Autonomous Crawl Space Inspection Robot Final Report

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I. Introduction

A. Problem Formulation and Motivation

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 that is capable of navigating, traversing, and recording pictures, humidity levels, temperature levels, and moisture levels of a crawl space environment.

B. Background information

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.

In order for the inspection robot to navigate autonomously throughout the crawl space, it utilizes measurements of optical and sonic inputs from LIDAR 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 [3]. A LIDAR sensor is commonly mistaken for 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 [3]. Sound sensors, commonly referred to as ultrasonic sensors, utilize a clock, transmitter, and receiver in order to determine the 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 [3]. These sensors can be used to avoid collision with walls and other obstacles in the crawlspace.

Mapping can be done using an algorithm called Simultaneous Localization and Mapping (SLAM)/ SLAM is an algorithm that 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 [4,5]. 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.

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 [6]. Depending on the level of resistivity, a humidity value can be determined, thus

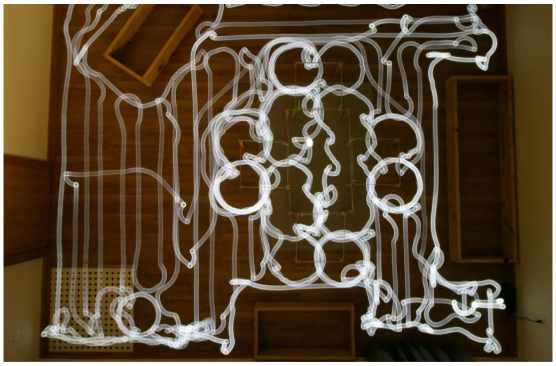

Fig. 1. SLAM Mapping [5]

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 [7]. 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 [8].

The power system for this inspection robot utilizes a rechargeable battery as a voltage source. Buck converters can also be used to ensure the voltage source will be constant. These devices work by taking an input power and outputting a constant voltage with a current value that keeps the power equal on both sides of the device. Finally, fuses are devices that will fail at a certain current and turn into an open. This means that if an overvoltage is experienced in one branch of the system, that branch will be cut off and unable to affect the rest of the components.

C. Constraints

The crawl space inspection robot adheres to certain constraints and specifications 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 [9]. This limits how tall the robot can be 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 power system of the device was chosen to 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. Constraints were also placed on what frequencies can be used for manual control. This part of the system operates on 2.4 GHz to fit within the standardized frequencies which do not require a license [10].

Specifications were also placed on the robot by the team based on the planned robot operation. First, the device was designed to 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 [9], 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. To ensure moisture content accuracy, feedback sensors will be added to the arm to ensure the probe is applied with the correct pressure at all heights. The batteries chosen allow for the system to operate for a minimum of four hours which should provide sufficient time to navigate the space. All parts, including the battery and sensors, were picked with heavy consideration of 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 in its final form. This specification will prevent rust and deterioration of the contacts from limiting the battery's performance.

D. Overall idea

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 GPK32 Wireless Robot from SuperDroid Robots that is capable of capturing high resolution video for inspection through manual operation [11]. 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 [12].

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

E. Salient outcomes

Although this project includes lofty long-term goals, many exceptional systems were able to be incorporated in the first iteration of the project. The mapping was found to be accurate to 93% or more in each test that was run. While this is useful information for an inspector to have, it will also provide an invaluable framework for future updates to the autonomy. Power was successfully applied to all parts of the system with no over-currents or under-voltages experienced by the system. All back EMF from the motors was successfully filtered out as well. Environmental sensing was found to be exceptionally accurate. Temperature and Humidity were both found to be 96% accurate or greater while moisture content was successfully measured to within 2.5% MC. Finally, the movement system was able to control speed and direction with a linear speed of around 1.08 ft/s.

F. Report Organization

Firstly, this report consists of a literature review where the relevant information is detailed along with a critical analysis of that literature. Additionally, this report will discuss the team's position in the industry setting, and the relevant engineering standards as well. Secondly, in consideration of the team's methodology, the theory and overall idea of the solution, the complete design process, and other special items are discussed. Next, the project's experimental results are displayed along with a small section of the deliverables. Then the logistics of the project are shown with a Gant chart, cost estimate, and final BOM. The report concludes with a discussion of the ethical and professional responsibilities, lessons learned, and a final summary of the project. At the end, each team member writes their own statement where he discusses the relevant information he acquired for this project either in other courses or otherwise.

II. Literature Review

A. Relevant Literature

Throughout the design of the Autonomous Crawl Space Inspection Robot, the capstone team consulted various pieces of literature for guidance on how to develop the best product possible. The literature examined by the capstone team ranged from online articles to papers to forums and various Github repositories outlined in this section.

A substantial portion of the project code was influenced by online robot operating system (ROS) and Arduino/Raspberry Pi forums. The robot operating system (ROS) wiki outlines, in detail, the process for developing a robot that can operate efficiently with Ubuntu and ROS [13]. From setting up Ubuntu 20.04 to what version of ROS should be used to library installation processes, the capstone team specifically followed all instructions and tutorials outlined in the main pages of the ROS wiki. Additionally, the team often consulted the Ubuntu wiki for questions on installation, command line (shell) programming, and common instructions [14].

While determining how to develop a communication protocol for the inspection robot, team members often examined many pages of the Arduino/Raspberry Pi forums and wiki's, which have a bountiful amount of helpful information for debugging USB and serial peripheral interface (SPI) library issues [15,16]. In fact, after spending countless hours debugging communication protocols for SPI, the team found forum and wiki posts that detailed common issues of implementing SPI and solutions for adapting the system to work with USB hubs within python [17].

In the beginning of the design and implementation of the inspection robot, team members simulated navigation and mapping algorithms with the commercially available Turtlebot 3 packages [18]. While these algorithms were not explicitly implemented into the inspection robot's design due to compatibility issues, the information supplied by Turtlebot served as a helpful introduction to ROS, SLAM, and Autonomous SLAM. The Turtlebot 3 E-Manual was specifically helpful to the capstone team, as this document outlined the processes of getting started with Ubuntu, ROS, and various forms of SLAM [19]. Additionally, the Hackaday article, "Build Your Own Turtlebot 3 Backbone", served as a great guide for implementing custom ROS and Arduino packages to communicate with a robot over ROS manual control protocols, such as turtlebot teleop keyboard control [20].

