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A Remotely Operated Multi-Tracked Vehicle for Subterranean Exploration of Gopher Tortoise Burrows

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science
Department of Mechanical Engineering
College of Engineering
University of South Florida

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Rasim Guldiken, Ph.D.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The gopher tortoise is a land tortoise living in the southeastern United States. It is a species in decline and is listed as threatened or endangered in six different states. The gopher (as commonly referred) digs burrows that it uses for many reasons and spends most of its time underground. Problems occur when trying to estimate a population because a gopher tortoise digs more than one burrow. This thesis demonstrates an innovative way to survey and investigate a gopher tortoise burrow hole by using a multi-tracked remotely operated vehicle. The vehicle carried two cameras (fore and aft) and was equipped with a microphone and LED illumination. It has tracks on four sides to increase its propulsion ratio. Its performance was evaluated in a sand pit where parameters such as incline could be controlled, and in an actual tortoise burrow. This research was done in conjunction with the Hillsborough County Parks and Recreation Department.

CHAPTER 1: BACKGROUND

1.1 Fundamentals

The gopher tortoise (Gopherus polyphemus) is a moderately-sized, land turtle, averaging 9-11 inches in length. The gopher (as commonly referred) is distributed in upland habitats throughout the coastal plain of the southeastern United States. Most of the vegetative regions include longleaf pine-oak, xeric hammock, and sand pine-scrub oak ridge. The majority of the population is located in north-central Florida and southern Georgia [1].

Figure 1: Gopherus Polyphemus (Gopher Tortoise Council).

Figure 2: Geographical Range of the Gopher Tortoise (Gopher Tortoise Council).

The gopher tortoise spends about 80-90% of its time underground in its burrows. One gopher will have several burrows that it digs with its spade-like claws [2]. These claws have allowed the gopher tortoise to adapt to its habitat and utilize the dug burrows in many useful ways.

Figure 3: Gopher Tortoise Forefoot with Claws for Digging (Gopher Tortoise Council).

The burrow is the center of the gopher's habitat. It is used for shelter, escaping inclement weather, and a site for feeding and reproduction, among others things [3]. One of the most important jobs of the burrow is keeping the gopher tortoise cool during the hot summer months. It's used heavily for thermoregulatory purposes [4]. Over 362 different species, including the gopher frog (Rana capito), eastern indigo snake (Drymarchon corais couperi), Florida pine snake (Pituophis melanoleucus mugitus), and Florida mouse (Podomys floridanus) use the burrows in one way or another. For this reason, the gopher tortoise has been referred to as a "keystone species" [5].

Figure 4: A Gopher Tortoise Burrow.

Populations of the gopher tortoise have been decreasing at an accelerating rate since the 1980s and are continuing to diminish today [1][6]. Researchers continue to study the decline of the gopher tortoise population. The three major factors contributing to the decline are habitat loss, fragmentation, and degradation [6]. For this reason, the gopher tortoise is listed as a threatened species in Alabama, Georgia, Florida, Mississippi, Louisiana, and South Carolina (as endangered). They are given legal protection and a permit is required to "possess, study, directly take, harass, or relocate gopher tortoises" [7].

There has been a growing need for more research on gopher tortoise conservation. Since gophers spend most of their time underground, a problem arises when trying to estimate population. A challenge is the act of surveying and investigating the gopher burrows. This thesis involves developing a unique, multi-tracked (tracks on 4 sides) robotic vehicle that could be operated underground to give the user a view of the burrow and any potential occupants. The Hillsborough County Parks and Recreation Department requested a solution to this problem and were helpful in providing a test site for the vehicle.

1.2 Burrow Characteristics

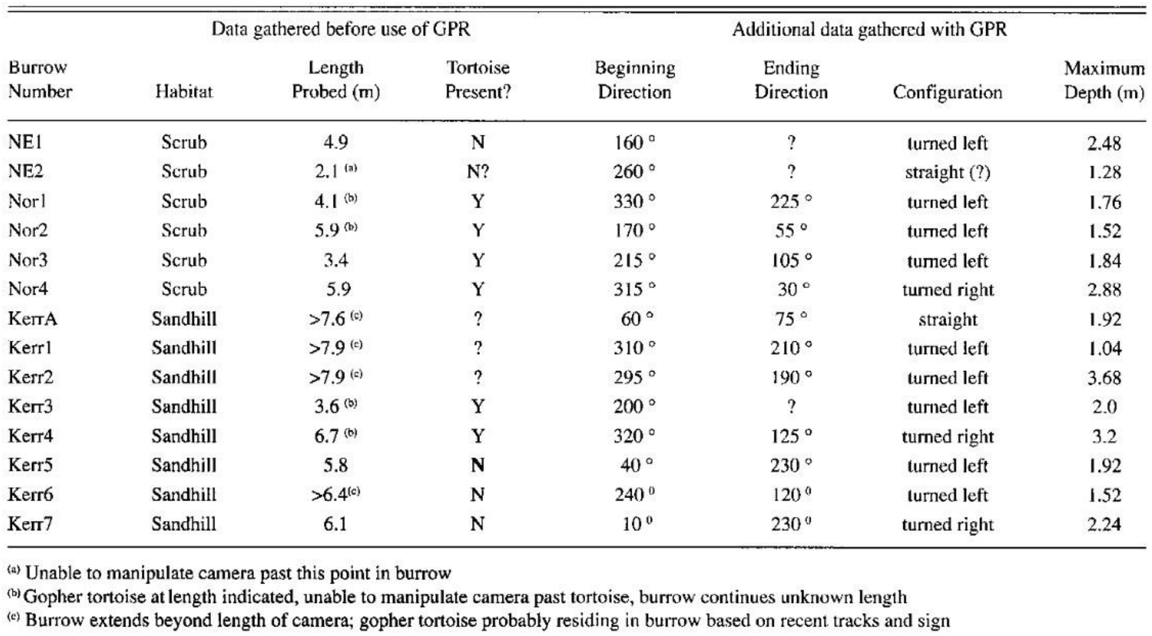
The gopher tortoise most commonly burrows in sandy and well-drained soils [1]. The gopher prefers easy digging, although in northern regions, they have been known to dig in dense clay soils [1]. During winter months or times with heavy rainfall, burrows can become flooded. Researchers have observed on multiple occasions gopher tortoises that were completely submersed in water flooded burrows [8].

On average, burrow length ranges between 3-6 meters (9.8-19.7 ft), depth 2 meters (6.6 ft), and angle of decline about 20-35 degrees [7][9]. The gopher tortoise digs a hole just big enough for itself, meaning the size of the tortoise is very close to the size of the burrow. By measuring burrow widths in a given region, an estimation of that entire population's physical size can be determined [10]. Burrow widths start at 5 cm (2.0 in) for hatchlings and increase to at least 23 cm (9.1 in) for adults. This thesis will focus on adult size burrows that are big enough for a motorized vehicle to fit inside.

Figure 5: Rear of Gopher Tortoise Inside Burrow (myFWC).

The burrow path and structure varies with the habitat it is dug in. In soft sand, burrows are straighter than in other soil types where roots and rocks cause the tortoise to change direction [7]. In fact, some burrows make multiple direction changes, 180 degree turns, and may even descend in a steep corkscrew trajectory [7][9][11]. As can be seen from Table 1, only 2 out of 14 burrows in this Florida study had straight configurations.

Table 1: Ground Penetrating Radar Burrow Data [11].



Data gathered before use of GPR				Additional data gathered with GPR			
Burrow Number	Habitat	Length Probed (m)	Tortoise Present?	Beginning Direction	Ending Direction	Configuration	Maximum Depth (m)
NE1	Scrub	4.9	N	160 °	?	turned left	2.48
NE2	Scrub	2.1 (a)	N?	260 °	?	straight (?)	1.28
Nor1	Scrub	4.1 (b)	Y	330 °	225 °	turned left	1.76
Nor2	Scrub	5.9 (b)	Y	170 °	55 °	turned left	1.52
Nor3	Scrub	3.4	Y	215 °	105 °	turned left	1.84
Nor4	Scrub	5.9	Y	315 °	30 °	turned right	2.88
KerrA	Sandhill	>7.6 (c)	?	60 °	75 °	straight	1.92
Kerr1	Sandhill	>7.9 (c)	?	310 °	210 °	turned left	1.04
Kerr2	Sandhill	>7.9 (c)	?	295 °	190 °	turned left	3.68
Kerr3	Sandhill	3.6 (b)	Y	200 °	?	turned left	2.0
Kerr4	Sandhill	6.7 (b)	Y	320 °	125 °	turned right	3.2
Kerr5	Sandhill	5.8	N	40 °	230 °	turned left	1.92
Kerr6	Sandhill	>6.4(c)	N	240 °	120 °	turned left	1.52
Kerr7	Sandhill	6.1	N	10 °	230 °	turned right	2.24

(a) Unable to manipulate camera past this point in burrow
(b) Gopher tortoise at length indicated, unable to manipulate camera past tortoise, burrow continues unknown length
(c) Burrow extends beyond length of camera; gopher tortoise probably residing in burrow based on recent tracks and sign

The burrow height is usually very close to half the burrow width, resulting in a distinctive "half moon" shape to the burrow entrance [9]. This shape continues until the very end of the burrow, which is usually enlarged slightly so that the tortoise can more easily turn around.

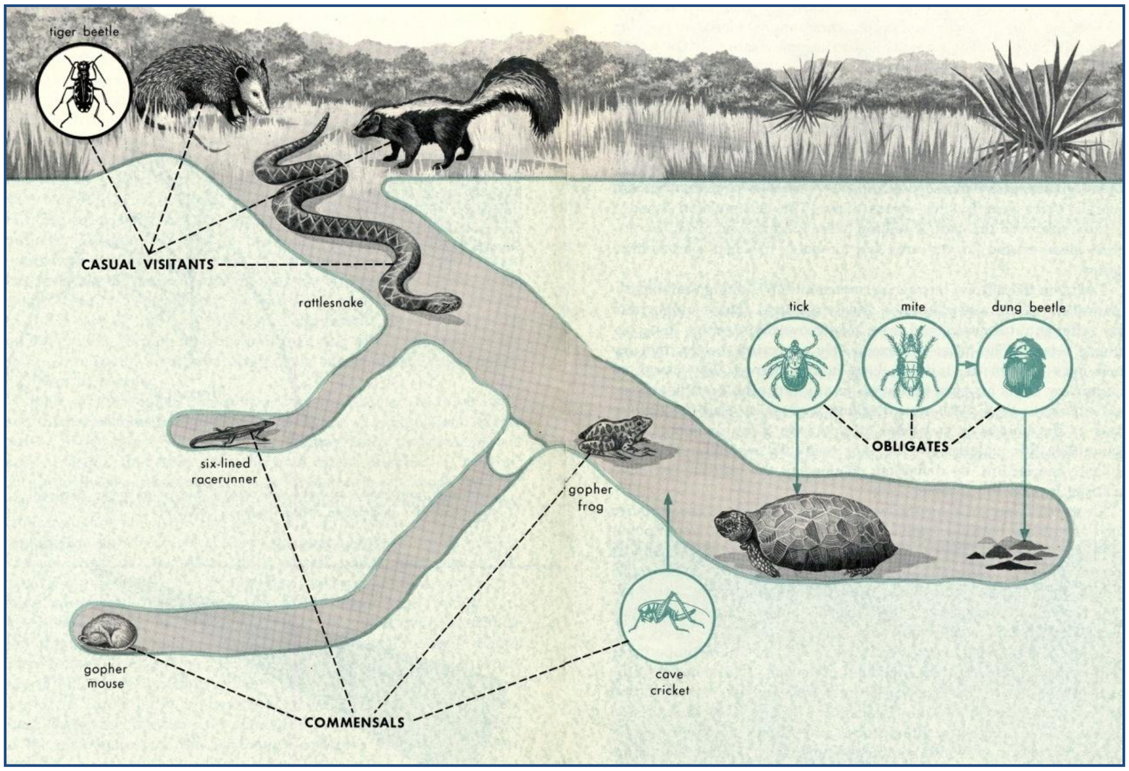


Figure 6: Gopher Tortoise Burrow with Associates (Gopher Tortoise Council).

CHAPTER 2: PRIOR RESEARCH

2.1 Previous Gopher Tortoise Survey Methods

It is essential that population estimates are accurate. These estimates are used in determining which habitats are destroyed for human development and also if relocation projects are needed [7].

There are various methods that have been used to estimate gopher tortoise populations. Since tortoises dig more than one hole, counting the burrows will give you a greatly inflated, inaccurate representation of the population size.

The first step in estimating gopher tortoise populations is to first find the number of burrows. As this can be a lengthy process of its own, there are many developed methods that are used to estimate the number of burrows. The most popular methods are strip transect, line transect, total count, and sample count methods [12]. The strip transect method uses “striped” width areas in the study location that are surveyed. Then, this data is extrapolated to find population for the entire region.

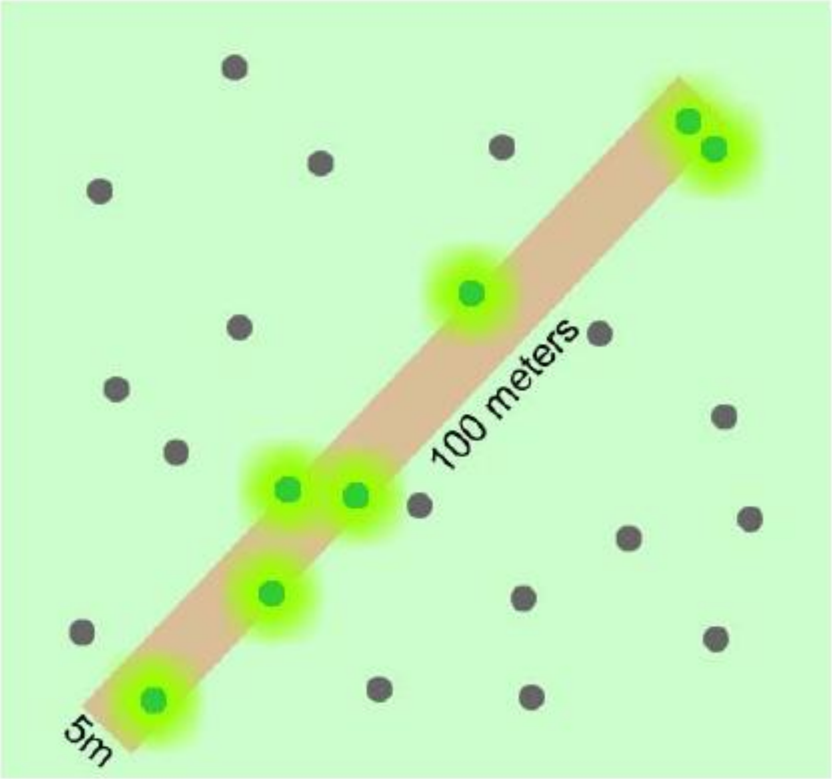


Figure 7: Strip Transect Survey Method [12].

