Autonomous Crawl Space Inspection Robot Project Proposal

James Camp, John-Caleb Williams, John Harris, Joseph Thomas
Electrical and Computer Engineering Department
Tennessee Technological University
Cookeville, TN
jrcamp42@tntech.edu, jawilliams46@tntech.edu, jharris44@tntech.edu, jwthomas43@tntech.edu

I. Introduction

Crawl spaces grant convenient access to the plumbing, duct work, and electrical wiring of a house, but they often present unique dangers to maintenance professionals and residents alike, such as exposure to harsh breathing conditions and hanging obstacles. Areas that are incredibly difficult for humans to reach can also present challenges for inspectors. This capstone project will focus on the design and assembly of a robot prototype that can perform these inspections autonomously while also providing sensor data to operators and homeowners.

The end product will be an autonomous vehicle that is capable of traversing crawl spaces and recording conditions for operators and residents to review. An inspector will be able to drop the robot off at a client's house and leave it there to collect the data freeing the operator up to work on other tasks. While navigating under the house, the robot will be constantly taking temperature and humidity data which allows users to see exactly what areas of the space will be prone to mold growth. A moisture probe will also be included to measure the moisture content of wooden beams found in a crawlspace.

Members of the inspection industry stand to benefit greatly from this new product through its efficiency and convenience. Having a robot that can record inspection data without an operator present allows the time of company personnel to be spent on more important tasks. It also allows multiple people to look at the same data instead of only the people who went under the house seeing the information. An increased level of convenience is also provided. Not only is the operator no longer required to squeeze into a tight crawlspace, but the robot will also save all acquired data for the user to access at any time. In future iterations, a 3-dimensional model of the space will be created as well to create even more convenience. Inspectors stand to benefit greatly from the development of this robot.

The scope of the first iteration will include the ability to autonomously navigate through a simplistic crawl space with only a few obstacles present, collecting sensor data at certain intervals, and taking pictures that cover the majority of the crawl space perimeter. To prepare for future improvements the robot will also be outfitted with a receiver for manual control, although this may not be programmed within the time period. The sensor subsystem will be built with full modularity so that future iterations can replace the module with better sensors or new types of sensors. Other future improvements include continually improving autonomy and the ability to create a gradient of sensor data. The objective of this capstone project is to design a robot that will utilize optical and physical sensors that measure distance in order to navigate throughout a crawlspace environment, while simultaneously recording different environmental measurements including: humidity, temperature, and wood moisture levels.

II. Formulating The Problem

This section of the project proposal will introduce the required background information needed to make informed decisions about the project. This includes the industry standards we will be bound by when working on an engineering project. Specifications and constraints will also be detailed to narrow down the initial design parameters. Finally, a survey of the current solutions will be given to demonstrate where the product provides room for innovation and improvement.

A. Scientific Background

Much of the project's importance lies within the scientific background associated with it. The scientific background also supplies the project with guidelines for the measurements and movement systems. The project will require background information in a variety of fields: biology, meteorology, and topography.

Fifty percent of the air that cycles through the first floor of a home comes from the crawl space, so the air quality and status of the crawl space's climate has a direct impact on the air that the residents of the home intake [1]. If the crawl space is a humid, cool environment then mold will be extremely likely to grow in those areas. Mold causes a multitude of negative health effects for humans including stuffy nose, cough, red and irritated eyes, itchy skin rashes, fever, and shortness of breath [2]. The robot will be able to make autonomous measurements that a technician can use to determine whether or not mold is likely to grow in those spaces, and the pictures taken by the robot will ideally be able to show any mold that is growing within the space.

Every crawl space is different. Some spaces may have rocky, hilly terrain, whereas others may be flat but filled with puddles of standing water. With all of the different possible terrain that the robot may need to navigate, it is important that the robot be able to navigate in an ”all terrain” fashion or be suited for the average crawl space, which consists of a dirt floor and is decently level. In some circumstances, animals and pests may take up residence within a crawl space. It is not within the scope of the project to have any sort of extermination methods, but that would be a possibility for future groups.

B. Engineering Background

The objective of the autonomous crawl space inspection robot project is to develop a system that is capable of autonomously navigating, measuring sensor data, and moving throughout a crawl space environment.Navigation algorithms using optical and physical sensors as input information will be used, while simultaneously capturing images and recording humidity, moisture, and temperature measurements of the crawl space environment. As a mid-level autonomy device, operation will be performed without human interaction unless a critical error arises and human interference is needed in order to help the device succeed [3]. In order for the inspection robot to navigate autonomously throughout the crawl space, it will utilize measurements of optical and physical inputs from LIDAR, touch, and sound sensing.

