop and implement a wireless mouse data communication to communicate between the 6DOF input device and the computer.
5) To develop a mouse driver on PC. This driver is based on USB communication protocol.
6) To develop and implement tick, scroll, and click mouse events, while those events are the most needed for the user while he / she is rooming inside the presentation hall.
7) To develop a screen / board calibration program to calibrate the flying air gyro mouse.

The goals of this thesis will be achieved with contributions. The methodology contains many contributions in the interactive technology. Those contributions could be summarized as the following:

1) The use of MEMS motion sensors (Accelerometer, Gyroscope, and Magnetometer) in order to detect the free three dimensional space mouse device movements.
2) The six degree of freedom motion detection will be available now by the means of gyroscope angular rotation measurement and accelerometer linear translation measurement.
3) The frame of reference is capable to be determined by implementing an algorithm to process the data of the 3-axes magnetometer.
4) To develop a board / screen calibration algorithm that works properly with the contributed 6DOF free air model

These contributions on interactive displays technology are expected to change the way the technology going on and add a new scope of reliable, efficient, small size, light weight, and cost efficient absolute coordinates mouse controlling device in three dimensional spaces. The use of MEMS in interactive boards to measure 3D free space running is a complex methodology because of the drifts and errors in micromechanical parts that the MEMS motion sensors depends on, so, getting position localization on this thesis represent a novel contribution.

This thesis will demonstrates these contributions and open a wide discussion and research area in that field.

1.5 Thesis Organization

This thesis is organized in seven core chapters. The chapters describe the complete work and the detailed thesis research.

The first chapter is an introduction to the thesis. It illustrates the thesis goal and the theory principle behind it. The motivation of the work and the scope of the research field are shown followed by the problem statements which shows the problem corners that is subjected to be solved. And the suggested solutions for the stated problems are presented in terms of the thesis goals. The contribution points are described significantly at the end of chapter.

Literal survey was made in the second chapter. It shows some most related researches. Those researches are related to this thesis work from one side at least. The selected related work could be related to this thesis either in algorithm, one or more goal, generalized system or sub-system, measurements and analysis, or such.

Theory behind the presented thesis research is shown in chapter three. The presented theory is related to all fields of this research, including physics, technology, and related considerations.

The fourth chapter presents the engineering system architecture; hardware and firmware components and hierarchy. The detailed hardware components are demonstrated and explained. The firmware architecture and programming techniques also presented, in addition to computer interface, and calibration.

The methodology of research illustrated in the fifth chapter. The research process, design considerations and strategies, implementation, and issues are discussed in this chapter.

The results that are shown in chapter six are concerning the estimation parameters, performance measurements, evaluation, and measurements. In addition to analysis of results and comparison with the most known and related researches that concerns on the same goals.

In chapter seven, the conclusions were discussed. The conclusions include important remarks on the research, in addition to suggestions for future works over the same research.

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CHAPTER TWO

RELATED WORKS

In **[11]** *Anand Bora, Abrar Chaapalgaonkar, and Vanita More* were presented an ultrasonic model for three dimensional air mice. The presented interactive model is three degree of freedom (3DOF), as that, the ultrasonic transmitter is considered to be single point in the geometric model, so, there is no way to measure the rotational angles of the motion. Thus, only translational motions was been considered. The main principle was the three dimensional space triangulation of ultrasound signal. The system was developed in terms of three ultrasonic receivers and one non-echo ultrasonic transmitter. The non-echo ultrasonic transmitter represents the mouse device itself. It continuously transmits a 40 KHz ultrasound waves that are received and sensed by the three receivers those are located on three corners of the computer screen. The processing core (i.e. an AVR microcontroller) was designed to receive the signal from the three ultrasonic receivers, process that signal, estimate the three dimensional space location of the transmitter point, and interface this location with the computer system. The first problem of this design is that the ultrasonic transmitter is power hungry device that is not suitable in the stand alone battery -based embedded system. Also, the analog circuit design of the ultrasonic receivers is complex and costly. And, the triangulation itself is not appropriate for the interactive technology due to its bad resolution and constrained display area. The selected 40 KHz frequency is industrial ultrasonic frequency range, so, it's conflict able with the surrounding environmental devices. The ultrasonic triangulation is very old in the military and navigation fields. But actually, it is hard and very constrained to embed and evolve it in the modern interactive technology. Even though, some computer gaming like "Wii" are based on the ultrasonic triangulation, but it comprises all problems that are exist in this paper. So, this thesis will not be based on the triangulation principles in any way, and the contributed methodology will overcome all described problems and contents.

In **[12]** *M. Cimolini* presented and IR based 3D space computer mouse. The triangulation principle is used in this paper, where six infrared signal receivers were implemented and placed on predefined points on the computer screen. The mouse pointer itself is designed to be an IR transmitting point. The brain of the system reads the IR receivers signals, process it, calculate the triangulation parameters and equations, and localize the 3D space location of the IR transmitter target. The location of IR target are then calibrated and converted to a cursor location of the mouse pointer on the screen. The calibration resolution that is used in this paper is not good (i.e. 2m x 3m x 2.5m), and this comes from the fact that, the resolution of IR triangulation is bad in indoor applications. The IR transmitter (as the ultrasonic) represents a single point in the geometry of the triangulation, thus, it is not possible to measure the rotational motion by this way. This limits the degree of freedom to 3DOF only, which are the translational motions. The use of six IR receivers improves the triangulation accuracy of calculations over the work of *[11]* where it implements only three ultrasonic receivers. The 3D space geometry calculations are more efficient when increase the number of reference points (i.e. IR receivers or ultrasonic receivers). The minimal number of receivers that could be used in3D triangulation is three receivers, each one represents a variable of the trigonometric equations that describe the transmitter location in the space, so, to solve an algebraic equation with three variables (i.e. each variable is the angle with respect to independent Cartesian axis) three equations are needed, as minimum. Each receiver generates an equation, so, the minimum number of receivers is three.

But the increasing number of receivers will increase the accuracy of calculations by substituting the error in each one with respect to other receivers.

Pietro Garofalo presented a motion analysis based on MEMS as Ph.D thesis in the University of Bologna **[13]**. The major of Pietro Garfalo is biomedical engineering, thus, the application of motion analysis on his thesis was human body and it rehabilitation tools. The relatedness of Pietro thesis with this presented thesis is the use of MEMS based motion (inertial) sensors, analysis of those sensors and generate algorithm for variable substitution. In addition, the aim of Pietro's Thesis is to avoid the limitations of literature methodologies of motion measurements that are mainly vision systems, tactile sensing, and the other used in medical and clinical applications, where that purpose is similar to this presented thesis purpose, to design new methodology of 3D input device to avoid the literature vision systems, tactile sensing, triangulation based systems and such, through the deployment of MEMS based motion sensors. To build his motion analysis protocol, Pietro used 3-axis gyroscope to measure the angular motion and 3-axis accelerometer to measure the translational motion in all directions. Also, the gyroscope data is used to substitute the drift of accelerometer tilting. The motion sensor's scheme is capable to analyze 6DOF motion of human body joints.

In **[14]** *A. Mannini and A.M. Sabatini* presented accelerometer implementation for human body motion activity. This paper is related to this thesis in the accelerometer implementation for interactive application, even though this application is related to human body physics. But the specs, requirements, problems, and implementation are very similar. This paper used on body MEMS accelerometer sensor, in order to build Hidden Markov Model (HMM) for machine learning. The accelerometer drifts are not substituted in that work and the whole accelerometer data are loaded to machine learning patterns. Machine learning can substitute and cancel a very small drifts and error, but to get high accuracy, external substitution is required, especially for tilting.

In **[15]***D. Roetenberg, H. Luinge, and P. Slycke* presented a six degree of freedom (6DOF) MEMS based system, with the application of human body motion tracking. A sensors' data fusion algorithm processes the collected data from different distributed accelerometers, and estimates model for motion events. The motion sensors are based on all of them; 3-axes accelerometer to measure the translational movements, 3-axes gyroscope to measure the free space rotational motion in addition, and 3-axes digital compass (magnetometer) to reference the direction of motion with respect to ground geographic orientation axes. This principle is near to the principle of the presented thesis, where a 9-axes MEMS sensor model is being used and the 9-axis data are processed, thus, final decision making process will be triggered. In fact, that paper is present different motions measurements to establish in the whole system 6DoF motion tracking. Whereas this thesis develops a point tracking via the complete 9-axes measurement data processing in order to gets 6DOF motion tracking for a single geometric point.

The authors in **[16]** demonstrated an accelerometer implementation system to reconstruct motion. Motion reconstruction is very similar to this presented thesis goals, where in this thesis, accelerometer data is processed to reconstruct motion, and then process that reconstruction physically by dynamics principles to localize the pointer locations map. The literature paper used four to six 3-axes accelerometers to form motion of complex body (i.e. basic human body). Hence, large number of accelerometers is used; the substitution of drift and accelerometer systematic and non-systematic error was done for each accelerometer in terms of other accelerometers. This comes from the fact that, there is a predefined and known relation between the motions of the different joints of the body, so, the accelerometers already should follow constrained diagram. This makes the substitution of each accelerometer error and drift reliable without introducing other measurements. This approach is applicable only when dealing with predefined system with predefined motion scheme.

[17] The researchers in *University of Alberta* were aimed to develop three dimensional object interactions via mouse cursor. The authors depend on stereoscopy to build their principal approach. The stereoscopy is a three dimensional imaging techniques that are primarily based on dual camera based system. The computer vision system initially acquires images from the two imaging devices - or even reconstruct those images -, then process the input images in order to establish three dimensional data from them, which are related to depth perception of the free space. This technique was originally based on the virtual reality in order to realize the acquired depth information in real computer scene. This technique when applied in hardware requires very costly and large size system. Initially, two camera systems are very costly in hardware and due to its heavy load on the microprocessor, and also, the image acquisition hardware itself is a high cost device interface. In addition, the system brain should monitor a reference mouse pointer in 3D, this cursor should be very distinguishable than any other object in the vision space in order to avoid the wrong illusion of the scene. The main assumption of that research is to build a three dimensional system in order to estimate 3D mouse cursor that could be used in virtual reality processing. The principle is succeeded to proof the concept that was introduced in comparison with conventional two dimensional mice. But it was not really comparable with the most of other works, and specially this thesis work, due to its complexity, high cost, and heavy processing load.

A new computer mouse design was been presented by the design team of **[18]** in the *Shiraz University of medical Science*. Even though, the presented study in this literature is two dimensional, but it studied an important parameters that are helpful for the geometry of free air mouse. To meet the ergonomic principles and the functional parameters (i.e. movement time and response) this group design was improved and presented. This research stated that, the common computer mouse has many disadvantages on the user over long time of use. The problems that the usual mouse could cause include the musculoskeletal injuries, wrist deviation and such problems. The intended research stated that, some human pain may be small sensed and prolong for long time without clear reason is affecting the users who use the conventional mice for more than 20 hour per the weak. Those problems enhance the chance to work with three dimensional mouse, absolute mouse, and interactive technology that is presented in this thesis, hence the described problem are easily solved by the air flying mouse, and non-hovering mouse principles.

Comparison between the conventional two dimensional mice and the higher degree of freedom (DoF) - three dimensional mice was demonstrated in the **[19]**. This research studied one conventional 2D mouse, and three devices of 3DoF / 3 Dimensional space mice. This conducted study is related to the replacement of the two dimensional mouse with three dimensional one in 3D computer applications - specially, 3D desktop applications -. The three dimensional devices that were used in the study consists of three dimensional tracking ball which are 3DoF and expandable for higher DoF, regular mouse that includes a wheel on top of it in order to add one DoF, and the same 3DoF regular mouse with tilt capability to add another DoF level. This paper study shows that, in some study cases the higher degree of freedom mouse or input device is higher performance and efficiency, where in other cases it is less performance. The performance evaluation was basically the personal human usage, perception, and view point due to the different technologies of input devices. This test was not scientific, because of that, the study sample of human users was collected from field experts - drafts men for example - where those people are so professional in the use of the conventional 2D mouse to do their daily jobs. Thus, any new device needs more use experience to build the professionalism level that could be considered reasonable for scientific comparison. In addition, this paper studied pure input task, in the meaning of, the 3D devices. It was tested on pure 3D input tasks, and the 2D input device was tested on pure 2D input tasks. So, the result of the study in this paper has many limitations, where this thesis aims to avoid those constraints and invent a universal input device for both, 2D and 3D tasks.

Research **[20]** presented a model for computer input via natural human hand gesture. It introduces new hardware device with virtual reality based new software mouse cursor model. The mouse cursor model introduced was in the same human hand shape geometry. The hardware model is physical stress based sensing devices. Micro sensing elements placed on the main tips of the hand fingers to sense the hand pressure strength. In this structure, a space navigator was built to control the virtual motion in terms of pressure. The virtual motion means that, the user will touch the hardware input device model by his / her hand, and tries to move by pressing in that mode, the micro sensors will sense the pressure of the fingers press. The processing brain is intended to process the results of those micro sensors, and due to the on computer data fusion, the desired motion will be transferred to the invented model of the mouse pointer. The proposed system is a desktop input device for 3D computer tasks. It doesn't handle three dimensional space control of mouse. Thus, this model couldn't be adapted to be used in interactive technology or interactive white board. In addition, the measurement signals are resistance, which is processed to measure the pressure, then, the matrix of pressure signals will be processed in sensor's data fusion to measure the real controlled variables; motion direction and / or speed. In addition, the hardware implementation and calibration is costly. Another constraint of this system with respect to interactive technology is the hovering mouse implementation, where it measures the relative mouse movement, and no absolute referencing is used. The authors of this paper considered that, their model are universal for different interactive applications, but in fact - as they demonstrated - their model are very constraint and limited to some desktop virtual reality input task.

The paper of **[21]** introduces higher degree of freedom input model that grows up from the touch panel based screen. The main problem of that research is that, the rise of touch screen panels, and the growth of multi-touch panels induce to develop a modern techniques for 3D input tasks for computers. From that point, the authors introduce dual hand input scheme through dual multi-touch input pads, one separate service for each hand. This research is a trial to solve the gesturing, drafting, and virtual reality problem scope for desktop input task only.

The magnetometer was developed in the **[22]** paper for gesture interactive applications with mobile devices. The researchers in that paper presented a gesture control algorithm for mobile phone users and built a case study for music playing tool. Most of the modern mobile phone has embedded magnetometer inside it. So, the researchers depended on that magnetometer and used a ring that used with human finger, where the user moves that ring - through movement of his/her finger - to change the magnetic field around the digital compass magnetometer. The ring represents a target for 3D mouse while the embedded compass sense that ring and process its 3D data to determine the space location of the ring pointer. This work is capable to measure 3DoF motion, and it is specialized for mobile phones. Mobile phone means that, the area or working space of the pointer is small and very limited. While applying the same concept for large scale screens (e.g. 96" interactive board) will not be possible, due to the interference between the ferrite objects around or inside the working space, in addition to the bad reading resolution of the magnetometer itself. Thus, when trying to extend that principle for large scale space, more sensing elements and more measured variables should be manipulated in order to estimate the accurate controlled variables – that are the 3D Cartesian coordinates and 3D spherical coordinates - .

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CHAPTER THREE

THEORITICAL REVIEW

3.1 Interactive Technology and Smart Education

The advances that raised by the researches and continuous improvements in electronics, computer technology, and communications causes the way that human interacts with the machines to be more realistic, easier, and efficient. Those advances and continuous researches are changing the way of human lives to grow on toward the computerized systems. The term interactive technology is related to the technology that allows the user to interact with computer based devices and tools, including the multimedia devices, input devices, and displays [23][24].

The conventional computer system has a non-flexible input and user interface, like input switches or keyboard, sound alarms, etc. The pretty definition of computer work interaction could be done via touch, human-like voice, and movements, in addition to lighting. Since, the commercial implementation of touch screens in 1992, it considered the first interactive input / output device. The researches and development was continues to replace the most computer I/O devices with more human interactive replacements. The interactive technology is the realization of information technology integration to establish the vertical structures concatenate the technology with commerce, rather than searching about the product opportunities far away from the commercial structure [23] [25].

The last 5 years faced wide contributions interactive I/O and the consumer electronics market start to deal with such technologies as basic human life tools. It rose in interactive home appliances (i.e. specially in TV's), education, and multimedia space. The traditional TV's had been implemented in very tough basic input actions, starting from the input keys, and growing to remotely controlled keys. The interactive TV's or ITV's adds intelligence level with high technology data services to the conventional TV. The ITV's are interactive in inputs that are presented in terms of voice control, hand motion recognition, three dimensional remote pointers, interactive media center, and also, it includes interactive internet, shopping, online voting on the TV screen and much. An example of the quantum technology in interactive TV's output is the volume rise up and down according to the audience surrounding [6].

The interactive technology is a generalized term for interactive learning and interactive media, where those are the most common applications field of the interactive devices and tools. The interactive media supports the media contents like video, audio, text, games, and such. The interactive TVs are the most common applications of interactive media. Interactive gaming like WII and XBOX is also common interactive media in consumer electronics. The interactive gaming is large business scale in the last 10 years. The virtual reality and augmented reality are examples of the interactive media technology that has a history in researches, implementation, and development [6] [26] [27].

The interactive learning is the technology that incorporates the computer technology and the use of that technology in public environments, with the learning strategies and techniques, throw the interaction between human and the environment with respect to computer and information technology [27] [28].

In Dubai 2012, Muhammad Bin Rashid announces plan and program to apply the interactive learning technology in Dubai as generalized program. He defined the program goals as the integration of the modern learning processes and education systems with the technology. The plan includes the combination of technology tools and devices with the learning programs and supervisory role of instructors and parents in and outside the class rooms. His highness sheikh named the program smart learning program "SLP”. The SLP shows the importance of interactive technology and the role of modern efficient researches of that field in development of the future learning and education overall, rather than individual improvements of systems, like presentation tools[29] [30].

The interactive white board is an individual part of interactive learning technology that replaces the conventional white board that was being used for writing. The replacement involved two directions of interactions with computer; writing and pointing as input, and display as output [26] [28].

3.1.1 Interactive white boards

The interactive white boards are actually display screen that could be data show display area or flat screen (i.e. LED display, LCD, etc.). As the most handheld screens today implement a touch pad for input, the interactive white boards also implements the input capability as touch screens but with different principles. As the data show projector shows the projection of computer screen on a white board, it becomes real screen that interacts directly with the computer [24].

To build real interaction, an input is needed to replace the mouse of the computer, and may be, the keyboard. So, interactive white boards, implements the input device capabilities.

Thus, the categorizing, classifications, optimizations, and performance of the interactive white boards are functions of the input functionality in major.

Normally, the user could control the projected computer screen by the use of special electronic pen, or his finger. Since, 1991 different technology was introduced to implement the interactive white board input functionality. Some of those technologies stopped in its mile stone, some of them improved and developed, and some of them was canceled and died [24].

The interactive white boards are used mainly in the classrooms, presentations, demonstrations, studios, and others. In the white boards, no ink, so the user can write on the board without any side effects on his fingers or breath, and no need to physically erase the writing. Also, stylus may be used to implement dual input device that points on the computer interactive screen and writes on the board by chemical ink in the same time. Figure (3.1) shows a sample interactive white boards that is capable to use figures or any passive pointing element to point on it [31].

The display part of the interactive board is conventionally computer screen or data show projection area and the related technology to it is pure display technology. Whereas variety on the different boards categories is function of the input technology, and the most researches focus on the input devices, algorithm, and technologies.

According to the input strategy, the interactive boards are divided into active and passive boards. The passive boards are those have no electrical operation or functionality, it is pure passive material, while the interaction with computer is being done via pointing input device; electronic pen, mouse, etc. In contrast, the active boards implements the complete electronic functionality in the board itself and the input tool is passive (dummy) element. The electronic structure of the board is continuously sensing the touches on the board area, process it, and generates coordinates according to it.

The advantage of passive board over the active one is that, the passive board are very simple and don't has any electronic structure, thus, no maintenance needed, no calibration, and the output resolution is controllable and could be relatively high [5].

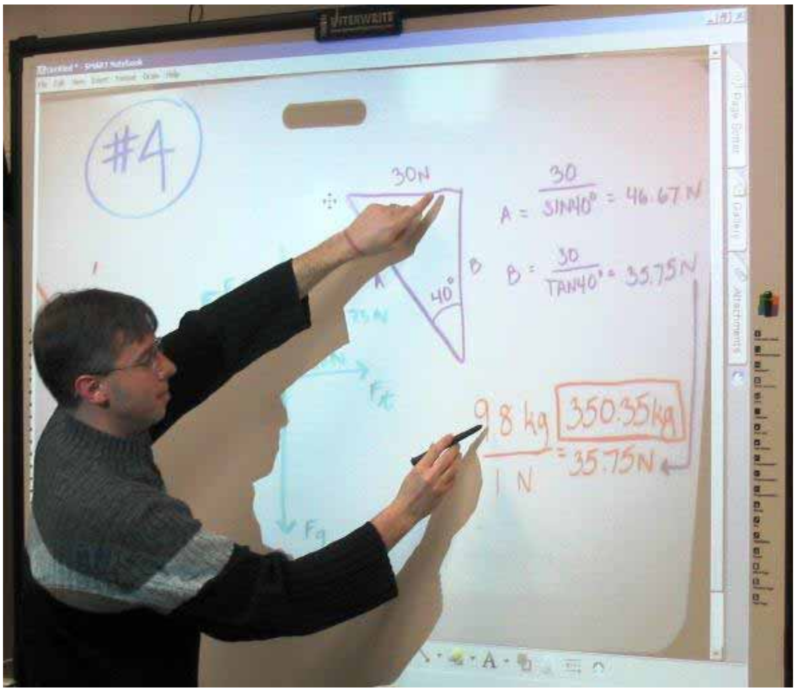


Fig. 3.1: Sample interactive white board in use [32]

Weather the board is active or passive; the device driver is running as human interface device (HID). The calibration of the board is the process that maps the input digital data to the screen resolution. The user has to calibrate the screen with the input tool at the installation process.

The keyboard functionality could be implemented in two methodologies; either by implementing an on-screen keyboard by the HID driver, or by implementing an inline optical character recognition to convert the life hand written to printed characters text. The optical character recognition is not as low level as to be implemented in the driver firmware, instead, it should be implemented in an intermediate application layer that mostly known as board agent [31].

3.1.2 Pointer localization in white boards

The interactive board nowadays improves many physical and engineering concepts to get the location of the pointer coordinates with respect to the board. Ultrasonic and resistive are older technologies; infrared and vision based are the mostly wide technologies that falls under research at this time [17].

When thinking about a defined point moving in 2D plan, the question is how to find its location. The localization could be determined by detecting the existence of the defined pointing head over specific coordinates of the plane could be categorized to:

- Infrared (IR) / Ultrasonic triangulation
- Vision based triangulation
- Infrared mesh grid scan
- Resistive touch
- Electromagnetic pen
- Dot patterns
- Some researches involves the MEMS, including this thesis

The triangulation principle is the oldest localization principle and it was used in military, ships, and different navigation applications. Figure (3.2) shows the 2D triangulation geometry. It basically consists of one wave transmitter and two receivers for that wave [11].

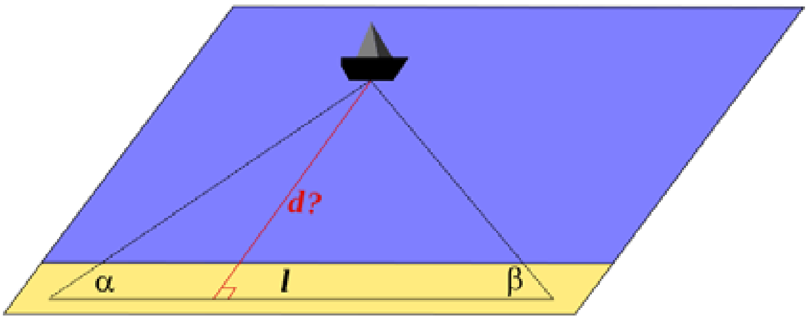


Fig. 3.2: 2D triangulation principle [33]

The transmitters are conventionally designed to transmit either infrared wave (IR) or non-echo ultrasound waves. The selection of those two types of signals was done based on their propagation characteristic, power, human and machine safety, and availability. But it could be implemented using any other waves that have good characteristics like LASER. Equation (3.1) illustrates how to calculate the triangle parameter in the triangulation process derived from figure (3.2).

$$\frac{1}{d} = \frac{1}{l} \cdot \left(\frac{1}{\tan\alpha} + \frac{1}{\tan\beta}\right) \tag{3.1}$$

When dealing with ultrasonic, non-echo ultrasonic generator should be used. That’s because the echo of the sound disturbs the receivers and conflicts the detection. Figure (3.3) shows how the echo affects the detection of the original transmitted waves. In addition, the ultrasonic waves are common in industry, and life electronics; the variety of ultrasonic products makes the system affect able the external signal sources, rather than the physical distortion of lower band of the ultrasound with audible signals.

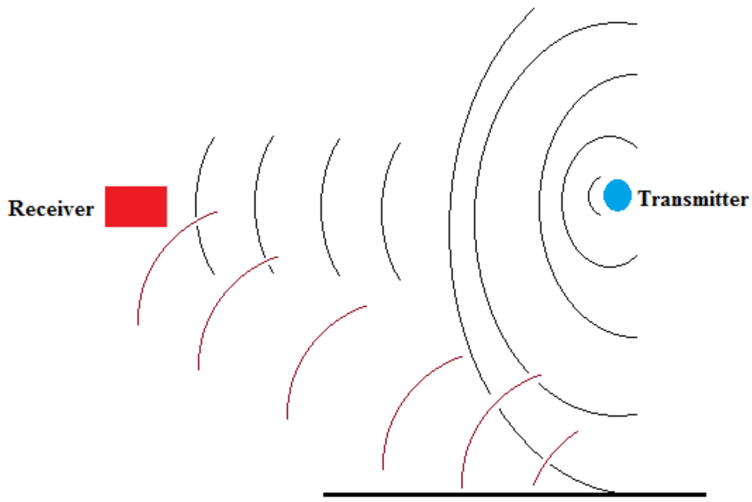


Fig. 3.3: Ultrasonic echo effect on triangulation; the black waves are the original, while the brown are the echo

The infrared has also bad characteristic that make it weak in such applications and especially in indoor environments. It easily could be distorted by other life product lightening, and has bad characteristics when has to reflect over glass, water or any transparent material [12].