The line transect method is similar to strip transect. The surveyor walks along a straight line while angles and distance of sighted burrows are recorded. This data is then fed into conversion equations that will estimate the total population based off the sampled data [12].

Total count method is usually done for only small areas. This method involves finding all the burrows in an area and assuming 100% were found. A lot of man hours are required for this and surveys usually will take a lot longer [12].

The sample count method is the last major method to estimate burrow numbers. This method works well when the vegetation is too dense to effectively walk through using strip or line transect methods. Randomly located plots are surveyed and then total burrow count is extrapolated.

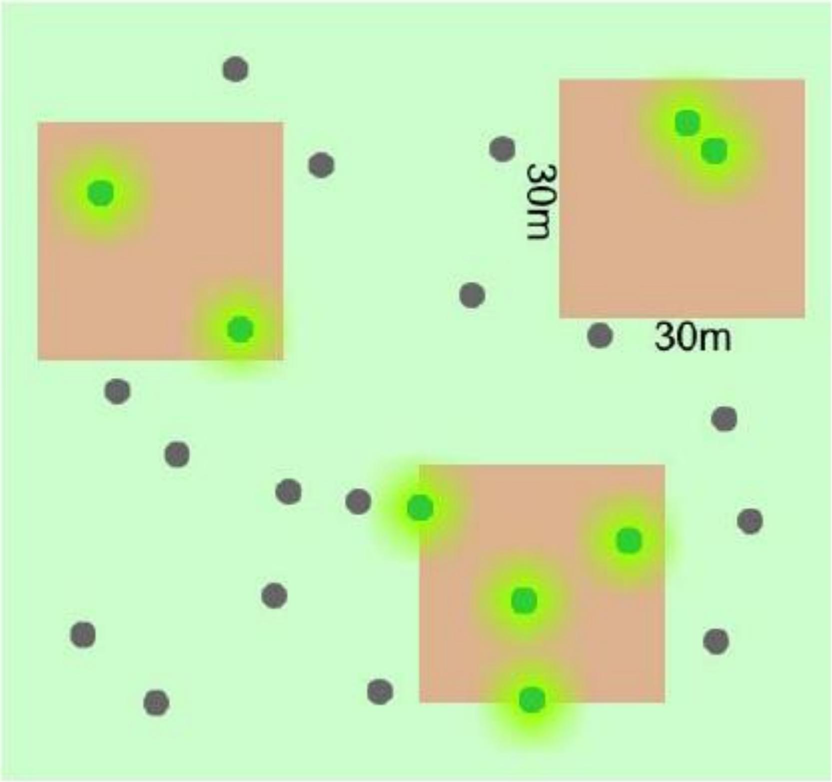
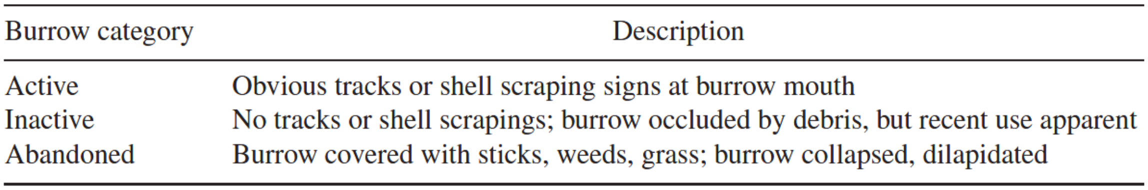


Figure 8: Sample Count Survey Method [12].

2.1.1 Burrow-to-Tortoise Correction Factor. Once the numbers of burrows are known, there are different ways of estimating the burrow occupancy rate, and thus the gopher tortoise population. The most popular method is using a burrow-to-tortoise correction factor that was developed by Auffenberg and Franz [1]. This method is currently used by the Florida Fish and Wildlife Conservation Commission (FFWCC) for habitat development permitting purposes [7]. There are three different categories that a burrow can be classified as, according to this method. "Active" burrows show obvious tracks or markings at the burrow mouth, most likely housing a tortoise. "Inactive" burrows show no signs of tracks but recent use is apparent. There may be a tortoise inside inactive burrows. "Abandoned" burrows are either covered with debris or collapsed. No tortoise is assumed to be inside an abandoned burrow [1].

Table 2: Burrow Categories and Descriptions [7].

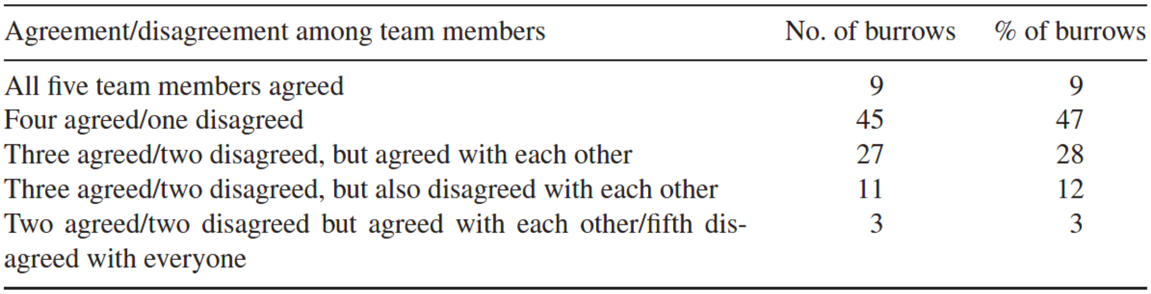


Burrow category	Description
Active	Obvious tracks or shell scraping signs at burrow mouth
Inactive	No tracks or shell scrapings; burrow occluded by debris, but recent use apparent
Abandoned	Burrow covered with sticks, weeds, grass; burrow collapsed, dilapidated

The surveyor would make an educated guess which category to put each burrow in. This method could be very inaccurate if the surveyor isn't familiar with gopher tortoises and their burrows. The active and inactive burrows would then be summed and multiplied by the correction factor to give an estimate of tortoise population size. For instance, one popular correction factor is 0.614, which takes the sum of the "active" and "inactive" burrows, and multiplies it by 0.614 to estimate the number of tortoises [13] It is very important to point out that there is no one correction factor that is accurate for all regions. Each region and habitat will be very different from the rest. For example, correction factors range from .04 to .75 according to some studies, so the surveyor needs to take caution when using this population estimate method to insure accuracy [13].

Overall, this method for estimating populations can be very subjective. One researcher studied how well five biologists agreed on classifying burrows based on these external characteristics. The results showed that there was "poor agreement among the five team members for 43% of the burrows surveyed" as shown in Table 3 [7].

Table 3: Burrow External Characteristics Classifications [7].



Agreement/disagreement among team members	No. of burrows	% of burrows
All five team members agreed	9	9
Four agreed/one disagreed	45	47
Three agreed/two disagreed, but agreed with each other	27	28
Three agreed/two disagreed, but also disagreed with each other	11	12
Two agreed/two disagreed but agreed with each other/fifth disagreed with everyone	3	3

The biggest reason this method is so subjective is because of the vague burrow descriptions given. "Distinguishing between an inactive burrow that is 'occluded by debris' versus an abandoned burrow that is 'covered with sticks, weeds, and grass' is strictly an interpretation made by the observer" [7]. Another problem is surveyors are not required to meet a set of minimum qualifications in order to conduct assignments [7]. This returns data that is inaccurate and could lead to actions that would make the gopher tortoise population status worse than it already is.

2.1.2 Burrow Cameras. The use of burrow cameras to survey gopher tortoise burrows has gotten more popular over the last 10 years. Most cameras are made with a flexible pvc tube that has a camera housed in the end of it. The camera is pushed and twisted down into the burrow as video is fed to the user via monitor [7]. These cameras have become relatively inexpensive (around $1,000) compared to when they first started being used (around $15,000) [7] [13]. The advantage of the burrow camera is that you can directly survey the burrow to get a more accurate description of any inhabitants inside. This allows researchers to better understand how other species use the gopher tortoise's burrows.

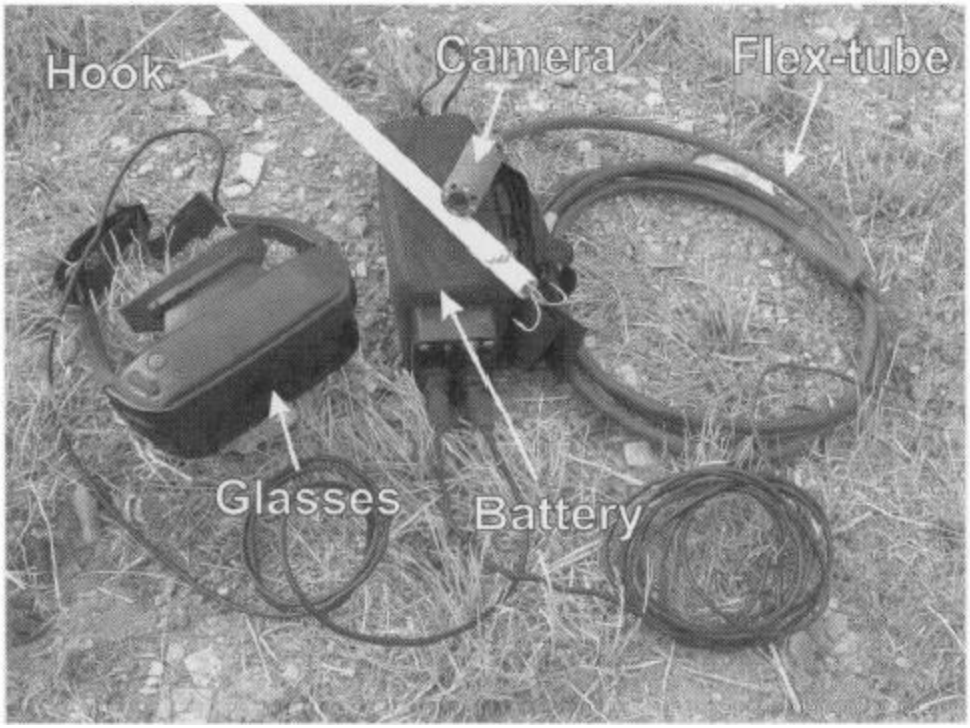


Figure 9: Burrow Camera Equipment [14].

There have generally been good reviews on the effectiveness of the burrow camera, although there are some downfalls. It is best used with straighter burrows, as the user cannot maneuver the camera down twisted burrows. One study surveying burrows using a camera was able to verify

83.6% of burrows, while another was able to determine occupancy in 97% [15] [16]. Both studies blamed convoluted and twisted burrows as a problem for the burrow camera. As stated in Section 1.2, most burrows are not perfectly straight.

Ground penetrating radar (GPR) was used in a study to image gopher tortoise burrows. Kinlaw [11] and others were able to capture accurate images (3D and 2D) of 14 burrows in three different Florida study sites. Even though these sites were in sandy soil habitats, the results were that "nine burrows turned left within two to three meters of their opening, three turned right, and one was fairly straight". Twisted, corkscrew burrows are most likely formed due to a tortoise that is trying to escape the heat. The gopher will dig steeper down until it reaches the cool hardpan layer under the sand [7].

Another study tested the accuracy of using burrow cameras. Two out of a total of 57 burrows were falsely reported as unoccupied when actually they contained tortoises [7]. This error would be considered acceptable compared to other survey methods, but still could result in the destruction of a gopher tortoise population and habitat.

2.2 Other Survey Robots

There have been other studies that investigated the use of robots and/or cameras for survey and exploration of burrows or dens. None of these studies have used a multi-tracked design, such as one the discussed in this paper. Also, these other survey robots studies have focused on other burrows besides the gopher tortoise.

2.2.1 Other Animals' Burrows and Dens. There has been research into developing cameras and robots for animals other than the gopher tortoise. A video camera system was built to study white-tailed prairie dog (Cynomys leucurus) burrows. This study focused on developing a low-cost ($3,100 in 1984) video camera system to explore burrows and dens [17]. The results were generally positive, although obstructions in the burrows (dirt plugs) were frequently a problem.

Another study used a specially made camera and hook system to view and retrieve rodent carcasses from burrows [14]. It was proved to be a problem to maneuver the camera around sharp turns and up steep grades, as noted by the author. This paper stated that it would be helpful if the operator had more control of the camera head so that it could be used to penetrate deeper into burrows [14].

Previous research developed a burrow vehicle to investigate spotted hyena (Crocuta crocuta) in their burrows. This remotely controlled motorized 4-wheel drive vehicle was able to survey burrows and relay information to the user via its front-mounted infrared camera. The burrow robot performed well except for some noted low performance in loamy (partially sandy) or wet, muddy soils [18]. As gopher tortoise burrows are usually dug in sandy soils, this robot design would most likely not perform well in the present application.

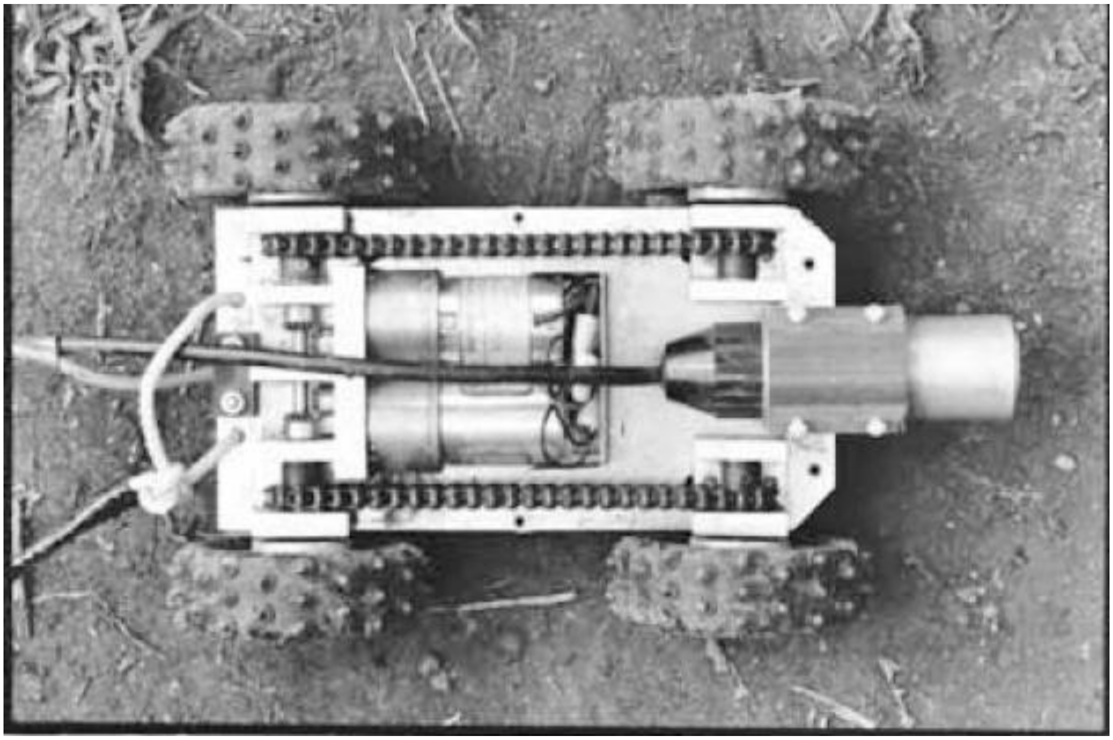


Figure 10: Survey Robot Used for Spotted Hyenas Burrows [18].