One of the largest helps with implementing Hector SLAM into the Autonomous Crawl Space Inspection Robot was the following ROS wiki/forum posts, which outlined in detail the specific parameters that needed to be changed within the header files of ROS and Ubuntu libraries [21,22]. Without guidance from these online sources, team members would have struggled much more with implementing a mapping system onto the robot in ROS. While these sources may not be typical academic papers, the individuals writing the forum/wiki posts have a large amount of knowledge which the capstone team found to be extremely helpful in the success of their Autonomous Crawl Space Inspection Robot.

B. Engineering 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 [23]. 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) [24]. 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 with the standard.

III. Methodology

A. *Theory and Overall Idea of your Solution*

To develop a working autonomous inspection robot, team members began the design process by researching commercially available products that possessed similar capabilities with what was to be designed by the team. Household autonomous vacuums, such as the iRobot Roomba, were thoroughly examined along with the navigation and mapping algorithms implemented onto the devices. Additionally, team members compared commercially available inspection robots, such Husky and SuperDroid, to determine the "common practices" for developing an industry-ready inspection robot. The power and mechanical systems of these devices were also investigated by team members so that appropriate specifications and constraints could be created for the design process. Finally, handheld moisture probes were examined so that customized hardware could be created for the robot to use for measuring the moisture content of the crawl space ceiling.

After completing their literature review, team members agreed on what parameters would be best fit for the inspection robot and a design plan was put into place for each subsystem. The Navigation subsystem was to utilize a Raspberry Pi 4B, equipped with Ubuntu 20.04, robot operating system (ROS), Python 3.7, light/sound sensors, and Hector Simultaneous Localization and Mapping (SLAM). The Mechanic subsystem was to utilize a tank like chassis, an Arduino micro-controller, and two motors/motor drivers. The Environmental Sensing subsystem was to utilize commercially available temperature and humidity sensors, along with a custom designed moisture content sensor. The Power subsystem was to use a 12 Volt 6.6 Amp-Hour battery, along with custom designed buck converters and fuse boxes.

By combining the previously mentioned subsystems, the Autonomous Crawl Space Inspection Robot would be a device capable of navigating autonomously throughout a model/actual crawl space environment at a speed of roughly one foot per second, while simultaneously generating a two-dimensional map. Additionally, the inspection robot would be capable of collecting images and temperature, humidity, and moisture content readings of the crawl space and its ceiling structure. Finally, the robot would be able to operate for over two hours of full run time and be controlled wirelessly if manual control is needed for mapping success or robot recovery.

B. *Complete Design Process*

Before jumping in to a detailed design, the team looked at the high level view of the project. Using this method, a plan was put in place for what systems would be included in this iteration of the project. It was also decided which interconnections would be needed between each part in the system to ensure that all parts chosen in the detailed design could interface with each other. Once this high-level design was completed, the team was able to move into it's detailed design phase.

The detailed design process focused on modularity which allowed the design to be parallelized. This means that each group member was given a subsystem that could be designed largely separate from the other subsystems allowing for maximum efficiency in the design. Modularity also ensures that errors in the separate subsystems will have as minimal an effect as possible on the other parts of the project. Following this principle, four subsystems were chosen for the design: power, navigation, sensing, and movement.

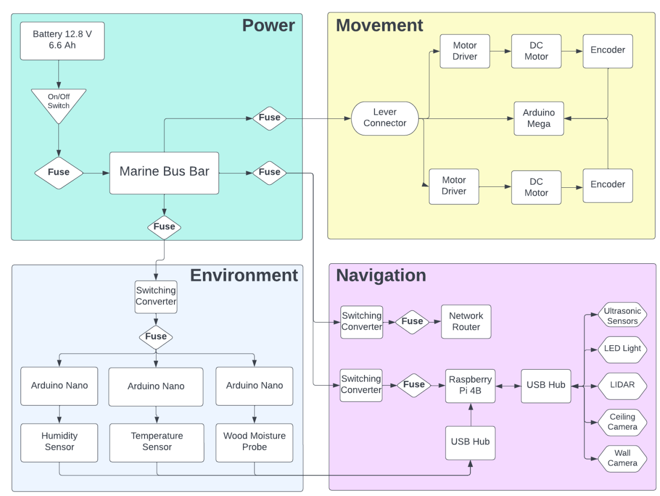

Fig. 2. Model Crawlspace

The hardware of each subsystem was designed concurrently during the design phase 2 period. After the individual designs were approved, the group shifted focus to interfacing the modules and ensuring that all information and power that needed to pass between systems was able to. This process brought the electrical design of the system to a close. From that point, the physical system had to be mechanically mounted. A multi-tiered system was chosen as it allowed us plenty of space for all parts. This mounting system also allowed each sensor to be placed at varying heights based on its individual requirements.

The final part of the design was the software. While a basic framework had already been created for much of the system's code, this portion was unable to be fully operational until the hardware was ready to be tested. For this reason, the bulk of the software writing had to wait until the majority of the hardware assembly was complete. The software used Robot Operating System (ROS) which is a mid-ware designed to run a variety of robotic systems. This program handled mapping while separate code was written in python to allow for autonomy, image collection, and image stitching. Finally, the code to collect environmental sensor data and control the motors was written in C on the Arduino IDE. Because the system included five separate microcontrollers, most of these pieces of code are running independently of each other. This meant that the last step of software design was interfacing with the different programs. Once this was complete, a final test run could be completed in a realistic crawlspace environment.

C. Design Considerations

During the design process detailed above, many factors had to be taken into consideration. The most obvious of these considerations was the professional standards explained earlier in the report. Outside of standards, safety was also taken into consideration as the robot will be operating in peoples home. The power system had to take precautions such as circuit protection and appropriately gauged wires to prevent fires from occurring on board. The autonomy program also had to be written to avoid collisions in order to prevent damage to the home.