A light detection and ranging (LIDAR) sensor is a device that fires a narrow, infrared, pulse of light, commonly referred to as a laser, from a transmitter terminal. The LIDAR sensor then utilizes a clock in order to track the time taken for the pulse to refract from an obstacle back to a receiver [4]. A LIDAR sensor is commonly mistaken with a non-laser, infrared (IR) sensor, which utilizes infrared light in order to detect when an emitted beam is broken, revealing that an obstruction is present and outputting an appropriate logic signal [4].

Physical sensors are another available option which can be used to alert a controller of possible obstructions. A Roomba, for example, is a device that utilizes a bump sensor that upon colliding with an obstruction, outputs a signal, alerting the controller that an object is in the way [5]. A trigger sensor is one example of a physical touch sensor which, upon colliding with an obstacle, will activate a trigger mechanism. This trigger mechanism will output a logic bit of one when a contact is pushed down onto the switch, and a logic bit of zero when a contact is no longer touching the switch [5].

Sound sensors, commonly referred to as ultrasonic sensors, utilize a clock, transmitter, and receiver in order to determine distance from an object. Ultrasonic sensors are able to determine the distance from an object by tracking the time taken for a transmitted sound wave to be received after reflecting off an object [4]. Since the crawl space inspection robot will be operating within an enclosed space, an algorithm could be developed that would determine the appropriate direction for the robot to move. By establishing an ultrasonic sensor on each side of the robot, a direction could be determined by computing which sensor had the longest time taken for a sound wave to be received. This algorithm would allow the robot to constantly move in a direction with the least amount of obstacles present.

By applying a combination of optical and physical sensors, a robot could achieve a higher level of accuracy for its autonomous navigation. One example is a higher level Roomba device, which utilizes an algorithm called Hector SLAM Mapping. Simultaneous Localization and Mapping (SLAM) is an algorithm which allows an object to mark data points whenever an obstacle is reached. The device will continue placing data points until enough points have been marked for the device to develop a map and navigate throughout a room [6]. By utilizing physical and optical sensors, a device could develop an even more accurate map of the environment and increase the efficiency of its navigation. An example of the SLAM algorithm, executed by a Roomba cleaning robot, is shown in figure 1 [7].

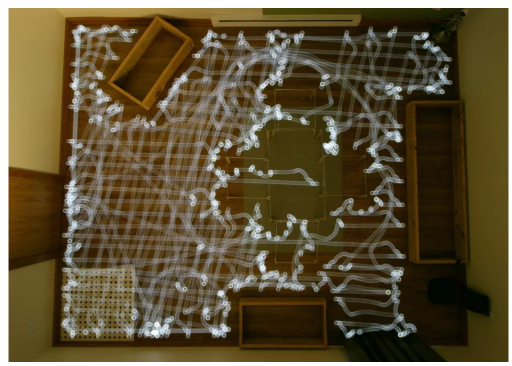

Figure 1: Hector Slam Mapping

In addition to autonomous movement, a foundation will be laid for a fail safe mechanism in which a human can intervene and operate the device manually, allowing for the device to return to its origin if an error arises. Radio controllers (RCs) are devices which utilize radio waves in order to transmit control signals to a device [8]. Through the use of a radio controller, commands could be sent from a transmitter on the manual controller to the receiver on the inspection robot. Additionally, with a camera mounted onto the inspection robots as well as a transmitter, video feed could be sent from the inspection robot to a receiver on the manual control. As outlined by the Federal Communications Commission (FCC), individuals without an amateur (HAM) radio license are legally allowed to transmit and receive control and video signals on specific bandwidths such as 27 MHz, 75 MHz, 2.4 GHz, as long as transmitter and receiver devices are properly certified for unlicensed use by the FCC [9].

Humidity, temperature, and moisture levels are relatively common measurements taken with module sensors designed for the Arduino microcontroller. The humidity of an environment is measured by applying an electric charge to a medium, placed between two electrode plates [10]. Depending on the level of resistivity, a humidity value can be determined, thus allowing the humidity of an environment to be measured with a typical accuracy of five percent. Additionally, the temperature of an environment can be measured through the use of a thermistor, a resistor device whose resistance value has a direct, linear relationship to temperature [11]. Moisture levels are commonly measured in the same context as humidity levels. In order to measure moisture level, two probes are placed into a material or space and an electric pulse is sent between the probes of the device. The resulting resistance is measured and then a correlated moisture level can be determined [12].