2.2.2 Industrial Inspection Robots. The need for industrial robots is apparent in sewer inspection. Sewer inspection robots are similar to the gopher tortoise burrow robot that has been proposed in this paper. They both involve a motorized robot to be driven into a hole while a camera relays visual information to the user.

A prototype robot was developed for sewerage system inspection and maintenance. Some interesting features about this robot is that it’s wireless and autonomous controlled. This robot was designed to survey hundreds of feet of sewers, which explains why it is wireless [19]. This is in contrast to the gopher burrow robot which only has to travel around 30 feet.

Figure 11: Autonomous Robot for Sewerage System Maintenance [19].

CHAPTER 3: MULTI-TRACK DESIGN

3.1 Requirements for Design

The robot's main purpose and goal is to reliably and accurately survey a gopher tortoise burrow. The importance of getting true representations of the gopher tortoise populations have been explained in previous sections. As of now, there are limitations with the current methods of achieving population estimates. Using correction factors is a habitat-specific method that can only be done when a reliable factor is already known. The burrow camera probe is a more direct way of surveying gophers, but has some limitations when used on twisted burrows.

In order to overcome these pitfalls, the robot must be able to maneuver the turns and twists of a burrow. The vehicle must also be able to drive through sand, which is usually the soil of choice for the gopher. Sand is one of the toughest terrains to overcome in mobile robots because of its high coefficient of friction, caused by frictional resistance between grains and minimal particle cohesion [20].

3.2 Locomotion System

In order to achieve ideal performance in sand, one would try to minimize the slip ratio of the vehicle. Slip ratio is defined by the "non-dimensional value calculated from the motor revolutions and actual distance traveled" [21]. The slip ratio varies between 0 (no slippage) and 1 (total slippage) and is expressed by

$$i = (r\omega - v)/r\omega \tag{1}$$

where:

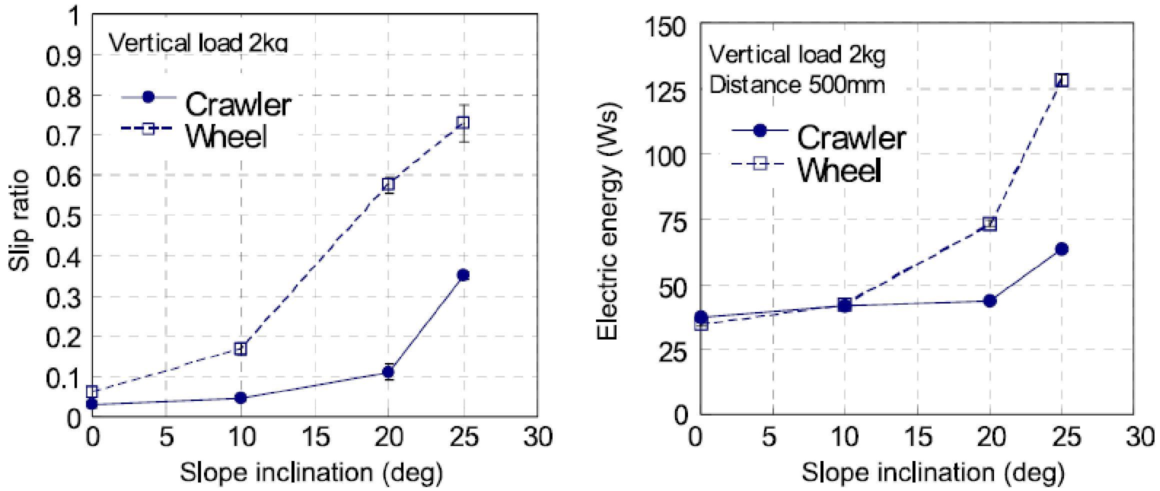
$i =$ slip ratio
$r =$ radius of wheel (mm)
$\omega =$ revolution speed of wheel (rad/s)
$v =$ actual traveling speed of wheel (mm/s)

The key to obtaining a low slip ratio and therefore less sinking and more forward motion is reducing ground contact pressure. Pressure is defined by force per unit area. So in order to reduce contact pressure, the robot should be lightweight and have a high area contacting the ground [21].

Previous research would help decide the type of locomotion system that would be best fit for this problem. The options would be narrowed down to wheels, tracks, screw drive, or legs. As legged robot systems are generally more complicated and usually more expensive, this option was ruled out.

Screw drive was another option that could be used to drive the robot down the burrow. As screw drive was researched, it was quickly realized that sandy soils are a difficult terrain type for this mode of locomotion. According to previous research, all types of screw drive configurations that were tested had difficulty traversing sand [22]. This ruled out this option fairly quickly.

In comparing wheeled to tracked locomotion, a study testing slip ratios of both systems were examined [21]. A tracked crawler setup was compared with a similar parameter wheel, both with widths of 50 mm. Looking at Figure 12, contrasts can be seen in slope inclination performance tests as well as electric energy consumption. In order to maintain a desired speed, the slip ratio needs to remain stable. This study also showed how a wheeled vehicle's slip ratio increases as distance traveled increases, compared to the stable slip ratio of the crawler tracked vehicle (see Figure 13) [21]. Most likely this will cause the wheeled vehicle to eventually get stuck and slip ratio turn to 1. As stated before, gopher tortoise burrows have inclines as high as 30 degrees. According to the graph, at only 25 degrees the wheeled robot's slip ratio was already at 0.75. If the test continued to 30 degrees, then the robot most likely would get stuck.



(a) Comparison of Slip Ratio (b) Comparison of Electric Energy

Figure 12: Comparison of Slip Ratio and Electric Energy Consumption of Tracked Versus Wheeled Vehicles in Sand [21].

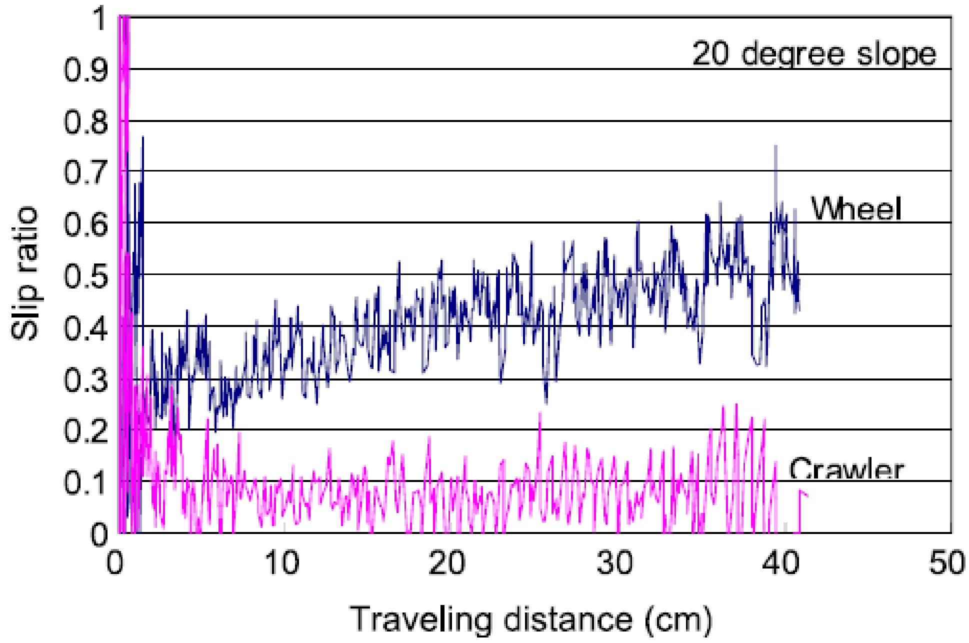


Figure 13: Comparison of Slip Ratio of Tracked Versus Wheeled Vehicles in Sand along Distance [21].

According to this research, tracked locomotion is far superior in sandy soils than wheeled robots. Therefore, the burrow robot was selected to have a tracked design to reduce slip ratio and ground pressure. In order to reduce weight, which also decreases ground pressure, plastic (delrin) tank treads were chosen instead of heavy metal treads. In order to save resources, tank treads were used from previous research projects and are originally a part of the VEX Robotics Kit (Figure 14). These tread links are 1.5 inches wide and a set of 10 links weigh 0.5 ounces. The links are all master links so one can make a custom length with as many links as needed.

Figure 14: VEX Tank Tread Weight.

3.3 Multi-Tracked Vehicle Design

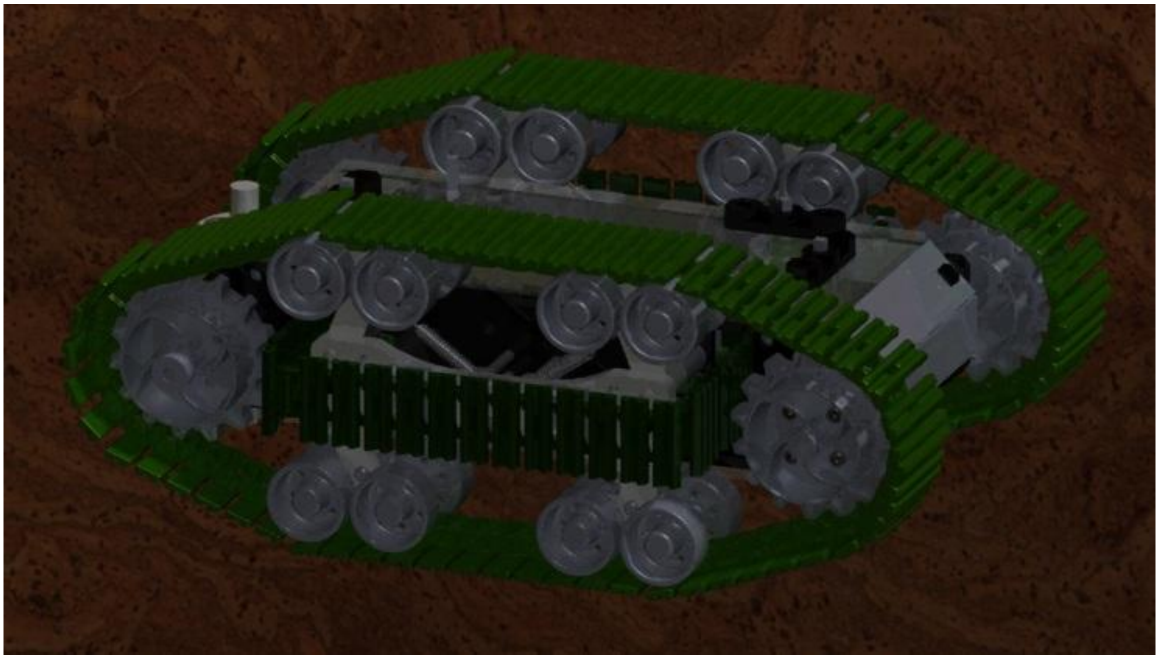


Figure 15: Final Burrow Robot Design (Render done in Solidworks).

Tracks have been explained as the best choice for the locomotion system. In a burrow, there may be obstacles such as roots or rocks that obstruct the robot’s path. In order to achieve the greatest mobility, tracks were designed on the top, bottom, and both sides of the robot. This will allow the robot to progress forward even when flipped upside down or on its side. If the robot contacts an object on its side, propelling motion will be created pushing the robot forward.

A literature search of previous designs involving multi-tracked designs returned an interesting “snake-inspired” robot. The “OmniTread OT-8” has tank treads on all sides of each one of its links. Both the OmniTread and the

Gopher Tortoise burrow robot use this design to maximize the "propulsion ratio", defined by "the ratio of surface area that is active in propulsion to the surface area that is not" [23]. The propulsion ratio is defined by the equation

$$P_r = A_p/(A_p + A_i) \qquad (2)$$

where:

P_r = propulsion ratio (surface that provides propulsion)

A_p = sum of all surface areas that could provide propulsion

A_i = sum of all surface areas that could not provide propulsion

The propulsion ratio of the final gopher tortoise robot was calculated. The area of the main tracks is a total of 71.7 in^2. The area of the side tracks is a total of 10.1 in^2. The area of the surface that cannot provide propulsion is 128.9 in^2. Thus, the propulsion ratio of the gopher tortoise robot is a significant 0.39. The propulsion ratio of a wheeled vehicle is considerably lower.

Figure 16: Snake-Inspired Robot "OmniTread OT-8" (Courtesy of Johann Borenstein, University of Michigan) [23].

3.3.1 Technical Details. The robot would need to be small enough to fit into most adult burrows in order to be effective. Adult burrows are at least 23 cm (9.1 in) wide and about 11.5 cm (4.5 in) high. Since the burrow is a "half-moon" shape, the robot's width needs to be significantly smaller than the burrow's width because of the sloping side walls (refer to Figure 17).