Another design consideration was the environmental and economic impact of the project. Because the robot is solely operating underneath homes, the only environmental impact the team needed to consider was the parts purchased. When possible, all parts were chosen to be ROHS compliant to ensure minimal environmental impact from the robot. As for economic impacts, some concern was given to the possibility of the robot taking jobs from the inspection industry. However, an operator would still be needed to drop off the robot and inspect the results. This means the Croomba would only require the retraining of inspectors and not a full replacement.

IV. Results and Discussion

A. Experimental Results

Power

In order to verify the power subsystem is meeting all requirements, 5 trial runs measuring the voltage and current of each main subline coming off the battery were carried out, and the results are in the tables below. Over an hour and fifteen minutes of trial runs were performed while programming. The power system successfully powered all subsystems without outside assistance for the duration of these tests. This proves the two constraints laid out in the proposal that the power subsystem will provide correct current and voltage to the subsystems for a time that would allow mapping of a crawlspace environment.

Main Power LN 2 & 5

Trial Number (N)	Current(A)	Voltage (V)
1	0.526 A	13.26 V
2	0.627 A	13.26 V
3	0.675 A	12.85 V
4	1.265 A	12.68 V
5	1.326 A	12.75 V

Navigation LN 7A & 8A

Trial Number (N)	Current(A)	Voltage (V)
1	0.7 A	5.33 V
2	0.6 A	5.34 V
3	0.79 A	5.33 V
4	0.7 A	12.68 V
5	1.326 A	12.75 V

Network Router LN 9A & 10A

Trial Number (N)	Current(A)	Voltage (V)
1	0.1 A	5.3 V
2	0.12 A	5.32 V
3	0.12 A	5.31 V
4	0.28 A	5.31 V
5	0.33 A	5.3 V

Movement LN 11A & 12A

Trial Number (N)	Current(A)	Voltage (V)
1	0.526 A	13.26 V
2	0.627 A	13.26 V
3	0.675 A	12.85 V
4	1.265 A	12.68 V
5	1.326 A	12.75 V

Environmental Sensing LN 13A & 14A

Navigation

The Model Crawlspace

To test the navigation functionality of the autonomous crawlspace inspection robot, a rectangular-shaped model crawlspace was created, with a length of 16.5 ft, a width of 6 ft, and a resulting area of 99 square feet. Floor tiles were used as a reference for quantifying the crawlspace area, with each floor tile having an area of 9 in by 9 in. The walls of the model crawlspace were made with various materials available

Trial Number (N)	Current(A)	Voltage (V)
1	0.0642 A	5.24 V
2	0.0645 A	5.23 V
3	0.0644 AA	5.26 V
4	0.0.065 A	5.31 V
5	0.064 A	5.3 V

in the laboratory and had a minimum height of 17 in and a maximum height of 36 in.

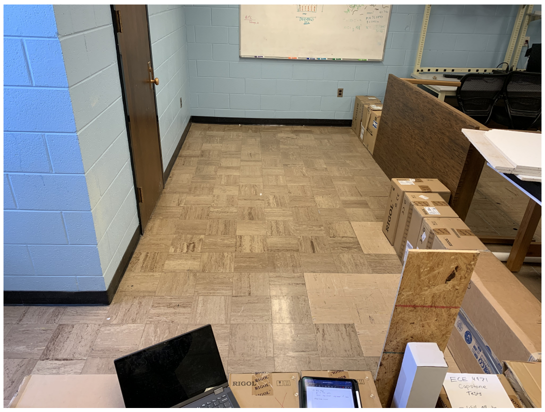

Fig. 3. Model Crawlspace

Mapping

The main job of the system's lidar is to create a map of the surrounding area without having to be provided a manually drawn map by the operator. To ensure that the map is being generated correctly, the perimeter of the test area was found by measuring the picture at a set zoom and creating a proportion from that value, and the percent error was calculated. The areas missed were then measured on the screen and the proportional value was applied to convert into the physical distance. The focus of this experiment was to identify the areas along the perimeter that the lidar missed as the additional points it caught past the perimeter are blocked by the true wall.

Perimeter (ft)	Measured Perimeter (ft)	Percent Error (%)
47.75	45.74	4.39
41	38.63	6.14
41	38.68	6.00

The results show that the lidar was able to successfully map the majority of the perimeter as it navigated throughout the crawlspace. In the worst case, the robot only failed to map 6.14% of the model environment. However, this percentage should be mostly negligible because none of the gaps in the walls of the model crawlspace are large enough for the robot to fit through.

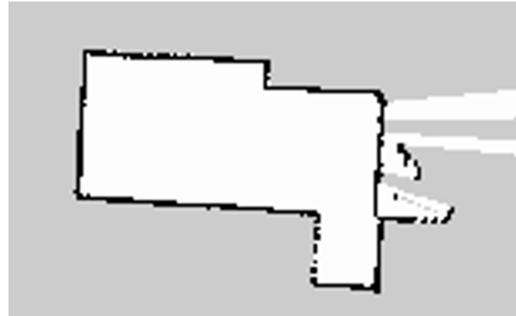

Fig. 4. Model Crawlspace Map

Maneuvering

In adherence to movement specifications, the robot needs to be capable of maneuvering through 70 % of the model crawlspace. To test adherence to this requirement, the team members counted which of the floor tiles in the model crawlspace the robot had not touched, and therefore how much of the total area of the crawlspace the robot had not maneuvered through. Additionally, the robot was initially placed in different corners of the model crawlspace to test the behavior from different initial positions.

In this experiment, the total area of the crawlspace was roughly 100 square feet and the total area covered by the robot is calculated and listed, along with the total percentage of the crawlspace area covered during the test. It is worth noting that in addition to the area listed in the table below, the robot often crossed back through past squares, effectively increasing the total area covered by the robot.

Area Where Present (ft^2)	Percent of Area Covered (%)
86.50	86.50
91.00	91.00
82.00	82.00
76.38	76.38
85.94	85.94

As shown in the above table, the crawlspace inspection robot was able to maneuver through more than 70 % of the model crawlspace area, often maneuvering through more than 80 % of the space without getting stuck or needing assistance from the operator. It is important to note that while the robot did not enter 100 % of the tiles in the crawlspace area, not every tile must be entered for an incredibly detailed map to be created within the ROS software using the LiDAR sensor.