The proposed power system for this inspection robot would utilize cordless drill batteries as voltage sources. Cordless drill batteries can allow for modular application and ease of use due to the batteries being easily removed and replaced with charged versions should they fail. These cordless drill batteries would need to be utilized with specific adapters due to connectivity constraints, shown in figure 2 [13]. The suggested battery adapters will have fuses and kill switches built in or added by the team in order to ensure that safety voltages are not exceeded, and allow for a manual kill switch if necessary. Most cordless drill models come with LED indicators built in so that power level can be observed. Circuit options for reducing voltages for various components will be carried out with voltage dividers, and Zener diodes can be used to ensure the safety of microprocessor components. The team believes one 20 V battery might be sufficient for the power system of the crawl space inspection robot, however, if necessary, a second battery may be added in parallel to increase operating time.

Figure 2: Battery Adapter

C. Constraints

The crawl space inspection robot must adhere to certain constraints in order to be deemed appropriate and properly designed. The average height of the crawlspace of a home ranges from 44 to 48 inches but can often be much smaller [14]. This will create a limit how tall the robot can be in order to serve the maximum number of households. All components and wiring within the chassis must also be properly protected and sealed from water and dust exposure as these elements will be plentiful in most crawlspaces.

The chosen power system of the device must be able to supply the different voltage requirements of various components within the system, such as 12 Volt motors and 5 Volt controllers. It is also important that it can provide power long enough for the entire crawl space to be explored. Because a foundation will be laid for manual control through the implementation of transmission and receiving hardware, constraints will be placed on what frequencies can be used as well as the device range. The receiver and transmitter must be able to operate only on frequency channels which do not require an amateur license, like 27MHz, 75 MHz, and 2.4 GHz [9].

D. Specifications

The crawl space inspection robot must adhere to certain specifications in order to achieve the desired objectives. First, the device must be shorter than 16 inches, or two blocks, to allow practical utilization of the device in almost any home. However, because crawl spaces can be 44-48 inches [14], the moisture probe will be able to extend at least 32 inches from the top of the chassis allowing it to fit in most spaces while also reaching most wooden beams. As for the other sensors, because small sensors can often have accuracy problems, at least two temperature and two humidity sensors will be included to compare values and ensure accuracy in the measurements. This will not be the case for the wood moisture probe as that sensor will be custom built. To ensure its accuracy, feedback sensors will be added to the arm to ensure the probe is applied with the correct pressure at all heights. This ensures that the measurement will be accurate and consistent in most crawl spaces.

The batteries chosen must allow for the system to operate at minimum of four hours which should provide sufficient time to navigate the space. All parts, including the battery and sensors, will be picked with heavy consideration on environmental ratings to prevent parts from wearing out due to dust, dirt, or moisture. For this reason, the battery will not have any exposed electrical contact points during operation. This specification will prevent rust and deterioration of the contacts from limiting the battery's performance.

E. Standards

It is vitally important for the team to understand the standards put in place by the government and engineering societies because they act as restrictions and guidelines for the design of the robot. The IEEE sections 1872.2-2021 and 7007-2021 on autonomous robots and ethically driven robots and automation as well as the NEC within the NFPA in particular will have the greatest effect on the robot. The team will need to be familiar with the content of the above standards in order to create a product that adheres to the code of conduct specified in those standards.

For example, Article 310.10.C of the NEC states that insulated conductors and cables used in wet locations shall be moisture impervious or metal-sheathed or be of a type listed for use in wet conditions. Furthermore, section 310.14 contains the requirements for Ampacities for conductors rated 0-2000 Volts [15]. The constraints described in these sections and others will have a direct impact on the design of the Autonomous Crawl Space Inspection Robot.

Along with the design, the assembly of the first prototype will also have to follow industry standards. IPC sets international standards regarding the assembly of everything from soldering to Printed circuit boards (PCBs). Because this product will need to have a long lifecycle but does not perform any health or safety-critical operations, it will be classified as an IPC class 2 product. One member of the group holds an active certification in IPC-J-STD-001 and will be responsible for inspecting all soldering and PCB assembly to ensure compliance to the standard.