Both, infrared and ultrasonic systems are power hungry devices. That's what makes it not so appropriate for most power limited or battery powered embedded applications. In addition, both are bad resolution of triangulation. The resolution comes bad as the area of interest becomes larger [11].

The triangulation is being implemented in white board as shown in figure (3.4). An electronic pen is designed to have only wave transmitter (either it is ultrasonic or infrared) with battery. And two receivers with fixed distance from each other are placed directly on the board with HID interface to the computer. When the user writes on the board using the electronic pen, the pen transmits the waves in all directions over the board plane. Then, the receivers receive the signal, input it to the processor, and the processing unit will estimate the relative location of the pen and interface it with the computer as mouse pointer location [12].

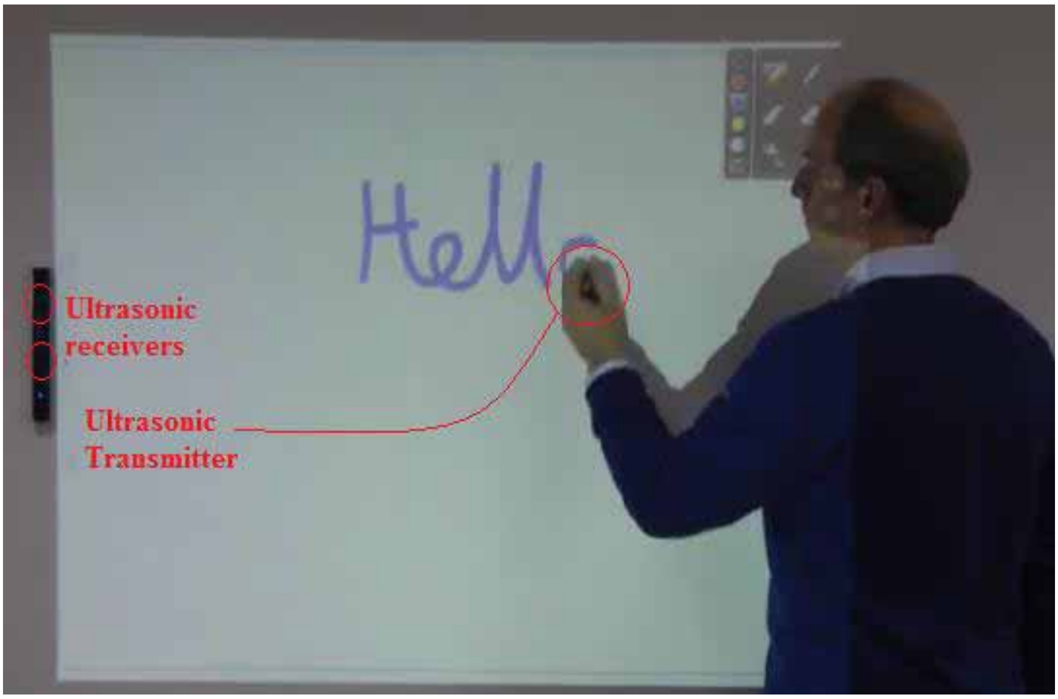


Fig. 3.4: Ultrasonic triangulation based interactive whiteboard [2]

The only two advantages of the triangulation based interactive white board are that; it is low cost and doesn't need any special structure on the board, while the receivers could be mounted on any flat surface considering it the board area.

The vision based triangulation is a similar principle of wave propagation triangulation. It's developed from two camera systems as receivers, but there is no transmitter any more. The two cameras are positioned and calibrated on two corners of the board. This enables them to detect any object that moves behind the board surface (behind means that the object is no longer as far as few millimeters). Then, any object could be used to touch the board surface; finger, pen, stylus, etc. The vision system detects the location of the pointer in each acquired image from the two camera systems. Then, the image processor triangulates the resulted location to get the relative x-y coordinates of the pointer.

The infrared mesh grid scan interactive board is completely different principle than the IR triangulation. In such, the board is active and the pointer is absolutely passive element. In such, a non-visible mesh is presented over the board area by large number of x-y aligned infrared transmitters, and infrared receivers are presented in the opposite direction of the transmitters. Figure (3.5) shows the non-visible IR mesh grid. The frame of the board is active with infrared devices, either transmitters or receivers, two sides of the frame are transmitters (representing corner of rectangle) while the opposite sides are receivers.

When no object comes across the path of infrared light, all receivers receive the light completely, but when the user puts his / her finger, pen, stylus, or any other pointing element near the board surface, the pointer will cut the path of the light and at least two rays will be cut; one in x-direction, and one in y-direction. The processor estimates the two cut rays to localize the relative pointer location on the board.

What is mostly known as touch screen is in fact the resistive panel. The resistive panel was introduced in many applications since 1991; computer systems, mobile phones, industrial fields, and such. The resistive touch screen is normal display that is covered with transparent touch panel. The touch panel is a membrane stretched material that is affected by pressure. So, when pressing in any point over that panel, two conducted plates will be conducted inducing a defined resistance. Thus, the processing unit processes the measured resistance to estimate the pressure point with respect to the panel origin.

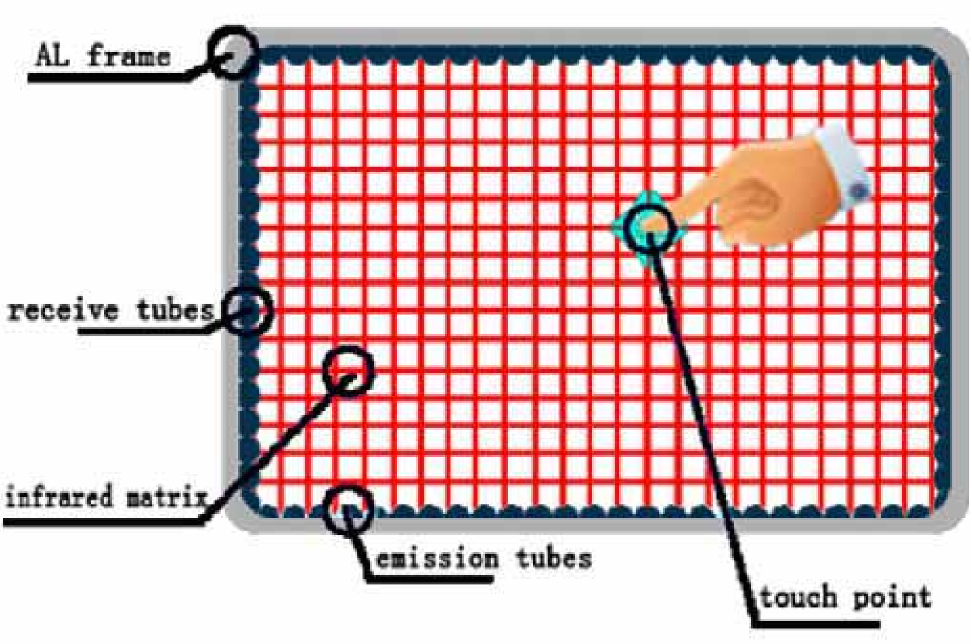


Fig. 3.5: IR interactive board mesh grid [34]

An old types of interactive white boards were been implemented using the resistive touch principle. The implementation of other interactive technologies causes the resistive board to obsolete, because of it comprises very large area of active electrical components, and weakness due to scratch, pressure, and the other hard user dealing, in addition to its high maintenance cost.

The magnetic interactive board is analogues to the resistive touch boards. It involved group of internal wires that carries magnetic field. Putting a ferrite pointer close to the board surface will induce the magnetic field and thus it will be changed. The processing is done in the way to estimate the magnetic field change; how much, and where. When putting the pointer behind the board, the magnetic field change will be different than when pressing the pointer to the board surface directly. This characteristic is useful to implement some important mouse events, such as hovering, and right click.

The problems that arises on the magnetic interactive board are the same that gotten in the resistive touch boards.

One of the common technologies in the market today is the dot pattern based interactive white boards. This technology is passive board technology that is based on micro-printed pattern on the board surface, and camera based electronic pen to recognize the dot pattern. The dot size is in tenth of micrometer scale, and that pattern represents coding for x-y coordinates, where each grid has its own dot code. The electronic pen system is structured form camera vision, where the camera lens is assembled in the head of the pen to capture the board surface directly when the pen is placed on the surface during the normal writing process. The processor catches the captured images, process it, analyze the dot pattern, and generate writing scheme. This methodology is used to store the hand writing on computer system [31].

Also, the dot pattern principle is applied in commercial applications. The most common example of it is the "Spoken Mus-haf" (i.e. المصحف الناطق). Figure (3.6) show a sample dot pattern.

The dot pattern resolution depends on the printing of the pattern and pattern encoding scheme, while the system performance is not depend only on the pattern, but most of performance criteria are related to the vision and processing system [31].

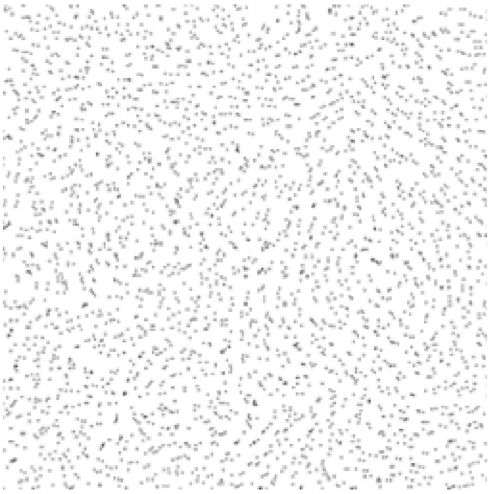


Fig. 3.6: Sample dot pattern

In recent, with the advances in nano technology and micro-machined electro mechanical systems (MEMS), some researches start to study the development of input method based on motion sensors. MEMS and motion sensors will be discussed in section 3.4. By theory, the MEMS based motion sensors implement the sensing of relative physical dynamic quantities measurements, where those devices are packaged in IC scale. Some researches study the adaptation of MEMS in 2D and 3D input devices. This thesis presents a MEMS based system for applications of 2D input in 3D space applications of interactive white boards.

3.1.3 Generalization of white board technology in other applications

The principle of interactive white board has been broadened in the smart education strategies. The smart education becomes wide and enveloping many technologies and techniques to integrate the modern high-tech education system.

The "Spoken Mus-haf" (i.e. المصحف الناطق), is a commercial example of the adaptation of interactive white board to different education scopes. The "Spoken Mus-haf" is simply a printed book with invisible dot pattern that is printed over the normal text language. A dedicated electronic pen is being used in the system with infrared camera that reads the dot pattern, process it, and play back record that reads the text (see figure (3.7)).

The technology of interactive board is not limited to white boards, large displays, and presentations. It is expandable to more daily life products like books, note pads, tablets, etc.

Fig. 3.7: Expansion of the interactive board technology to books [35]

The continuous development of interactive pointing tools leads the continuous development of variety of products that are part of interactive technology itself, but not white boards. The smart learning is rising from such large displays but it’s not limited to it. The broadening of continuous researches in technology also followed with emerging applications in life comes from the continuous researches in products development.

3.2 Motion Axes in Free Space

By concept, the motion measurement could be done with respect to different variables, where those variables are expressed as axes of the coordinate system. The Cartesian coordinates is the most common and well defined coordinate system. The spherical coordinates and cylindrical coordinates systems are common in solving complex physical problems. In physics, the coordinate's axis is virtual axis, and the origin could be defined relatively in each problem, there is no globe origin. The selection of appropriate coordinate system depends on the problem nature and the vector analysis in the domain space.

To measure motion, it should be referenced to predefined reference frame. Then, the motion origin is considered to be the reference frame origin, and all motions calculations are being done with respect to that relative origin. Physical quantities in motion analysis could be vector or scalar quantities, the vector quantity has value and direction, while the scalar has no direction; it only has a value. The speed, acceleration, distance, and momentum are example of vector quantities, while the mass is the most commonly known scalar quantity in rigid body's motion mechanical analysis.

Usually, when dealing with complex motion scheme, a general frame of reference could be set and describe all motions with respect to it. In such, all independent motions with respect to that frame are considered to be absolute motions in frame of reference, where the motion of particles with respect to each other in the same frame is defined as relative motion.

In relative mechanics, the proper velocity or celerity is relative to the observation frame in both, time and distance. In fact, the mass is not constant at old; the mass is changeable with its velocity. Equation (3.2) shows the mass equation with respect to speed, where “M” is the mass, “P” is the momentum, “t” time, and “a” is the proper acceleration.

$$M = a.\frac{dP}{dt} \tag{3.2}$$

Since, the motion sensors measures the motion parameters relatively with respect to its mounting frame and instantaneous motion, so, the measurements is being done in terms the proper velocity and proper acceleration. Where the mass that is designed in a physical structure to measure the motion (see section 3.4) runs in relative physics principles, so, the designer should get it into consideration. The proper acceleration is the companion of the proper velocity.

The measurement axes of motion could be physical motion axes in space or another physical axes that could be used as measuring variable that are capable to be manipulated to measure some motion properties[7]. The following axes are well known by concept:

- Linear translation with respect to Cartesian coordinates axes (x,y, and z)
- Angular rotation with respect to Cartesian coordinates axes (x,y, and z)
- Pressure
- Temperature
- Altitude with respect to see level
- Earth magnetic field

Working in Cartesian coordinates, the location of arbitrary point object in 3D space could be specified by x, y, and z coordinates of the object. When working with 3D objects (i.e. that have an x, y, and z non-zero dimensions) the x, y, z coordinates specifies the center location of the body but didn't offer any information about the orientation. To get the orientation descriptive way, angular coordinate's measurements should be introduced; those are θX, θY, and θZ.

In dynamics the number of independent parameters that defines the physical motion property of the frame or object with respect to the frame of reference as Degree of Freedom (DoF). The moving rigid body in space could has up to six degrees of freedom motion space; those are, three translational motion with respect to x, y, and z Cartesian coordinates, and three angular motion with respect to x, y, and z Cartesian coordinates, where each motion is a vector quantity that has a magnitude and direction. Figure (3.8) shows the six degree of possible motions for a single joint rigid body [8] [23].

The parameters that define the motion of a rigid body are the degrees of freedom (DoF). The three angular DoF of a rigid body in space rotations are commonly known as [23]:

- **Pitch**: it is the tilting in forward and backward directions as it is normally defined as rotation about y-axis - θY in figure (3.8)
- **Yaw**: it is rotating right and left as it is normally defined as rotation around z-axis - θZ in figure (3.8)
- **Roll**: the thirds pivot that completes the pitch and yaw rotations, so, it is the rotation about x-axis. - θX in figure (3.8)

The three angular degrees of freedom represent the possible motion of any rigid body around its center of mass without any translation. Where, the translational degree of freedom involves a motion in either Cartesian axis without any angular rotation. A combination of different DoF describes the kinematics of rigid object mechanical motion. In space, the maximum number of DoF that defines the physical rigid object is six, while those are three in 2D space.

Objects that has multiple joints comprises also six degree of freedom but with another physical definition that defines the moving ability of multi-joint systems; Degree of Mobility (DoM). The DoM of a mechanically linked object is the number of independent motions that is capable to do with respect to each other. Equation (3.3) illustrates how to calculate the DoM of multi-joint system, where each joint represents a movable connection point between two linked rigid objects [23] [9].

$$M = 6.n - \sum_{i=1}^{j}(6 - \mathrm{F}i) \quad (3.3)$$

Where,

n: number of moveable links

j: number of joints

Fi: DoF for each "i" joint

Figure (3.9) shows an object in 3D space, the location of the object could be calculated with respect to frame of reference origin as defined in the equations (3.4) in vector form. All analytical geometric operations will base on the equation (3.4).

$$\boldsymbol{R} = R.\cos(\theta x).\boldsymbol{i} + R.\cos(\theta y).\mathbf{j} + R.\cos(\theta z).\mathbf{k} \quad (3.4)$$

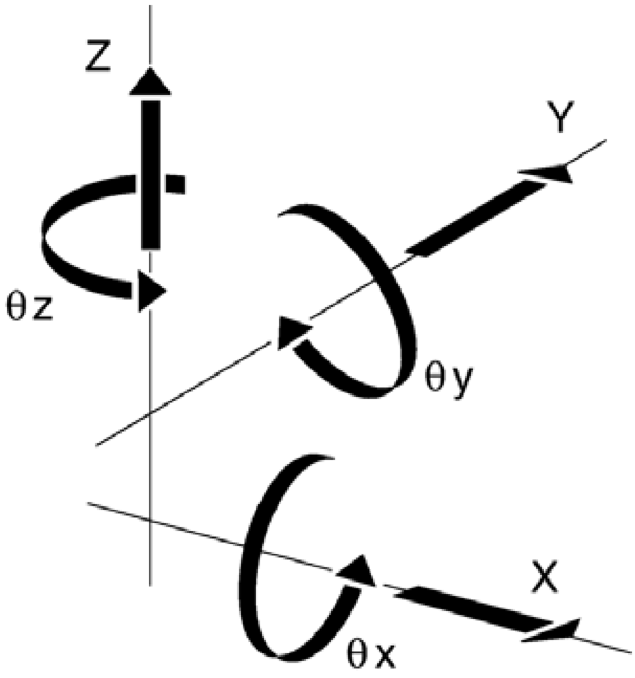


Fig. 3.8: DoF axes in Cartesian coordinates [36]

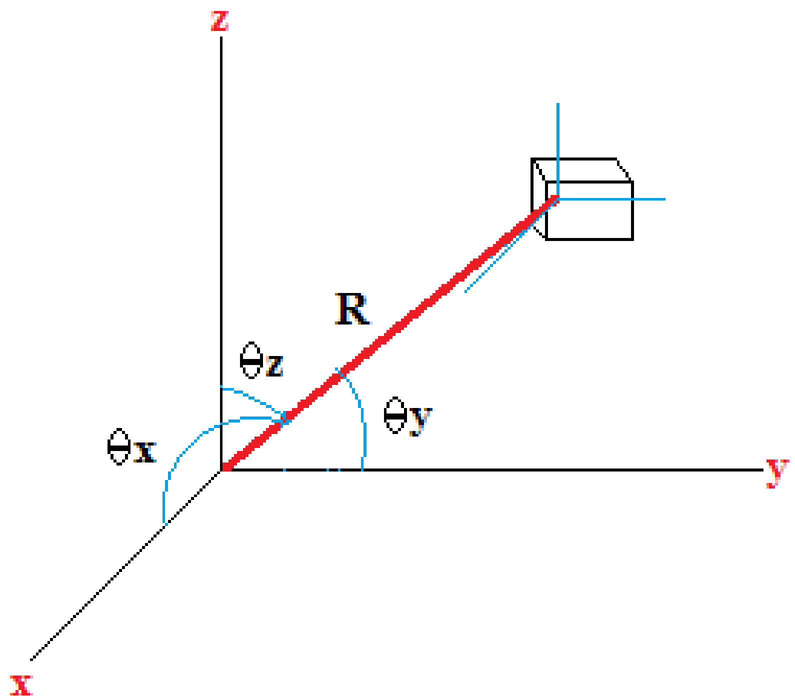


Fig. 3.9: Object location in 3D space

To localize the exact orientation of the object in figure (3.9) with respect to the origin of frame of reference, transformation matrix may be defined to define the rotational axis of the object.

3.3 Motion Measurements and Localization in 3D Space

The previous section shows the geometric and physical principles of motion in 3D space, while the section 3.1.2 presents an idea about how to localize an object in 3D space. In fact, the triangulation is the most common methodology to track moving object with a space. Section 3.1.2 shows the basic principle of triangulation. In fact, many techniques could be used in that methodology. The mostly known technique is to detect the location of ultrasonic transmitter that moves in plane. Instead of ultrasonic, infrared light, laser, electromagnetic waves, and such are also developed for such principle.

The triangulation by theory is to calculate geometric parameters by the use of trigonometry. The principle of receiving transmitted wave is one of the methods that used to localize the transmitting object. The radars differs in that, it transmits waves and receive the echo or reflection of that waves from the object.

Camera vision based systems use similar principles. Two cameras or more are placed in defined geometry taking instantaneous pictures of a scene. Analyzing that seen in computer vision will register a common shape or object in the image. Then, trigonometry and analytical geometry analysis determine the physical geometric parameters of the required location.

In fact, expansion of the triangulation principles (transmitted waves, echo, or vision) to 3D geometric analysis enables to localize object in 3D space with respect to receivers frame. But in order to determine the location of object in 3D, at least three angles are required, where equation (3.1) affords two angles only. So, depending on two receivers will not make sense. Thus, at least three receivers should be implemented. Figure (3.10) shows common topology that uses 5 receivers arranges in star shape. This topology enables to measure all variables that are needed to localize 3DoF object, with error substitution for the resolution. Figure (3.11) illustrates the use of single camera to triangulate the object location in 2D plane [11] [12].

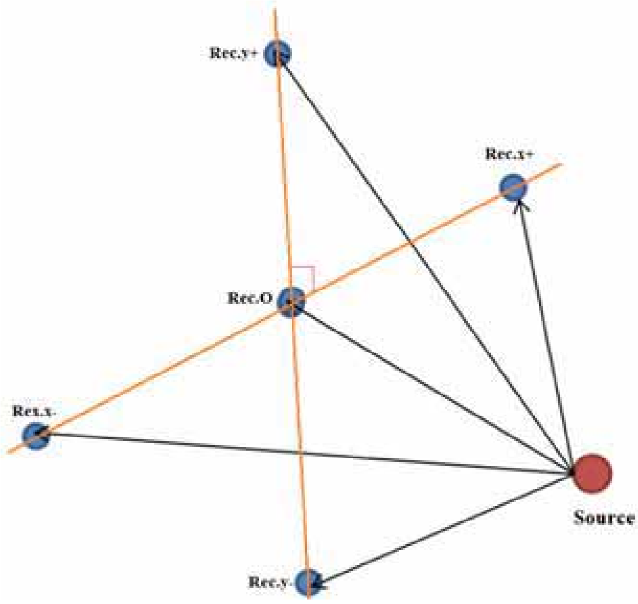


Fig. 3.10: Object localization in 3D space with multi-receivers triangulation

Now, the question that should be asked is that, why the vision systems use only two camera systems not three? In fact, many camera vision systems use two cameras but not all. Some expensive system implements three cameras. But this is not the answer, where the normal is to implement two capturing devices. The camera image is two dimensional record or measurement. So, a single image is capable to localize object in two dimensional spaces, only when the imaging system mounted perpendicularly to the motion plane.

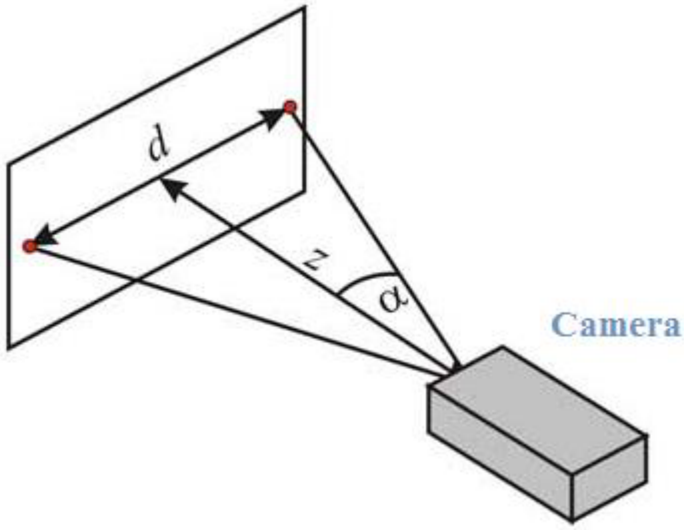


Fig. 3.11: Object localization in 2D plane using vision system [37]

Since, single camera gives enough data to process two dimensional object motions, thus, to expand the motion to 3D space, only another camera is needed. The second camera adds new degree of freedom (at least). The variable that is needed to make the 3D measurements makes sense is the depth and it's measurable by the meaning of image registration in image processing. Figure (3.12) demonstrates the topology of dual cam object localization in 3D space.

Fig. 3.12: Object localization in 3Dspace using dual vision system [38]

3.4 MEMS & Motion Sensors

The motion sensing principles that involved in this thesis are three types that would enable to measure the desired relative motion, proper speed, and other physical parameters in a relative space, those are:

- Accelerometer
- Gyroscope
- Magnetometer

The accelerometers are devices that specially designed to measure the linear translational motion of an object in terms of its linear acceleration. The gyroscopes are very meticulous devices are being designed in order to measure the angular motion in terms of angular speed, while the magnetometer measures the vector components of the Earth magnetic field [7] [8].

Originally, the gyroscopes were designed to be used in ships navigation depending on the conventional gyroscope dynamics physics. Also, traditional magnetic free running compass was designed to navigate with respect to Earth North Pole. Those devices were pure mechanical structure that based on human perception. Such concepts are still being used today in aircrafts and ships navigation. The mechanical structures are still under contributed modifications. So, large mechanical structures where adapted in order to enable converting the measured variable in terms of electrical signal. The large size, heavy weight and high costs of such measurement tools limits the use of that devices to military and naval, ships, aircrafts, and some industrial applications for long time, where the size, weight, and cost are not critical issues [8]. Figure (3.12) shows the conventional gyroscope mechanical structure.