Imaging Quantity

After adjusting the project's scope, imaging has been reprioritized and will take precedence over autonomous control. Because the plan is to stitch the images of the crawlspace together using python and OpenCV, it is essential to find what percentage of the ceiling can be successfully photographed. This metric was tested by treating the photographs taken as a jigsaw and then finding the area of any spots not recorded and comparing that area to the overall ceiling area.

Total Ceiling Area (ft^2)	Pictures Taken	Area Pictured (ft^2)
87	33	7920
87	36	8640
87	54	12960
87	51	12240
87	42	10080

After allowing the robot to run its course, the number of pictures taken can be seen in the table above. The real area captured by each picture was then multiplied by the number of pictures taken to find a value for the full area pictured. While this value will feature some overlap, it is significantly large enough to convince the team that the robot saves pictures that will cover the entire ceiling area. Along with this metric, the photos were flipped through and ceiling landmarks were used to confirm that no part of the ceiling was missed.

Imaging Quality

Python code was created using the OpenCV library to perform the image stitching. This test was performed using both real pictures taken of the ceiling using the robot's camera and pictures of a crawlspace ceiling. This allows us to confirm that the code will work both in a real crawlspace setting and will also work when using the camera.

Compared Pictures	Percent Overlap (%)
Test 1, 1 and 2	56
Test 2, 1 and 2	55
Test 2, 3 and 4	45
Test 2, 5 and 6	52

Tests were performed on the pictures taken to find the necessary overlap percentage between pictures. It was found that this overlap was around 50% for all the stitchings that worked correctly.

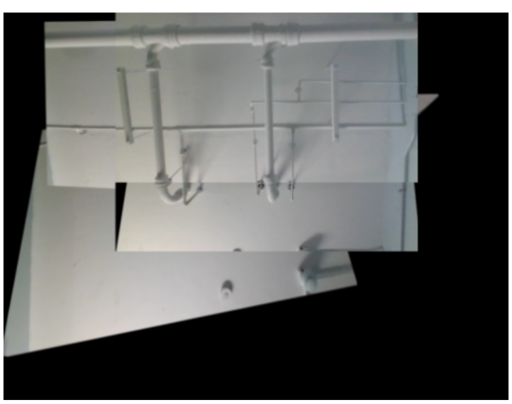

Fig. 5. Model Crawlspace

Wireless Access Point

The main job of the system's wireless access point is to create a wireless network for communication between the system's main control, the Raspberry Pi, and the system operator in the case that manual control is needed. Adhering to the given constraints, the wireless access point operates on 2.4 GHz and is a private network that requires a password for use. To ensure that the wireless access point was sufficient for use, the distance and overall connectivity, and control were tested four times.

In each of the four tests, a laptop was connected to the Raspberry Pi at a distance of 100 feet, first on the fourth floor of Brown Hall and then on the third floor of Brown Hall. The robot was pinged by the laptop with 32 bytes of information, and the response time in milliseconds from the computer to the Raspberry Pi and back was recorded. Finally, the overall system control was tested by opening applications and interacting with the system peripherals such as one of the USB cameras over Microsoft Windows Remote Desktop Protocol.

Distance From Robot (ft)	Average Ping Time (ms)
100	4
100	3
100	3
100	3

The results show that the wireless access point is sufficient for the application of the crawlspace inspection robot and that operators will be able to successfully control the robot from well over 70 feet away, allowing for manual control in more significant than average home crawlspaces, which would only require a max communication distance of 70 feet.

Environmental Sensing

Temperature

The sensor was placed outside at different times and compared to the ambient temperature given by Weather.com. The test was performed like this because the commercially available sensor turned out to be incredibly slow and inaccurate. It was also done in this way because an outdoor environment is where the robot will be used.

Sensor Temperature (°F)	Listed Temperature (°F)	Percent Error (%)
62.825	63	0.28
61.5375	61	0.88
57.925	59	1.82
62.2375	64	2.75
71.125	70	1.61
66.6875	67	0.47
66.5375	64	3.96
65.53	66	0.71

The table shows that the system temperature sensor has exceptional accuracy when compared to a purchased sensor.

The max error found was just under 4% which is well within the desired level of accuracy.

Humidity

The sensor was placed outside at different times and compared to the humidity given by Weather.com. The test was performed like this because the commercially available sensor turned out to be incredibly slow and inaccurate. It was also done in this way because an outdoor environment is where the robot will be used.

Humidity Sensor (%RH)	Listed Humidtiy (%RH)	Percent Error (%)
82.3	84	2.02
87.1	89	2.13
93.1	95	2.00
86.9	86	1.05
83.2	84	0.95
95.4	99	3.64
92.8	96	3.33
37.5	38	1.32

The table shows that the humidity sensor is well within the desired range for accuracy. The datasheet for the DHT22 sensor says the accuracy should be ±2 %RH. While this experiment found several points outside this range, it seems to mainly be at the higher humidity values where the accuracy decreases. However, even at these points, the accuracy is at a very acceptable level.

Moisture Content

The Moisture Probe was first tested using axial resistors so that a known value could be tested. The resistors were also checked on a multimeter so that the true value could be compared along with the listed value. This test provided limited results due to the availability of resistors to test. However, it is secondary to the full moisture content testing and was mostly used for troubleshooting.

Multimeter Result (MΩ)	Probe Result (MΩ)
1.02	1.02
2.23	2.23
4.83	4.82
9.88	9.78
51.0	46.0

The results above were all found to be accurate within 1% error except for the 47 MΩ test which had about 10% error. This is because it was found that the first two stages had greatly increased accuracy compared to the stages with larger resistors used in the voltage divider. After much research, it was found that Arduino analog read pins prefer a smaller input impedance which was unknown at the time of design. This could be fixed in future revisions by switching out the microcontroller used.

The system was used on blocks of wood with differing moisture contents and compared to the results given by a commercial wood moisture probe. Forcing a piece of wood to be a certain moisture content caused some problems with this experimentation. Leaving the wood pieces in a steamy room allowed values between 7% and 11% to be tested but the higher values could not be achieved this way. Instead, a piece of wood was soaked with water and tested at different times as the wood dried out and its moisture content fell. This allowed the higher values to be tested.