F. Survey of Possible Solutions

There are currently inspection robots available which can accomplish a variety of feats and assist individuals in the inspection of different environments such as crawl spaces. For example, one inspection robot currently available is the GPK-32 Wireless Robot from SuperDroid Robots that is capable of capturing high resolution video for inspection through manual operation [16]. Additionally, another available inspection robot is the autonomous ExR-2 from Energy Robotics which is capable of autonomously navigating through a hard environment in order to provide video footage [17].

A major benefit over the existing robots is the addition of the sensor module. This module allows the robot to make the recordings an inspector would have to manually make otherwise. The module allows the ability to record more points and display the recorded data overlaid with a map of the crawlspace. This gives operators more information and presents it in a more useful and aesthetic way than plain numbers.

Another piece of technology utilized by the inspection and crawl space industry is a wood moisture probe which shows how much moisture is in the wooden boards underneath a house. In order to get moisture measurements from wooden boards, a person must manually push the probes into a board. The team's robot will be able to perform this action autonomously which saves the operator from having any need to go underneath a crawlspace in the vast majority of cases.

While there are currently solutions which exist and are available for purchase, the cost of these solutions are high, ranging from thousands to tens of thousands of dollars. There does not appear to be an affordable inspection robot that can meet all required specifications given for this autonomous crawl space inspection robot.

G. Summary of the Problem

The current inspection of crawl spaces requires the use of human time and effort, which could be seen as inefficient management of time as well as result in a lack of recorded measurements that could be useful in the analysis of the crawl space environment. Using the gathered background information, specifications, constraints, and a summary of already available solutions, an important problem with crawl space inspection can be identified as well as an appropriate objective to address the problem. An autonomous crawl space inspection robot could be created in order to better manage the time of individuals who would be inspecting the crawl space environment, as well as provide a record of important measurements taken from the environment. The objective of this capstone project is to create an autonomous crawl space inspection robot which is capable of navigating, traversing, and recording pictures, humidity levels, temperature levels, and moisture levels of a crawl space environment.

III. Looking Ahead To The Solution

This section of the project proposal will outline how the capstone team will begin to craft an appropriate solution based on the gathered problem and objective. In order to begin to picture a solution, the project team must identify what key aspects remain as critical unknowns, which will need to be some of the first problems solved. Additionally, the team will look into how the success of a solution will be measured, both quantitatively and qualitatively. The team will attempt to emphasize what experiments could be performed in order to justify the success of a solution as well as provide proof of the success of the solution. The broader impacts, ethics, responsibility analyzed and the proper scope of the autonomous crawl space inspection robot will be determined along with an idea of a proposed solution to the determined problem.

A. Subsystems

To allow the project to develop with the greatest possible efficiency, the work will be divided into four subsystems and assigned to each member. The four systems will be power, sensors, navigation, and mechanical system which are assigned to John Harris, James Camp, J.C. Williams, and Joseph Thomas respectively. Power will focus on the voltage distribution as well as circuit protection. The sensor subsystem will be a modular device which handles all sensing and data collection. The navigation and positioning subsystem is responsible for the position and collision sensing as well as autonomous control. Finally, mechanical systems will involve the motors and physical movement of the robot. The subsystem breakdown can be seen in figure 3.

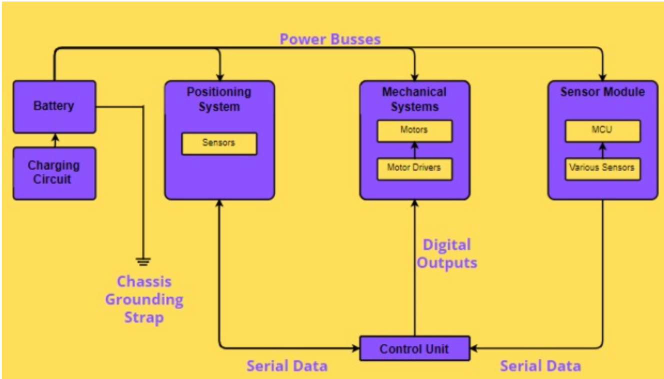

Figure 3: Subsystem Design

B. Critical Unknowns

The main unknown posing a risk at this time is the autonomous operations. The crawl space at each inspected home will be drastically different from the last inspected space. This presents the possibility of a new obstacle arising that the system is not able to handle. Because the team will not be able to predict every situation, this is a risk that can not be experimented away or solved with a new part. To mitigate the risk as much as possible, backup systems will be put in place for manual control but this addition can not be relied on heavily or the convince of the product is gone. This creates a risk to the operation overall and the usefulness of the device to its user.