Fig. 3.13: Conventional gyroscope, invented in 19th century by Leon Foucault [39]

In the last decade, the MEMS was introduced and evolved rapidly in association with electronics Nano-technology. MEMS is regarding to Micro (or Micro-manufactured) Electromechanical Systems. It is an application of nano technology where the parts of the system (mechanical parts) are designed in scale from 1 to 100 μ meter size. The MEMS generally are designed and manufactured from micro scale mechanical and electrical elements in addition to signal processing and conditioning circuits, and almost a microprocessor. In MEMS, basic mechanical elements could be manufactured inside an intergraded circuit (IC) like spring and mass, in addition, mechanical structures like gears. That micro design ensures the availability of building a system in IC, that build from silicon like every semiconductor based electronic design; The same concepts of waver semiconductor design and manufacturing technology where adopted in similar concepts and methodologies; Deposition, Patterning, and Etching[7].

The movable 3D structure of MEMS designed to move according to external displacements or motions. The main functionality of MEMS is to measure displacement (as will be illustrated in the following three sections). The displacement of mechanical parts could be converted into electrical signal by the use of different transducers principles. The most commonly used and known principle is the capacitance. The moving parts could be considered to be electrodes of capacitor; the capacitance then is function of displacement of those parts. Even though, the capacitance principle is the most commonly used and efficient, but also, resistance measurement, piezoelectric, inductive and other principles may be used. Figure (3.13) shows a microscopic example of waver level MEMS device.

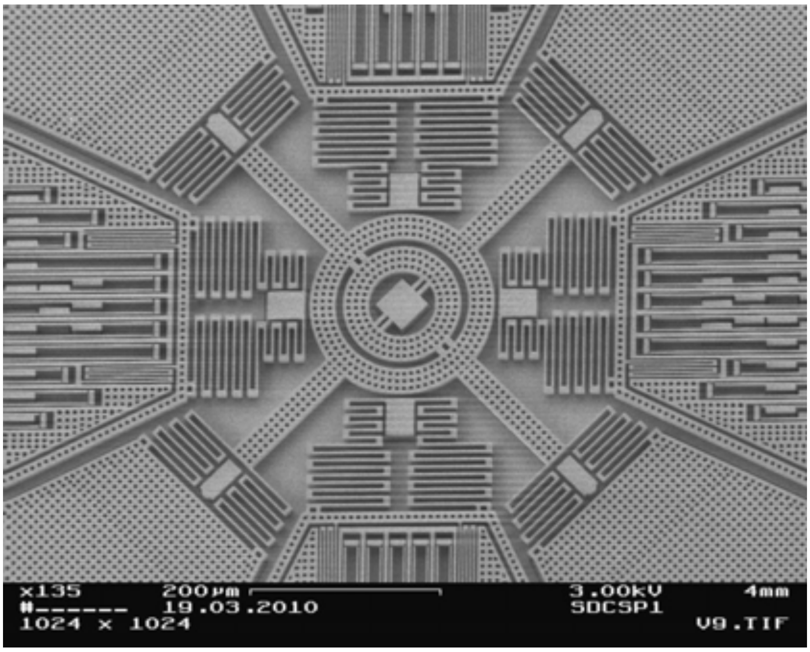


Fig. 3.14: Sample microscopic image of MEMS waver 40]

The rise of MEMS technology makes it available to build very small motion sensing devices like gyroscope inside an IC chip. That makes a high contribution on those devices making them available in constrained embedded systems. Nowadays, gyroscope, accelerometer, and magnetometers become available in consumer electronics like mobile phone. The evolution of MEMS opens new researches based on motion sensors in embedded systems [9].

The MEMS motion sensors application is not only gyroscope, accelerometer, or magnetometer, but also, the pressure sensors, sound sensors (microphones), and others are common. Such sensors are commonly used today in consumer electronics applications; in gaming and sport tools, mobiles, PDA, and players. Also, the MEMS are used in robotics, automotive, industrial and medical applications. The market of MEMS reaches thousands of millions per year since 2006.

3.4.1 Accelerometer

The accelerometer is an electromechanical transducer that is used to measure the linear translation in terms of linear acceleration. Once the linear acceleration component in one dimension is calculated, the motion parameters are then possible to be calculated. Equations (3.5) and (3.6) show how to calculate the immediate motion parameters from acceleration. Equations (3.5) and (3.6) are basic motion equations, but also, other calculations should be made to overcome the different conditions of geometric motion of the target object measurement [41] [42].

$$a = \frac{dv}{dt} \tag{3.5}$$

$$d = \int v.dt \tag{3.6}$$

Where:

a: the proper acceleration

v: the proper velocity

d: instantaneous traveled distance

t: time of calculation

The MEMS accelerometers are almost vibrating structure that is based on mass-spring structure to measure the acceleration. Figure (3.14) shows the illustration of how the vibrating structure acceleration could be measured. Let's consider the acceleration in vertical direction to the ground plane (z-axis). The basic principle of accelerometer is a mass spring couple. Figure (3.14-a) represents a known mass that mounting with the spring on the vertical orientation to the ground, the mass is fixed and the spring is free with elasticity factor (k). In figure (3.14-b) to the right, the mass is not fixes and made free running, so, the free falling of the mass will compress the spring with force of gravity weight of that mass. The elasticity of the spring will stops the mass movement, thus, an equilibrium state will be gotten as figure (3.14-b). The concept of accelerometer is that, by measuring the mass element displacement with respect to the original positions (i.e. new position of figure (3.14)) the acceleration could be estimated in terms of distance calibration. Hence the global gravity acceleration will move the mass spring couple with a known distance, then; any movement (compression or decompression) of the spring will be measured and converted to acceleration value [16] [42] [43].

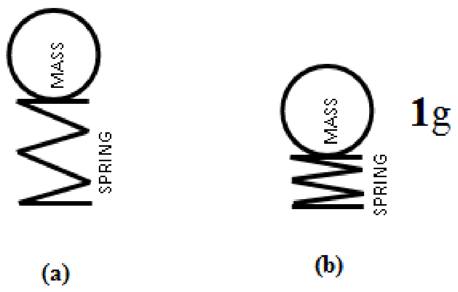


Fig. 3.15: How to measure the acceleration of using mass-spring couple

In fact, the string compression / decompression are being is the measureable variable. When measuring the spring compression, the acceleration could be measured as equation (3.7). The force is the spring compression / decompression which could be calibrated as figure (3.15) and the mass is the predefined structure element, where the variable "G" is regarding to the general gravity acceleration (i.e. 9.81 m/s^2 at the Equator line [16] [42] [44].

$$Acceleeration * Mass = Force \quad (3.7)$$

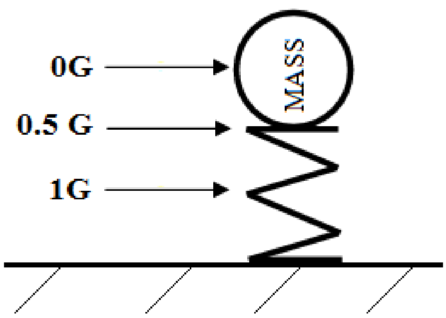


Fig. 3.16: How to calibrate the compression force using mass displacement

The concept that is illustrated in figures (3.14) and (3.15) is a single axis accelerometer, while to measure the linear acceleration in three dimensional space, three sensors should be used together. In figure 3.15, the static position of the mass is 1G when it has no movement, but when building x-axis horizontal orientation of the collection should be built, as in figure (3.17) the static position of the mass is zero acceleration [44] [42].

Fig. 3.17: Horizontal acceleration measurement mass-spring group

The frame of reference is global and the system developer will define it as the requirements and the system architecture. So, the proper acceleration measurement is critical issue, where the problem is that, where is the framer of reference, and how to make it more generalized? The solution was made as that, all accelerations are calculated in terms of gravity. The gravity is the more variable that is capable to be considered as global frame of reference. Thus, the measurement of acceleration was suggested and developed in terms of general gravity acceleration, and the unit of acceleration measurement is “G” [44] [16].

The use of gravity as reference frame solves the problem of frame of reference, which is the higher problem in the relativity physical measurements. But it causes a drift problem in accumulated measurements. Let’s consider figure (3.18); consider the gray object in figure (3.18-b) to be the accelerometer. The accelerometer is tilted (rotated) by the angle of “θ”, taking into account, there is no translational motion, the expected reading of the accelerometer is to be 1G, in the z-axis (the perpendicular axis to the ground plane). But actually, there is a component of gravity acceleration that could be calculated depending on analysis in figure (3.18-b), where “Gn” is the net measured acceleration component, “Gx” is the x-axis component of acceleration, and “G” is the gravity acceleration component (z-axis) [16] [42] [44].

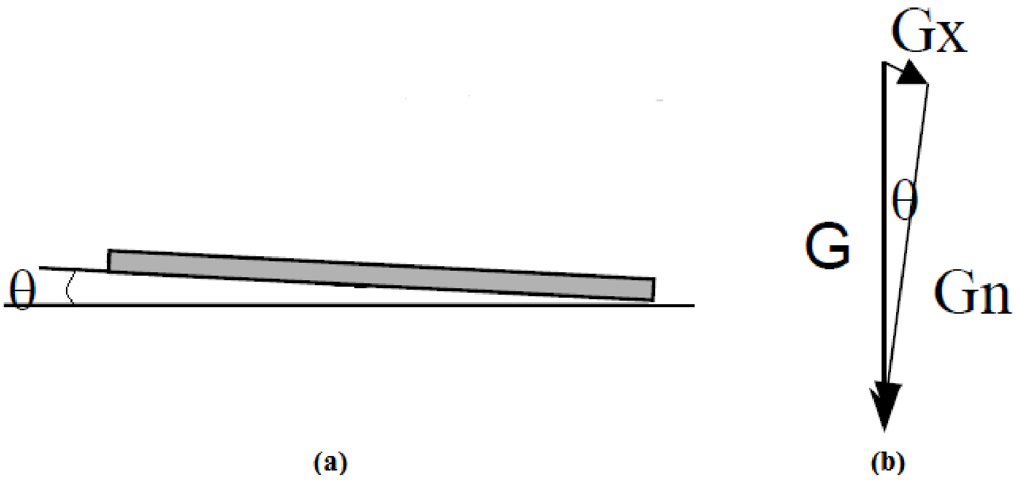


Fig. 3.18: Tilting drift illustration of accelerometer [42]

The measured acceleration "Gn" is measured as equation (3.8). Thus, when θ = 1° then the actual value of "Gn" will be Gn = 0.9998.G. And so on, as the angle "θ" increases, the measured acceleration will drifts more and more than the accrual one. Figure (3.19) shows the graph of the drift that is caused by the tilting of accelerometer with respect to tilt angle [16] [42] [44].

$$Gn = G\,.\cos(\theta) = 0.9998G \quad (3.8)$$

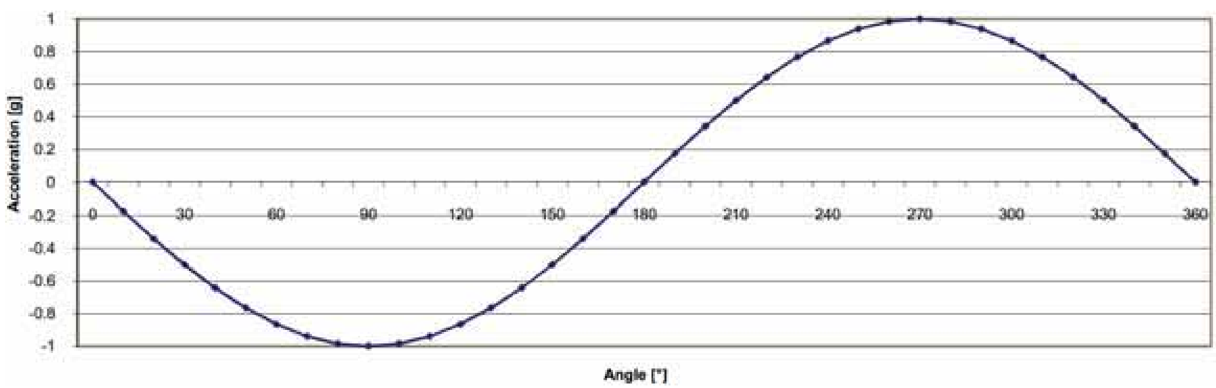


Fig. 3.19: Accelerometer drifts as function of tilt angle [44]

In practical use, there are many types of accelerometers; most of them use the same concept of mass-spring couple. The difference between the different types is the concept of converting the compression / decompression of the spring into electrical signal. Capacitive, Resistive, Piezoelectric, and Magnetic are the most common principles of accelerometers that are currently manufactured in MEMS 43] [42].

3.4.2 Gyroscope

In general, any device that is used to measure the angular velocity is called gyroscope. As in accelerometers, the gyroscope is a transducer that measures the angular velocity, some modern gyroscopes converts the angular velocity to an electrical signal, which enable to perform signal processing and accurate automatic measurements and control [13].

The gyroscope physics is based on the principles of angular momentum; figure 3.13 shows a conventional mechanical gyroscope that was designed in 19^{th} century. The spinning axis of gyroscope rotates with the external torque that is applied to it [13] [15].

The gyroscopes were used in ships navigation for many centuries ago, and were expanded to be used in modern ships and naval forces, in addition to aircrafts. The large size of mechanical structure of the gyroscopes limits its usage to price insensitive and non-size limited applications. The raise of MEMS in the nano technology make a revolution in the gyroscopes and introduces new designed that could be manufactured in low size as IC scale, and low price [15].

The main principle of gyroscope is to maintain its spinning axis, so, it rotates in opposite direction of the applied torque. The behavior of a single axis gyroscope is described as equation (3.9) [15].

$$\tau = \frac{dL}{dt} = \frac{d(I.\omega)}{dt} = I.\frac{d\omega}{dt} = I.\alpha \qquad (3.9)$$

Where,

τ: gyroscope torque

L: angular momentum

I: moment of inertia

ω: angular velocity

α: angular acceleration

So, if a "τ" is applied perpendicular to the gyroscope axis (axis of rotation), and also the angular momentum "L", thus, the resulted rotation will be perpendicular with respect to both, "τ" and "L". This is what is known as precession. The precession is the change of rotational axis orientation of a rotational rigid body. The velocity of precession is described as equation (3.10). Once the parameters of angular gyroscope rotation are measured, the angular rotation degree could be calculated [15].

$$\tau = \Omega_p . L . \sin(\theta) \qquad (3.10)$$

Where,

Ω_p: precession velocity

θ: the angle between the two vectors L and Ω_p

Many gyroscopes are being designed and manufactured differ in manufacturing methodology, and measurement principles, but share the basic gyroscope physics; such gyrostat, fiber optic gyroscope (FOG), vibrating structure gyroscopes (VSG), dynamically tuned gyroscope (DTG), London moment gyroscope and others. The MEMS gyroscopes are vibrating structure gyroscopes. The basic types of gyroscopes that are currently in common use are:

- Rotary gyroscope
- Optical gyroscope
- Vibrating structure gyroscope

The rotary and optical gyroscopes due to its weight and large size are used in applications that are not constrained for weight and mass. Even though, the optical laser gyroscopes are evolved in modern technology to be applied in MEMS, but it still limited and constrained. MEMS gyroscopes generally are of vibrating structure [15] [45].

The vibrating structure gyroscope basic principle is shown in figure (3.20); a mass spring group. In order to detect the movement of the mass that shown in the figure, sprigs are designed to hold the mass with inner square structure, while another springs are designed to hold the inner square structure with outer square structure. Any movement of the mass will move the internal square structure. The fingers those named in figure (i.e. pointed as Coriolis sense fingers) are designed to be capacitive terminal, where the capacitance between those fingers changes when the inner square structure moves. Thus, the output capacitance will change based on the mass displacement forming the equation (3.11), where "v" is the output voltage that is generated when making signal conditioning / processing to measure the capacitance change, "c" is the capacitance of Coriolis fingers, and "D" is the displacement of the mass unit.

$$v = f\left(\frac{dc}{dt}\right) = f\left(\frac{dD}{dt}\right) \quad (3.10)$$

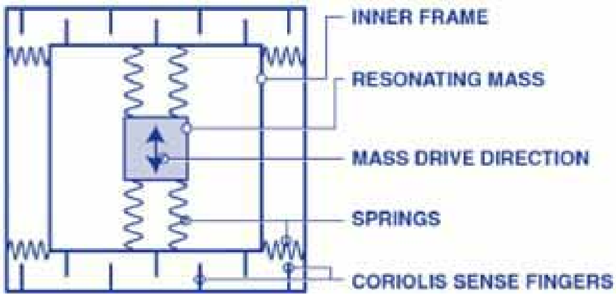


Fig. 3.20: Basic vibrating structure of MEMS gyroscopes [46]

Actually, the capacitive fingers are commonly used, but piezoelectric, capacitive, inductive, and such principles are also developed for the principle.

Now the question is, how is the mass velocity could express the rotation? The basic concepts of the vibrating structure gyroscopes are the angular momentum and Coriolis force [47]. The Coriolis force is effect of the rotation of the relative frame of reference on object movement with respect to that frame. Consider the scheme that is shown in figure (3.21), a moving point is subjected to move from the center of the disk to downward while the disk is rotating. The upper shows real movement direction with respect to the disk frame, while the lower shows the movement with respect to external frame of reference.

The apparent movement of the point in arc form was caused by what so called, Coriolis force. Thus, let apply the principle in opposite direction. When putting a point over rotary disk enabling the point to be affected by its friction with the disk, the rotation of the disk will move the point according to the disk by the cause of friction, thus, Coriolis force will be seen as reaction [48][49].

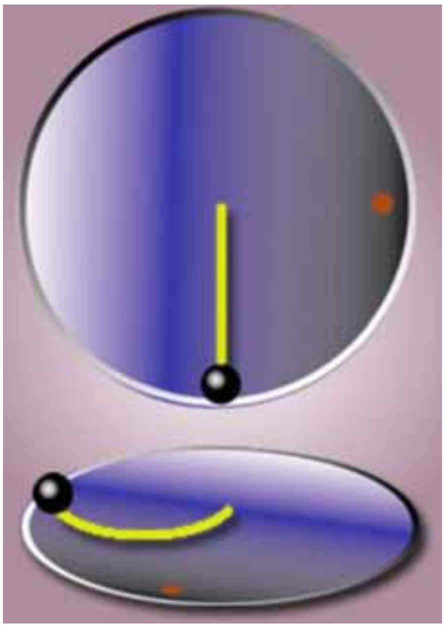


Fig. 3.21: Coriolis force effect on moving point over a rotary disk; the upper shows real movement direction with respect to the disk frame and the lower shows the movement with respect to external frame of reference [46]

Now, let consider the vibrating structure that is introduced in figure (3.20). Fixing that structure over rotary disk will enable the mass element to be affected by the generated Coriolis force with rotation. As could be gotten from figure (3.21) when the disk rotates counterclockwise, the Coriolis force that is generated will move the mass unit outside the disk, while when the disk rotates clockwise, the mass will move toward the center of the disk [48] [49].

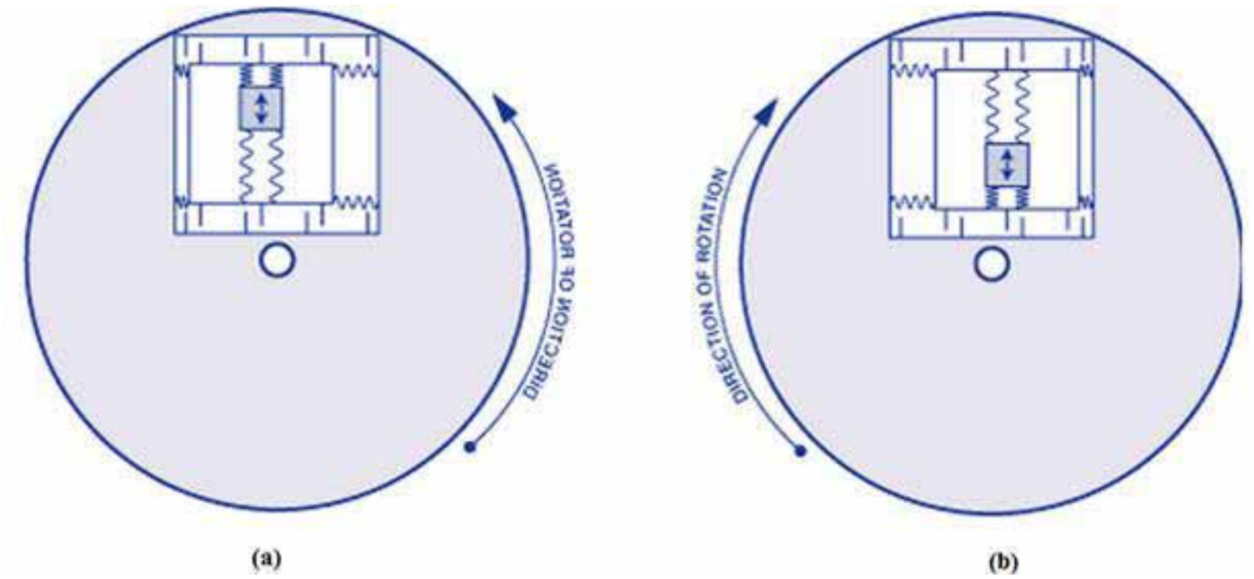


Fig. 3.22: Coriolis force effect on vibrating structure gyroscope [46]

The displacement of the mass unit inside the vibrating structure will be detected based on Coriolis fingers.

The structure that was described before measures the angular velocity in a two dimensional plane, this means one axis measurements. To extend the measurements to two or three axes, the same structure could be built for each independent axis.

3.4.3 Magnetometer

Hence, the Earth center is a big magnet, the magnetic field of the Earth is affecting a magnetized material, what is traditionally known as compass. Measuring the magnetic field of the earth can help in referencing the geometry with respect to fixed origin that is transformed from the ground origin. The new origin is described in the following vector (equation (3.11)) with respect to the earth magnetic field.

$$\boldsymbol{R_{origin}} = R_{east}.\boldsymbol{i} + R_{north}.\mathbf{j} + R_{nadir}.\mathbf{k} \tag{3.11}$$

The magnetometer is a device that measures the magnetic field, and in most cases, with respect to ground (i.e. earth magnetic field). The magnetometer also used to detect ferrite materials underground, by detecting the irregularities in magnetic field. Different principles are being used to implement the magnetometer. In general, a single axis magnetometer measure the magnitude of magnetic field in one direction, while the device that measures the total vector components of magnetic field in space is considered to be 3-axes magnetometer.

The 6DoFthat will be developed in this thesis is relative to the origin of the motion in Cartesian coordinates. In many cases, a common frame of reference is needed to reference all measurements and control motion actions. The most common frame of reference in dynamic analysis is the ground, that's because it is constant over the motion of particles in the Earth atmosphere. In automatic measurements, the ground could be measured and expressed by its magnetic field as manipulating variable in control systems literatures. In fact, the controlled variable in dynamic analysis is the Cartesian x, y and z projection vectors, and their projection vectors could be measured and manipulated via the vector components of the Earth magnetic field [50].

Those projection vectors are described in figure (3.23). Where, "B - Vector" is the original magnetic field line from the measurement point (i.e. the origin of Cartesian vector component frame) to the center of the Earth magnetic field.

The magnetic field of Earth surface is around 50nT (nano Tesla) and comprises very small variation due to weather strong changes. Since, Carl Gauss start publishing the modern instrumentation concepts in measuring the magnetic field of the Earth, that concept start to be adopted in military and naval forces, chips and air planes, and continue growth their applications. Nowadays, the Earth magnetic field measurement becomes available in commercial and micrometric scale [8] [50].

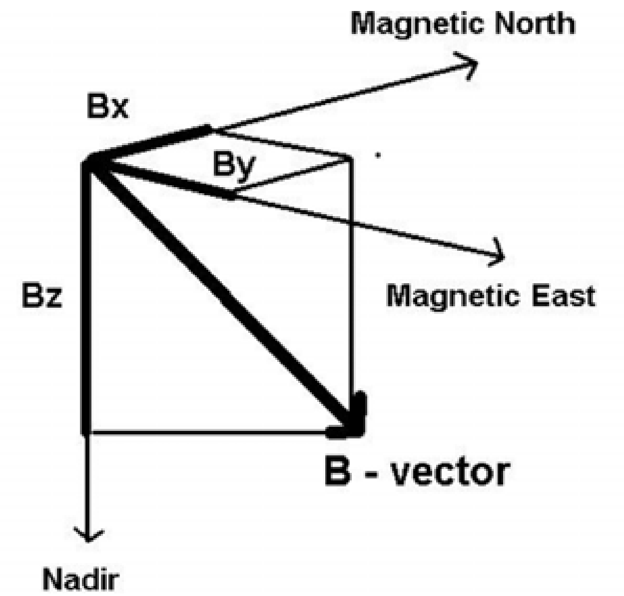


Fig. 3.23: Earth magnetic field projection vector [51]

As traditional compass that points to the north pole of Earth, the magnetometer uses magnetized material to measure variables that are function of Earth magnetic field, where that metal is very light and easily rotatable by the effect of very light magnetic force. The conventional compass measures the direction of magnetic field in one axis, while the magnetometers are usually used to measure the vector magnetic field, which has magnitude plus orientation. Figure (3.24) presents a conventional manual two axes magnetic compass [22].

Many principles where developed to build magnetometers; superconducting quantum interface device (SQUID), inductive pick-up coils, Giant magnetometer (GMR), Anisotropic magnetometer (AMR), vibrating sample magnetometers, etc. The small sized and electrical signal output magnetometers are being available commercially for industrial and consumer electronic product with the revolution of MEMS [50].

Fig. 3.24: conventional two axes manual magnetic compass [51]

The MEMS magnetic sensors are almost Lorentz-Force based, where it is based on the current flow in a conductor that is affected by magnetic fields around it. Protons (i.e. Hydrogen nuclei) are distributed around a ferrite solenoid that is involving a direct current follows inside it. The direct current induces a magnetic field for the solenoid that affects the protons orientation causing a mechanical motion of the particles depending on Lorentz force. In specified frequency, the artificial magnet field that caused by the DC current of the solenoid switched on and off. When switching on, the particles moves in orientation based on the solenoid's magnetic field, while it returns its orientation based on Earth magnetic field [50].

The motion of particles forms shape based on the applied magnetic field that is frequent motion that vibrating the protons between the orientation of earth magnetic field and the Lorentz-force magnetic field. Thus, the earth magnetic field vector could be measured by sensing the vibration of the protons.