COTS Moisture Content Probe	System Moisture Content Probe
7	6.86
9	7.34
10	8.13
10	8.31
11	9.51
13	11.31
13	14.44
14	15.89
15	12.26
16	17.55
17	16.87
19	18.55
24	22.4
25	23.26
26	23.54

As can be seen from the table above, the actual moisture content value is not 100% accurate for the commercial probe. However, all values fall within ±3 of the expected percentage value. The collected data shows that the system is detecting changes within the moisture content of the plank. Based on the raw resistance values which were seen in the previous section. It is believed some of this error comes from the equation created to convert resistance to wood moisture percentage.

MOVEMENT

The Height Constraint

For the first test, the height of the robot was measured with a tape measure. This was done to ensure that the 16-inch height constraint was met. This experiment was conducted twice and the results are displayed below.

Trial Number	Height of Robot
1	15.1875 inches
2	15.1875 inches

The above results show that the robot is 15.1875 inches tall. That number is less than 16 inches, and thus the height constraint has been met.

Motor Encoders

The purpose of this test is to confirm that the motor encoders and Arduino software are correctly measuring the rotational speed of the motors. The motor encoders are connected to GPIO pins on the Arduino, and the software reads the frequency of the signals and converts them into a rotational speed that is displayed on the serial monitor. Those values were compared against a measurement obtained by using a digital tachometer placed in contact with the drive wheel. The values in the table below are in units of RPMs.

Robot's Reading	Tachometer Reading	Percent Error
219.7	220	0.136%
218.5	219.2	0.319%
220.1	219.8	0.136%
219.2	219.9	0.319%
220	220.6	0.272%

These results show that the Arduino program for the motor encoders is correctly measuring its speed.

Linear Speed

For this experiment, the team wanted to measure the robot's linear speed. The desired speed is about 1 foot per second. To do this,10 feet was measured with a tape measure and then used a stopwatch to determine how quickly the robot covered that distance. This gives us the average velocity of the robot.

The measured values for average velocity were also compared to the instantaneous RPMs that were displayed in the Arduino Serial Monitor while the robot was in motion. Those values were recorded and are displayed below. The RPMs are also converted to feet/second for ease of comparison.

Travel Time	Average Speed(ft/s)	Instant. Speed(ft/s)	Percent Error
9.75	1.03	1.09	5.505%
9.68	1.04	1.07	3.21%
9.71	1.03	1.088	5.331%

These results show that the average speed of the Croomba is about 1 foot per second which is the desired value.

30 Degree Incline

Finally, a test was done to determine whether or not the Croomba could ascend a 30-degree inclined plane as described in the signoffs. To accomplish this, the team put together some pieces of plywood at a 30-degree angle and set the Croomba on a course to see if it could make its way up the hill. This test was conducted 3 times.

The Croomba was unable to go up the steep slope. The team believes this deviation is caused by a lack of traction on the treads as well as a high center of mass on the robot. That high center of mass pulls the robot back down the hill and the front of the bot begins to lose traction with the ramp. In short, the robot is too top and back heavy, and this leads to the robot wanting to flip onto its back like a turtle when ascending the incline.

However, the team conducted additional experiments by lowering the angle of the incline to find the maximum angle that the robot could traverse. All of the results are displayed in the table below.

Incline Angle	Croomba Ascension?
30	No
30	No
30	No
25	No
20	No
15	Yes!
15	Yes!

V. Project Deliverables

In the project proposal, the team stated that they will produce a robot that will 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. 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.

Now at the end of the project, the team has delivered the robot described above along with additional features such as image stitching and remote control. The team has also prepared the way for future renditions of this legacy project by making their designs with a focus on modularity.

VI. Timeline and Cost Estimates of the Project

When planning the design, the drving factor was the importance of each system. The very first signoff submitted focused on choosing the main controller for the entire robot as every other system would depend on that design. From there, each group member wokred on their individual design while keeping in mind what information would be needed by later steps. For example, much of the power system had to be designed later in the process because it depended on how much current the other systme components would require. Following this process allowed us to have minimal issues with pieces of the system not meshing in the assembly stage. The Gantt chart found in Appendix 1 details the stages of design which were loosely followed during that stage of design.

As the design matured, team checks had to be performed on each subsystem. Signoffs were shared between the team in order to ensure everything was double checked before being submitted. The group also held weekly meetings in which all members were updated on the changes happening in individual subsystems. These meetings also allowed the team to discuss system-wide decisions and ensure everyone was on the same page.

Budget had to be considered along with the timeline to ensure that the team spent a reasonable amount of money during the design. During the project proposal, a estimated budget was created to give a minimum and maximum estimation for the project. These estimates came out to $425 and $1097 respectively. After completing the project, a new budget was made which can be found in Appendix 2. It can be seen that the team spent about $763 which was within the budget estimated at the start of the project. However, this number does not include several parts included on the robot which did not have to be ordered including the Raspberry Pi and the battery. Once these parts are included, the actual cost is estimated to be around $1155. This would have put us slightly over budget if all parts had needed purchase

VII. Ethical and Professional Responsibilities

Damage to a person's home is the primary ethical consideration for this project; thus this consideration has affected many design decisions. The power system has redundant fuses to protect the wires from overcurrent and prevent any possible fire hazards that could result. The size, speed, and weight of the robot have been considered. A large, rampaging robot is a much more serious risk than a small controlled one. Limiting the robot's size and regulating the speed at which it operates ensures that important structures under the home are not damaged because the robot is incapable of generating the force required to do so.

Another major concern with sending a robot through a client's house will be privacy. Network privacy will be protected by using a separate, local router when further communication needs to be implemented for the manual control video stream. This video stream will also only be activated during times of manual control and will not include audio to avoid the recording of private data. Although this addition will likely not be a part of the first prototype, these considerations will be kept in mind throughout the hardware design to set the basis for future development.