The manual control system also remains a critical unknown at the time. Specifically, the method with which the user will be able to view the robot during manual control is unspecified. If manual control is needed when a direct line of sight is not available, the camera will have to provide a live feed to the operator. Wireless communication must be set up to provide this video feed but connecting the robot to the household WIFI is not ideal. This creates risk because if it is found later in the process that new peripherals are needed for this operation, significant redesigns may be necessary.

The final critical unknown which must be solved is the specifics of the battery. This system will not be able to be finalized until more detailed design is performed. Therefore, at the beginning of the design process, the necessary values will have to be estimated to allow for simultaneous development of all systems. Significant risk results from this because if the battery is found to not provide the sufficient time needed, the robot will not be able to complete the entire crawl space. This could result in a dead robot being lost under the house requiring a human to search for it. Although some analysis can be done to estimate the battery life, in a complex system with an evolving design it will be hard to accurately predict this and eliminate the risk.

C. Measurements of Success

Having a clear definition of success as well as a transparent system for measuring that success is an important part of any project. The success of this project will be measured in a few quantitative and qualitative ways.

The first item of success is Navigation. For the robot to successfully navigate a crawl space it will need to ”Roomba around.” The team will measure this aspect by constructing a series of model crawl spaces for the robot to navigate. These model crawl spaces will be based upon the team’s research of the terrain of crawl spaces. The team will track the robot as it traverses these model spaces in order to see how efficiently it maneuvers throughout the models and how much of the total area is covered. The goal of the first iteration is for the robot to maneuver through at least 70% of the area as this covers the majority of the crawl space.

The second item of success lies within the robot’s ability to collect and store correct measurements of the temperature and humidity of the space. The team will take manual measurements of a space and compare them to the autonomous measurements taken by the robot. If all of the measurements are found to be comparable to the correct measurements the sensing module will be considered successful for the first prototype. The wood moisture probe will be tested in a similar way with values measured by the robot compared to values recorded from a COTS probe.

D. Broader Impacts, Ethics, and Responsibility

Often when tasks are automated there is a chance of having a negative impact on the workforce. A person who previously collected a wage for the automated job might be forced into an uncertain labor market. There are several reasons why the project will not displace any members of the workforce. The level of autonomy implemented will require human intervention for full effect. The vehicle will not be able to find crawlspaces without assistance. The vehicle itself will not perform corrective measures on crawlspace locations. Operators will also be needed to inspect the pictures and sensor data recovered. This means although fewer workers would be needed out in the field at the houses, jobs would still be needed looking at the data and deciding what maintenance needs to be done. In addition to not being able to operate without human assistance, the vehicle has the potential to make a businesses more profitable. The capstone team believes this project could have a positive impact on employment for business overall.

Responsible engineers must always consider the broader impact of their work. There are worst case scenarios for the vehicle that we consider most serious. The first is the risk of fire. Because crawlspaces can contain flammable material, the vehicle must have redundant safety measures to ensure that it never reaches an unsafe temperature. The plan to increase fire safety is to use multiple fuses so that if one fuse fails another can break the circuit. Another major concern is the privacy of residents. There is a scenario where the recording abilities could be used to invade the privacy of occupants. The main defense against cyber attacks will be to keep the vehicle off Wi-Fi networks. The final concern stems from the scenario where the vehicle performs poorly. Poor performance could cost the operators time and money. The plan of action for this risk is to run extensive tests to ensure the correct operation of the vehicle.

IV. Resources

This section of the project proposal will address what resources are available to the capstone team and how the capstone team will attempt to use those resources throughout the engineering design process. The skills and knowledge of the team will also be detailed to demonstrate that the project will be within the team's abilities. Finally, the budget and timeline are attached and explained to ensure that it is possible to finish the robot in the available amount of time at a reasonable cost.

A. Personnel and Skill Sets

In order for the robot to be successful, the team must have the necessary skills and knowledge to begin such a project. Although it is expected that skill gaps will be found, it is believed that the team of four, senior electrical engineers possess the prerequisites to learn anything that is needed. One of the largest skill gaps the team will need to overcome is the management side of a large-scale engineering project. Experience will need to be gained in maintaining a budget, meeting deadlines, and communicating within the team.