Different methodologies were designed to measure the displacement and rotation of the protons inside the magnetometer electromechanical structure; voltage sensing, optical sensing, and frequency shift sensing is the most common and reliable techniques. The different techniques are all aims to sense both, the speed of displacement and its orientation. The orientation represents the measured field orientation, while the speed represents the magnitude of the field itself. The calibration between the applied Lorentz-force and the measured orientation and speed of moving protons enables to measure the outside applied magnetic field vector.

CHAPTER FOUR

SYSTEM ARCHITECTURE

The engineering system that is presented in this thesis consists of three parts; embedded system, wireless systems, and PC application software. The embedded system is the core of the complete presented system, which contains the sensors, control and processing, storage, power management, etc. The wireless system was designed to transfer data wirelessly between the PC and the embedded system. Whereas a human interface device (HID) driver and calibration algorithm are the two components of the PC application software.

4.1. General System Requirements

The requirements are stated to describe the needed engineering system from higher level perspective, where the specifications are intended to more depth details. The goals of the system should be achieved and expressed in terms of the engineering requirements.

The system that was proposed for this thesis was specialized to design an engineering system and algorithm for interactive white board input pen through 3D space scope. The engineering system should be hand held device that used to write like a pen. In the research thesis it is not designed in the form of commercial consumer mouse or writing pen, and no mechanical ID design will be considered, only the electronic system and the algorithm is considered.

Like normal computer mouse, the designed system has a push button for left click. Hence, the mouse control will be done in 3D space scope, then, the mouse should be wireless. The wireless transceiver ensures the wireless microwave communication between the designed embedded system and the PC, through a wireless dongle. The wireless dongle is a device that is connected to the PC through USB HID interface driver. It manages the wireless communication between it and the embedded system, processes the received packets of data, and implements a USB protocol to pass the data to the computer. The transmitted data between the embedded system and the PC includes the localization information of the 3D input device, headers, status, and control packets.

A computer HID driver manages the USB based wireless dongle, it includes USB communication protocol layer in addition to mouse driver. The calibration software represents the higher layer in the presented system. It comprises the calibration algorithm that matches the computer screen coordinates to the input plane scope.

The performance of the system depends on the complete integration of the subsystems in addition to the performance and reliability of each subsystem individually. The user shouldn't face any unreasonable or abnormal behaviors of the presented system. The mouse pointer should be localized correctly with respect to the interactive board space and computer projected screen in the interactive board. Then, the control events should be performed in very close behavior like the conventional mouse. Those criteria are human based criteria and couldn't be measured in analytical way; instead, it could be evaluated using survey and statistics.

The speed of human hand movement while using the presented system is a very important criterion that are really considered in the design and implementation of the system, where the fastest moving speed of the presented pen is the highest error percentage.

The system should be flexible in terms of both, the possibility of made any modifications on it ahead of future, and the portability. The portability means that, the contributed algorithm could be applied on different microcontrollers or microprocessors without the need to reprogram the system from scratch. In addition to that, any modifications on the system should be possible to be done without the need to rebuild the complete system.

The testability of the system has two considerations; software debugging and hardware debugging. The software debugging is possible in both, the firmware emulation via JTAG/SBW, and the software via virtual studio programming tools.

The upgradability could be achieved by building a flexible hardware and firmware system that is being built using modular design. Thus, the upgrade of each individual module could be done without affecting the complete system and without the need to break out the complete system. In addition, the software and firmware implementation of the most system layers enable to upgrade the system easily by new build and download principals.

The presented pen system should be hand held and used in 3D space freely while the user is moving around. Thus, the system should be power stand-alone battery-based device.

The device design is a part of consumer electronics scale. No special considerations will be taken into consideration. The temperatures, humidity, environmental conditions, life cycles, system standards and such, all are in the consumer electronic scale.

To achieve the availability of the system considerably, the components of the system shouldn't be rare or special purpose devices. It is really selected as very common, cheap and available consumer electronics based devices.

4.2. Detailed System Specs

To achieve the requirements of the engineering system that are described in section 4.1, detailed specs are stated here as the second step in engineering design process, and the first step of system architecture.

The modular design of the system simplifies the architectures, and enables to achieve the flexibility, testability, and upgradability in efficient and reliable design. The modular design basically concerning to design the system components in the way that each component represents complete subsystem that takes input and returns output. Thus, when working with modules as black boxes, the complete system could be structured.

The processor of the system should be a 16bit microcontroller, which has been selected to be one of MSP430 MCU's family devices. An internal oscillator of 32.768 KHz can derive the system via the internal phase-looked loop (PLL). Also, the ability to derive the system via a high speed external crystal oscillator increases the flexibility of the system with respect to system frequency requirements. The program implementation should consider the limitation of MCU internal program memory. Thus, and EXP430 development board of MSP430 microcontroller is a good choice for the implementation. The selected MCU is suitable for the required analytical geometry mathematics, in addition to the communication protocols, control, peripherals, and system architecture.

The EXP430 development board has on-board 3.3v voltage regulator. Thus, the complete embedded system is assumed to be run over 3.3V.

The motion sensor that is used in this design is the InvenSense MPU-9150 product. That is a 9-axes gyroscope with embedded ADC and I^2C communication protocol. A 3.3v power will be supplied to the MEMS sensor via the EXP430 on board voltage regulator. It will communicate directly to the MCU via the MCU's built in I^2C peripheral communication module.

A wireless module that transmits data between the embedded system (i.e. the MCU) and computer is assumed to be one of the common Nordic Semiconductors products, i.e. NRF24LU01+. It is 2.4 GHz wireless transceivers will 79 working channels; 1MHz channels hope each. This wireless module is designed to be powered up from the EXP430 development board via the on-board 3.3v voltage regulator. It communicates with the host microcontroller directly via SPI communication, with synchronous clock up to 10MHz. A two ways communication is implemented with acknowledgement to ensure maximum number of received packets in the receiver side.

The wireless transceiver module is considered to be a part of the embedded system, where its functionality is to transmit and receive the data between the embedded host microcontroller and the PC. So, a wireless dongle should be connected to the PC side to complete the communication loop. The wireless dongle consists of also a NRF24LU1+ transceiver. It communicates via 2.4 GHz microwave with the embedded system and interfaces the data to the PC via USB port.

The USB dongle is defined as human interface device (HID). The HID driver is med software that communicates directly to the dongle and interfaces its data to the PC application software. An interrupt only transfer is implemented in the developed HID driver.

The application software is mainly calibration algorithm which reads four real measurements of the MEMS data, process it in a 3D plane, and create a relative board plane with respect to it. So, the application software has two modes of operation; calibration, and running. In calibration modes, it should display one point for calibration, and then the user has to point the contributed system to that point, for a while of time. Then, the calibration program should display another point and the user will repeat this process until four calibration point's data are measured. Then, the calibration program will collect these data and build the 3D plane geometry.

In run mode, the software application, reads the HID data which represent the 9-axes MEMS measurement and - according to the calibration algorithm - computes the relative mouse pointer location according to the pre-calibrated 3D geometric plane. It doesn't do any processing, nether the calibration. It is implemented using visual studio.

In order to debug the MEMS sensor's output effectively, a serial communication was implemented to transmit the MEMS sensor's output directly to the PC screen via the HyperTerminal tool. An FT232 is used to bridge the UART serial output of the MCU to the HyperTerminal software via USB port. Thus, the UART port sends all MEMS sensor data read to the PC directly. This way help to debug the sensor's output directly, analyze it, and solve any related problem reliably.

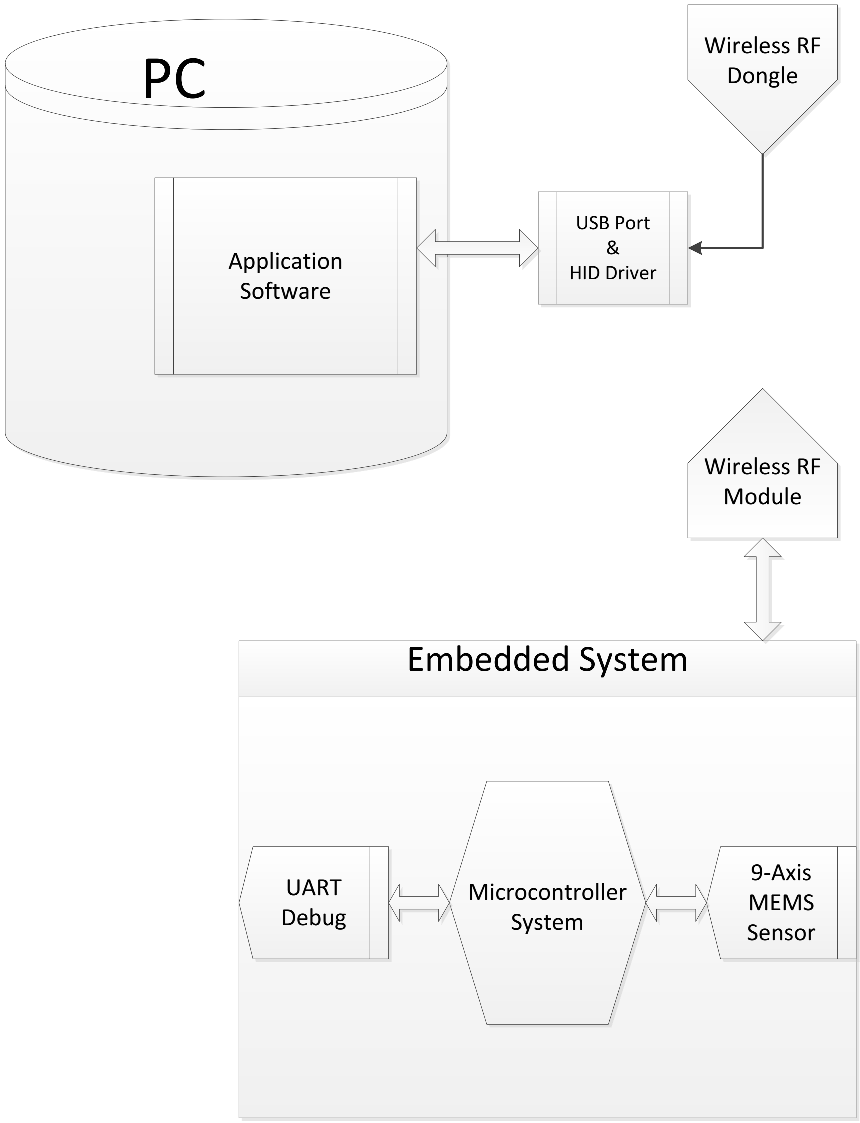


Fig. 4.1: General system diagram

A pulled-up push button is connected to a general purpose I/O pin of the MCU with interrupt source. This button is used to develop the mouse click function.

The system power will be supplied to the EXP430 development board via a 3.7v Li-Ion battery. The system is assumed to run in its complete power consumption continuously for a period of 4 hours. A LED indicator is used to indicate the user that the battery is connected and the system is powered on.

The mechanical design, device ID shape, and size are not considered in this stage of design. That is because of that, the purpose of this system design is to implement and develop the contributed research design and algorithms, and to achieve the goals of the thesis those are described in section 1.4. So, the mechanical specifications are not related to this thesis research and those only related to consumer electronic specifications.

The system design considerations were subjected to consumer electronic standards and specifications, in all steps of the design, including, components selection, circuit design and specifications, and materials.

All components that used in this design guarantee the green environment conditions, and specially the RoHS certificates.

Figure (4.1) shows the block diagram of the complete system design.

4.3. Motion Sensors [52] [53]

As illustrated in section 1.4, a 9-axes MEMS motion sensor will be implemented in this thesis. The design involves power up connection of the MEMS sensor, interfacing, and connection to the host microcontroller. Since May 2011, the InvenSense Company introduced the idea of 9-axes gyroscope in one chip and released the initial specifications as the world's first 9-axes motion sensor. The MPU-9150 device contains 3-axes gyroscope, 3-axes accelerometer, and 3-axes magnetometer.

Figure (4.2) shows the MPU-9150; figure (4.2.a) shows the real IC image of the sensor, while figure (4.2.b) shows the motion axes. The 4x4mm small QFN24 footprint IC package is good choice for size and weight constrained applications, and specially, consumer electronics.

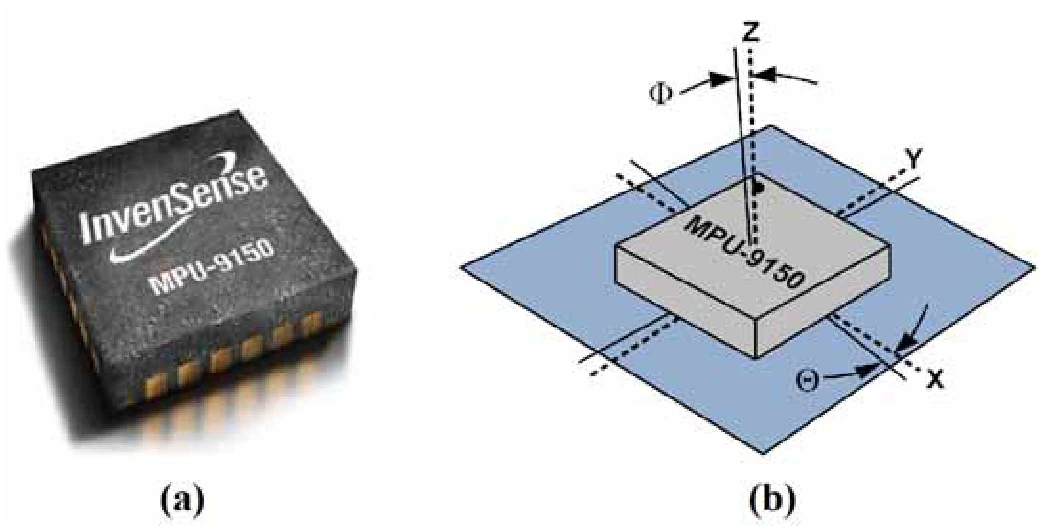


Fig. 4.2: MPU-9150; a 9-axes MEMS motion sensor [53]

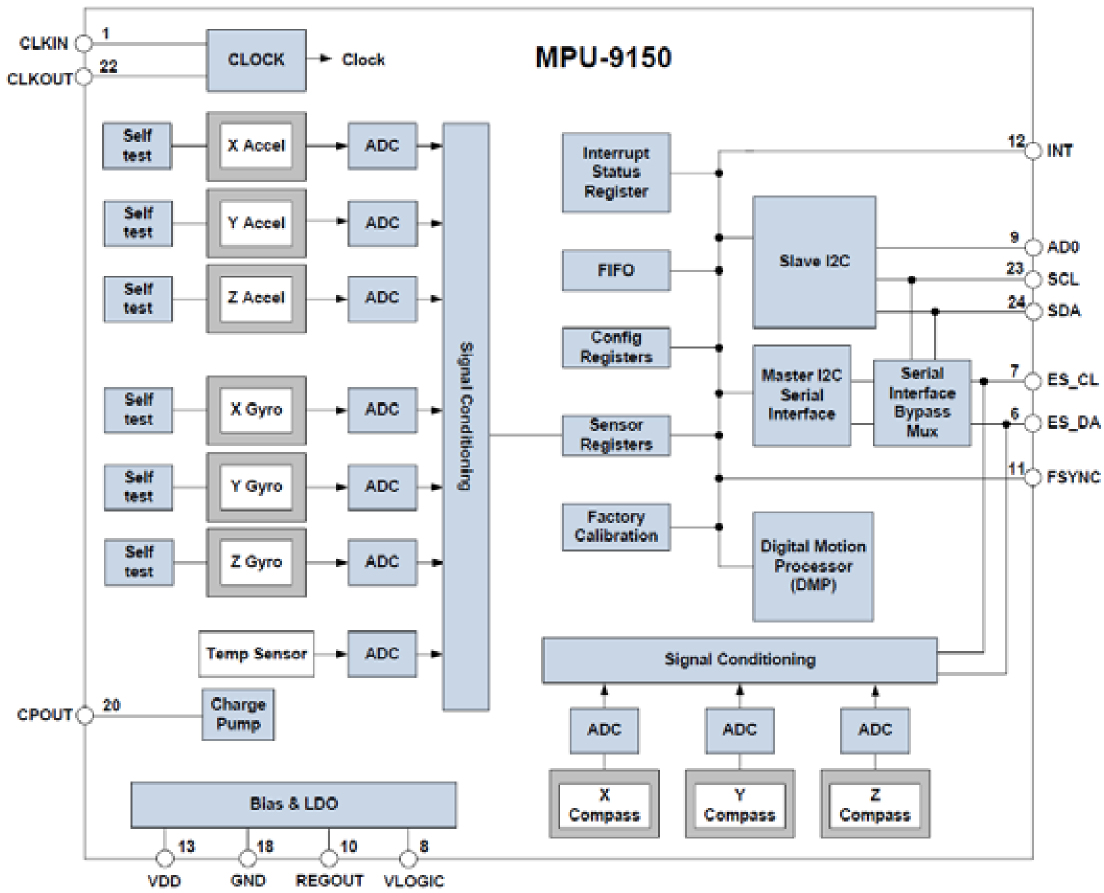
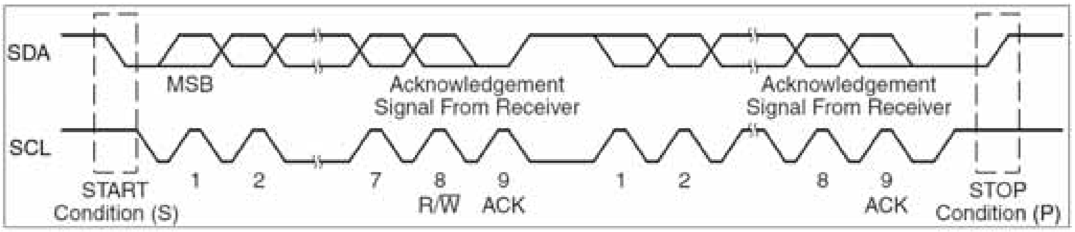


Fig. 4.3: Architecture of the MPU-9150 [53]

The MPU-9150 consists of 9-motion sensors, one temperature sensor, 10-analog to digital converters, signal conditioning units, memory registers, digital interface, and microprocessor, where the architecture is illustrated in figure (4.3). Each motion measurement axis needs separate motion sensor, e.g. three separated accelerometers are being used to measure the acceleration for the x, y, and z axes. The needed oscillator clock for the internal system could be generated internally via a 32.768 KHz clock oscillator with PLL, in addition to the capability to use higher precision external crystal oscillator via input pins to an internal oscillator control circuit.

The signal processor with cooperation of the analog to digital converters (DAC) and signal conditioning converts the bayer sensor data (which is analog) into digital quantized data, and then, sends it to the host controller serially via the serial communication engine. The I^2C is a well-known two wire synchronous interface protocol. It implies that, one bidirectional data line and one clock line. The device that generates the clock is the master device, while the other is considered to be slave. The salve is determined by its physical slave address, and multi-salves could be connected directly to the I^2C bus. The chip contains two I^2C engines; master and auxiliary. The auxiliary I^2C is specified to connect external pressure sensor to the chip, thus, adding one more measurement axis. The auxiliary I^2C works as master communicating device with respect to the externally connected device, and works as slave with respect the main I^2C engine that resides inside the chip. In that case, the pressure sensor is connected directly to the MEMS chip, and the host microcontroller accesses the pressure sensor via the master I^2C of the MEMS chip itself. In this thesis, there is no function for the pressure sensor, so, this option is ignored. Figure (4.4) shows the I^2C transfer diagrams; figure (4.4.a) illustrates the general timing diagram, figure (4.4.b) illustrates the master writing a single byte of data, figure (4.4.c) illustrates the master reading a single byte of data.



(a)

Master	ST	SAD + W		SUB		DATA		SP
Slave			SAK		SAK		SAK	

(b)

Master	ST	SAD + W		SUB		SR	SAD + R			NMAK	SP
Slave			SAK		SAK			SAK	DATA		

(c)

Fig. 4.4: I^2C data transfer diagrams [53]; general detailed timing diagram (a), master write of single byte diagram(b), and master read of single byte diagram (c)

A 16-bit ADC's are used for each one of the gyroscopes and accelerometers, while a 13-bit DAC's are used for each one of the magnetometers.

An on-chip temperature sensors with embedded DAC measures the internal die temperature. This temperature could be needed for complete physical parameters measurements and substitutions.

Figure (4.5) shows the schematic diagram of MPU-9150 that is connected to the embedded host microcontroller. The VDD is 3.3V, where the overall system runs on this voltage. The MEMS sensor communicates directly to the host microcontroller via synchronous serial I^2C bus. Actually, a very few interface circuit is needed, as shown in the figure. A well designed circuit with precise decoupling of power should be designed. The I^2C return path rules should be followed to prevent cross talk, EMI, and all types of circuit noise.

The physical measurements of MPU-9150 are flexible for the variety of motion speeds, to enable different applications adaptation, in addition to reliability in various speed grades. The gyroscope full scale measurement is programmable from ±250°/s up to ±2000°/s, where the angular speed is measured in degree per second (°/s). The accelerometer full scale measurement is programmable from ±2g up to ±16g, where g is the natural gravity acceleration (see section 3.4.1). And fixed magnetometer full scale measurement is about ±1200µTesla.

The programming / configuration of the MPU-9150 device are done by writing to the internal registers via I^2C engine. The device address represents I^2C slave address, while to access a specific register, the register address should be passed in the sub-address (RA) of the I^2C space. Finally, the device runs over 400 KHz I^2C clock.

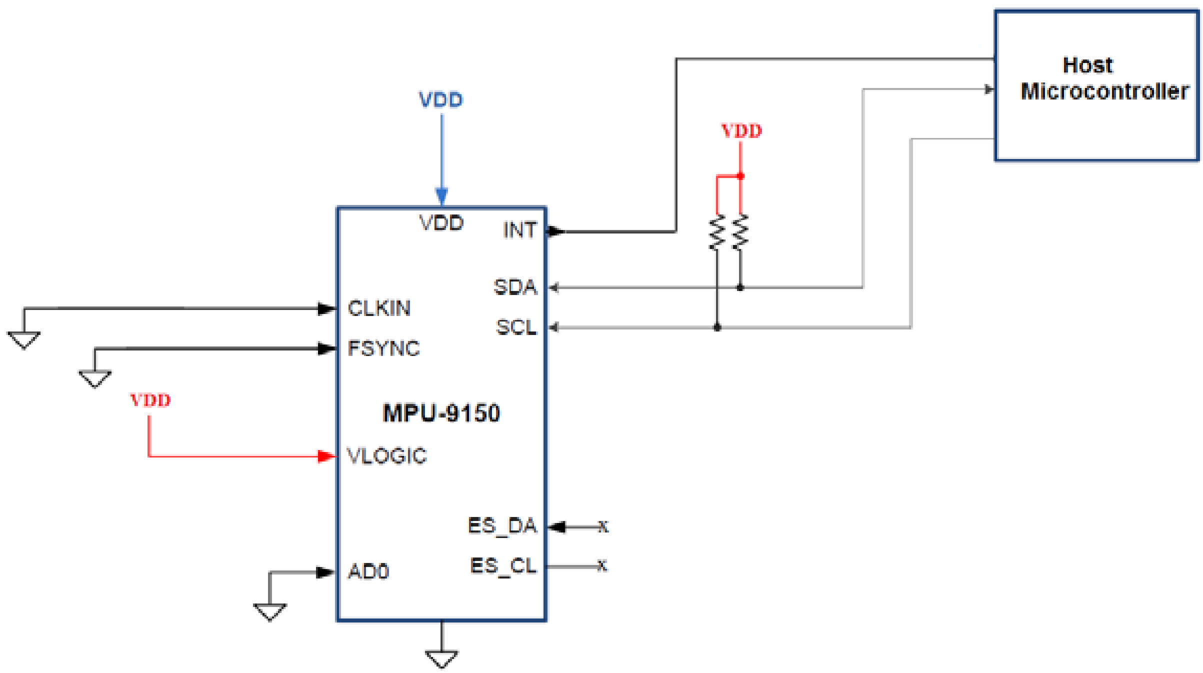


Fig. 4.5: Schematic design of the MPU-9150 interface with the host microcontroller [53]

4.4. Embedded Systems Architecture [54] [55] [56] [57] [58] [59] [60]

The embedded system is the handheld device that is contributed in this thesis. It consists of three main modules; MEMS sensor that is used to measure the relative motion in 3D space, microcontroller system, and wireless module. The microcontroller represents the core unit of the device which performs all processing, control, and interfacing operations. The MEMS sensor is illustrated in section 4.3, and the wireless module will be illustrated in section 4.5.

As stated before, MSP430 microcontroller is selected to be the core of the contributed system. The EXP430F5529 is a development board that is based MSP430F5529 microcontroller (i.e. that is described in section 4.4.1). It helps in power implementation of applications that is based on latest MSP430 MCU's family. It enables to program the MSP430 microcontroller via JTAG/SBW which is described in section 4.4.2.

The EXP430 development board is compatible with Federal Communication Commission (FCC) standards. In addition, it is RoHS compliant standard. Figure (4.6) shows the development kit diagram.

The development kit contains – in addition to the microcontroller – input push buttons, proximity touch input keys, LCD, mini-USB connector, micro-SD card connector, indication LEDs, battery power input connector, reset circuit, emulation circuit, analog potentiometer, I/O pins expansion headers, and others.

Three power input options are available on the board; USB, JTAG, and battery. The operating voltage of the MCU is 3.3v, and the complete board could be run in that voltage. USB port could power the complete board via a 3.3v low drop out (LDO) on board voltage regulator. The JTAG emulator also capable to supply the board with required operating power. The

MSP430 JTAG emulator runs over 3.3V. An external 3.7v battery could also power up the system. In this thesis, the system is configured to be operated using external Li-Ion battery – single cell. This helps to make the system runs stand alone to make it hand held without any external wiring.