The final ethical consideration is given to industry impact. Since the goal of the product is to automate a task normally carried out by a person thought had to be given on how this might impact the job market. This version of the robot was designed to be semi-autonomous. Meaning it still requires human interaction to operate. With this in mind, it is believed that the CROOMBA will have a positive effect on the job market by allowing home inspection business to operate more efficiently.

VIII. Lessons Learned

Throughout the ECE 4961/4971 Capstone Courses, the Autonomous Crawlspace Inspection Robot Team has experienced many difficulties, which allowed for positive reinforcement of best practices and some interesting learning opportunities. The most significant lesson learned occurred one evening, during a test of the power draw on the robot, the LiDAR sensor contacted the ammeter probes and was shorted through the USB ports of the Raspberry Pi 4B and back to the battery. The short caused damage to the RPi and the LiDAR sensor, both of which had to be replaced. Additionally, the microSD card connected to the RPi was corrupted. After many hours, the team was able to recover/recreate the ubuntu system and navigation algorithms. While this was disheartening at the time, the team members learned to be more careful with measuring current and voltage on a moving system as well as the importance of regularly backing up code.

The mechanical movement subsystem experienced a setback with utilizing real-time interrupts (RTI) on the Arduino microcontroller. By interfacing with speed sensing, RTI, and direction controls on one microcontroller, the RTI often caused the program to stop and become stuck within the interrupt functions. To solve this problem, team members discovered a way to detach and reattach the interrupts within the Arduino software, slowing down the program in the process. While the current use of RTI within the motor code works, the team members believe this program could be made much more efficient by using more than one microcontroller for controlling interrupts, speed, and changes in direction.

For the environmental sensing subsystem, building the wood moisture probe required significant research into different methods for measuring resistance. Thanks to this research, the sensor worked well with the first iteration while providing a lesson in designing a circuit. On the other hand, one of the most significant issues with this subsystem came from the PCB design. The first iteration of the boards had many problems including incorrect footprints, plugs that were hard to access, and misaligned parts. These problems provided invaluable lessons in PCB design but unfortunately came after the parts had already been ordered.

The navigation subsystem experienced issues with implementing common autonomy packages and previously simulated navigation programs into ROS. While the Hector p algorithm is currently working with ROS to generate detailed maps, the team members were not able to get 2D navigation goals to work with the current iteration of the robot, instead relying on a custom python navigation program. If time permitted, the team feels confident that a custom ROS package, based on the official ROS wiki tutorials, could be created for the robot which would allow for Autonomous SLAM to be implemented.

IX. Conclusions

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 is an effective solution to the problem formulated throughout this document.

The robot was able to successfully map out a variety of different environments while navigating autonomously through the space. Base-level image stitching algorithms were implemented to create a holistic image of the area's ceiling. While moving throughout the crawlspace, the robot collected sensor data to be visually represented on the stitched picture. Backup systems have also been implemented to allow the robot to be manually controlled in case of autonomy failure. Finally, the power system successfully filtered the supply to provide the constant voltages necessary for operation.

The modular nature of this project provides many opportunities for future work to be implemented on later iterations of the robot. Possible new features include upgrades to the hardware, a higher level of autonomy, improved chassis, and additional hardware for the sensing system. The image stitching algorithm will also be improved in future iterations. The Autonomous Crawl Space Inspection Robot will become a legacy project that future teams will continue to develop.

A. *Individual Statements*

I was responsible for the movement subsystem, which included the design and analysis of the motors, motor drivers, microcontroller, and chassis. My other courses prepared me for capstone in a variety of ways. My understanding of electric circuits from circuits 1 and 2 as well as electronics was particularly helpful. My experience with arduino programming from CSC 1300 and ECE 4370 was useful in the development of the movement system. I used the knowledge of motors and other electrical machines that I gained in ECE 3610 when selecting the drive motors in the system. Over the course of the project I gained new knowledge in numerous areas foremost in the aspects of mechanical power and serial communication. I learned most of the new information by researching the internet, but I learned from my teammates as well. - Joseph Thomas

I was responsible for the navigation subsystem, which included the implementation of the navigation hardware (LiDAR, HD Cameras, Ultrasonic Sensors, Raspberry Pi 4B, WiFi Router, and Flash Light). I was also responsible for the design of the navigation and mapping algorithms within ROS and co-authored the navigation algorithm in Python. Throughout this course, I was able to apply knowledge gained from past courses such as Optoelectronics Engineering and Electromagnetic Fields 1 and 2 when dealing with the LiDAR and Ultrasonic Distance protocols of the navigation subsystem. Additionally, when creating the private communication network, I was able to apply knowledge and skills from the Intro to Telecommunications. Additionally, when working with Joseph on the Movement subsystem, Finally, throughout this project, I have gained extensive knowledge with the Linux operating system Ubunutu, the Robot operating System (ROS) midware, and an overall sense of programming/troubleshooting complex robotics systems - JC Williams

I was responsible for the design of the power subsystem. I was also responsible for arranging the wires in the case in an efficient and effective manner using line numbers to aid in this task. I used alot of the material learned during the course of my undergraduate degree. Additionally, I was grateful for Mr. Robert's suggestion to make the buck converters for the project. Finally, throughout this project, I have gained extensive knowledge of what it can be like to collaborate with an engineering team to accomplish a goal. I have been lucky to work with such a mature group of people for the past two semesters and will always look back at the experience with a ”certain” fondness. - John Harris

My subsystem was the environmental sensing system This system handled receiving and processing temperature, humidity, and moisture content data. I also took over the image stitching and developed algorithms to form the basis of future work in this area. Because my system contained a mix of electrical, mechanical, and software, I had to pull information from a variety of sources. The main classes which informed my design were electronics, microcomputer systems, dynamics of machinery, and embedded systems. I also gained new knowledge in how to measure moisture content, cascading rail systems, OpenCV, and python. Most of this new information was learned through extensive online research as well as in-person help from the faculty at tech. This research was essential to the completion of my subsystem because these were principles that became foundational to the design. Finally, a significant learning curve for this project was during my PCB design which was heavily informed by Dr. Pierce's workshop. All these new areas came together to form the subsystem I ended up with and I am thrilled with the result. - Jim Camp