James Camp was chosen as the delegator of the capstone project team and is responsible for assembling suggested timelines throughout the project as well as confirming deadlines with individual team members. James, pursuing a concentration in mechatronics, is proficient in the following skill sets: Microcontroller operation, C++ and C computer programming languages, Solidworks 3D modeling, and PCB design.

J.C. Williams was chosen as the treasurer of the capstone design team and is responsible for the management of the capstone team budget by analyzing, recording, and updating the expenditure of the team's budget. JC is proficient in the following skill sets: computer vision programming through Python libraries such as "OpenCV", Raspberry Pi assembly programming, 3D modeling, and 3D printing.

John Harris was chosen as the secretary of the capstone project team and is responsible for compiling minutes from each capstone team meeting as well as recordings of task completion throughout the design process for the purpose of creating an accurate timeline. John is proficient in the following skill sets: Digital Signal Processing (DSP) through C, C++, and MATLAB programming as well as power system analysis.

Joseph Thomas was chosen as the communicator for the capstone project team and is responsible for communicating with each member of the capstone team to ensure inclusion and communication throughout the team. Additionally, Joseph is responsible for communicating directly with Mr. Roberts and other potential third parties on the project team's behalf. Joseph is proficient in the following skill sets: automation of mechanical and electrical systems through PLC programming, telecommunication system design, and electromagnetic fields.

B. Budget

The budget for the autonomous crawl space inspection robot capstone project is a tentative budget and is subject to change throughout the engineering design processes. The suggested budget, however, will serve as an outline for the capstone team project as well as a finite representation of the sustainability of the project, proving that the robot can be built within a reasonable budget. The budget, shown in figure 4, is categorized by the subsystems which will make up the design, allowing for clarification as well as a suggestion for the price of each subsystem. An error of ten percent and seventeen percent are allocated in this budget, allowing for both low and high error estimates which can be used to gauge the possible cost of the project. After estimating the possible components in each subsystem, the suggested cost for designing and building the autonomous crawl space inspection robot is shown in figure 4.

Crawl Space Inspection Robot Subsystem	Quanity	Cost/Unit	Cost Total
Main Control			$70:$80
Microcontroller (Arduino Mega)	1:1	$35:$45	$35:$45
Microprocessor (Raspberry Pi)	1:1	$35:$55	$35:$55
Power System			$65:$218
Battery	1:2	$30:$50	$30:$100
PCB Control Board	1:2	$15:$50	$30:$100
Fuses	5:9	$1:$2	$5:$18
Navigation System			$116:$336
Bump IR Sensor	1:4	$1:$3	$1:$12
LiDAR Sensor	2:4	$10:$30	$20:$120
Sonar Sensor	1:3	$5:$8	$5:$24
Camera	1:1	$40:$60	$40:$60
RC Controller	1:1	$30:$80	$30:$80
LCD Screen	1:1	$20:$40	$20:$40
Movement System			$155:$315
DC Brushless Motor	4:6	$5:$15	$20:$90
Servo Motor	1:3	$10:$20	$30:$60
Motor Control	1:1	$15:$25	$15:$25
Wheels	4:4	$10:$20	$40:$80
Tracks	2:2	$25:$30	$50:$60
Enviroment Sensor System			$9:$28
Humidty Sensor			
Temperature Sensor	1:2	$4:$6	$4:$12
Moisture Sensor	1:2	$5:$8	$5:$16
Structure and General			$50:$120
Structure	1:1	$10:$20	$10:$20
Wires	N/A	N/A	$20:$50
Connectors	N/A	N/A	$20:$50
Total			$468:$1284
Total			$425:$1097
Error	10%		$43:$110
	17%		$72:$187

Figure 4: Estimated Budget

C. Timeline

The project timeline will focus on finishing the design before focusing on assembly and testing. The first step will be to experiment and make decisions on the unknowns so that we can move forward with the design with as little risk as possible. Next, individual subsystems will be worked on separately until reassembling for group check after phase 1. Once the phase 1 design is signed off on, each member will begin picking parts and fleshing out their individual system design for phase 2. It is expected that phase 2 will end in the early part of the fall semester so that a month can be had for assembly and a few weeks after that can be dedicated to testing.