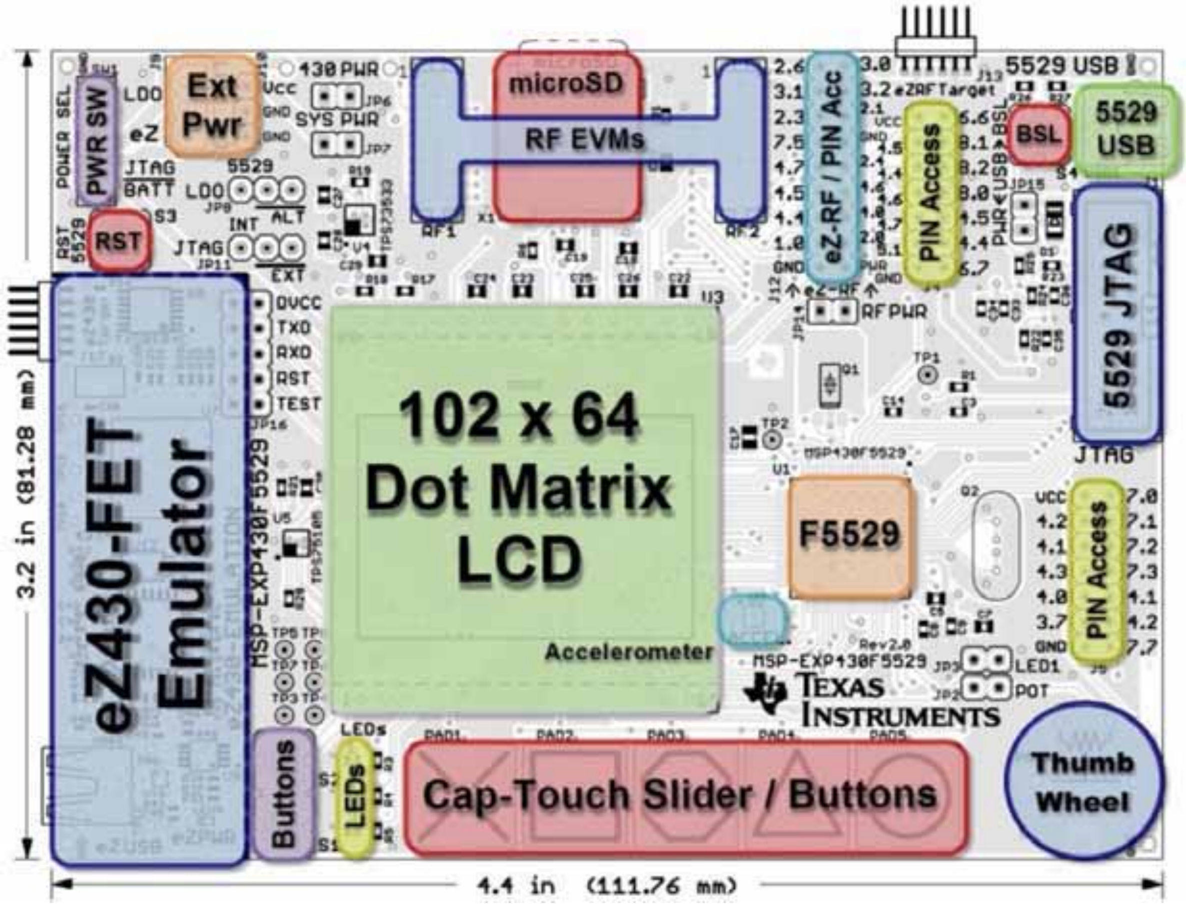


Fig. 4.6: EXP430 development board diagram [57]

The embedded system design in this thesis has four main separated components; the EXP430 development board, the wireless module, MEMS sensor, and the battery. The wireless module is a completely designed module to achieve the purpose of this thesis in generic modular design form. The development board implies the other needed modules in order to develop the algorithm and system design.

The size of development kit is appropriate for prototyping, testing and verification. In addition, the cost of the system is reasonable for such research. The embedded system connection is illustrated in figure (4.1).

4.4.1 Microcontroller system

The first question that should be answered when designing embedded system is that, what is the required specification of the processing unit. The device that introduced in this thesis is a hand held stand-alone device and will be powered through battery. So, it should be a low power or ultra-low power with efficient power management modes. Also, in such applications, the final designed product should be cost efficient.

The main issue of this contributed system is to perform the required control, interfacing, and processing operations. The microcontroller should interface the MEMS sensors (i.e. MPU-9150, see section 4.3), so, I^2C communication is required. It also will be interfaced to the wireless transceiver module via serial peripheral interface (SPI), thus, it should contain SPI communication engine module. For debugging, the MCU should implement the interface to the PC via HyperTerminal tool, so, it's preferred to have universal asynchronous receiver transmitter (UART) serial communication module. The digital I/O that is required is limited, one is used for input key push button (i.e. click button) and two are used for indication LED's. Figure (4.7) shows the detailed schematic diagram of the embedded microcontroller circuit and interface. The wireless modules, MEMS sensor, and UART interface are connected on the expansion pen access headers (i.e. J4 and J5).

An important thing in any embedded microprocessor / microcontroller selection process is the availability, processing power, and memory. For all pervious reasons, the MSP4305529 was selected to be the core processor of the contributed system.

The ultra-low power MSP430F5529 is featuring different core, memory, and peripherals. It is a 16-bti reduced instruction set computing (RISC) core, with 16-bit registers. The rigid system architecture with unified clock source (UCS) and digital controlled oscillator (DCO), and the precise power modes, wake up, and interrupts make it appropriate selection for high code efficiency applications.

The tools, sheets, and all resources that help to initiate any design based on MSP430 microcontrollers' core are all available, and the resources are rich. In addition to that, it's easy to get help from the Texas Instrument (i.e. the manufacture of MSP430 MCU's) regarding any non-experienced problem. This is an important point in any process includes initiating new embedded systems design.

The Code Composer Studio is the IDE that is used to write firmware programs, down load it the MSP430 MCU's, and debug it. This tool is available free online with limited code size up to 16KByte. Even though, the selected MSP430F5529 microcontroller has a 128KByte of flash program memory, but in fact, the developed program size is less than 16KByte, so, the free tool release completely helps the implementation of this thesis system.

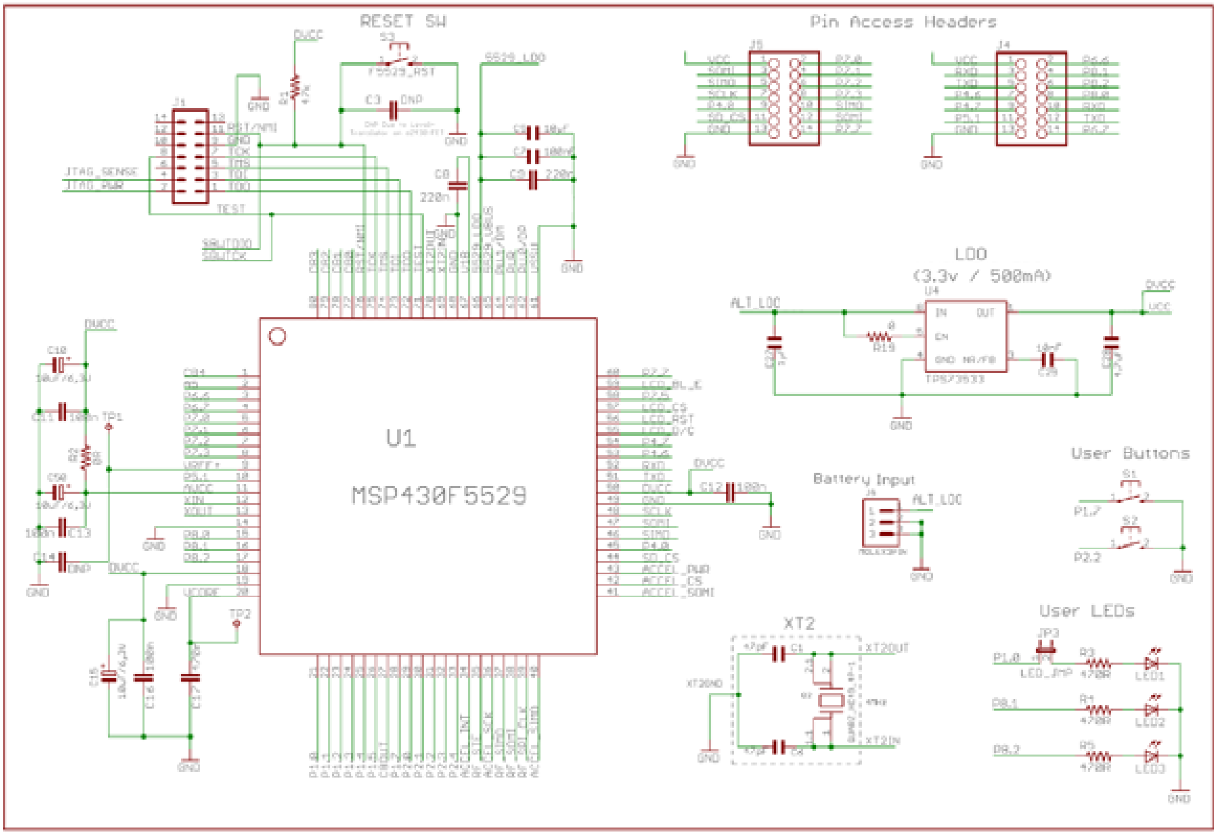


Fig. 4.7: Embedded system - microcontroller schematic diagram [57]

An 8KByte of open user SRAM enables to freely implement the required buffers, programming variable, and to save the needed arrays. The Flash memory is an embedded on-chip program memory, while the SRAM is also an on-chip user memory space.

The RAM is divided into sectors, while those are physically separated. This minimizes the power consumption of the microcontroller; unneeded RAM sector is powered down. The target microcontroller MSP430F5529 RAM consists of four memory sectors, a 2Kbyte each.

4.4.2 Debugging [61]

Hardware debugging of embedded system is being done by constrained programming of the firmware system, oriented hardware design, and engineering expertise. The oriented hardware design is including specific design points either in system or in circuit that enables to check the system validity, progress, and failures. The LED indicators are the simplest debugging method in hardware that is used in the contributed system to blink in a specific system events. LED indicators are used for the following purposes:

- UART transfer in progress
- SPI transfer in progress
- I^2C transfer in progress
- Power up

Test points pads on the circuit should be considered in the circuit design level in order to enable probing the important signals to scope. The test points could be separated pad for specific signal trace on the circuit, or even, a circuit component pad. The separated test point pad is needed when no component pen is mechanically available to be probed.

Sequence detection of logic signal could be measured and debugged by the use of logic analyzer (i.e. USB XBee 24 is used during this design). This enables to trace the logic signals, sequences, communication protocols, and checking timing diagrams.

The gap between hardware and firmware based debugging goes smaller in the advances of embedded technologies. This solves the problem and complexity of pure hardware debugging. The constrained programming should implements some functionality in the firmware structure to detect hardware events. Such constrained programming includes the initialization of modules and startup check, continuous handshaking with the peripherals, and so.

In contrast, firmware debugging is easier and clearer than hardware debugging, which could be done by investigating the software integrated development environment (IDE) and in-circuit debugging (ICD) tools.

Programming and debugging via JTAG enables to access the microcontroller during run-time in the circuit. This is implemented by the means of ICD / emulator hardware.

The MSP430 uses standard JTAG (Joint Target Action Group) interface, in addition to spy-bi-wire (SBW) interface over JTAG port. IEEE 1149.1 standard JTAG defines the specs for boundary scan and test access port, that is very efficient and common in IC programming and debugging. It enables to access the internal microprocessor / microcontroller registers, configuration words, and memory spaces. The JTAG debugging is done in-circuit, which means that, the microprocessor / microcontroller is running and functioning on-line with computer debugging software.

Standard JTAG implies four lines interface that are shown in figure (4.8.a), while SBW could be implemented with less (i.e. only two wires) that is shown in figure (4.8.b). SBW is just a serial JTAG port and licensed for Texas Instrument co, with synchronous clock that develops three periodic clocks to support TMS, TDO, and TDI in addition to bidirectional data line.

The SBW engine is a JTAG with additional logic for serializing the four JTAG lines, as shown in figure (4.8.b). Thus, the SBW debugging interface minimizes the physical pins of the JTAG standard.

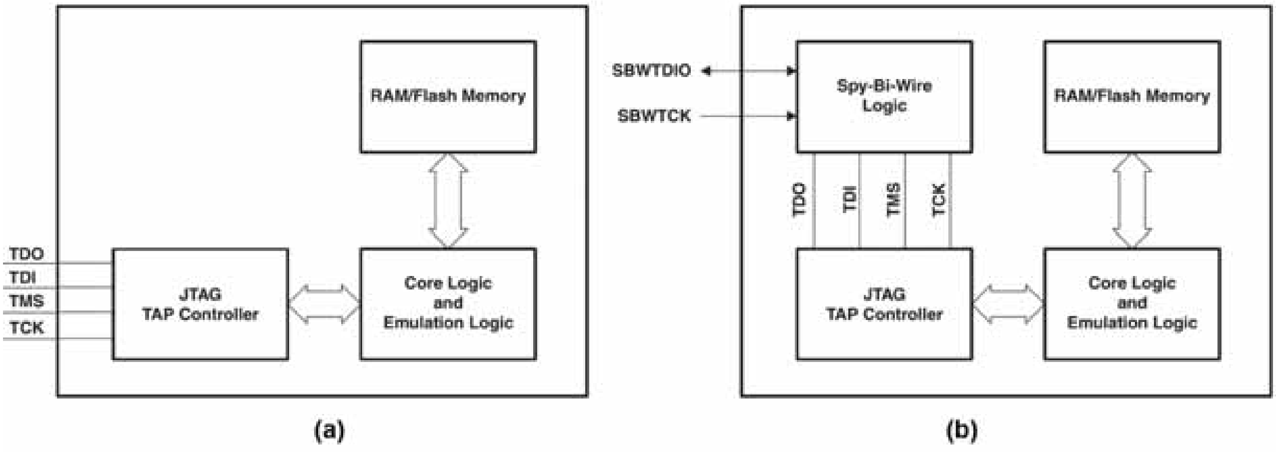


Fig. 4.8: Embedded MSP430 debugging schemes [58]; JTAG (a), SBW/JTAG (b)

4.5. Wireless Transfer [62] [63] [64]

The wireless transfer is used to transfer the relative coordinates that is measured by the embedded system via MEMS motion sensor. The wireless systems consist of a 2.4GHz module (i.e. nRF24L01+ and nRF24LU1+). The wireless module is connected to the embedded system via serial peripheral interface (SPI). The 2.4GHz band falls into the industrial, scientific, and medical (ISM) standard.

Two wireless sides are the wireless transceiver module, and the wireless dongle. The dongle is attachable to the PC side, while the transceiver should be mounted in the device side.

The operating frequency range is 2.402 GHz to 2.480 GHz, where 1MHz each channels hop. Thus, 79 wireless channels could be implemented. This is useful in multi-transceiver or in channel hopping transfer layers. But those are not the goal of this thesis. This function required in this thesis is high received packet rate wireless single channel.

Since the wireless data should be transferred to the PC in HID format, the transmitted data format is shown in figure (4.9). The click byte indicates the mouse click event, where the data consists of two bytes for relative X-coordinate and two bytes for relative Y-coordinate.

The header byte is two parts; the four most significant bits represents the packet type, while the least significant four bits are flag bits. The packet ID is used for acknowledge transfer.

Packet ID (2 Bytes)	Header (1 Byte)	Click (1 Byte)	Data (4 Bytes)

Fig. 4.9: Wireless packet payload format

The wireless transfer payload that is shown in figure (4.9) is sent within the wireless packet in the format that is shown in figure (4.10). The address bytes should contain the receiver address, to ensure that, the correct packet is received by the correct receiver. The Preamble byte is a bit sequence which either “01010101” or “10101010”. This sequence is used to detect if there are enough edge transitions to stabilize the receiver. If the Preamble sequence not correctly detected, the receiver will ignore the packet assuming that, sequence error is detected.

The acknowledgement transfer is done in ShockBurst scheme. In ShockBurst, automatic packet assembly, automatic acknowledgement and automatic retransmission are implemented. Figure (4.11) show transmit-acknowledge scheme between the transmitter and receiver that is adopted by ShockBurst mode. The transmitter sends the data in the RF channel and waits the receiver to acknowledge the received data, while retransmission timer (RT) is cleared once the transmission is done. The RT is the time that the transmitter waits the acknowledgement to be received form the receiver side. If the acknowledgement isn't receive within that time, the transmitter will assume that the packet has been loosed, thus, it may retransmit the packet again.

Preamble	Address	Payload	CRC
(1 Byte)	(3-5 Bytes)	(0 - 32 Bytes)	(1-2 Bytes)

Fig. 4.10: Wireless packet format

The ShockBurst implements automatic acknowledgement and detection, automatic retransmission, and automatic transmission initiation, with predefined re-transmission times and predefined RT.

In fact, the ShockBurst also features automatic packet assembly and error detection. If there is an error in the received packet, the ShockBurst layer will consider it damages, and will ignore it. Thus, no acknowledgement will be sent to the transmitter, forcing the transmitter to retransmit that packet again.

In transmitter layer, the ShockBurst can retransmit the non-acknowledge packet finite times. If the maximum retransmissions reached, the transmission will skip the packet and proceed in the next packet.

The system developer should be aware of the timing issues that is related to the transmission rate, packet size, acknowledge, and retransmission. Such calculations are illustrated in the next section (4.5.1).

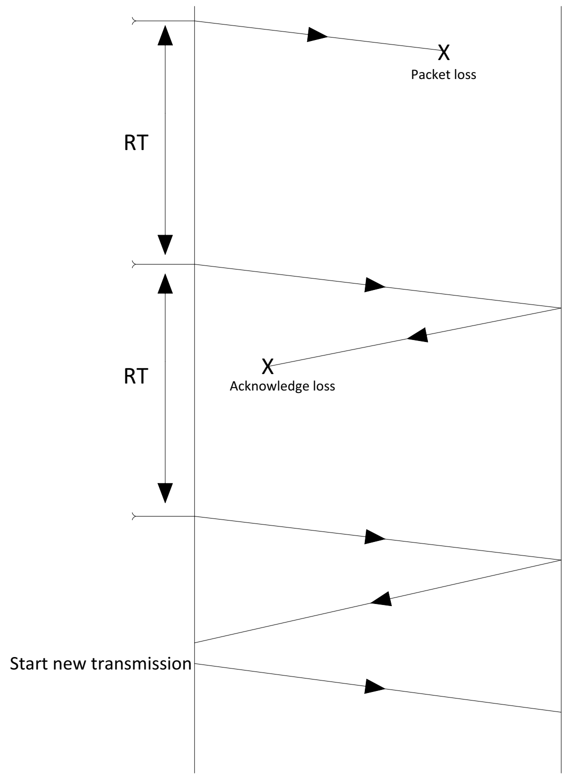


Fig. 4.11: Wireless transmits acknowledge schemes

4.5.1. Wireless transceiver module

The wireless module nRF24L01+ consists of two sides; digital side and analog side. The analog side is the radio frequency (RF) channel, modulation, and carrier generator. The digital side is a digital state machine device with internal control registers, flags, and oscillator management.

The digital size implements SPI communication protocol. In such a way that, the embedded microcontroller transmits the data that is intended to be sent wirelessly to the wireless module serially. The digital side of the wireless modes receives the data, process it, build the communication layer, and pass it to the analog side.

Data transfer could be done in three programmable rates; 256 Kbps, 1 Mbps, and 2 Mbps (Mbps regards to mega bit per second). When working with 1Mbps, a 1µseconds for each bit transfer is needed. The packet size in bits could be calculated as in equation (4.1), where the total packet contains 13 byte. Thus time that is required for transferring complete packet is 104 * 1 = 104 µSecond ideally. When working with shock burst acknowledged transmission, the maximum retransmission time is selected to be 15, where the retransmission period is selected to be 250 µSecond (i.e. approximately double the ideal transmission time). In that way, each packet may take maximum transmission time that is calculated in equation (4.2).

$$packet\ size = 8\ x\ (payload\ size + crc\ size + \ address\ size + 1) = 104\ bit \qquad (4.1)$$

$$max.transmission\ time = no.of\ repeats\ x\ (packet\ time + retransmission\ period) =$$
$$15\ \ x\ \ (104 + 250) = \ \ 6810\ \mu\text{Second} \qquad (4.2)$$

So that, the number of coordinates that could be sent via the wireless RF channel is at least:

$$\frac{1\ second}{6810\ \mu\text{Second}} = 146\ packet$$

For packet transmission reliability and security, the nRF24L01+ implements Advanced Encryption Standard (AES) encryption / decryption in hardware.

In order to test the wireless module RF efficiency, carrier test is established. The carrier test is simple application that sends a 32 byte payload each with the value of 0xAA. This packet is being sent continuously via the wireless module. Using spectrum analyzer, the spectrum will be measured. In fact, the distortion shouldn't be greater than -1dB when using co-axial cable instead of air RF channel. Figure (4.12) shows the spectral analysis of the received carrier test signal that is transmitted via co-axial cable. The result shows a spectrum with distortion value about -0.45dB, which is excellent in comparison with the required distortion to be not greater that -1dB.

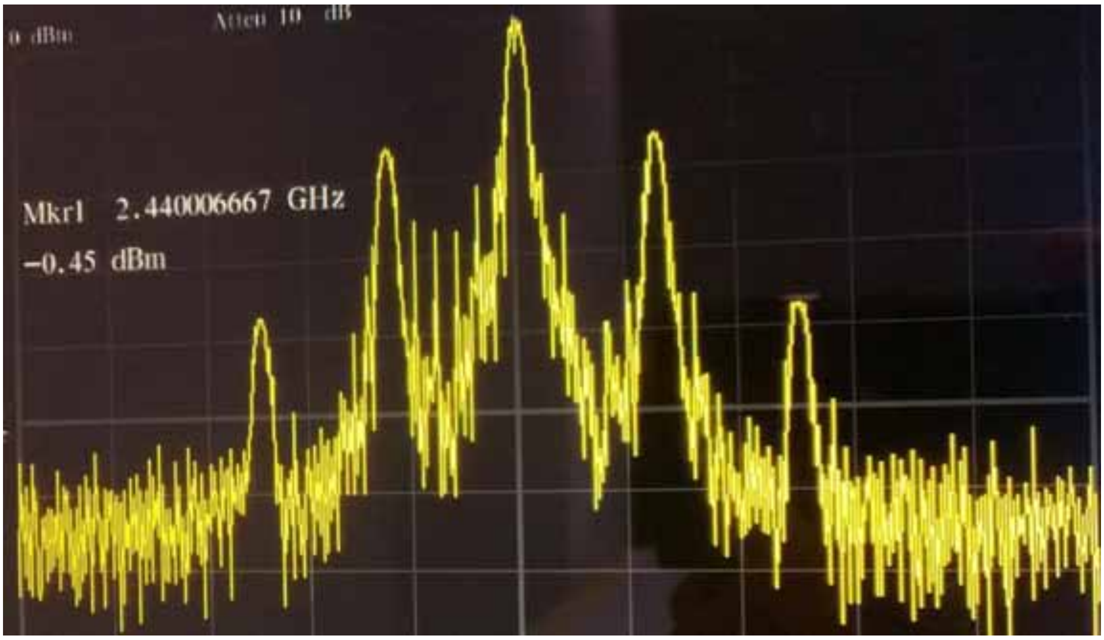


Fig. 4.12: Spectral analysis of the received signal via co-axial cable in carrier test

The nRF24L01+ interface, oscillator, and power circuit is shown in the figure (4.13). The module runs over 16 MHz crystal oscillators, 3.3V power VDD. A chip antenna is being used.

The host embedded system controls the wireless module and communicates with it via serial peripheral interface (SPI) port, where the SPI-based control interface enables the host controller to access all nRF24L01+ features. The SPI is a synchronous serial protocol with master and slave topology. The master and slave communicate over 3 serial lines, those are

- MISO: Master input, slave output
- MOSI: Master output, slave input
- SCLK: Serial clock

The master is the device that initiates the clock line. It's capable to communicate with multi-salves, thus, to enable a specific slave device, slave select line is used. The slave select line is a fourth SPI line in the slave, and typical I/O line in the master, which is separated than the SPI port. The slave select (SS) line is active low, and any slave on the SPI bus that is not selected will not respond to the SPI master. On the other hand, the slaves couldn't communicate to each other directly, just through the master.