X. References

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Appendix I: Phase 1 Timeline

Crawlspace Inspection Robot

Group 1

Jim Camp, J.C. Williams, John Harris, Joseph Thomas

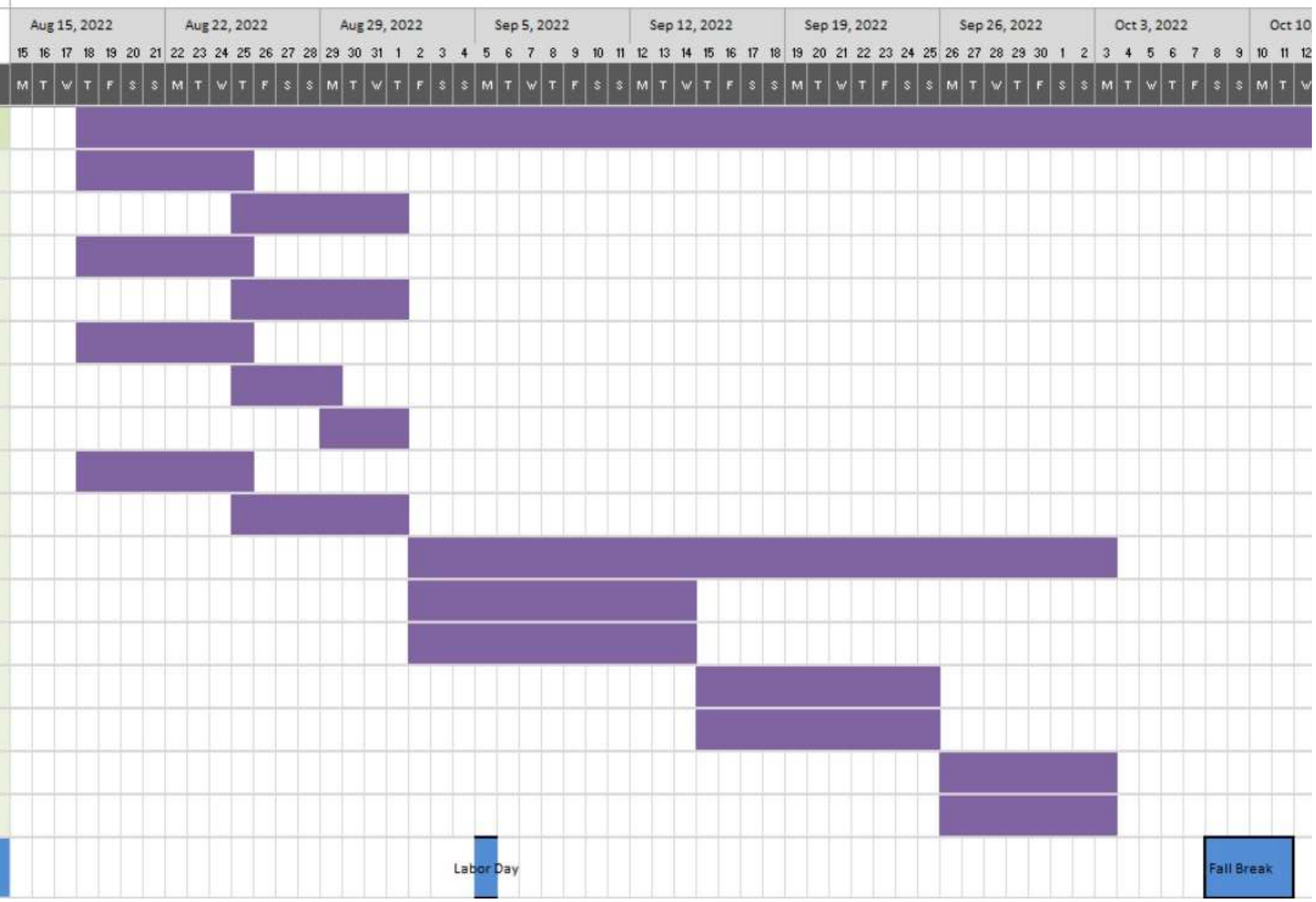
Project Start: Thu, 8/18/2022

Display Week: 1

SIMPLE GANTT CHART by Vertex42.com

https://www.vertex42.com/ExcelTemplates/simple-gantt-chart.html

TASK	ASSIGNED TO	START	END
Design Phase 2		8/18/22	12/2/22
Humidity Sensor Signoff		8/18/22	8/25/22
Wood Moisture Sensor Signoff		8/25/22	9/1/22
Mechancal Parts Signoff		8/18/22	8/25/22
Motor Filtering Signoff		8/25/22	9/1/22
Circuit Protection Signoff		8/18/22	8/25/22
Power Filtering Signoff		8/25/22	8/29/22
Power Distribution Signoff		8/29/22	9/1/22
Ultrasonic System Signoff		8/18/22	8/25/22
Camera System Signoff		8/25/22	9/1/22
Assembly Process		9/2/22	10/3/22
ROS Setup		9/2/22	9/14/22
Mechanical Build		9/2/22	9/14/22
Chasis Build		9/15/22	9/25/22
Sensor Setup		9/15/22	9/25/22
Autonomy Testing		9/26/22	10/3/22
Full System Testing		9/26/22	10/3/22
Holidays			