At the end of the document, two Gantt charts can be found. The first of these charts seen in figure 5 presents a detailed semester view with the majority of the design tasks for the semester laid out. These tasks are split into the subsystems and assigned on the chart to individual members. Figure 6 shows a more holistic view of the project stretching into the next semester. Because summer break causes a large gap in the middle it was difficult to combine these charts so a second was created to show the full class plan.

V. Conclusion

Crawl Spaces are an important but often forgotten section of a residential home. The environment and climate of a crawl space not only have a direct impact on those that live in the home, but also on the professionals that are exposed to the crawl space environment. The purpose of this capstone project is to provide a safer, more efficient, and autonomous method for collecting environmental data within a crawl space. The Autonomous Crawl Space Inspection Robot will be an effective solution to the problem formulated throughout this project proposal.

VI. References

[1] “You Breathe the Air from your Crawlspace.” Aquaguard Foundation Solutions. https://www.aquaguard.net/resources/crawl-space-repair/your-breathe-the-air-from-your-crawlspace/ (February 13, 2022).

[2] “Mold.” Center for Disease Control and Prevention. https://www.cdc.gov/mold/default.htm (February 13, 2022).

[3] Rachel Gordon. “Explained: Levels of autonomy in self-driving cars.” MIT CSAIL. https://www.csail.mit.edu/news/explained-levels-autonomy-self-driving-cars (February 15, 2022).

[4] Shawn. “Types of Distance Sensors and How to Select One?” Seed Studio. https://www.seeedstudio.com/blog/2019/12/23/distance-sensors-types-and-selection-guide/ (February 15, 2022).

[5] Jfieldcap. “Cheap Bump Sensors for Arduino Robots.” Instructables. https://www.instructables.com/Cheap-Robot-Bump-Sensors-for-Arduino/ (February 15, 2022).

[6] Charlotte Dorn. “Creating a map with just LIDAR using hector slam.” Charlotte Dorn. https://medium.com/@chardorn/creating-a-map-with-just-lidar-using-hector-slam-231f3bab45e2 (February 13, 2022).

[7] Brian Bennett. “This is why your Roomba’s random patterns actually make perfect sense.” Cnet. https://www.cnet.com/home/kitchen-and-household/this-is-why-your-roombas-random-patterns-actually-make-perfect-sense/ (February, 14, 2022).

[8] Matt Robbs. “How an RC Remote Control Works: An Interactive Guide.” Race n’ RCs. https://racenrcs.com/how-an-rc-remote-control-works-an-interactive-guide/ (February 15, 2022).

[9] “Frequency Control of Non-2.4 GHz Spread Spectrum R/C Radio Systems.” https://www.modelaircraft.org/sites/default/files/928.pdf (February 15, 2022).

[10] Sachendra003. “Arduino - Humidity Sensor.” Arduino Project Hub. https://create.arduino.cc/projecthub/sachendra003/arduino-humidity-sensor-288146 (February 15, 2022).

[11] Limor Fried. “Thermistor.” Adafruit. https://learn.adafruit.com/thermistor (February 15, 2022).

[12] ElectroPeak. “Complete Guide to Use Soil Moisture Sensor w/ Examples.” Arduino Project Hub. https://create.arduino.cc/projecthub/electropeak/complete-guide-to-use-soil-moisture-sensor-w-examples-756b1f (February 15, 2022).

[13] “Battery Adapter for Dewalt 20v Max - 18v Dock Power Connector - Upgrade Your Power Wheels Truck, Robot - 14 Gauge - Tool Only - - Amazon.com,” Amazon. https://www.amazon.com/Battery-Adapter-Dewalt-20v-Max/dp/B0925D9M42 (February 16, 2022).

[14] TechSpaces. “A builder’s blueprint for construction technologies.” Home Innovation. The Closed Crawl Space: Making the Transition (February 13, 2022).

[15] NFPA. ”National Electric Code.” NFPA. https://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards/detail?code=70 (February 27, 2022).

[16] “GPK-32 Tracked Inspection Robot.” Super Droids. https://www.superdroidrobots.com/Robots/professional-inspection-robots/product=2729 (February 13, 2022).

[17] ”OUR FLAGSHIP, FULLY AUTONOMOUS EXR-2.” EX Robotics. https://exrobotics.global/robots/exr-2 (February 16, 2022).

[18] Tom Laurenzi. “HOW TO MEASURE THE MOISTURE CONTENT OF WOOD FOR DIY PROJECTS.” Delmhorst. https://www.delmhorst.com/blog/measure-the-moisture-diy-projects (February 13, 2022).