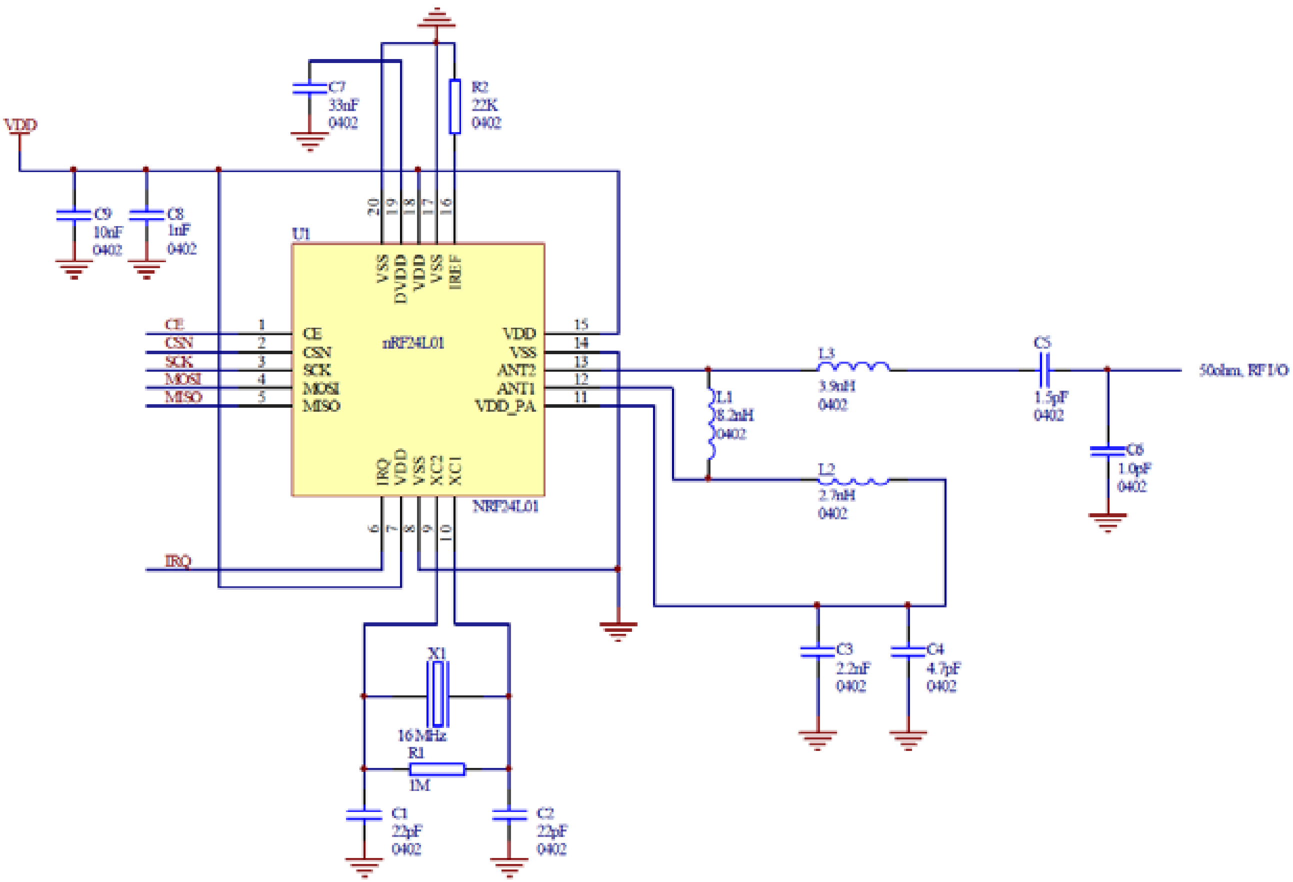


Fig. 4.13: Schematic design of the wireless module based on nRF24L01+ [63]

The nRF24L01+ works in SPI frequency up to 10MHz enabling to access all internal registers by SPI commands, where all commands are 8-bits. Every SPI data transmission should be done in the presences of associated synchronous clock for each data bit. The SPI incorporates half-duplex serial port. Each command is sent to the wireless chip from the host microcontroller through MOSI line, is associated with status register value returned from the chip through MISO line. The commands are includes that, read command of the received payload first in first out (FIFO) register, and write command to the transmit payload FIFO register. Two FIFO registers are implemented in the nRF24L01+ chip; one to store the received data from the receive shift register, and one to store the data that is ready to be transmit through the transmit shift register.

Figure (4.14) shows the timing diagram of the SPI commands and data transfer, where the part (a) of the figure illustrates the read operation, and part (b) illustrates the write operation. The read operation starts by sending command via MOSI and receiving the status register via MISO, followed by receiving the data bytes via MISO line. The write operation starts by sending command via MOSI, and receiving the status register via MISO, followed by sending the data bytes via MOSI line.

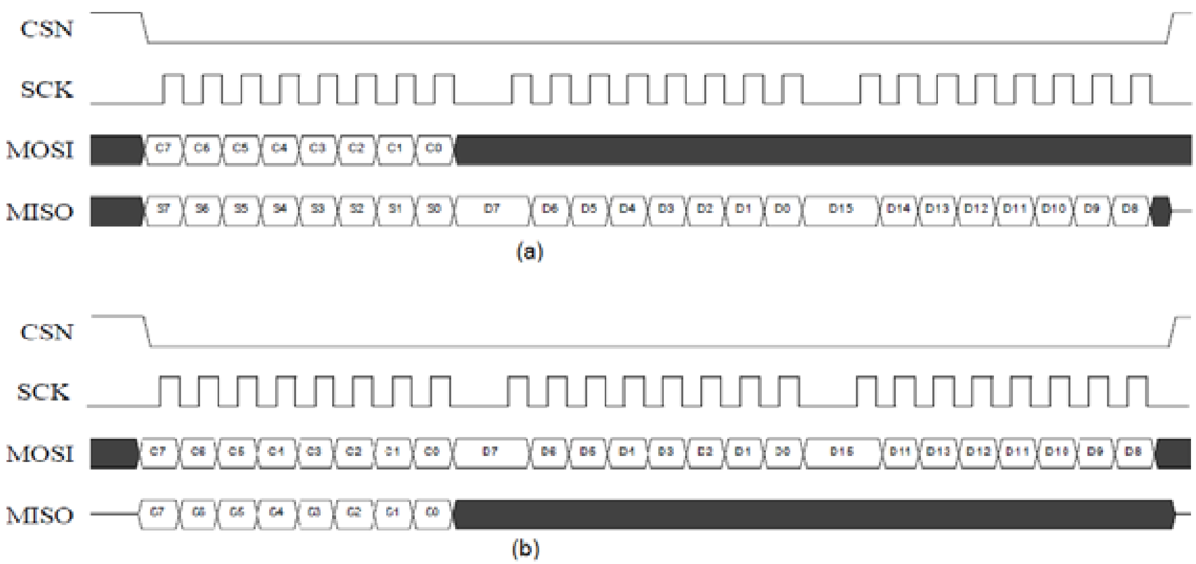


Fig. 4.14: SPI timing diagram for nRF24L01+ commanding and communication [63]; read operation (a); write operation (b)

4.5.2. Wireless dongle

The dongle is nRF24LU1+ wireless based transceiver module with embedded microcontroller, while the one that is used in the embedded system side (nRF24L01+) is just a wireless microwave device and has no embedded microcontroller. It dedicated to implement a USB-HID device interface. It operates on 16MHz crystal oscillator. It also incorporates full-duplex wireless channel, so, it can send and receive through microwave simultaneously.

The nRF24UL1+ is typically nRF24L01+ in the wireless stack and analog side. The difference is just in the embedded microcontroller, and the USB protocol.

0000 0000 0000 0000	1010	0000	xxxx xxxx	xxxx xxxx	xxxx xxxx	xxxx xxxx

(a)

0000 0000 0000 0000	1110	0000	xxxx xxxx	xxxx xxxx	xxxx xxxx	xxxx xxxx

(b)

Fig. 4.15: ping packet format (a); ping-acknowledgement packet format (b)

The dongle develop a received power detecting (RPD) engine that is used to determine if there is an RF signal on the selected channel. The channel is assumed to have a received signal if it detects a power of -64dB or higher. The dongle is the host of the wireless system. When start, it searches about the valid RF channel, then, start communicate with it. The system that is implemented in this thesis implies that, fixed RF channel is used to communicate between the embedded system and the host PC. Thus, the dongle and the wireless transmitter module will never change their RF channels. In fact, other than measuring the RPD, there is no way to measure the RF channel.

In fixed channel configuration, the dongle is programmed to work on channel “40”, thus, the frequency of that channel is 2.400GHz + 40MHz = 2.44GHz. The dongle will initialize the channel communication with wireless module by sending a ping packet. The receiver when receives a correct ping packet, it responds by returning a ping-acknowledgement packet. The ping and ping-acknowledgement packets are 7 bytes long each. The formats of those packets are shown in figure (4.15). Once, the ping-acknowledgement has been received by the wireless dongle, the pairing is initiated. And the RF wireless channel becomes ready to send and receive data packets between them.

When no wireless channel is established and used for communication, the dongle sends a ping packet every 50msecond.

The nRF24LU1+ dongle has an imbedded 8051 microcontroller core, in addition to, 32Kbyte of on-chip flash program memory, 2Kbytes of on-board data SRAM, embedded timers, and USB 1.1/2.0 compliant port device controller with full speed facility. The embedded microcontroller on the chip of wireless dongle enables to implement the HID device and USB protocol on the same nRF24LU1+ without the need to use external system on chip (SOC) device.

Figure (4.16) shows schematic diagram of the wireless dongle with USB interface. The nRF24LU1+ runs over a 16 MHz crystal oscillator, and it is also 3.3V powered, but it has an internal 3.3v embedded voltage regulator to generate the required 3.3V of VDD from input Vbus of the USB port. Thus, no external voltage regulator or power supply is needed; it just draws its power from the USB connected port.

Same carrier test was been made on the wireless nRF24LU1+ dongle. The spectrum analysis that was gotten is very close to the nRF24L01+ test result. For air RF channel, a PCB antenna is used for the dongle unit.

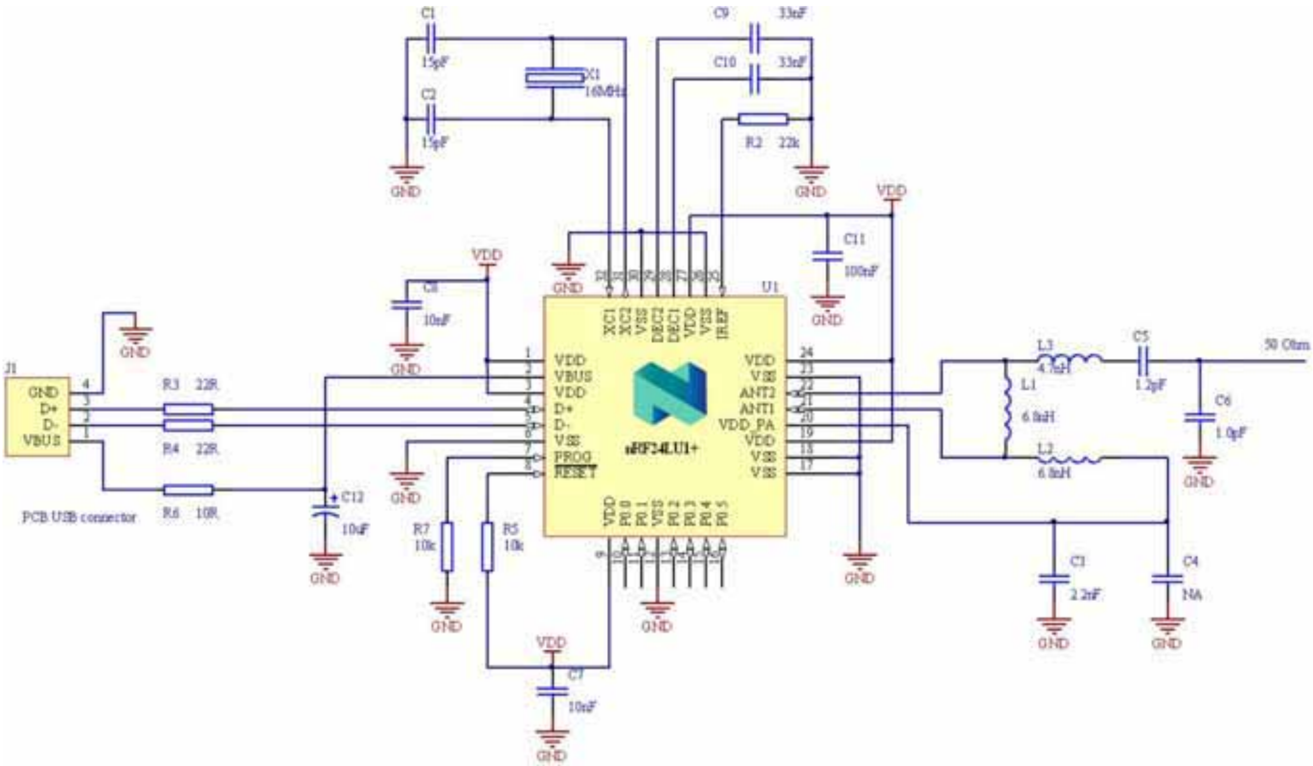


Fig. 4.16: Schematic design of the wireless dongle based on nRF24LU1+ [64]

4.6 USB-HID Driver [65] [66] [67] [68] [69] [70]

The universal serial bus (USB) is a computer interface that was designed to connect different types of peripherals to the computer via universal bus protocol. USB simplifies the development of input, output, and communication devices; also it simplifies the driver structure and operating system related functions, with up to 127 devices can be connected to the same processor. The USB signaling consists of differential serial communication lines, with speeds up to 4.8GHz, and four different transfer modes; control transfer, interrupt transfer, bulk-only transfer, and isochronous transfer. The USB-HID devices uses interrupt transfer.

The USB basic structure is represented as a network of hosts, functions and hubs. The functions are the peripheral devices, while the hubs are an extension or adaptor for power and signal port. The hub connects multiple functions to the host. The USB hardware devices are either functions or hosts. Figure (4.17) shows the network hierarchy of the USB attachments; figure (4.17.a) shows the physical hierarchy, and figure (4.17.b) shows the logical hierarchy. The host is the master of the USB system, and it keeps tracking all physical functions and hubs.

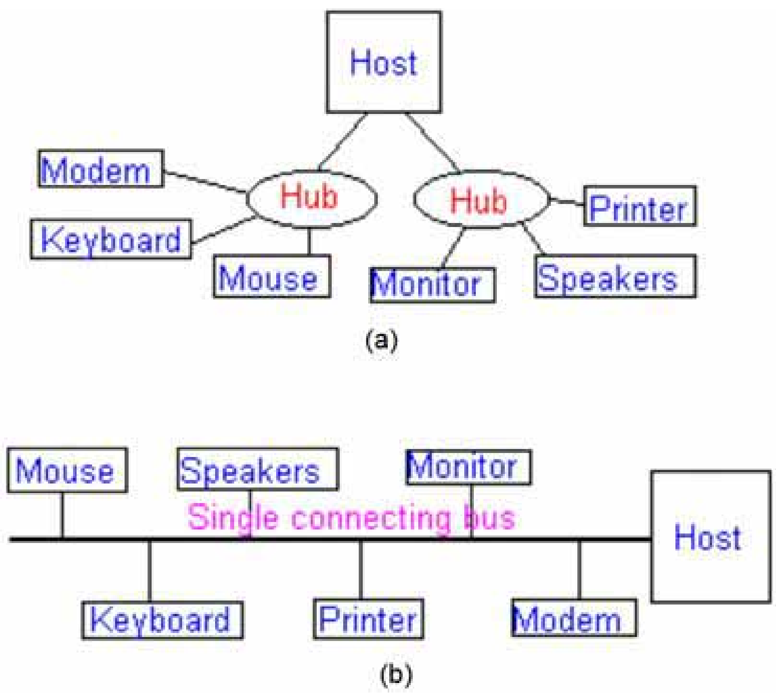


Fig. 4.17: USB attachments hierarchy [71]; physical connection (a), logical connection (b)

Each device that is attached to the host takes an address. This address is relative to the host, and it could be changed when the device is disconnected and reconnected again. The communication between the host and the devices is being done through a number of endpoints, which is a collection of destinations and sources. The endpoint implements simplex communication path. Each USB device has 15 end points, where endpoint 0 is the control endpoint that is used to initiate the communication between the host and device.

The USB communication and data transfer is being done through packets and requests. When the device or host requires data, it sends a requests packet, and the other side responds to the request. Each endpoint has limited size for packet transfer. Figure (4.18) illustrates a typical packet format, where it consists of a number of fields. The synchronization field consists of 8-bits, and used for timing configuration of the inputs. The packet identification field (PID) specifies the types of packet (i.e. four packets types are defined in USB; token, handshaking, data, and special packets) and includes a check bits for the packet. The address field includes the address of the devices at the specified endpoint. The endpoint number varies from 1 to 15, where the 0 endpoint is specialized for initializing communication between host and the device. The data field is varies according the data size or the maximum data size possible to be transferred by the specific endpoint pipeline.

Sync (8-bit)	PID (8-bit)	Address	Endpoint number (4-bit)	Data (0 - 1023 bytes)

Fig. 4.18: Typical USB packet format

The human interface device (HID) is the computer device that interacts directly with the human, through input or even output events. The common sense using HID terminology is related to USB-HID drivers and specifications. In such, the device is defined through set of control events, and data fields, and there definitions are part of the USB specifications. An example of USB-HID devices is the computer mouse, keyboard, and game controller, where each device has its HID class that is defined in the USB-HID specifications. The HID specs make the computer devices and peripherals compact, portable, robust, and enables to avoid unknown information.

The driver building of any USB-HID class device is well defined in the USB specs, without any limitations to the computer hardware or even specific software. This generic description makes it easy to add the driver functions to the operating system (OS), in addition to faster implementation and easy installation.

In this thesis implementation, the PC is the USB host, while the wireless dongle is the USB device. The USB-HID device class describes how it will communicate with the USB host. The HID device passes its report to the host USB during the USB enumeration process; this report includes descriptors of the HID to make the host capable to interpret the HID data. Thus, when enumeration process finished, the host becomes has the HID report that contains all information that it needs to communicate correctly to the USB-HID device. When the device needs to send data to the host, it sends a report as poll-token reply. The device sends all data to the host though reports.

The host USB can request report from the device in all its operation period. The most basic report is the HID report descriptor. The descriptor is bytes array that describes the data packet of the device. The packet descriptor includes the number of packets that the device supports, and length of the packet, in addition to the functionality of each packet parts (i.e. byte or even bit).

Hence, the HID device that is implemented in this thesis represents a special type of pointing input devices. The data structure that is needed to describe the pointing events is presented in figure (4.19). The data that should be sent in HID is regarding to location and button click. One byte is needed to describe the click event, because each click is represented by 1-bit. The location coordinates in x-y form is represented by two bytes for each axis.

	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
Byte 5	Useless	Useless	Useless	Useless	Useless	Useless	Useless	Left Button
Byte 3-4	X Axis Relative Movement as Integer (unsigned)							
Byte 1-2	Y Axis Relative Movement as Integer (unsigned)							

Fig. 4.19: The contributed HID report data structure

4.7. PC Application

The computer application is designed in this system to enable the user to calibrate the projection screen. The calibration aims to map the x-y data that is measured by the MEMS sensors to the computer screen. The measurements of the sensors represent physical data that needs processing to represent a coordinate system in x-y plane. The computer screen resolution and coordinates is measured in pixel, where the top left corner of the screen is the origin (0, 0) pixel point.

As clarified in section (4.6), the x-coordinate, and y-coordinate of the computer screen are represented in 16-bit unsigned integer for each axis. The computer screen resolution in pixels represents the most left corner to be 0x0000 in x-axis, and the most right corner to be 0xFFFF in x-axis too. The y-axis is then calculated by the proper aspect ratio of the screen resolution. Figure (4.20) shows the computer screen coordinates topology.

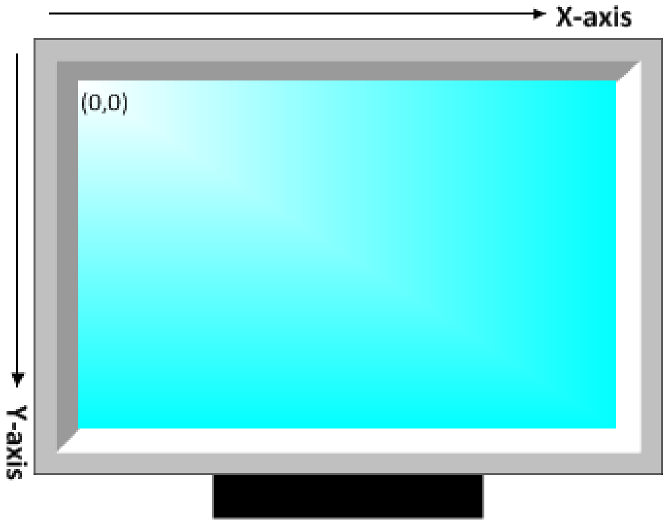


Fig. 4.20: Computer screen coordinates axes

The computer screen resolution is variable and fully selectable by user settings. Thus, the pixel count those are represented by 16-bit will be changed according to the user settings. The calibration software measures the screen resolution and determines the screen aspect ratio and how many digital numbers represents the pixel in one-axis coordinates. Then, the software maps the HID input from the wireless dongle to the computer screen. In fact, the data that is transferred to the computer via the wireless channel is absolute x-y coordinates in millimeters, while the software application maps it to an absolute pixels number.

Initially, the calibration of the projection screen is needed. Thus, the software application displays the calibration screen to the user, while contains four points that the user should point over them serially. The embedded system will measure a relative coordinates for the calibration points assuming that, the most top left corner is the coordinate origin, and the computer software will map the coordinates according to that.

Figure 4.21 shows the implemented hardware system of the presented system. It consists of the embedded system and the wireless dongle, as illustrated carefully previously in this chapter.

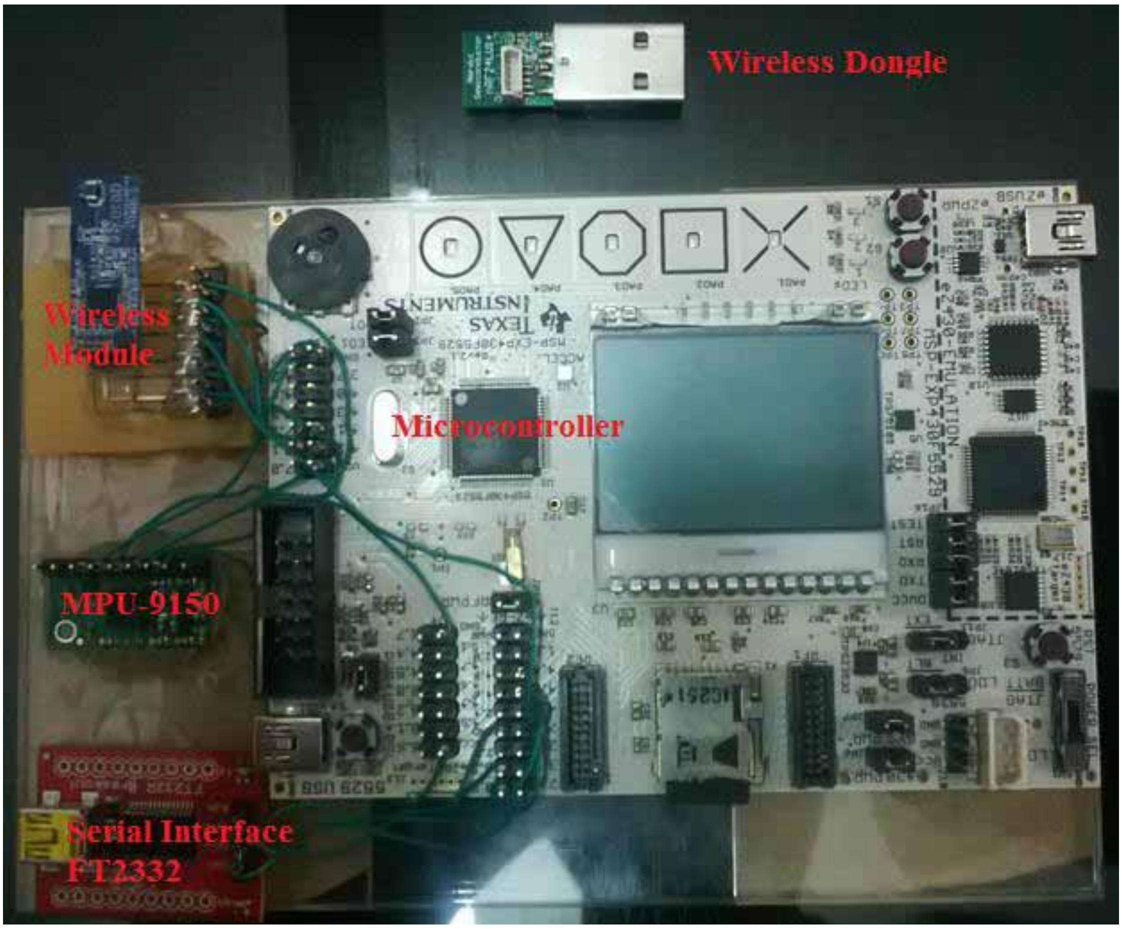


Fig. 4.21: Snapshot of the final implemented hardware

CHAPTER FIVE

METHODOLOGY

5.1. Research Methodology

This thesis was aimed to design MEMS based 6DoF air gyro-mouse. The research was started by formulating the physical requirements and electromechanical considerations of the required system as illustrated in chapter 3 and chapter 4. In fact, as the goals those are illustrated in chapter 1 this thesis aimed to achieve mouse events not mouse accurate cursor motion; where those events include scrolling, clicking and ticking. The mouse events are button clicks but in order to point on the required location on the screen a mouse motion should be performed. While the requirements and goals of this thesis research were clearly defined, it divided into two concepts; the first is the system design and architecture, and the second is the algorithm.

The system design that is presented in chapter 4 as it constructed of individual modules. The modular design is the best engineering design methodology. It simplifies the design since the designer concentrates on single unit that performs specific task(s) independent of other system modules. For example, the MEMS sensor module was designed based on MPU-9150 sensor (see chapter 4) and the module was designed in order to enable the sensor work through I^2C communication bus and 3.3V power supply. Once, the module is connected to 3.3V supply and host microcontroller, it will be ready – by the means of hardware – to start data collection and communication with the host microcontroller. In that way, any problem that could be faced in the MEMS sensor will be capable to be solved regardless of the other systems' components.

On the other hand, the modular design is best suitable for system upgrade and modifications. That comes from the fact that, changing of any components of the system will comprises handling of only its specific module without any adoption of the complete system. For examples, when trying to modify the debugging module that is used to trace out the system response via UART port, only FT232 module will be modified without any engagement of the microcontroller systems, MEMS sensor or any other module. Figure 5.1 illustrated the modular design as a black box with respect to other system modules. The module itself is a black box with respect to other system modules, that means, the other modules are not intended to handle the internal architecture of the specific module, it just knows the input format that should be used to communicate with it, and the output format that will be gotten form it.