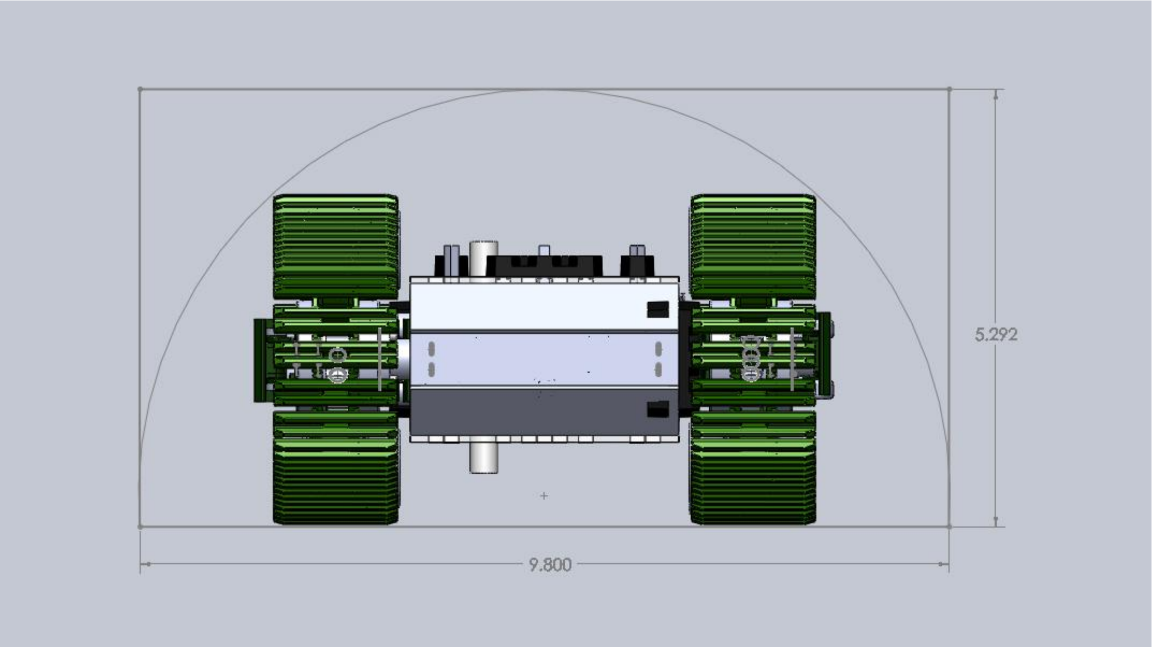


Figure 17: Simulated Burrow Drawn in Solidworks.

After nine design iterations, the burrow robot width and height are 7 inches and 4 inches, respectively. This should allow it to fit in a minimum burrow width of 9.8 inches. According to a Florida gopher tortoise study involving measurements of 105 burrows, this robot should fit in 92% of adult burrows. The major factor limiting how small this design could be built was the size of the drive sprockets. These sprockets were used because they were available from a previous research project.

In order to keep the weight down, and thus decrease contact ground pressure, delrin and polycarbonate were the main materials used for construction of the robot. Both materials were machined using a laser cutter machine to achieve great accuracy. Delrin was used in the main frame rails (1/8" thick) and suspension components (1/4" thick). Clear Polycarbonate (1/8" thick) was used in the top and bottom frame plates in order to see inside the robot without disassembling it. Aluminum square bar (3/8" thick") was used as mounting nut bars for assembling the top and bottom plates to the frame rails.

The original motors used were four "Fingertech Spark" motors, each providing motion to a tread. These DC brushed motors were the 83.3:1 gear ratio versions. At 11.1V and no load, the motor's revolutions per minute (rpms) measure 210 rpms and they supply 80.69 oz-in of torque. This gives a calculated maximum speed of 0.88 ft/s (0.6 mph).

Table 4: Fingertech Spark 83.3:1 Motor Data.

Fingertech Spark	Volts (V)	RPMs	Torque (oz-in)	Sprocket Dia (in)	Vehicle Speed (ft/s)
83.3:1 Gear Ratio	11.1	210	80.69	0.96	0.88

The robot has separate drive trains for each track. The main tracks are independently controlled and are direct drive from the motor shafts. The side track's drive train starts with a bevel gear set to rotate transmission 90 degrees. After that, power is transferred via chain and sprockets to the side track drive sprocket. This was chosen because of the space efficient and reliable design. Refer to Figure 18 and 19 for detailed views of the 3D Solidworks model.

The side tracks proved sufficient enough to keep the robot from getting stuck on its side. When driven intentionally off the side of a ramp, the robot would land on the side tracks and continue until it flipped over upside down. This design is advantageous because it is invertible and allows the robot to continue driving even if it flips over.

A 3 megapixel USB computer camera was is used in conjunction with software on a laptop to view inside the burrow. The color camera's frame rate is 30 frames per second at 320 x 240 resolution. The sensor size is 0.19 x 0.14 in^2 and unit dimensions are approximately 2.25 inches long by 1.5 inches in diameter. Since the camera was mounted sideways on the robot, video editing needed to be done to rotate the video feed for easy viewing. Also, in order to see in the dark burrow, there are three bright white led lights on the front of the camera.

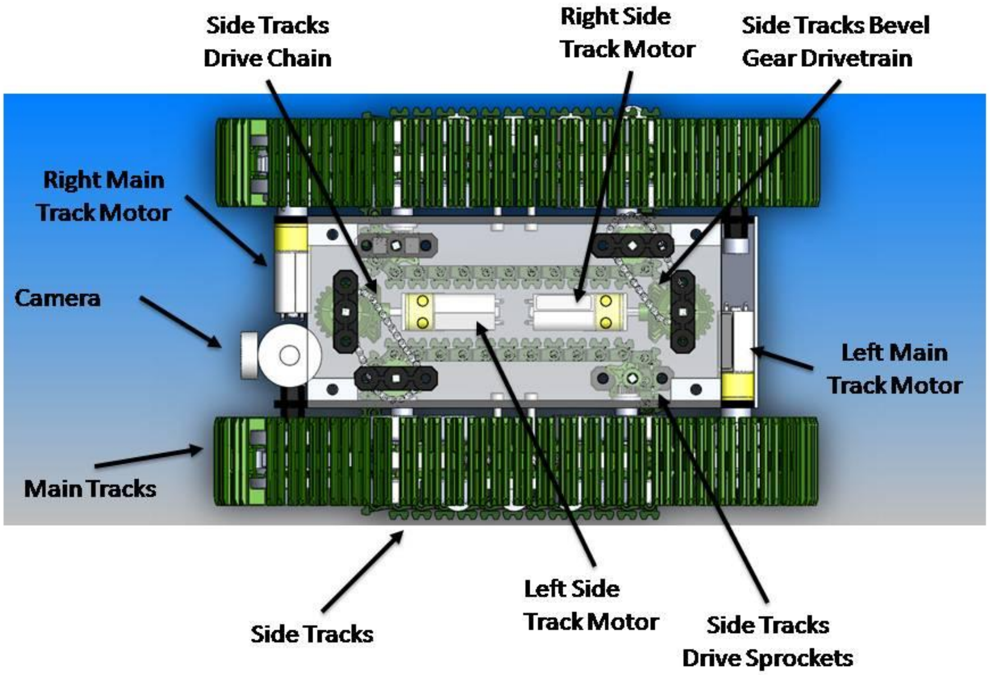


Figure 18: Top View Labeled of Burrow Robot.

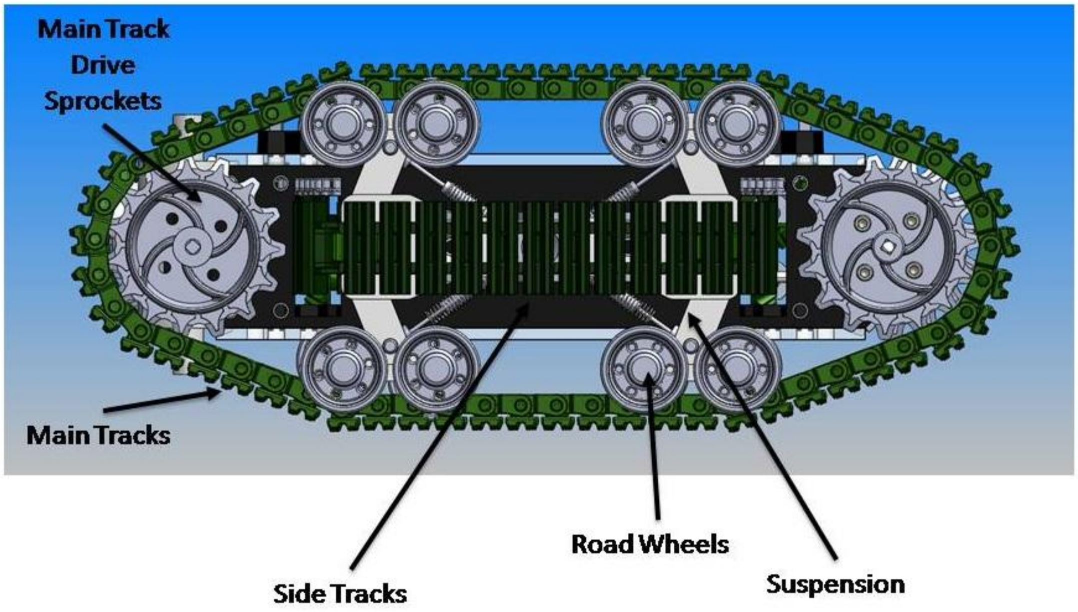


Figure 19: Side View Labeled of Burrow Robot.

The control system was made using existing parts from previous research experiments. The robot required a safety tether, such as a wire cable, in case there was a problem demanding manual recovery. Since a cable would be always connected anyways, wired control of the robot was selected to avoid wireless communication signal interference.

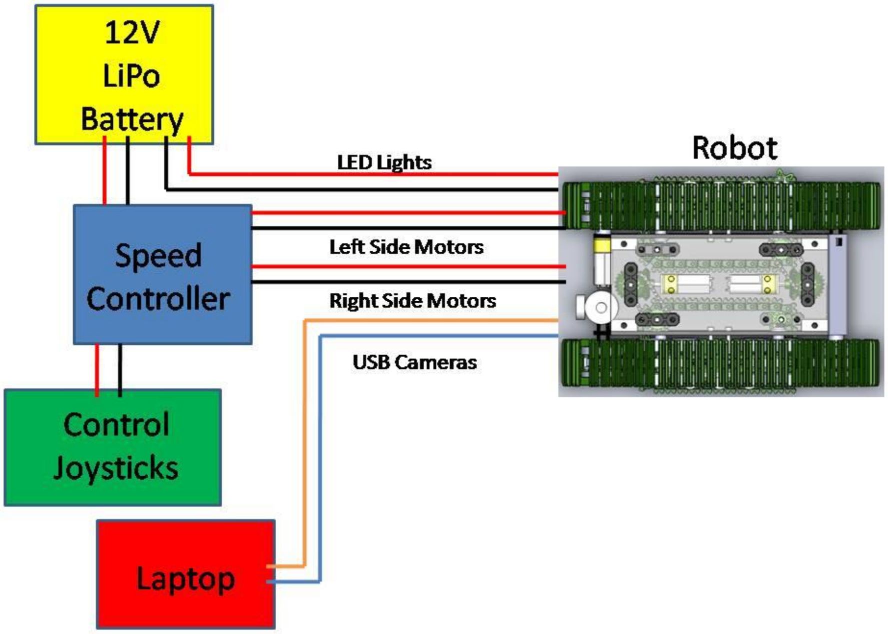


Figure 20: Control Scheme of Robot.

The robot was controlled with two joysticks on a remote controller. Each joystick controlled a side of the burrow robot's tank treads. The camera view was transferred to a laptop above ground at the control station via USB cable. Originally, the long length of USB cable (30 feet) caused a signal loss problem that resulted in poor video quality and visual lag. This was solved by using "active" USB cables which boost signal, allowing for longer cables to be used.

The power source of the robot was a lightweight Lithium Polymer battery. This was rated at a nominal 11.1volts (three 3.7 volt cells) and 1350 mAh capacity. A lightweight battery was important in order to field test efficiently. If testing all day, a battery with a greater capacity would be helpful in order to avoid recharging.

A speed controller was used to control the robot more effectively. The Sabertooth 12 RC Dual Motor Speed Controller was chosen to perform motor control duties. This controller can supply two motors up to 12 amps each and runs on 12 volts. A lower cost alternative would be to use two 3-way switches, one controlling each pair of motors independently. This would not allow the speed of the motors to be controlled.

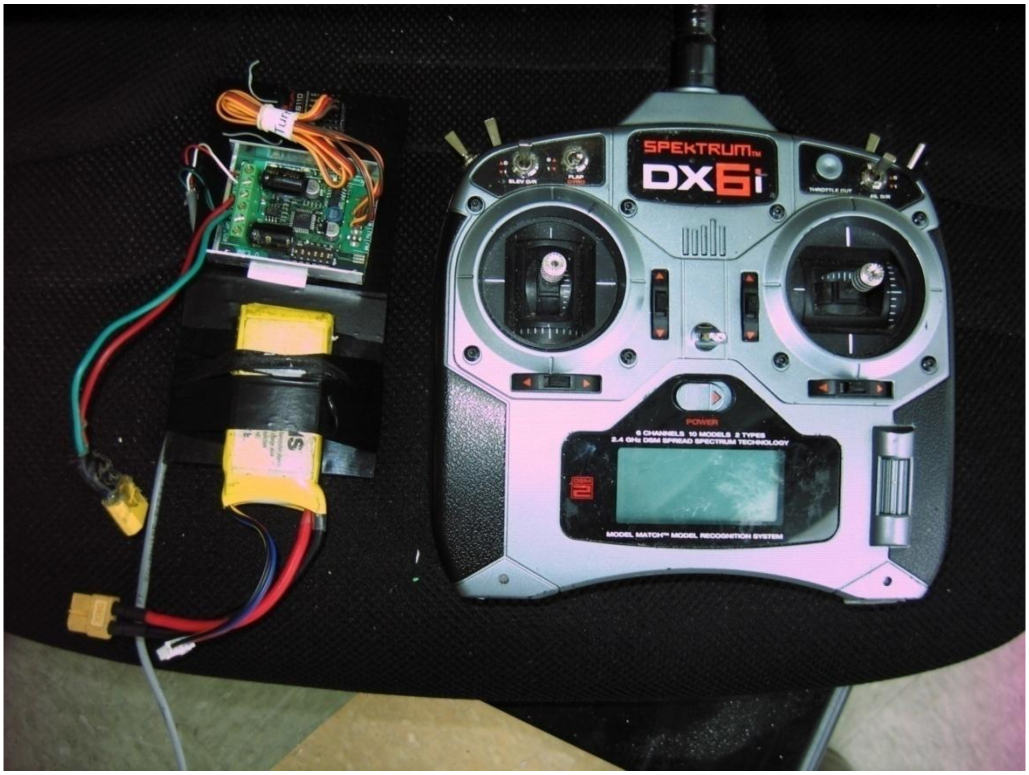


Figure 21: Robot Controller, LiPo Battery, and Speed Controller.