Appendix II: Full BOM and Budget

Part Number	Description	System	Manufacturer	QTY	Unit Price	Total Cost	Required Purchased
12-Way Marine Fuse Block	12V Fuse Box	Power	Docosu	1	$17.99	$17.99	YES
30 PCS Lever Wire Connectors Nuts Assortment Kit	Terminal Blocks	Power	XHF	1	$8.99	$8.99	YES
MUYI 2 Set Mini Blade Fuse Holder	Blade Fuse Holder	Power	Muyi	1	$7.99	$7.99	YES
MGI SpeedWare Latching Metal Toggle Switch	2-Pin Swich	Power	MGI	1	$7.99	$7.99	YES
Micro USB Terminal	Micro USB Breakout Harness	Power	Poyiccot	1	$7.79	$7.79	YES
USB C Terminal	USB C Breakout Harness	Power	XMSJSIY	1	$7.50	$7.50	YES
ERJ-6ENF4321V	4.32k Resistor	Power	Panasonic	1	$0.10	$0.10	YES
ERJ-6ENF1182V	11.8k Resistor	Power	Panasonic	1	$0.10	$0.10	YES
ERJ-6ENF6342V	63.4k Resistor	Power	Panasonic	1	$0.10	$0.10	YES
ERJ-6ENF4532V	45.3k Resistor	Power	Panasonic	1	$0.10	$0.10	YES
ERJ-6ENF6982V	69.8k Resistor	Power	Panasonic	1	$0.10	$0.10	YES
C2012C0G1H682J060AA	6800 pF Capacitor	Power	TDK Corp	2	$0.22	$0.44	YES
08053C104JAZ2A	0.1 µF Capacitor	Power	Kyocera	1	$0.34	$0.34	YES
CC0805JRNPO9BN120	12 pF Capacitor	Power	Yageo	1	$0.10	$0.10	YES
CL10A106MQ8NNNC	10 µF Capacitor	Power	Samsung	1	$0.11	$0.11	YES
35SVPF22M	22 µF Capacitor	Power	Panasonic	1	$1.45	$1.45	YES
GRM31CR61A476KE15L	47 µF Capacitor	Power	Murata	1	$0.68	$0.68	YES
SDR1307-8R2ML	8.2 µH Inductor	Power	Bourns Inc	1	$1.11	$1.11	YES
LM20343MH/NOPB	Buck Regulator	Power	Texas Instruments	1	$2.15	$2.15	YES
282837-2	Terminal Block - Board Mount	Power	TE Connectivity	2	$0.99	$1.98	NO
L16-P	Linear Actuator	Enviromental Sensing	Actuonix	1	$80.00	$80.00	YES
PIND4E	Moisture Meter Probes	Enviromental Sensing	General Tools Store	1	$15.58	$15.58	YES
Arduino Nano 3 Pack	Atmega MCU	Enviromental Sensing	Arduino	1	$14.83	$14.83	YES
AT-K-C-26-6-B/7	Spiral Cable	Enviromental Sensing	Assmann Components	1	$3.83	$3.83	YES
24316	Standoffs	Enviromental Sensing	Keystone Electronics	8	$1.25	$10.00	YES
TBL009-254-08GY-2GY	Screw Terminal - 8 pin	Enviromental Sensing	CUI Devices	1	$2.11	$2.11	YES
TBL009-254-06GY-2GY	Screw Terminal - 6 pin	Enviromental Sensing	CUI Devices	1	$1.67	$1.67	YES
TBL009-254-02GY-2GY	Screw Terminal - 2pin	Enviromental Sensing	CUI Devices	1	$0.73	$0.73	YES
CC2D25S-SIP	Humidity Sensor	Enviromental Sensing	Amphenol	1	$19.23	$19.23	YES
1782	Temperature Sensor	Enviromental Sensing	Adafruit	1	$4.95	$4.95	YES
SSA-103-W-T	Header Pins	Enviromental Sensing	Samtec	3	$0.54	$1.62	YES
93805A312	M6 Threaded Rod, 18-8 Stainless Steel	Enviromental Sensing	McMaster-Carr	1	$9.12	$9.12	YES
2N3906	MOSFET	Enviromental Sensing	Diotec	5	$0.05	$0.26	YES
C1206F104K5RACAUTO	Capacitor	Enviromental Sensing	Kemet	1	$0.49	$0.49	YES
RH73X2B10GKTN	Resistor	Enviromental Sensing	TE	1	$4.57	$4.57	YES
CRCW1206470MJPEAHR	Resistor	Enviromental Sensing	Vishay	1	$0.69	$0.69	YES
CRCW120647M0JPEAHR	Resistor	Enviromental Sensing	Vishay	1	$0.69	$0.69	YES
CR1206-FW-4704ELF	Resistor	Enviromental Sensing	Bourns	1	$0.10	$0.10	YES
CR1206-FX-8203ELF	Resistor	Enviromental Sensing	Bourns	1	$0.10	$0.10	YES
31:1 Metal Gearmotor 20Dx41L mm 12V CB	Motor	Enviromental Sensing	Pololu	1	$28.95	$28.95	YES
Pololu 20D mm Metal Gearmotor Bracket Pair	Mounting Bracket	Enviromental Sensing	Pololu	1	$6.95	$6.95	YES
637211	Cascading X-Rail Slide Kit	Enviromental Sensing	Servocity	1	$122.99	$122.99	YES
L298N	Motor Driver Board	Enviromental Sensing	Qunqi	1	$6.99	$6.99	NO
XR-Y	Smart Robot Car Tank Chassis Kit	Movement	WiFi robot	1	$74.99	$74.99	YES
4845	47:1 Metal Gearmotor 25Dx67L mm HP 12V with 48 CPR Encoder	Movement	Pololu	2	$48.95	$97.90	YES
MD20A	20A 6-30V DC Motor Driver	Movement	Cytron	2	$21.00	$42.00	YES
ABX00033	Arduino Nano Every with Headers	Movement	Arduino	1	$15.00	$15.00	YES
Raspberry Pi 4	ARM Microcomputer	Navigation	Raspberry Pi	1	$152.98	$152.98	NO
RPLIDAR A2	360 Degree Lidar	Navigation	Slamtec	1	$229.99	$229.99	NO
ZP-0110	Rpi MCU Fan	Navigation	GeeekPi	1	$10.59	$10.59	YES
Ultrasonic Ranger 2.0	Distance Sensor	Navigation	Grove-SeeedStudio	4	$4.30	$17.20	YES
TL-WR802N	WAP/WLAN Router	Navigation	TP-Link	1	$29.99	$29.99	YES
SVPro - HD USB Camera	HD Cam 60 Deg Lens	Navigation	SVPro	1	$60.99	$60.99	YES
HD USB Camera	HD USB Camera	Navigation	FiveBelow	1	$5.99	$5.99	YES
Emergency USB LED	USB LED 200 Lumens	Navigation	Voltaic Systems	1	$13.99	$13.99	YES
				75		$763.23	