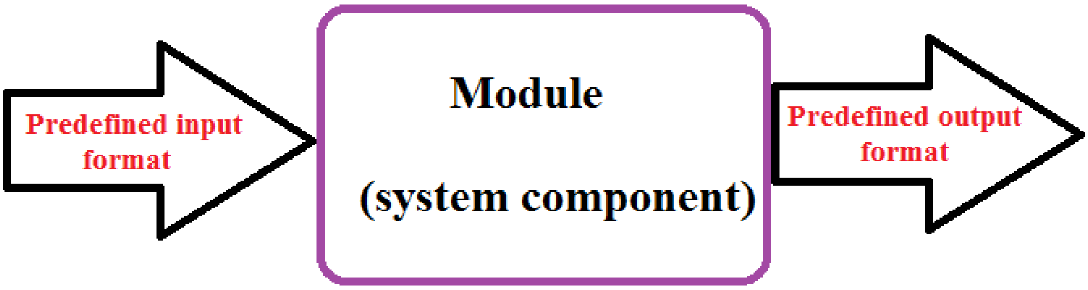


Fig. 5.1: Modular design as black box

The dependence of this thesis research on modular design makes the system design simpler and easy to be modified. It’s important to make the system easily modifiable, because of that, any scientifically successful research should undergo a scientific process that enables to change the concepts, system components, and algorithm many times to reach the target.

Spiral research and design approach was followed during the research and implementation of this thesis that is illustrated in figure 5.2. The spiral approach starts by problem formulation and requirements determining that include the available resources and tools. This is an important step because of that, it's definitely wrong to start a research without clear knowledge about the available resources. The problem formulation is the first step in the research that represents the concepts those are illustrated in chapter 1 of this thesis. Then, the block diagram of the system was designed initially before starting of the detailed system design.

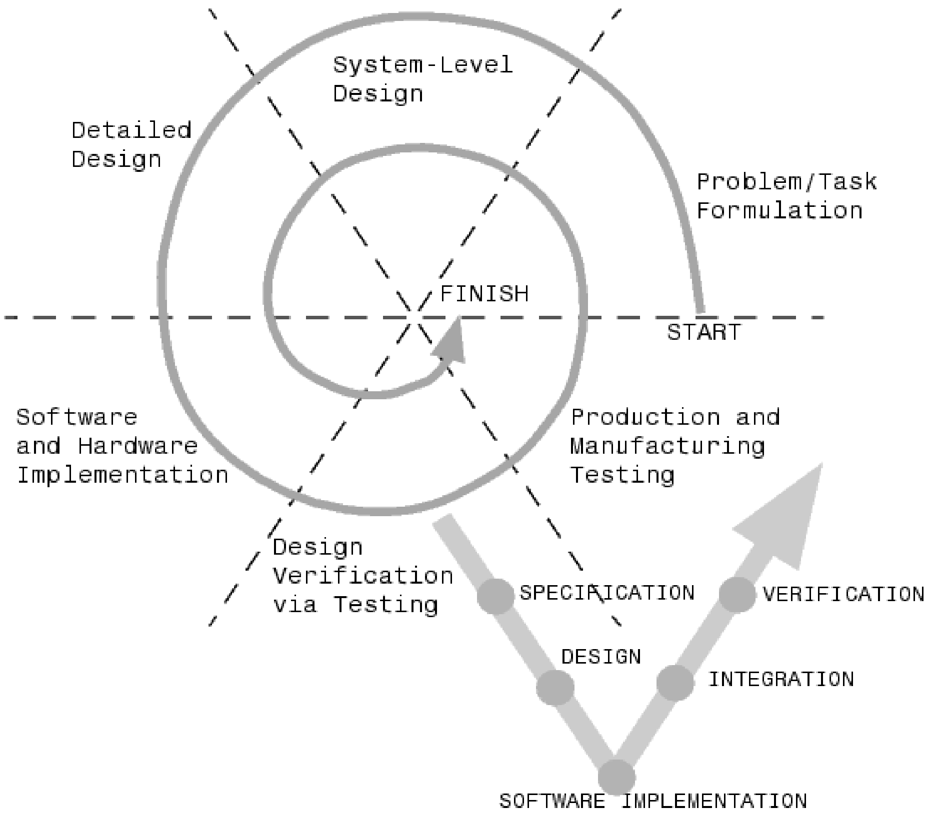


Fig. 5.2: Spiral research and design approach [72]

The detailed system design includes every hardware component and the definition of all firmware / software components that could be used, in addition to the architecture of both, firmware and hardware. The next step is to implement the hardware and software / firmware components. This step includes the algorithm research and development. Normally, the algorithm that is designed in this step represents the main ideas and points of the required algorithm, which will be gotten after modifications of the initial algorithm.

The final step of spiral research and design is to integrate the system and start testing. System integration or engineering system integration means that, connecting all individual modules together forming the complete system and running it at once. Actually, even though all system modules are working individually, problems could be faced after integration that couldn't be seen before it. Thus, after integration and testing, modifications are needed in almost. The required modifications are possible to be in hardware, firmware / software, or the system requirements. So, the loop back again is required to complete the previous process again in order to formulating, design, implementation, and verification / testing of the gotten system.

The spiral process should be still active until reach the required target that is considered to be satisfactory with respect to the system requirements and testing performance.

5.2. Algorithm

The algorithm is the core firmware part of this thesis. The firmware was structured in three layers; hardware abstraction layer, modular layer, and application layer. The hardware abstraction layer (HAL) consists of drivers and direct hardware handling functionality, such as, interrupt initialization, watchdog timer, and power options. The modular layer is based on the HAL layer to complete the flow and control operations of the system. The communication between all modules, computer interfacing, and decision making are functions of this layer.

The third layer is the application layer which consists of the invented algorithm that reads the sensors data and derives the pointer location.

The initial process of the algorithm is to receive the measurement data (i.e. nine separated measurements that represent one measurement for each axis) and to process it to prepare that data for further use. The magnetometer resolution is 13-bit, that means its reading range varies from 0x0000 to 0x1FFF, whereas the accelerometers and gyroscopes resolutions are 16bit all, that means its readings varies from 0x0000 to 0xFFFF. This difference in resolution makes a complexity in data fusion of those sensors. The solution is to normalize all sensors to the same range. Equation 5.1 illustrates the normalization of the magnetometer readings, where “mag” is the original magnetometer reading, and “n_{mag}” is the normalized magnetometer reading. Hence, the normalization of all reading is done for 16bit, and the accelerometers and gyroscopes are already 16bit, then, there is no need to normalize it.

$$n_{mag} = 8 \, . mag \qquad (5.1)$$

Each individual axis sensor sends its measurement as a two byte unsigned short variable, forming 9 unsigned shorts that are subjected to be processed in data fusion process.

The calibration process is the process that determines the corners of the working screen, as four points on the Cartesian coordinate system. Figure 5.3 shows the calibration points. The four corner points determine the working plane of the pointing device. In mathematics, the plane could be determined by three points on space, or two vectors on space. The two vectors in space are shown in figure 5.3 and named **R1** and **R2** respectively.

Initially at start up, the zero calibration of the sensors measurements is determined. The origin is determined by the magnetometer. This comprises that, the measurements of the accelerometer and gyroscope is sets to be (0, 0, 0) in translation and (0, 0, 0) in rotation. And the origin (x_0, y_0, z_0) is determined by equation 5.2 and any further measurement of translation (x_t, y_t, z_t) or rotation (x_r, y_r, z_r) are determined by the equations 5.3 and 5.4.

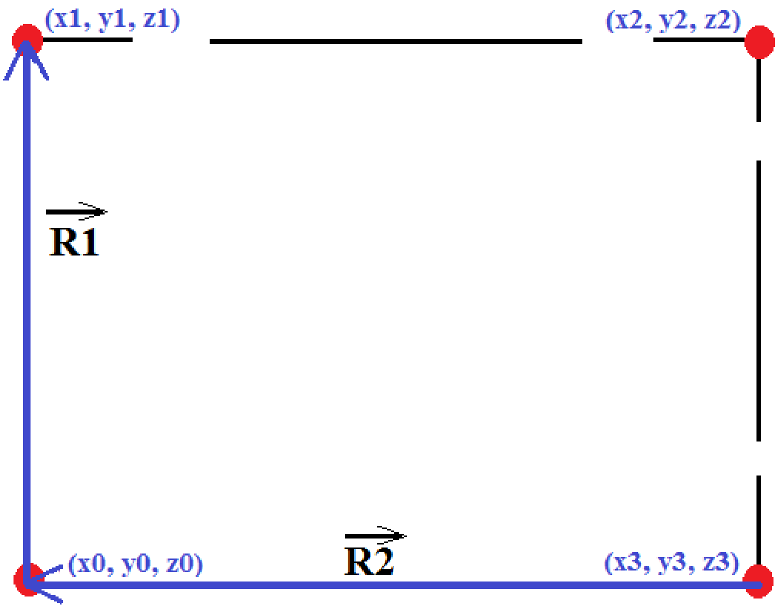


Fig. 5.3: Calibration points of the computer screen

$$(x_0, y_0, z_0) = \left(mag_{x_0}, mag_{y_0}, mag_{z_0}\right) \quad (5.2)$$

$$(x_t, y_t, z_t) = (x_{ti} - x_{t_0}, y_{ti} - y_{t_0}, z_{ti} - z_{t_0}) \quad (5.3)$$

$$(x_r, y_r, z_r) = \left(x_{ri} - x_{r_0}, y_{ri} - y_{r_0}, z_{ri} - z_{r_0}\right) \quad (5.4)$$

Where, x_{ti}, y_{ti}, z_{ti}, x_{ri}, y_{ri}, z_{ri} are the translational and rotational immediate measurements of the correspondent axis, and (mag_{x0}, mag_{y0}, mag_{z0}) are the initial measurements of magnetometers at start of the calibration.

Once the calibration is done, the work plane should be determined by the two vectors **R1** and **R2**. The two vectors is being defined as illustrated in equations 5.5 and 5.6 respectively, where the bold symbols represents vector quantities.

$$\boldsymbol{R1} = (x_1 - x_0)\boldsymbol{i} + (y_1 - y_0)\boldsymbol{j} + (z_1 - z_0)\boldsymbol{k} \quad (5.5)$$

$$\boldsymbol{R2} = (x_0 - x_3)\boldsymbol{i} + (y_0 - y_3)\boldsymbol{j} + (z_0 - z_3)\boldsymbol{k} \quad (5.6)$$

Specifying the coefficients of the equations 5.5 and 5.6 finishes the calibration stage and directly moves the algorithm in the normal running mode. In normal running modes the algorithm is assumed to convert the measurements of the sensors into (x, y, z) Cartesian coordinates with the relative origin (x_0, y_0, z_0) that is the origin of the frame of reference. The frame of reference now is the plane that is defined by the two vectors **R1** and **R2**.

Figure 5.4 shows the new point vector localization that is localized in the normal running modes of the algorithm with respect to reference plane (i.e. frame of reference). Point p(x_p, y_p, z_p) location is defined by the vector **P** that is described in equation 5.7.

$$P = (x_p - x_0, y_p - y_0, z_p - z_o) \quad (5.7)$$

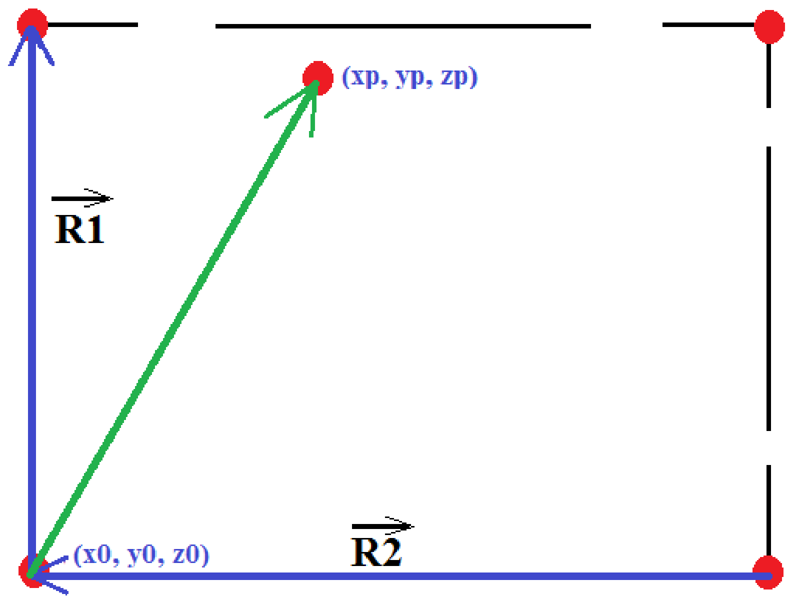


Fig. 5.4: Pointer localization with respect to reference plane

At this point, the physical data is continuously measured and the corresponding vector **P** is calculated to keep tracking of the pointer location. This process continues as long as the calibration process is not repeated. When the calibration process repeated, the overall algorithm will be rested and new origin will be determine and also, new reference plane will be specified according to the previously specified equations and procedure.

This algorithm handles all conditions of the physical measurements from the MEMS sensors except the drift that is caused by the mass-spring collection of the MEMS. This drift is very low and in the modern MEMS it goes smaller and smaller with time division. In addition to that, the calibration will resets all drifts and prevents its accumulation. The goals of this thesis are not to handle the accurate pointer position as well as it aims to handle localization in order to perform the predefined mouse events. Thus, the accurate mouse localization that needs to substitute the drift is oriented to future work and further improvement of the presented research and system.

5.3 Problems and Issues

Many problems and constraints were faced during this research. Some of them solved easily, some of them solved hardly, and some of them remains unsolved and oriented to be solved in the future works. The higher importance to be mentioned problems and constraints are the micromechanical structure issues, the wireless issues, and the resources constraints.

Hence, this thesis is based on 9-axes MEMS, the mechanical structure of the sensors are very critical. The micromechanical structures that are illustrated in section 3.4 are based on mass-spring collection. The calibration of the mass-spring collection also are critical because of that, it's has low shock immunity. Thus, the handling of the sensors should take into accounting the shock behavior of the system. This problem was solved by adding a constraint requirement on the system to re-handle the complete device when it shocks. The solution was that, calibrating the device in every time it powered on, ensuring that, at every power on event the sensors readings will be rested and no accumulating of error is available.

Another point is the problem of the accelerometer principle that is illustrated in section 3.4.1 and shown in figures 3.18. The solution was that, measuring the angle of rotation of the accelerometer device and substituting the physical measurement based on the curve that is shown in figure 3.19. The rotation is being measured by the gyroscope. Thus, the gyroscope has two tasks, the first is to enable the three rotational degrees of freedom (DoF) and the second is to substituting the accelerometer measurement.

The wireless issue that was faced in this research was in fact a resources problem. It was caused by building the wireless system on a development kit that is made by NORDIC Semiconductors that is borrowed by a third party organization. But this development kit was no longer available to complete the development. On the other hand, there was no other equivalent development kit available within the budget and time schedule in order to change the development to be based on it. Thus, and standing from the fact that the wireless functionality is not basic function of this research, the solution was to ignore it and orient it to be future modification point.

The resources constraints are the biggest problem – and especially in Jordan – that faces such contributed and novel researches. In fact, there's no special market in Jordan or even the border countries for the emerging researches resources. Thus, any required component should be supplied from an overseas supplier. This process are being used continuously and repeatedly but it also has many constrains includes the higher prices that the components is gotten, the large delay that is needed to supply some components. Actually, some components could be supplied form the supplier to the researcher in one week, and some could be supplied in one year. In addition to that, the Jordan customs don't handle the issues in simple way, and thus, some components could reach the customs from supplier within one week, but it takes months to become on the hand of the researcher.

Also, some suppliers and manufacturers don't have a predefined way to send part to Jordan. InvenSense is one of those companies, which is the manufacture of the core sensor of this thesis (i.e. MPU-9150). Event though, one sensor has been gotten that was enough to complete the research, it was hard to get it, and it will be hard to get another one.

CHAPTER SIX

RESULTS

6.1 Performance Evaluation

The invented algorithm, design, and concept is resulting a pointing device that works as computer pointer with clicks. Thus, the performance evaluation and testing criteria are similar to those for computer mouse with few modifications and elaborations that comes from the absolute pointer localization without hovering (i.e. mouse HID like input device).

The first criterion that should be achieved is the speed of response with respect to human hand writing. Normally, the human hand writing speed in a 98" whiteboard could be reach to 1m/s. The top speed (i.e. 1m/s) could be reached when the user draws a large circle quickly.

The second criterion is the time response with respect to mouse cursor lag. The lag of the cursor means that, when the pointer is placed on specific location on the computer screen, the software mouse pointer take a noticeable time to move to the pointed location. Many reasons could cause this lag; the software driver design, the firmware driver delay, the computer hardware architecture itself, etc. A good performance pointing device is the device that minimizes this lag to un-noticeable effect.

On the other hand, this thesis uses microcontroller with fixed point calculations. That forces to use mathematical approximations that cause an accumulated error in every single point location estimation process. The error is accumulated over many approximations that include the origin estimation, the normalization of the magnetometer measurements, the vectors algebraic equations, and the substitutions of sensors data fusion. In addition to that, the use of gyroscope to substitute the accelerometer tilting is based on lockup table, while this lockup table is discrete causing a negligible error when working on the accelerometer and gyroscope for single readings, but when making mathematical operations the error may increase and accumulate over the approximation errors. This research shows in the next section the mathematical calculation error with respect to all axes.

Generally, in absolute positioning pointing devices, the projection area that represents the screen has fixed structure that should be mapped to the computer screen which in almost has different aspect ratio. In this case, aspect ratio conversion must be done, which implies a value of conversion error. This thesis will show in the next section that, the aspect ratio of the computer screen is always the same of pointing projection area, and thus, achieving 0% aspect ratio conversion error.

The last criterion that this thesis concerns is the most important one, which is the user satisfactory and evaluation. This criterion is personal and don't depend on any scientific or engineering base. It just could be measured by statistics, when enabling number of people to use the invented device and say their evaluation about it. Their evaluation is very simple which could be in one word like, slow or fast, and may regards to accurate localization and the degree of availability to perform specific task for the contributed device such as clicking, ticking, or scrolling.

The five criteria those are described above in this section were taken into account during the research and design. The next section illustrates the analysis and measurements results of the performance with detailed illustrations.

6.2 Measurements and Records

The contributed algorithm and system design was built and tested using two separated computer machines; one use Windows7 OS and the other uses Windows8 OS. The use of two different machines ensures that, the system has no clear limitations and not based on very limited API's on the machine itself. Four different people used the contributed system and recorded there evaluations due to its performance and idea. The overall results was taken by the two computer and windows machines and by the four users those used the contributed device. The idea of recording the results based on different people ensures that, the results are not selective and don't depend on specific environmental effects or conditions. Those environmental conditions are based on the use, where one may use the contributed device in specific way over the time, thus, some bugs may not be capable to be seen or measured.

The response of the system with movement speed of the cursor is directly depends on the number of efficient measurements of the pointer locations per second that reaches the computer through the HID driver, which is expressed as number of frames per second (fps). Most pointing devices that uses dot pattern or triangulation uses 60fps at max. In fact, the working number of frames per second differs from the actual efficient number of frames per second. Since, there are errors in some frames enforce the system to ignore them. The main error causes are the transmission errors, measurement errors, and delay. So, when working with 60 fps, then the actual efficient number of frames per second will be less than 60.

Figure 6.1 shows the effect of changing the number of frames per second in computer mouse movement. Actually, when drawing a circle using computer mouse, discrete samples of the points that represents the surrounding of the circle will be passed to the computer and the resulted circle will be a connection between those points. When the resolution becomes low, the circle will looks more like straight lines those are connected to gather. But when increasing the resolution, the number of points will increase, and the corresponding straight lines length will be smaller, and thus, the drawing will look more like a real circle. Actually, the resolution depends on the number of frames per second (fps) that represents the number of sample points of that are being passed to the computer in the time unit. As shown on the figure 6.1, when increasing the number of frames per second, the resolution increases significantly.

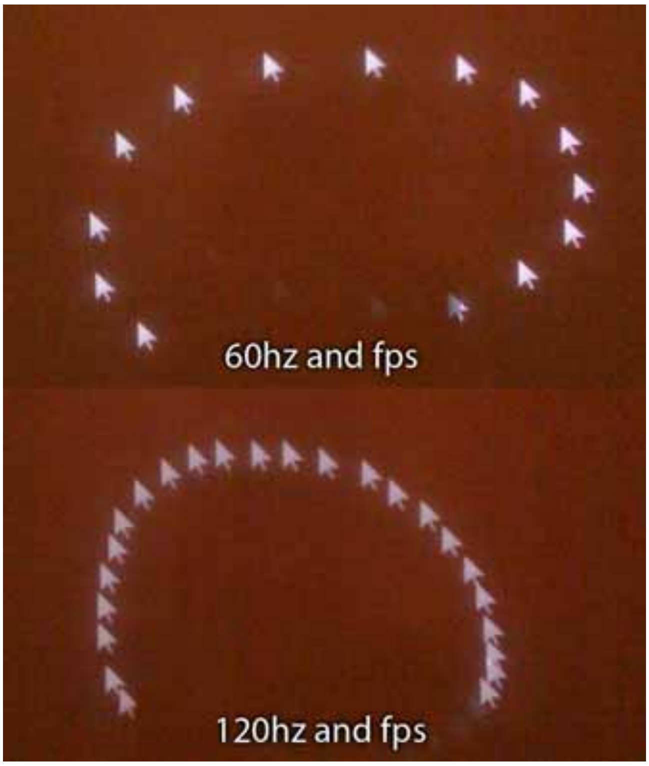


Fig. 6.1: The effect of number of frames per second on the pointer cursor movement [73]

The contributed system is capable to be used in different tolerable values of the number of frames per second. A 30 fps is possible but it is worse, 60 fps is moderate, and 120 fps is very smooth and enough for normal human writing. Also, higher resolution is possible to be enabled such as 240 fps. Figure 6.2 shows the actual result of drawing a circle using the contributed device with different values of frames per second; 30 fps, 60 fps, and 120 fps.

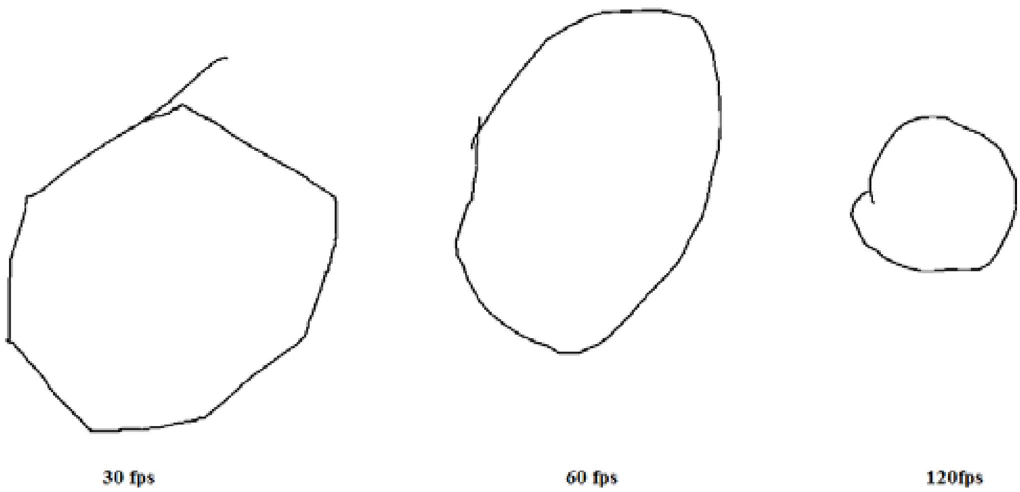


Fig. 6.2: Drawing a circle quickly by hand with different number of fps

The result in figure 6.2 shows that, 120 fps ensures the better performance that is near to normal human writing in ink based whiteboard. The drawn shapes seem to be continuous and no contours are noticeable. The 60 fps is acceptable but it also implies some discontinuities that could be noticeable in some cases, where some of the users those tested the invented device noticed this problem and some of them didn't consider it.

Table 6.1 shows the result of personal users satisfactory regarding to using the contributed device in this thesis. The users were used this device in different ways, almost with internet browsing that includes features of clicking, scrolling, and sometimes ticking. In addition, they tested the contributed device using "Paint Brush" software application in Windows, to test the availability to use the device in normal human writing and drawing (even though this is not the goal of the research but it was somewhat possible), and it's good tool to test the effect of different resolutions (number of frames per second). The results were taken in two resolutions; 60 fps, and 120 fps.

Table 6.1: Results of user's personal evaluation and satisfactory

User number	Is there a lag in cursor	Is there is a problem when moving it quickly (60 fps)	Is there is a problem when moving it quickly (120 fps)	Accurate positioning
1	Not clear	yes	No	No but accepted
2	Not clear	Small	No	No but accepted
3	Not clear	Yes	No	No but accepted
4	Not clear	Yes	No	No but accepted

As it noticeable from the table 6.1, this thesis presented a device with no lag. This comes from the fact that, the calculations that are being made in the invented algorithm are limited, small, and has no overhead on the host microcontroller. Thus, when the measurements are recorded by the MEMS sensor, it directly calculated and passed to the computer via HID driver with very low time with respect to system response.

Table 6.2 bellow illustrates the results of accumulated calculation error in addition to the result of aspect ratio conversion error. It shows that, there is zero error in the aspect ratio conversion. That comes from the fact that, there is actually no aspect ratio conversion. Because of that, the projection screen is always typical to the actual computer viewed screen.

The fixed point calculations result in accumulating error as illustrated in the previous section. Even though this error is small, but it could be avoided by using floating point calculations and ignoring the approximations at old, and this is left to the future work. Table 6.1 shows three trials to measure the localization error. Each trial represents separate experiment with different measurements of the pointer. The process was done as that, a snap shot is to be taken for a specific pointer location, then, the vector **P** is saved. Then, the actual location of the screen pointer is measured and the error is calculated between the actual measurement and the value of P amplitude with its two components x, and y.