3.3.2 Suspension Design. In order to maneuver obstacles, it is helpful to have a suspension system in conjunction with tread tracks. This will insure the tread follows the contour of the surface and maintains optimum traction. Research was done into past and current military tank suspension. The most advanced suspension system that is adopted on current generation military tanks is the hydro-gas suspension. This design was not investigated due to the complexity and slow speeds of the burrow robot.

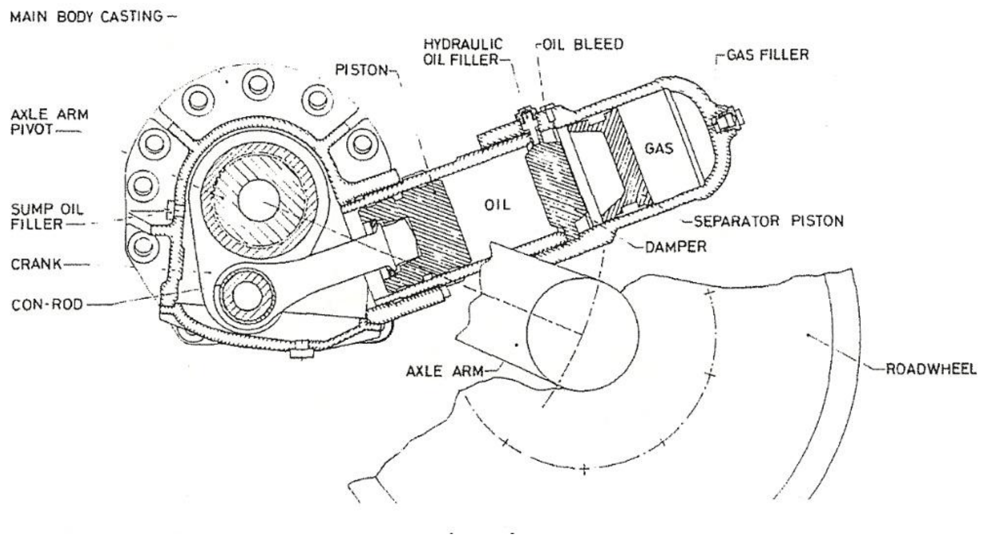


Figure 22: Hydrogas Suspension Design from Challenger Tank [24].

Torsion bar suspension has been used on tanks for many years. Bars are usually run the width of the hull, fixed at one end, and attached to a swing arm on the other end. The road wheel would then be fixed at the other end of the swing arm allowing suspension travel [24]. This design was not chosen because of the space it would take up inside the robot, which is used for the side track drive train.

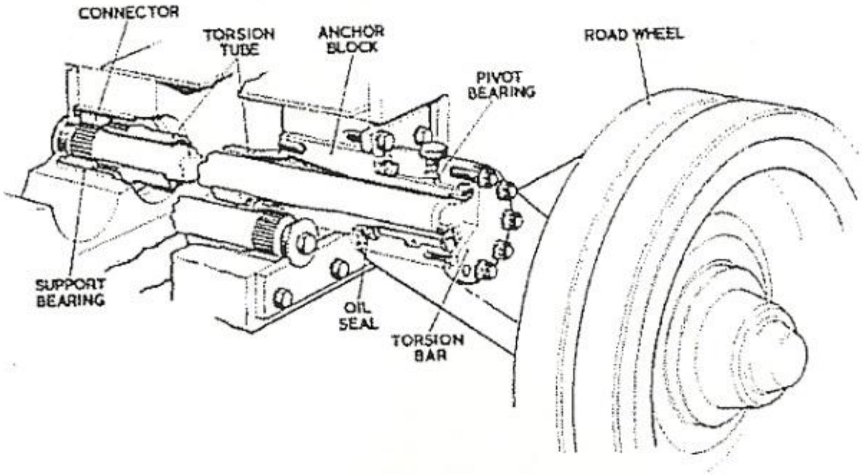


Figure 23: Torsion Bar Suspension [24].

Coil spring suspension is also used and has the advantage of being able to be mounted outside the hull [24]. A study fitted a coil spring suspension system to a tracked vehicle that was developed to study tractive performance on soft terrain [25]. The shock-coil dampered system contained two swing arms connecting the road wheel to the hull.

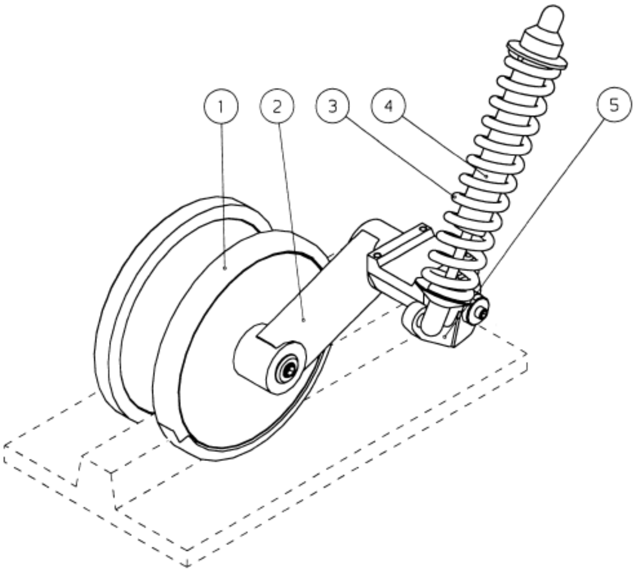


Figure 24: Coil Spring and Damper Suspension for Testing on Soft Terrain [25].

The final studied suspension system is similar to the NASA Mars rovers. The "rocker" suspension system allows great maneuverability and allows the robot to climb over obstacles. This was researched further in a paper studying the mobility of a tracked lunar vehicle.

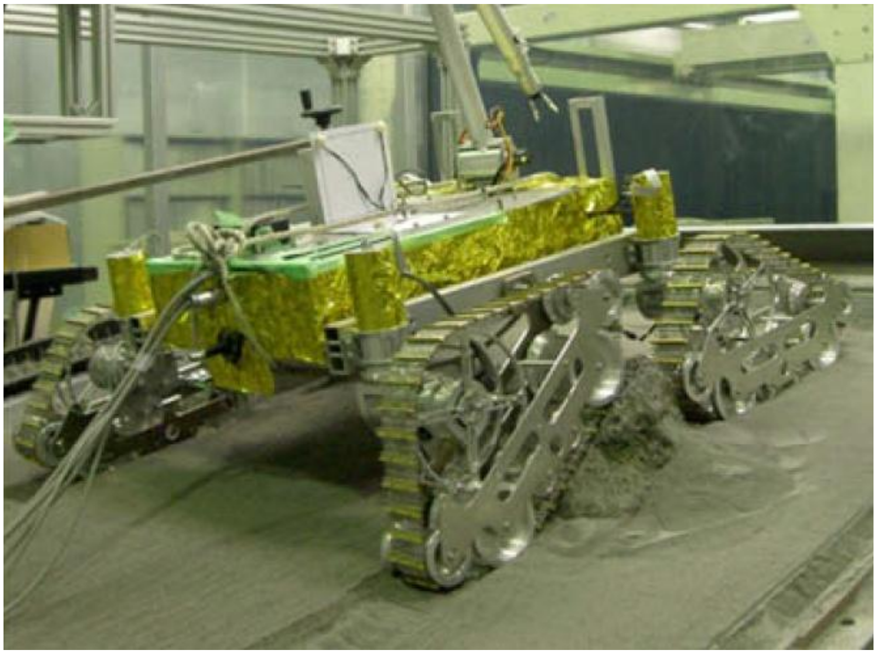


Figure 25: Rocker Suspension Displayed on Lunar Tracked Vehicle [21].

In order to keep the design functional and simple, a mix of coil springs and the rocker suspension was used. A coil spring and swing arm pivots from the robot's hull to the rocker swing arm. The rocker swing arm is free to rotate about its pivot axis. Two sets of road wheels are attached to the ends of the rocker swing arm. This suspension system has the advantage of climbing over obstacles as well as following the terrain (Figure 26 and Figure 27). Different spring rates were tested to find the best setup for a smooth ride over terrain. The final spring rate chosen was 4.93 lbs/in. This allowed minimal deflection at the robots weight alone, but enough to compress when driven over bumps and obstacles.

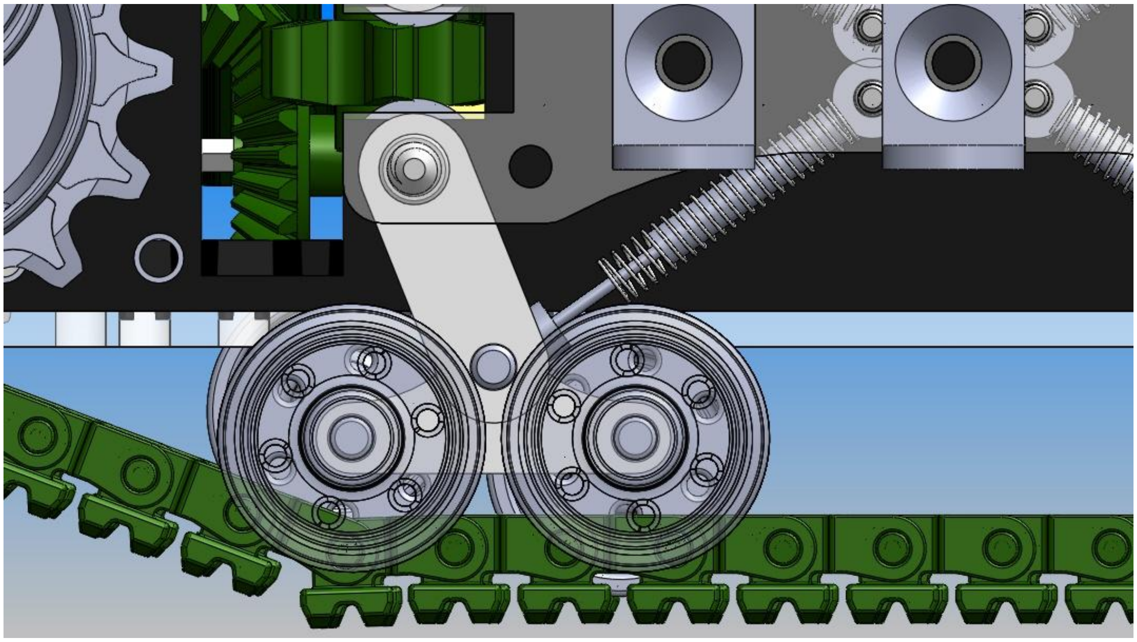


Figure 26: Model of Burrow Robot “Coil Spring-Rocker” Suspension.

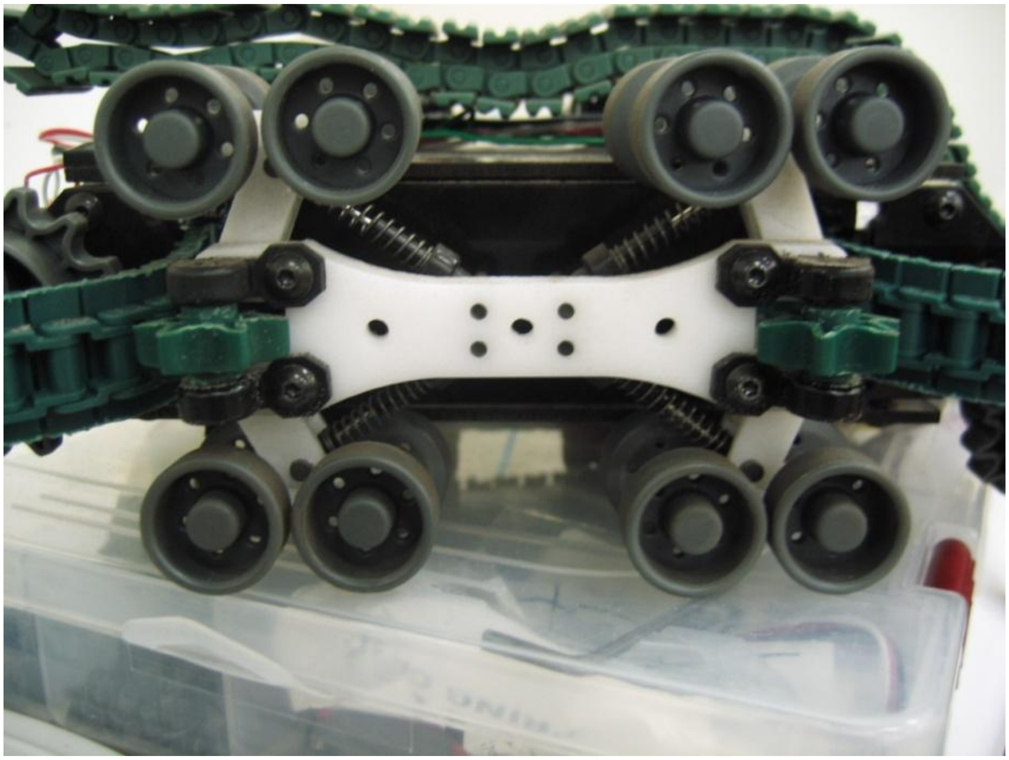


Figure 27: Burrow Robot “Coil Spring-Rocker” Suspension (Side Track Removed for Clarity).

CHAPTER 4: EXPERIMENTS

4.1 Experiment Goals

The experiment goals were to investigate the effectiveness of using the burrow robot to survey and explore gopher tortoise burrows. In order to do this, the vehicle went through a series of tests. A test-bed was made out of 2x4 wood sections and a 45” square sheet of steel. This was filled with soil taken from surrounding locations of the gopher tortoise burrows. A series of performance tests took place using this test bed. Also, the robot was tested in the field, on an actual gopher tortoise burrow to prove its effectiveness.

Figure 28: Test-Bed Used for Performance and Incline Tests.

4.2 Experiment Methodology

The robot was first put in the test bed to record a series of parameters. These included vehicle ground speed, slip ratio, turning radius, side track effectiveness, maximum ditch crossing, incline performance, and water crossing ability. Then, the robot was taken to Fish Hawk Creek Nature Preserve, and with the help of the Hillsborough County Parks and Recreation Department, was tested in a gopher tortoise burrow.

4.2.1 Sandbox Tractive Testing. The sandbox test was helpful in evaluating the tractive properties of the robot and also improving driving skill. A “simulated” burrow could be set up in the sandbox to test the robot before traveling to an actual burrow location. Since the soil was the same sand from the actual gopher burrows, the results could be directly predicted with regard to a real burrow.

Figure 29: Robot Testing in Sandbox on a 30 Degree Slope.

Many parameters could be changed while testing in the sandbox. For instance, the slope could be changed by raising one end of the box. For all tests, the sand was first mixed and then compacted to achieve the same consistency as that observed at actual tortoise burrows. A tarp covered the box when it was not in use to protect the soil from the wind and rain. An inclinometer was used to measure the slope of the sandbox (see figure 30). This was a very useful tool to ensure accurate testing.

Figure 30: Inclinometer on the Sandbox Set at 30 Degrees.

Blocks of wood were set in the sand to simulate the restricted width of a gopher tortoise burrow (see figure 31). These were spaced apart the same distance as the walls of an actual gopher tortoise burrow. This testing was very helpful in practicing driving the robot. In order to successfully travel down a burrow and back, it is necessary to avoid repeatedly driving into the burrow walls. This could cause the robot to sink and dig a hole which it may not be able to get out of. The driver also needs to be aware when and if the robot is starting to sink and get stuck. It was found that to avoid sinking in and getting stuck, it was better to approach an obstacle at a small angle.

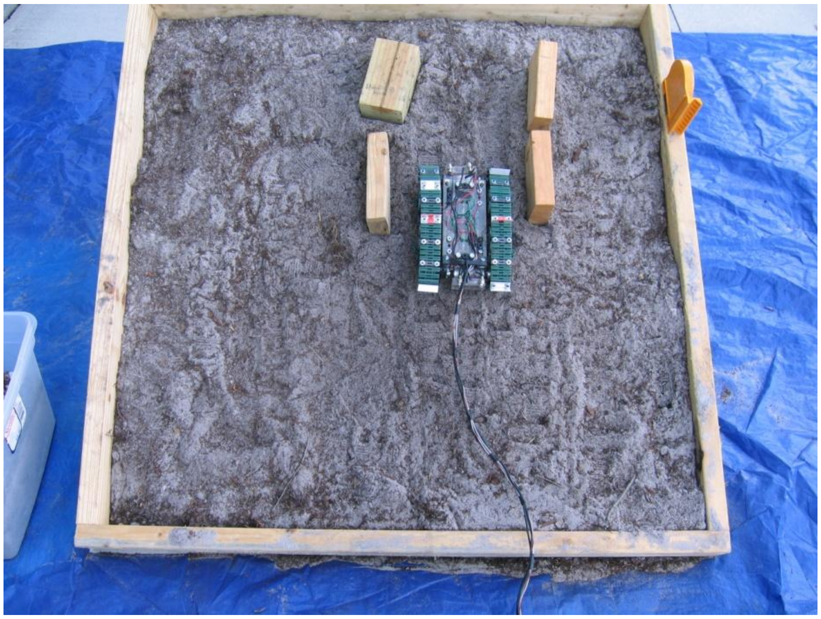


Figure 31: Robot at a 30 Degree Incline and “Simulated” Burrow Walls.

This sandbox testing was most useful in learning how to successfully climb a high angle slope (>25 degrees). Most vehicles, such as wheeled or screw drive robots as previously shown, would sink in the sand and get stuck. The treads provide less contact ground pressure and therefore allowed the robot to negotiate slopes over 30 degrees. At 35 degrees, the robot experienced difficulties maintaining forward motion. The robot couldn’t climb a 35 degree slope straight up but was sometimes successful if it climbed at an angle (weaving from left to right as it climbs).

In order to prove that the robot can drive through water flooded burrows, a simple water driving test was conducted. The robot’s waterproof camera cases were tested by driving the robot through a ditch filled with water in the sandbox. The cameras were underwater multiple times and did not fail. The motors were also sealed enough so that they continued to work without problems. This was an important test as gopher tortoises are known to stay in their burrows during flooding.

Figure 32: Robot Driving Through Water Test.

4.2.2 Burrow Testing. The Hillsborough County Parks and Recreation Department, who requested this work, was able to meet on several occasions to field test the robot. The first meeting was a preliminary meeting to mostly survey burrows that could be used to test the robot. A survey of burrows was done in about a 30 min period at Bell Creek Scrub Preserve. Five burrows were found rather quickly and burrow widths were measured.

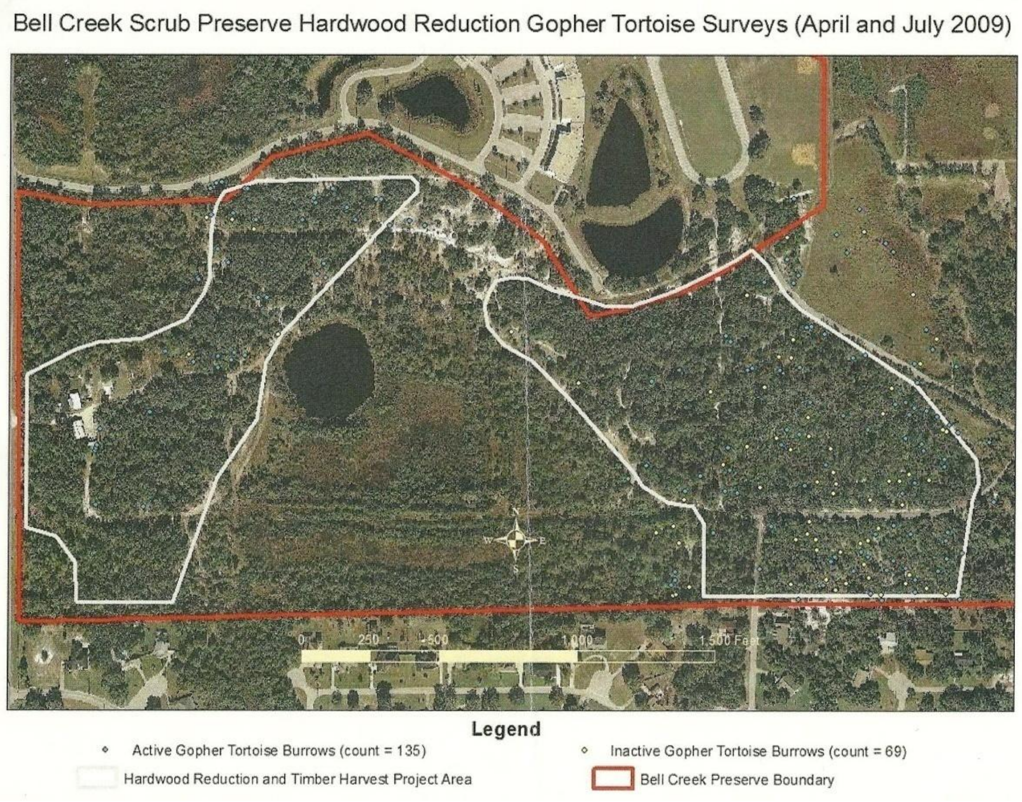


Figure 33: Bell Creek Scrub Preserve Preliminary Testing Grounds.

The standard way to measure burrow widths is with two yard sticks pinned together in the center like scissors. This yard stick tool is inserted 50 cm into the burrow. The user then expands the ends inside the burrow to touch the two walls. The distance between the two ends of the yard sticks are then measured to find the burrow width (see Figure 34). This is a very effective and accurate way to measure burrow widths.

Figure 34: Measuring a Gopher Tortoise Burrow Width Using the Yard Stick Tool.

The five burrow widths from the first meeting were evaluated to determine if they could be used to test the robot. The first burrow was 43.9 cm (17.3 in) wide and 17 cm (6.7 in) tall, which is considered an adult size (Figure 35). Tracks could be seen at the burrow entrance and this would be classified as active. This burrow was more than big enough to test the robot in, as the minimum required width is 9.8 cm (3.85 in).

Figure 35: First Burrow Found During Preliminary Meeting at Bell Creek Scrub Preserve.

The next burrow found was 29 cm (11.4 in) wide and 14 cm (5.5 in) tall. This burrow turned right about 45 degrees immediately after the entrance. Again, this burrow could have been used to test the burrow robot. The third burrow found was very shallow, only about 50 cm (19.6 in) deep. This burrow was most likely collapsed or the gopher tortoise was still in the digging process. The width could not be accurately checked because the yard stick measuring tool could not be properly used. The last two burrows that were found were too small for the robot, most likely dug by juveniles.

The preliminary meeting was a success. Even though the search was only about 30 min, multiple burrows were found that the burrow robot could easily fit into. As previously stated, the design could be shrunk down if different sprockets were used, but a lot of parts were taken from previous projects to reduce prototype cost.

A second meeting was scheduled to test the burrow robot on a gopher tortoise burrow. This test would try to prove the effectiveness of the prototype robot. The location was changed to Fish Hawk Creek Nature Preserve. The habitat was mostly sand-hill, which the gopher tortoise prefers most. Almost immediately, three burrows were found that were big enough to fit the robot down. The first burrow ("Burrow #1") was very large and was most likely dug up by another animal. As the original gopher tortoise burrow dimensions were enlarged, a realistic test could not be done. Very close to the first burrow was another one ("Burrow #2") that measured 26 cm (10.24 in) wide. Another burrow nearby ("Burrow #3") was also found and measured to be 25.5 cm (10.04 in) wide. Both these burrows were very likely dug by the same gopher tortoise as their size and location were close.

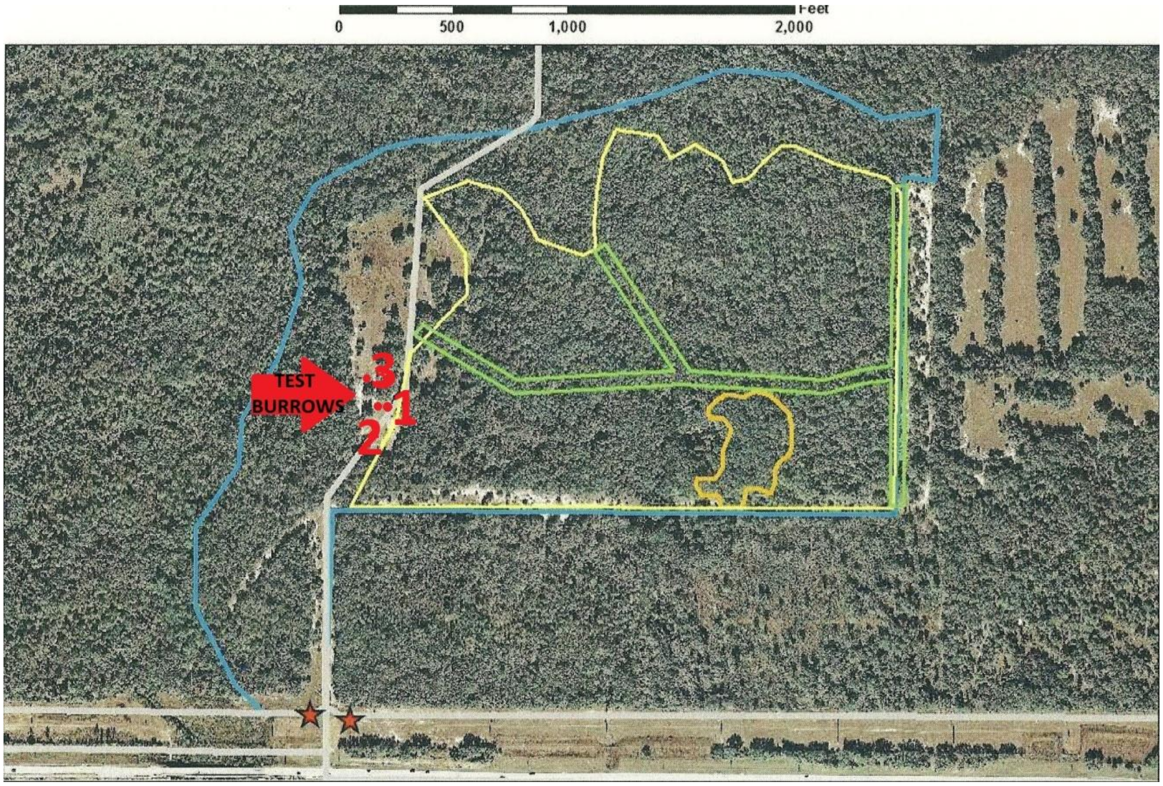


Figure 36: Testing Location at Fish Hawk Creek Nature Preserve.

The robot was setup at Burrow #2 for testing. The testing setup consisted of the robot, a battery, a controller/joysticks, a laptop, and a chair to rest the laptop on allowing the user to control the robot easier. It was also useful to create shade to make laptop screen viewing easier, as viewing the computer screen in full sunlight is difficult with intense glare. An umbrella was setup behind the user to aid in this process.

Figure 37: Robot and Testing Setup at Burrow #2.

A lot was learned on the first burrow test at Burrow #2. The robot was slowly driven into the burrow while the driver used the camera onboard to direct it. Shortly after, the first problem came from the camera itself. The visual lag created from the webcam while exploring the burrow was very noticeable. The time it took for movements to be registered on the computer screen was too much to be able to drive effectively. This caused the robot to be hard to control, and consequently run into the burrow walls. Also, the video quality was very low as the native resolution was only 320x240. Nothing can be done to improve the performance of the camera as it stems from the hardware itself. The camera used had three built-in LED (light emitting diode) lights on the front housing. This provided just enough light to see in front of the robot, but more light would be helpful in seeing farther ahead down the burrow.

The next problem came while trying to back out of the burrow. The burrow went straight for about 3 feet and then turned about 45 degrees to the left. Originally, only a front camera was thought to be needed but the necessity of a back camera was quickly realized. As the robot maneuvered down the burrow and around the turn, it continued only a foot before stopping. A test to see how well it could reverse was done and without a back camera, it was very challenging. The robot needs to be able to drive down and back up the burrow. If there is no camera in the rear of the robot, the driver will be backing into walls while driving out. The viewing angle of the front camera was not wide enough to accurately predict which way the burrow was turning behind the robot.

Figure 38: Robot Loading into Burrow #2.

The last problem was that since the robot was driving backwards into walls, it was sinking in the sand and getting stuck while driving out. The robot's main tracks were not providing enough traction, so the robot had to be pulled out by its safety tether. Video of this attempt was recorded on the laptop and studied later for documentation and improvement purposes.

Another test was done at Burrow #3. This burrow had a very similar size as Burrow #2 but turned left immediately after the entrance. Similar problems produced by the camera's hardware and lack of a rear camera forced the same results from Burrow #2. The robot could not be successfully maneuvered backwards up the burrow.