Table 6.2: Localization error measurements

Trial	X-axis error	Y-axis error	Total error in the vector **P**	Aspect ratio conversion error
1	1.8%	4.2%	4.6%	0%
2	2.3%	3.9%	4.5%	0%
3	7.0%	7.3%	10.1%	0%
Average	3.7%	5.1%	6.4%	0%

Finally, a comparison of the presented thesis work with a literal works is shown in table 3.6 bellow. The comparison was made in resolution and the response time, in addition to the localization error. Actually, most of researches didn't mention full useful results in their papers. So, there are some not assigned (N/A) criteria in the comparison.

Table 6.3: Results comparison with literal researches

Comparison	**[20]**	**[11]**	**[18]**	**Presented thesis**
Resolution	Stepping is clear, so the resolution is pad in the testing 20" screen	0.2mm / step for low sizes screens but it is not tested over large screens	N/A	1 unit / pixel
Response time	8.4 msec	5.8 msec	<1msec	< 1 msec
Position localization error	N/A	N/A	19%	6.4%

As it well known and illustrated in this thesis previously, the ultrasonic is very pad resolution, this is what make the result of [11] pad in its resolution, in addition to that, it depends on the sound speed making the response time very large relatively with the presented thesis. The position localization error in [18] work is very large, and it didn't mention any information about the resolution.

The table 6.3 ensures that, the results of this thesis is unique and represents advances in the interactive technology world.

A discussion about the recorded results and performance evaluation will be shown in the next chapter; conclusions.

العنوان:	A NOVEL DESIGN FOR MEMS BASED 6-DOF AIR GYRO MOUSA
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الدولة:	الاردن
قواعد المعلومات:	Dissertations
مواضيع:	الخوارزميات، التطور التكنولوجي، المعايير، هندسة البرمجيات
رابط:	https://search.mandumah.com/Record/719068

CHAPTER SEVEN

CONCLUSIONS AND REMARKS

7.1 Conclusions

A 6DoF air gyro pointing device was demonstrated in this thesis research. It aimed to achieve tick, scroll, and click mouse events away from the computer screen and in 3D space. A 9-axes MEMS with 3-axes accelerometer, 3-axes gyroscope, and 3-axes magnetometer was used to trace the position of the pointing device and localize the pointer on the computer screen with HID pointer computer interface. The research was passed through scientific research process and the results was recorded, analyzed, and discussed in chapter 6 of this thesis. The following points were concluded from the thesis research:

- Localization of computer mouse pointer is capable to be designed and implemented using MEMS sensor, but it needs a rigid processing algorithm, accurate calculations, and data fusion of different measurements.
- The MEMS is physical devices measures more expressive data than the traditional sensors that are being used in interactive whiteboards and interactive technology. This measurement needs extremely less processing, thus, extremely less overhead in processing that help in many points. The main point is to remove the lag in the pointer cursor with respect to the user and operating system. In addition to that, the less processing means less engineering system cost.
- The drift and mechanical structure effect in the micromechanical architecture of MEMS needs more sensors data fusion to substitute it, and thus performing accurate pointer localization over time. The basic mouse events (i.e. click, tick, and scroll) could be

achieved in high accuracy with pointer localization that comprises acceptable error, but other functionalities such as drawing needs accurate localizations.

- The use of MEMS can move the interactive technology toward new scope. Hence, it covers large area of applications, not only interactive whiteboards, but it covers all areas of applications that need absolute positioning of mouse pointer.
- Extending of the interactive pens that is used with interactive whiteboards is done in this thesis for 3D in terms of that, the user can handle the board or screen surface without keeping in touch with it. The user can move away from the screen or the board plan and write on it away.
- A 120 fps is enough to get excellent resolution in drawing and fast pointer movements. Also, higher value of frame per second is available when using the presented system. But 60 fps or less shows noticeable problems in the system.

7.2 Future Remarks

The main error that has been gotten in the contributed device was caused by the approximations of the fixed point calculations. The fixed point is simple and needs fewer calculations, but in order to perform better accuracy, the floating point should be implemented. So, the future work should implements the floating point in the contributed algorithm and all mathematical formulation of the model.

To improve the localization and handle the micromechanical structure errors, more research should be done to substitute the drift and errors. Also, more research in data fusion of the nine sensors those are used is required to achieve higher accuracy and precision.

The problem of accelerometer that is presented in section 3.4.1 was solved in this thesis by using gyroscope to measure the tilt angle and then substituting the accelerometer measurement by the tilt angle based on the curve that illustrated in figure 3.19. This thesis implemented a lockup table for figure 3.19. To achieve better accuracy and smoothness, analytical model for the figure could be implemented.

The MEMS sensor should be selected in the future to be shock resistive, because of that, the low shock resistance devices is easily to be damaged. This comes from the fact that, the mass-spring collection of the MEMS is very sensitive to chocks.

On order to simplify the work on this thesis, the angles of the plan are handled implicitly in the measurement scale. Thus, the algorithm doesn't show the formulation and vector calculations in case of that, the user are moving in the room. Actually, this movement of user represents a movement of the working plane in 3D space. This movement is being handled intentionally implicitly in the measurement itself not in the algorithm. So, in order to make the algorithm more rigid and clear, modifications should be made in such, the angles of movement should be handled explicitly in the algorithm formulation.

ABSTRACT

Ahmad Mahmoud Bisher. A Novel Design for MEMS based 6DOF Air Gyro Mouse. Master of Science Thesis, Department of Computer Engineering, Yarmouk University, 2014 (Supervisor: Dr. Mahmood Al-Khasweneh).

The wide adoption of interactive technology through a daily personal use encourages the researchers to continue research and modifications on this field. Nowadays, the interactive whiteboards becomes essential asset in wide number of schools, universities, presentation halls, and others. The problems of passive and active interactive whiteboards induced this research to look behind to adopt new technology on that field. On the other hand, the rise of MEMS technology enabled to handle an IC that could be implemented in any consumer electronics device to measure motion. This thesis contributes a design and methodology for using MEMS to build a 6 degree of freedom (DOF) pointing device to be used with interactive whiteboards, where a 9-axes MEMS device that consists of 3-axes gyroscope, 3-axes accelerometer and 3-axes magnetometer was adopted and used in embedded system that is implementing air gyro mouse functionality. The system was built and tested using performance evaluation criteria, where in such, no special passive whiteboard is needed, and no active whiteboard is being used. Just, a pointing device that is capable to deal with any plane surface as a computer screen when calibrating it using the contributed calibration algorithm.

ABSTRACT (عربي)

التطور الكبير في التكنولوجيا التفاعلية والذي وضعها في الاستخدام اليومي والشخصي يمثل حافزا كبيرا للباحثين للمضي قدما بابحاثهم وتطويراتهم المقترحة لتنمية هذه التكنولوجيا. الالواح التفاعلية اصبحت في الوقت الحاضر من المكونات والادوات الاساسية في نطاق واسع من المدارس, الجامعات, قاعات العرض بالاضافة الى العديد من الاستخدامات الاخرى. التحديات والمشكلات التي تواجه الالواح التفاعلية النشطة والسلبية – كلاهما – تثمل محفزا رئيسا لهذا البحث بحثا عن تكنولوجيا متقدمة مغايرة نوعا ما لحل هذه المشكلات و لتطوير احتياجات المستخدمين المتنامية. ان التطور الحاصل في الانظمة الالكتروميكانيكية الميكروية المصاحب للتكنولوجيا النانوية جعل بالامكان تطوير مجسات لقياس الحركة على شكل دارات متكاملة بحيث تمكن الباحثين من تضمين هذه المجسات في تطبيقات الكترونيات المستهلكين التجارية لقياس مختلف انواع الحركة. ومن هذا المنطلق فان هذا البحث المقدم على شكل رسالة ماجستير يقوم بابتكار تصميم وخوارزمية لاستخدام الانظمة الالكتروميكانيكية الدقيقة لبناء جهاز مؤشر كمبيوتر ذو 6 درجات من حرية الحركة بحيث يستخدم مع الالواح التفاعلية للتأشير والكتابة. تم استخدام دائرة متكاملة تحتوي على مجسات لقياس حركة 9 محاور والذي يتكون من 3 محاور لقياس الحركة الدورانية, 3 محاور لقياس الحركة الانزلاقية, و3 محاور لقياس المجال المغناطيسي, وتم تصميمه بحيث يستخدم كجزء من نظام متضمن للتمكن من اداء مهمات فأرة كمبيوتر ثلاثية الابعاد تعتمد على الدوران والحركة الدورانية للاحداثيات. تم بناء النظام المقدم وفحصه حسب معايير تقييم الاداء وتم تحقيق اهدافه بدون الحاجة لأية الواح سواء سلبية او فعالة. تعتمد فكرة التطبيق من وجهة نظر المستخدم على اعتبار اي سطح بحيث يكون هو شاشة الحاسوب او اسقاطها ويتم تحديد حدود هذا السطح ومعادلاته البارامترية من خلال خوارزمية معايرة السطح المبتكرة في هذه الرسالة.

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A NOVEL DESIGN FOR MEMS BASED 6-DOF AIR GYRO MOUSE

By

Ahmad Mahmoud Bisher

Supervisor

Dr. Mahmood Al-khassaweneh

Program: Master of Science in Computer Engineering / Embedded Systems Engineering

July, 2014

A NOVEL DESIGN FOR MEMS BASED 6-DOF AIR GYRO MOUSE

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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in the Department of Computer Engineering, Yarmouk University, Irbid, Jordan.

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DEDICATION

To them

… more than any time before

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Ahmad Bisher

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ABSTRACT

Ahmad Mahmoud Bisher. A Novel Design for MEMS based 6DOF Air Gyro Mouse. Master of Science Thesis, Department of Computer Engineering, Yarmouk University, 2014 (Supervisor: Dr. Mahmood Al-Khasweneh).

The wide adoption of interactive technology through a daily personal use encourages the researchers to continue research and modifications on this field. Nowadays, the interactive whiteboards becomes essential asset in wide number of schools, universities, presentation halls, and others. The problems of passive and active interactive whiteboards induced this research to look behind to adopt new technology on that field. On the other hand, the rise of MEMS technology enabled to handle an IC that could be implemented in any consumer electronics device to measure motion. This thesis contributes a design and methodology for using MEMS to build a 6 degree of freedom (DOF) pointing device to be used with interactive whiteboards, where a 9-axes MEMS device that consists of 3-axes gyroscope, 3-axes accelerometer and 3-axes magnetometer was adopted and used in embedded system that is implementing air gyro mouse functionality. The system was built and tested using performance evaluation criteria, where in such, no special passive whiteboard is needed, and no active whiteboard is being used. Just, a pointing device that is capable to deal with any plane surface as a computer screen when calibrating it using the contributed calibration algorithm.

CHAPTER ONE

INTRODUCTION

1.1 Introduction

Interactive technology is focuses on direct human interaction with computer systems. Basically, the touch screen with multi touch features is simple interactive methodology that makes the gap between human and computer less than ever. The main concern in interactive input / output devices is to replace the conventional computer I/O devices by direct human commanding; like voice, touch, or body language. The interactive writing boards become a hot area of research in addition to its large scale of use in the market [1]. For example, around 1000 interactive board were sold in Jordan market during 2012 [2].

Interactive boards in modern technology replaces the conventional whiteboards with a lot of advantages; there is no ink, so, it's clean and green; the use of ink for whiteboards causes healthy effects in addition to many environmental effects. In addition, the interactive boards are smart in such a way it enables to use full computer features on class board. Figure (1.1) shows a sample interactive board that is capable to be used for writing using pen, or data show presentation, or even both in the same time. The interactive boards could be considered as large touch screens of a computer [1] [3].

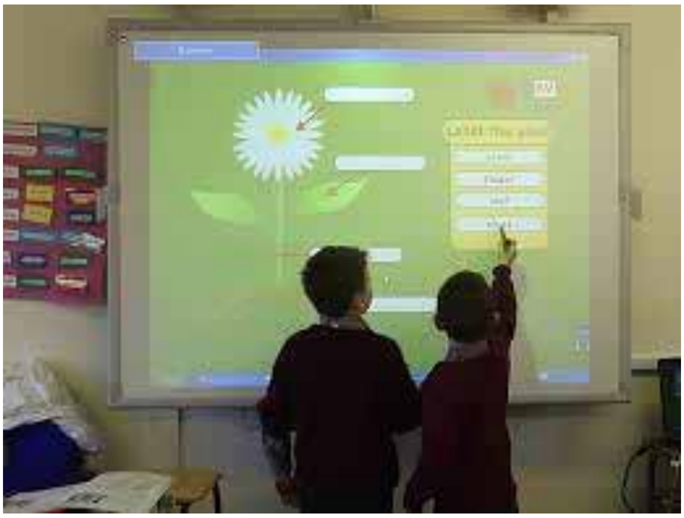

Fig. 1.1: An interactive board [4]

In general the whiteboards are divided into two categories; active and passive boards. The user is able to write using his / her finger or any pointing tool in the case of active boards, while in passive interactive boards, a dedicated pen is designed to write and to point on the board. The advantage of passive board over the active one is that, the passive board are very simple and don't has any electronic structure, thus, no maintenance needed, no calibration, and the output resolution is more controllable and could be relatively high [5].

The interactive boards are being used in education, class rooms, presentation and training rooms, studios, and other applications. Where the user are pointing directly to the board in order to write or perform a mouse event. In presentations, the instructor or presenter are moving inside the room, but when he / she needs to perform any action on the board he / she should return back near the board and directly click on it. Some actions that the user do frequently is not writing, but scroll, tick or click [1] [6].

The interactive boards nowadays implement many physical and engineering concepts to get the location of the pointer coordinates with respect to the board. Ultrasonic and resistive are older technologies; infrared and vision based are the mostly widely used technologies that falls under research at this time. This thesis presents a MEMS (Micro Electro Mechanical Systems) interactive pointing in 3D with respect to an interactive white board. This is basically the adaptation of MEMS sensors to measure the free space 3D location of mouse pointer absolutely. The MEMS motion sensor falls under emergent researches that suspected to make revolutions in the area of interactive boards and interactive technology [6].

In order to perform the mouse events in 3D space with high reliability, all of them will be used in this thesis; accelerometer, gyroscope, and magnetometer. The core unit of the proposed system is 9-axes MEMS motion sensing device. The concept of nine axes is that, there are different measurements with respect to either axis of motion or the measurement type itself. Three axes accelerometer enables to measure the translation of the target in 3D space, three axes gyroscope returns instantaneous angular rotation in 3D space, and the magnetic field of the Earth is capable to be measured using three axes magnetometer. Thus, the total is 9-axes motion sensing.

With respect to interactive boards, the writing pen could be represented as mouse pointer in either 2D or 3D. To calibrate the writing pen with PC software mouse pointer the 3D localization sensors should measure the 3D coordinate of the pen and calibrate it with the computer screen parameters, and interface it with the PC.

To measure the mouse motion in 3D space, this thesis presents relative and absolute motion detection, the relative done via six degree of freedom motion measurement by the use of accelerometer and gyroscope to measure the relative translation and rotation. The 3-axes magnetometer will be adopted in this thesis to measure the absolute referencing of the frame of reference, in addition to calibrating the interactive board.

Interactive board calibration is the process that used to determine the frame of the board or the area of display with respect to touch. This task is done by a procedure that displays a reference points on the screen and command the user to touch these points successively. The calibration program measure the relative geometry between the calibration points and set the border outline dimensions of the screen.

By concept, the motion measurement could be done with respect to different variables, where those are expressed as axes. The measurement axes could be physical motion axes in space or another physical axes that could be used as measuring variable that are capable to be manipulated to measure some motion properties[7].

The motion sensing principles that involved in this thesis are three types that would enable to measure the desired relative motion, proper speed, and other physical parameters in a relative space. The involved sensors are [7]:

- Accelerometer
- Gyroscope
- Magnetometer

The accelerometers are devices that specially designed to measure the linear translational motion of an object in terms of it linear acceleration. The gyroscopes are very meticulous devices are being designed in order to measure the angular motion in terms of angular speed. While the magnetometer measures the vector components of the Earth magnetic field [8].

From large mechanical device to an integrated circuits (IC), the motion sensors where adapted through decades. The nano-technology enables to build the accelerometer, gyroscope, magnetometer, and others in small chips. That part of the nano-technology is known as MEMS which regards to Micro (or Micro Machined) Electro Mechanical Systems [8].

The rise of MEMS technology makes a high contribution on those devices making them available in constrained embedded systems. Nowadays, gyroscope, accelerometer, and magnetometers become available in consumer electronics like mobile phone. The evolution of MEMS opens new research based on motion sensors in embedded systems [9].

1.2 Motivation

Interactive boards are big displays that transfer the computer screen on a large whiteboard via data show projector. The size of interactive board varies from few inches to hundreds of inches. As normal white boards, the presenter or instructor should be close to the board when writing on it, while he / she move inside the room during the lecture or meeting. The reason that force the instructor or presenter to be close to the board is that, the sensing devices that sense the pen or pointer location are two dimensional sensors. It's two dimensional sensors by the means of its scale, where the pointer should be close to the board to be sensed and it’s localized. Thus, the localization is done in two dimensional scopes (i.e. plane) only. This comes from the fact that, the most interactive white boards use sensors placed on the board itself. It could be mounted cameras on the board corners, IR detectors, ultrasonic receivers placed on predefined line on the board, or such.

When the presenter or instructor moves away from screen, many tasks he / she could do while moving away. There shouldn't be a need to get back to the board in order to do some simple and repetitive functions, like sliding. In traditional data show screens, a laser pointer is being used to point on the screen while the presenter is away. In addition, a pointer with control keys is being used with very simple functionality that is to control sliding forward and backward only.

When scrolling the presentation slides - for example - the user should be close to the board, while he / she almost need to stay away. This makes a need to invent a solution for the user; it should not be the traditional presentation wireless pointer. Conventional pointer are a wireless keys with laser pointer, it enables to slide on and back. The interactive technology should try to solve this problem [1] [3] [6].

To enable user input out of the plane, a three dimensional scope should be introduced. When moving inside an indoor area, free space input device should be used. Modern researches were involved in implementing three dimensional input devices for personal computer applications. The most modern and efficient researches will be discussed in chapter two. Those researches generally are specified for specific application with many limitations and constraints. This induce to keep going in that field to present novel researches in the field of interactive technology in general, and in the field of three dimensional interaction with interactive devices in different applications and generalized forms.

Another issue - rather than sliding-, the user needs to tick a checking box, or press a button while he moves around in the class room, ticking are shown in figure (1.2). This couldn't be achieved using the wireless pointer that is commonly used in slide show scrolling with laser pointing.

Fig. 1.2: ticking event [MS-Windows pictures]

KETAB Technologies Inc. is a Jordanian entrepreneur company working in interactive board's technology and educational supplies, while their market is Middle East. KETAB's market analysis strongly recommends starting researches to solve these problems. Hence, the interactive technology aims to make the computer system more life realistic, more reliable, and more friendly, such problems should be solved even though it do not considered as simple problem that could be implemented in classical way.

The companies that work in interactive technology like KETAB Technologies, and others, are continuously pushes the researchers to start researches in the advances of interactive technology. Those researches are either new solution of existed problems, or optimizations of current solutions. This thesis presents a novel research for interactive board technology interaction that is specialized in input device to make it more user satisfactory, generalized, and optimized.

The researches that concerns interactive technology in either two dimensions or three dimensions is not consider the modern motion sensors. The rise of MEMS based relative motion sensing will definitely assists in advances of space motion measurements in interactive technology in either output or input devices.

1.3 Problem Statement

The motivation of this research was started from the needs and problems of the current interactive screens, boards, and technology tools. The main events that the user needs to perform while he / she is locating away from the screen are:

- Ticking
- Scrolling
- Clicking
- Sliding
- Pointing

The creative solution of such problems needs three dimensional mouse events without mouse hovering. While the user entertains with the interactive board normal pen close to the board, he / she needs to make that pen realistic in 3D while moving away from the board. To implement such system, measurement of motion in 3D space should be contributed in reliable and efficient methodology resulting of a meaningful sensing or measurement that can be processed to localize the location of user's hand in order to move the mouse cursor into board coordinate that is relative to the user's hand, assuming that the user catches a device in his / her hand. Calibration of the board with respect to the contributed device is necessary.

While some researches try to solve the 3D mouse issues, the methodologies of those researches were concerns an ultrasonic triangulation, infrared triangulation, and multi-vision systems in most.

In fact, the resolution of such device is critical issue, in addition to size, and cost. The most practically applied researches on 3D mouse, uses conventional techniques that have many constraints and many disadvantages. The most known 3D air bat - SMK Link Electronics - are based on ultrasonic triangulation principle. But as it is scientifically known, the resolution of ultrasound triangulation is not proper for such technology usage, it has very bad resolution while working in standard common display area (i.e. 48" - 99"), further of working in large display size (i.e. more than 99" diagonal).In addition, the ultrasound transmitters / receivers are highly affected able by any ultrasound source that speaking around and power angry with respect to embedded systems scale [10].

The common three dimensional mice, are commonly known as bats, wands or flying mice, and those are almost three degree of freedom and uses either ultrasound triangulation (like SMK Link Electronics gyration mouse) or infrared (IR) range estimation (like Wii tracking mouse). The IR range estimation air mice have the same disadvantages of the ultrasonic mice, in addition to its higher cost and the affectability by high wavelength lighting [6] [10].

Another problem in such devices is that, the orientation of the device couldn't be accurate, the ultrasonic device transmits the sound in all directions and if it positioned in opposite direction of the board, it may be detected by the receivers due to reflections. This problem is common in IR devices, since, it is very noticeable in TV remote control devices (when the battery of the remote controller is good, the TV will receive the control key even though the remote controller are pointed out of the TV with 90^o degree, or even more). The orientation of the mouse device is important and the PC shouldn't recognize a mouse event unless the devices are pointing on the board or screen [6] [10].

The vision systems are very costly, and needs very heavy processing power, in addition to its large size with respect to consumer electronics scale, while this size could be avoided using other emerging technologies.

Also, the degree of freedom could be one problem of air gyration 3D input devices. Three degrees of freedom could measure the movement of the pointer in x-y coordinates, only 3DOF. The novel research that considers 3D input device should handles 6DOF. The question will be that, what is the need of 6DOF. The 6DOF is consists of three translational degrees of freedom, and three rotational degrees of freedom. The translational DOF's localizes the movement of the pointer where the rotational DOF's detects the orientation of the pointer; in addition, it is needed for substitutions of translational motion drift errors.

So, this thesis aims to contribute a 3D air gyration device that generates mouse events in 3D space with high resolution cursor localization and accurate orientation detection. The motion detection in 3D space is assumed to be 6DoF via MEMS motion detection device.

The MEMS motion sensors ensure high reliability design in terms of cost, performance, size, power, accuracy, and tolerance.

1.4 Contribution and Objectives

The last two sections, "Motivation" and "Problem Statement", presents the market needs and the recommendations plus problems that lead to start this research. So, the objectives of this research are the following:

1) To study, design, and implement MEMS motion sensors in order to measure the 6DoF motion of an air flying device. This flying device represents an input device for personal computer to simulate the performance of conventional mouse.
2) To implement a significant resolution algorithm that process the MEMS motion sensors and localize the mouse pointer position. The MEMS output is a relative physical variables data that represents proper linear acceleration, proper angular speed, and the magnetic field measurement.

3) To develop and implement orientation measurement algorithm via MEMS motion sensors.
4) To develop and implement a wireless mouse data communication to communicate between the 6DOF input device and the computer.
5) To develop a mouse driver on PC. This driver is based on USB communication protocol.
6) To develop and implement tick, scroll, and click mouse events, while those events are the most needed for the user while he / she is rooming inside the presentation hall.
7) To develop a screen / board calibration program to calibrate the flying air gyro mouse.

The goals of this thesis will be achieved with contributions. The methodology contains many contributions in the interactive technology. Those contributions could be summarized as the following:

1) The use of MEMS motion sensors (Accelerometer, Gyroscope, and Magnetometer) in order to detect the free three dimensional space mouse device movements.
2) The six degree of freedom motion detection will be available now by the means of gyroscope angular rotation measurement and accelerometer linear translation measurement.
3) The frame of reference is capable to be determined by implementing an algorithm to process the data of the 3-axes magnetometer.
4) To develop a board / screen calibration algorithm that works properly with the contributed 6DOF free air model

These contributions on interactive displays technology are expected to change the way the technology going on and add a new scope of reliable, efficient, small size, light weight, and cost efficient absolute coordinates mouse controlling device in three dimensional spaces. The use of MEMS in interactive boards to measure 3D free space running is a complex methodology because of the drifts and errors in micromechanical parts that the MEMS motion sensors depends on, so, getting position localization on this thesis represent a novel contribution.

This thesis will demonstrates these contributions and open a wide discussion and research area in that field.

1.5 Thesis Organization

This thesis is organized in seven core chapters. The chapters describe the complete work and the detailed thesis research.

The first chapter is an introduction to the thesis. It illustrates the thesis goal and the theory principle behind it. The motivation of the work and the scope of the research field are shown followed by the problem statements which shows the problem corners that is subjected to be solved. And the suggested solutions for the stated problems are presented in terms of the thesis goals. The contribution points are described significantly at the end of chapter.

Literal survey was made in the second chapter. It shows some most related researches. Those researches are related to this thesis work from one side at least. The selected related work could be related to this thesis either in algorithm, one or more goal, generalized system or sub-system, measurements and analysis, or such.

Theory behind the presented thesis research is shown in chapter three. The presented theory is related to all fields of this research, including physics, technology, and related considerations.

The fourth chapter presents the engineering system architecture; hardware and firmware components and hierarchy. The detailed hardware components are demonstrated and explained. The firmware architecture and programming techniques also presented, in addition to computer interface, and calibration.

The methodology of research illustrated in the fifth chapter. The research process, design considerations and strategies, implementation, and issues are discussed in this chapter.

The results that are shown in chapter six are concerning the estimation parameters, performance measurements, evaluation, and measurements. In addition to analysis of results and comparison with the most known and related researches that concerns on the same goals.

In chapter seven, the conclusions were discussed. The conclusions include important remarks on the research, in addition to suggestions for future works over the same research.

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