Figure 39: Screenshot from Robot in Burrow #2 with Original Webcam.

4.2.3 Revised Camera Design. In order to effectively operate the robot, the user must be able to get a real-time live camera shot from the vehicle. The previous camera created a big delay that prevented the driver from being able to successfully maneuver down the burrow. In order to improve the camera system, two new webcams were installed. Logitech C110m webcams brought many improvements to the system. Resolution was set at 640 x 480 for ideal video streaming. The C110m webcams were a huge improvement on video quality and they did not cause a visual lag. Also, these cameras featured a built-in microphone. This was very important because audio feedback was helpful in driving the robot. If the robot was being stopped by an obstacle, the motors could be heard under load, and the robot would be immediately backed up. The only downfall of the new cameras was that they did not have any night time viewing option, neither infrared nor white leds. Some "high-brightness" white leds were bought and wired up to the robot. These were 5mm round leds with light intensity of 7000mcd.

Now there were two cameras, one in front and one in back. Each of these cameras had two leds attached to provide ample amount of light to drive the robot underground. This provided a huge improvement over the previous camera design and allowed the driver to more easily drive backwards up the burrow.

Figure 40: Leds Providing Light for Subterranean Exploration.

In order to keep the cameras functioning and reliable, custom camera boxes were made to house the webcams. The camera was removed from the standard case and was fitted into a custom clear acrylic case. This allowed the camera also to be more durable as all seams were sealed to keep moisture, water, and sand out. Waterproofing the cameras was an important step as gopher tortoises have been observed in flooded burrows [8].

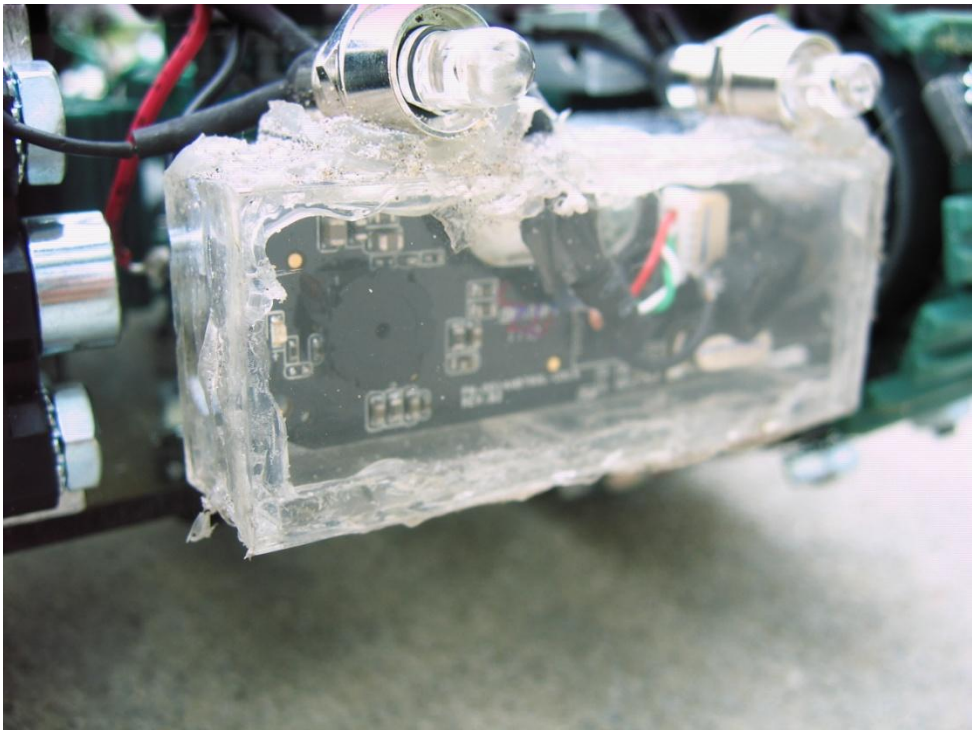


Figure 41: Custom Waterproof Acrylic Camera Case for Webcams.

4.2.4 Revised Tread Design. The robot in the first test at Fish Hawk Creek did not have enough traction to climb the steepest parts of the burrow. In order to improve the performance of the tracks, different designs were experimented with and tested in the sandbox.

In order to give the tracks more forward motion, “paddles” were attached to about ¼ of the links. These paddles would claw and dig at the sand, providing more motion than the standard “flat” tracks. These modified tracks can be seen in Figure 42. A hypothesis was made that with these modified tracks, the robot could successfully climb a 30 degree slope.

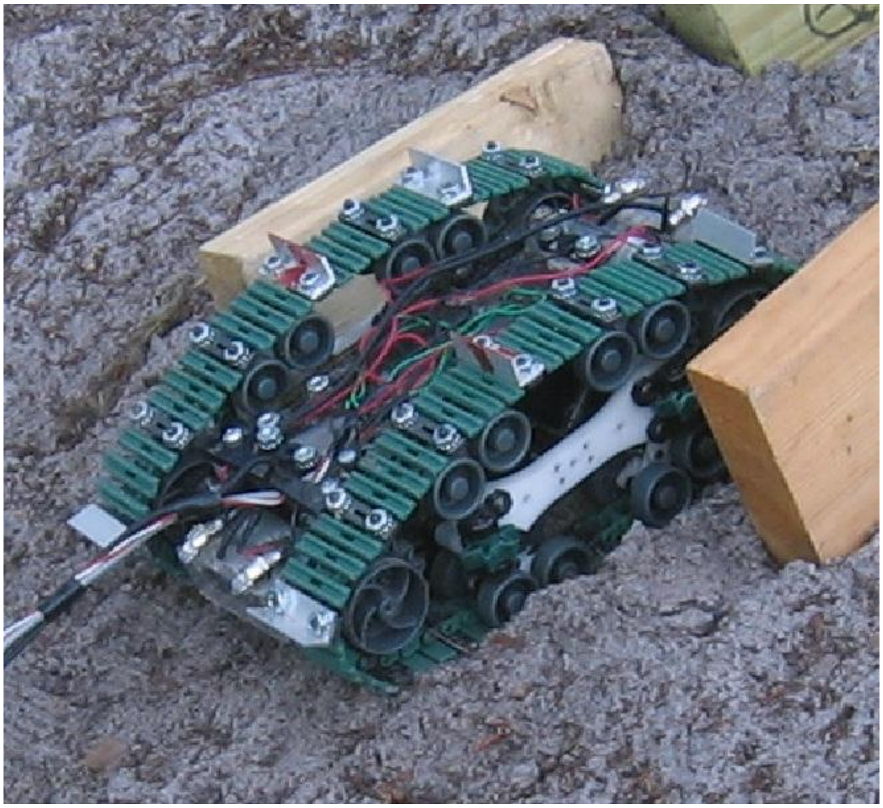


Figure 42: Modified Tracks on Burrow Robot.

In order to investigate whether these tracks provided better performance than the flat tracks, a series of tests were conducted. The slip ratio as previously defined is the value comparing the track progression with the actual forward motion of the robot. This value directly relates to the traction properties of the vehicle.

Every four links, a modification was made that added screws which protruded from the bottom side of the track. These screws were intended to dig into the sand to provide more traction. Also, every 12 links, a piece of aluminum angle was attached to the track to act as a “claw” or “paddle” to supply more forward motion to the robot.

A test of the robot's slip ratio and average vehicle speed was conducted. First, the travel distance was measured and recorded as 33 inches. This corresponds to the actual traveled distance of the robot. Then, one of the tread links was marked in order to observe how many links traveled forward during the test. Finally, the slope of incline was gradually varied over 0 to 30 degrees in 5 degree increments throughout the testing as the flat tracks were compared with the modified tracks. As can be seen from Figure 43, the modified tracks performed significantly better than the flat tracks. In fact, the flat tracks could not climb a 30 degree slope, whereas the modified tracks could. Another interesting fact is that the slip ratio rises dramatically with the incline slope. This was predicted as similar results were shown in previous research [21]. In looking at slip ratios with the tracked lunar vehicle mentioned previously, they are similar to the burrow robot values; although soil types are different so direct comparisons cannot be made [21]. These results supported the hypothesis that was made previously as the modified tracks allowed the robot to climb the 30 degree slope.

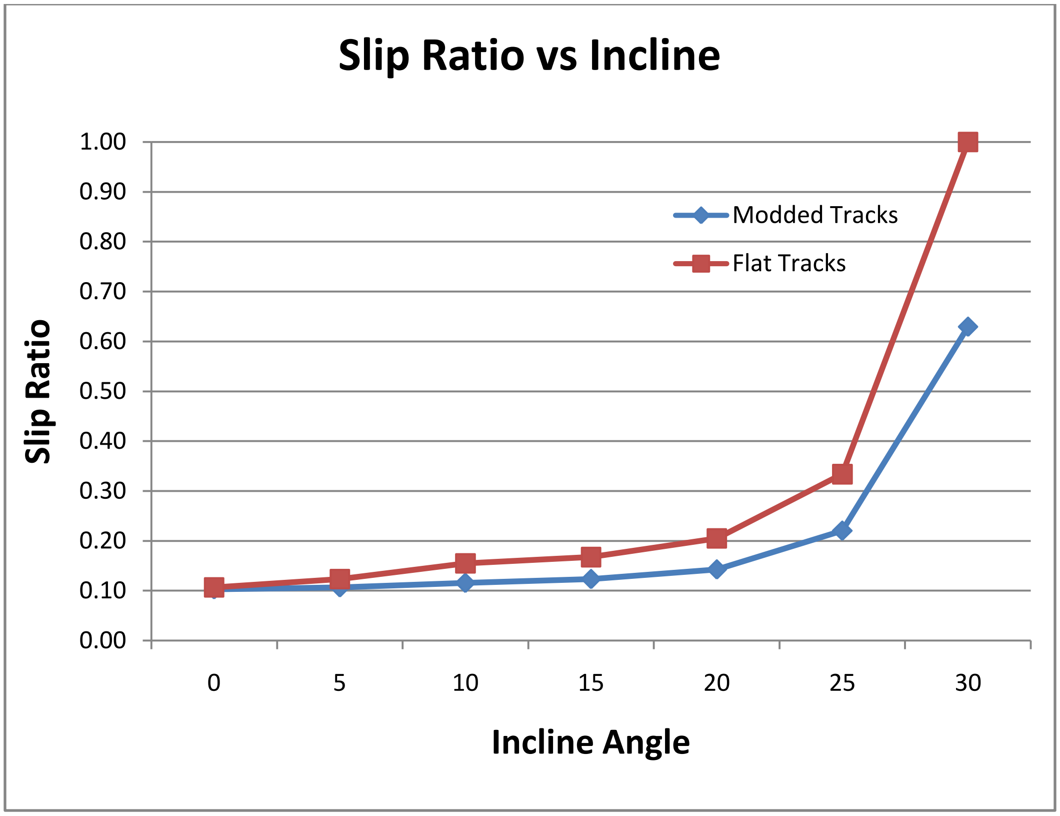


Figure 43: Slip Ratio vs Incline for Flat and Modified Tracks.

Another test that was conducted was Speed vs Incline. This data can be seen in Figure 44 below. Both track types had similar speeds even though the slip ratio of the modified tracks were lower. This could be explained by a slower rpm of the motors with the modified tracks. The button head screws located on the bottom side of the track would slightly interfere with the road wheels. This had an effect on the overall vehicle speed as seen on the 0 degree slope, where the flat tracks are faster than the modified tracks. Also, seeing how there was more ground friction with the modified tracks; this would also lead to a slower rpms. This can be seen in Figure 45 where tracks from the robot can be seen digging into the sand.

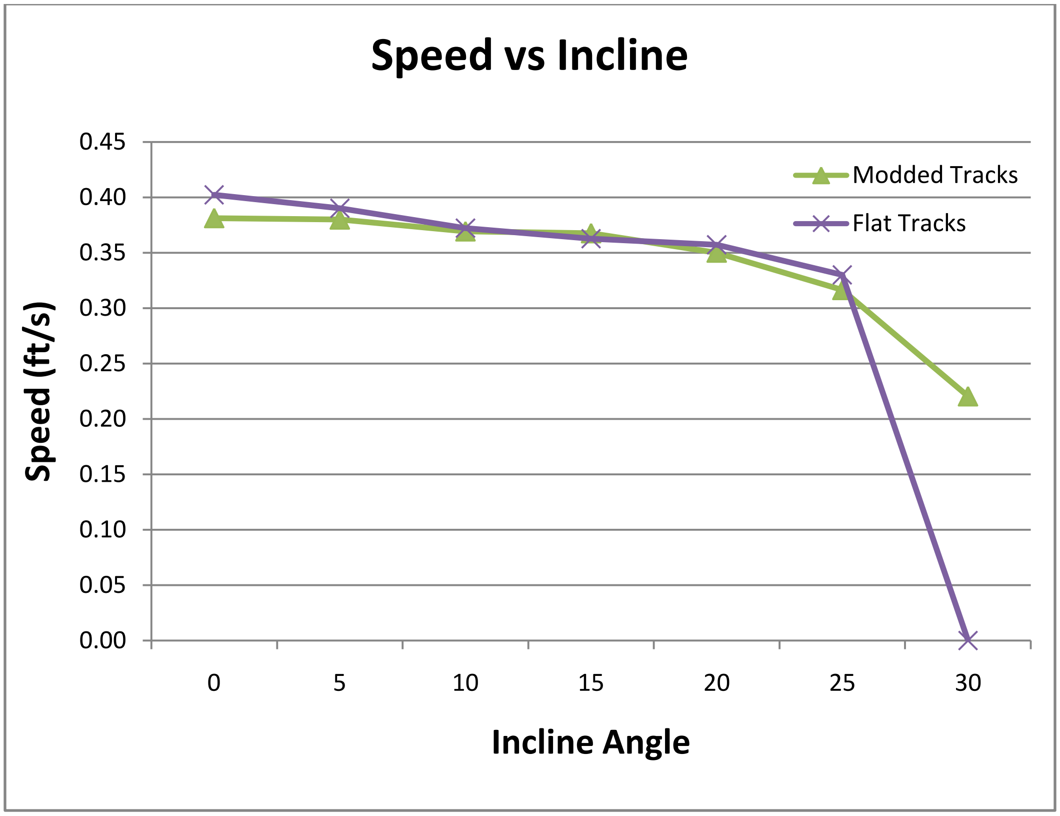


Figure 44: Speed vs Incline for Flat and Modified Tracks.

Figure 45: Tracks in the Sand from the Modified Tracks.

4.2.5 Revised Design Burrow Testing. With the new cameras and tracks fitted to the robot, another round of testing was done at Fish Hawk Creek Nature Preserve. The robot and testing equipment was setup at the entrance of burrow #2. It was driven down into the burrow and immediately the improvements could be seen from the new cameras and modified tracks. The vehicle was much easier to control while maneuvering down the burrow than in previous attempts. It traveled down successfully for about 15 feet until one drive motor’s gearbox started experiencing problems, as could be heard on the microphone. This was most likely caused by previous tests and inexperienced driving causing damage and wear to the output stage of the gearbox. The safety tether was used to help the robot drive out of the burrow. Other than the gearbox problem, this testing session was partially successful as it proved the robot could traverse down a burrow and relay information about what is inside to the user.

Figure 46: New Camera Used in Burrow #2.

4.2.6 Revised Motors and Third Burrow Test. With the previous motors experiencing problems, new motors were chosen for the main tracks. The Fingertech Spark motors had spur gears in the gear box which were weak and subject to failing. A new motor was chosen with a planetary gearbox for higher strength and greater torque with a 231:1 gear ratio. At 12 volts the output shaft spins at 70 rpms. The motors were close to the same size as the previous ones, so no major design changes were needed. Although the motor speed is slower, more torque was helpful in climbing up and out of the gopher tortoise burrow.

Table 5: B231 231:1 New Motor Data.

B231 Motor	Volts (V)	RPMs	Torque (oz-in)	Sprocket Dia (in)	Vehicle Speed (ft/s)
231:1 Gear Ratio	12	70	370	0.96	0.29

A third test was done at Fish Creek Nature Preserve Burrow #2. Again, the revised and improved robot was launched into the burrow. The new motors were slower and more controllable. The sound from the motors was monitored to avoid unnecessary loading which could lead to damage. Depth markers were added to the safety tether so that the length of the burrow could be determined. The robot had no problem driving the entire burrow length of 25 feet (Figure 47). The descent took a little under two minutes, putting the total time to check a burrow quicker than most burrow camera tests. At the bottom of the burrow, a gopher tortoise could be seen tucked in its shell. After the successful descent, the robot started its ascent up the burrow. A wall was hit once while going up around a turn. After retrying the turn once more, the robot finished the ascent and drove out of the burrow.

Using scientific engineering processes, a unique robot was designed to survey and explore gopher tortoise burrows. Tracks on four sides gave this robot a high propulsion ratio and allowed motion under many circumstances that would otherwise cause it to become stuck. Also, after proving the hypothesis that the modified tracks would climb a 30 degree slope, they effectively allowed the robot to negotiate the sandy incline of the burrow.

Figure 47: Gopher Tortoise Identified at Bottom of Burrow #2.

CHAPTER 5: CONCLUSIONS

5.1 Conclusions and Future Work

The experiments showed how a burrow robot can play a big role in estimating population sizes of the gopher tortoise. An active burrow can be confirmed in a few minutes, leading to greater accuracy than previous methods. This then leads to better understanding of the gopher tortoise and its habitat. Biology and Conservation departments such as the Florida Fish and Wildlife Conservation Commission would like to use this robot as a tool in evaluating the gopher tortoise species. The Hillsborough County Parks and Recreation Department plans on using the prototype or a future version during its population surveys.

The robot can be developed further in the future by designing a smaller version that could fit into tortoise burrows other than adults, and other animal burrows. This could be done by using smaller sprockets for the drive train. Also, a camera that could pan and tilt would be helpful in exploring more of the burrow.

It was clearly shown how tracks are the best form of locomotion for the sandy terrain of the gopher burrow. Track design also was explored in order to find an effective way to climb the required 30 degree slope. Using these modified tracks, the robot was able to successfully explore the burrow and able to identify a gopher tortoise occupying it.

The side tracks on the robot could be further developed so that they have a greater width and contact area. This would allow the robot to drive on its side more effectively. Overall, this is a capable vehicle that can relay visual information better than existing umbilical camera systems.

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APPENDICES

Appendix A: Gopher Tortoise Robot Pictures

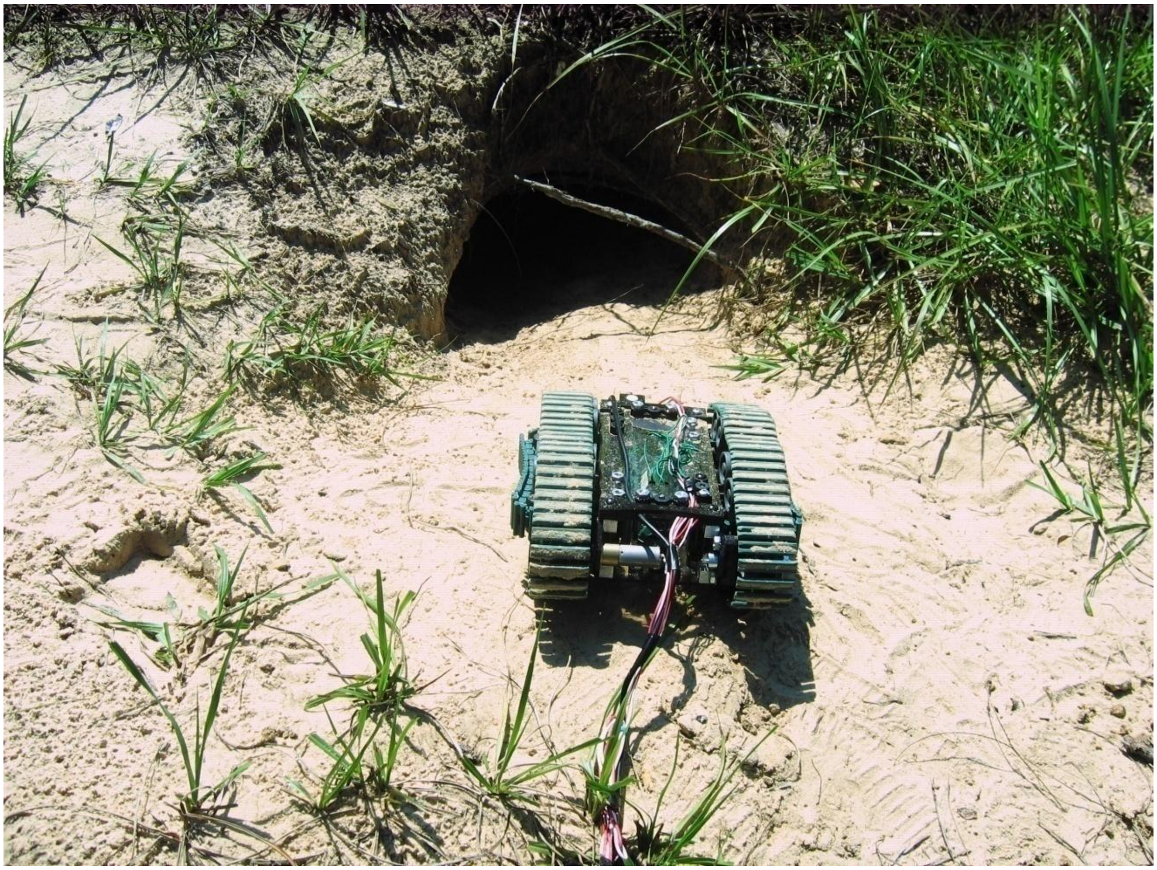

Figure A1: Gopher Tortoise Robot In Front of Burrow #2.

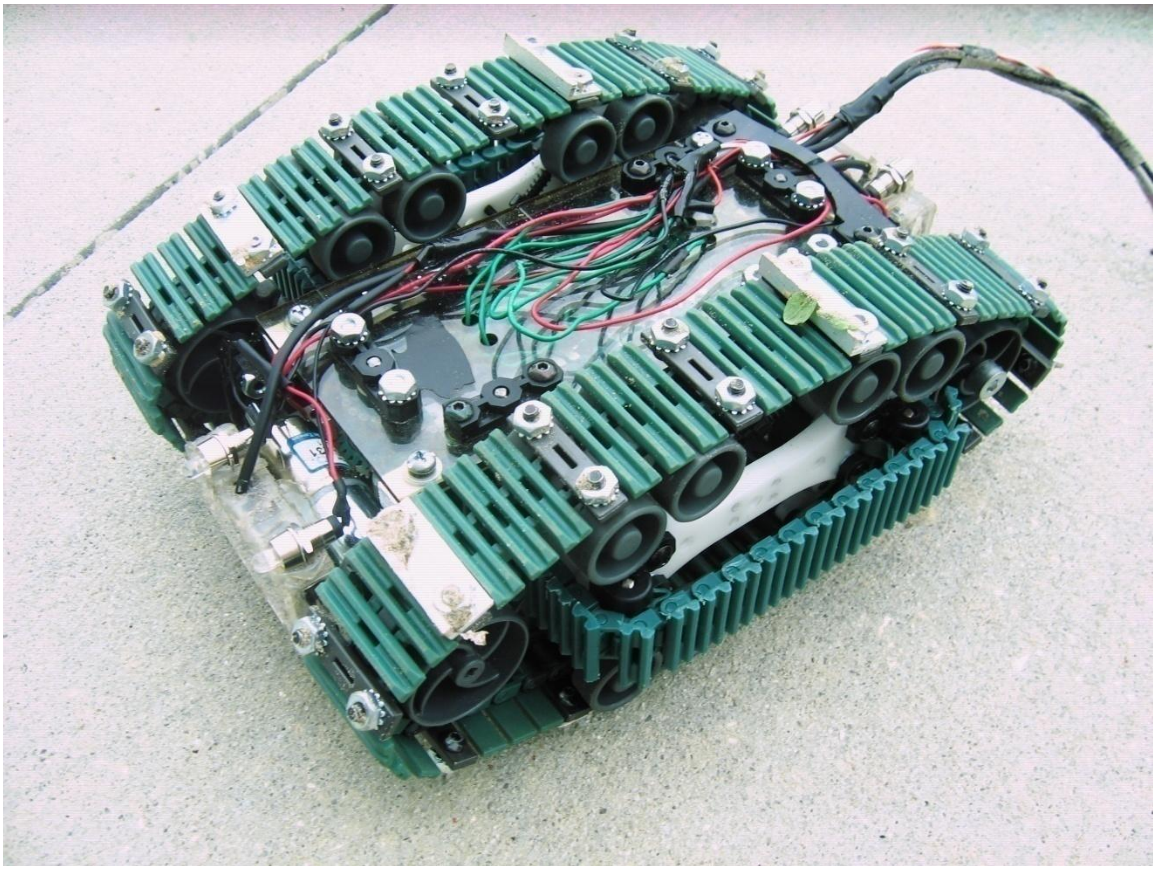

Figure A2: Gopher Tortoise Robot Angle View.

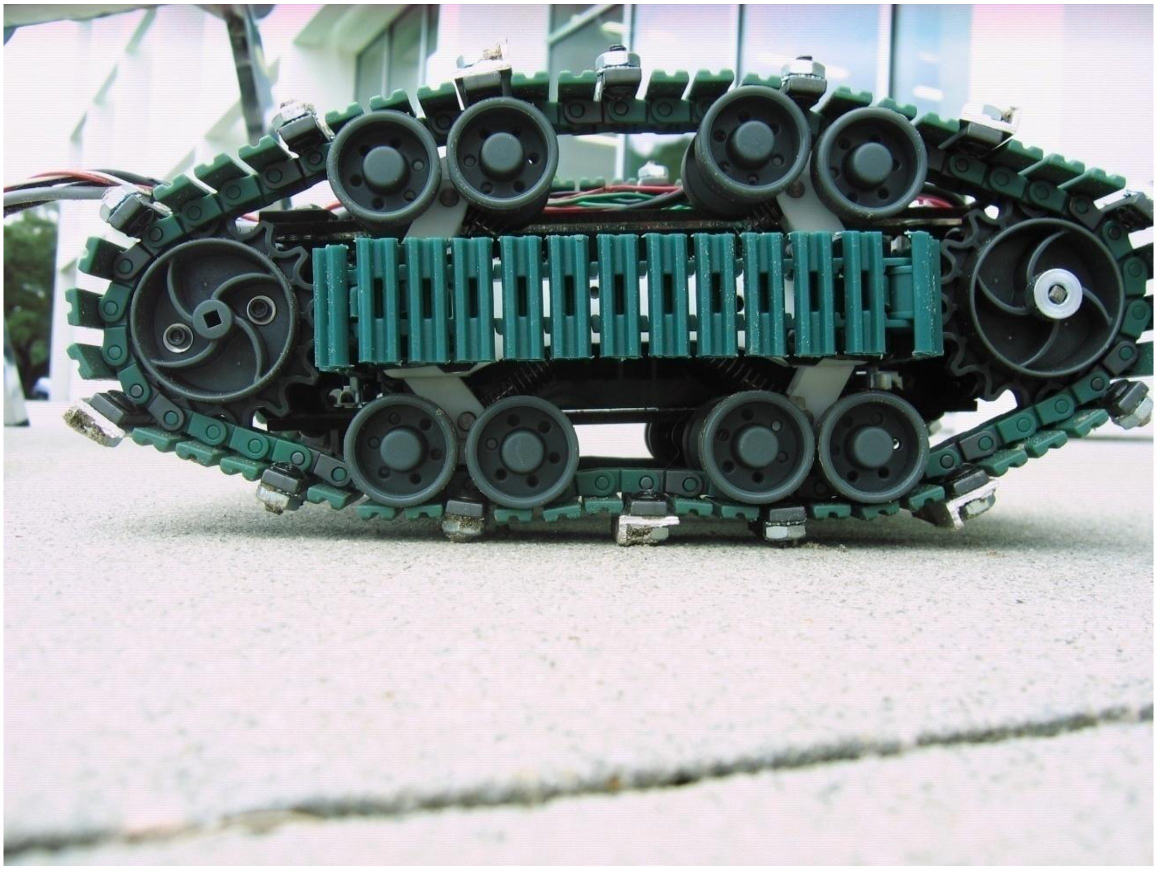

Figure A3: Gopher Tortoise Robot Side View.

ABOUT THE AUTHOR

William Keese was born in Niagara Falls, New York in 1987, and in 2005 he started studying in the field of Mechanical Engineering at the University of South Florida. For two years he worked as a mechanical engineering co-op student at Key Safety Systems in Lakeland, Florida where he worked in the automotive manufacturing industry. His responsibilities, among others, included designing tooling for new products, applying root cause analysis and lean manufacturing techniques to the assembly lines, and providing support for other engineers.