Letter of Transmittal:

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Date: 12/18/2021

To whom may concern,

Attached is the following Senior Honors Capstone Project written report regarding Bailey R. Norman's contribution to the Autonomous Swarms for Extreme Conditions (ACEC) Senior Design group project. The senior design project was a two-semester course where the ASEC design group (consisting of Bailey Norman, Trey Jennings, Garrett Burrows, and Nic Robinson) completed assembly of autonomous swarms/agents as requested by the client, Dr. Borowczak and the CEDAR lab. These agents would incorporate a solution to flaws that typical swarms have and was presented to the client on May 1, 2021.

In this report you will find the final report that was submitted to the instructors for the mechanical engineering senior design course that was written in collaboration with the entire senior design group. Additionally, this report was evaluated by the senior design course instructor and faculty mentor, Dr. Coon for the Senior Honors Capstone.

If any questions or concerns arise, feel free to contact Bailey Norman at the emails below or by cell.

Sincerely,

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ME/ESE 4070 : Final Design Report

Autonomous Swarms For Extreme Conditions (ASEC)

Authors: Trey Jennings, Bailey Norman, Garret Burrows, Nic Robinson

Client: Dr. Mike Borowczak

Date: 5/11/2021

PROJECT DESCRIPTION

Swarms consist of numerous entities that work together to achieve an objective. There are two broad schools of swarms, centralized and decentralized, which refers to the method of organization employed by the swarm. With the abundance and readiness of modern processing equipment, most modern swarms use a centralized model where control and instructions converge at one point, usually at a controller station. While practical, the centralized model opens the door for problems that can be avoided with some compromise by a decentralized system. However, one of the primary benefits of using a decentralized swarm model, security, is undermined by the inclusion of onboard central processing units (CPUs). Our project, *Autonomous Swarms for Extreme Conditions* (ASEC) project aimed to demonstrate the feasibility of using a decentralized swarm with no central processing units. Specifically, we were tasked with:

1. the design and fabrication of three rover-like swarm agents.
2. creating a swarm agent that could withstand “extreme” conditions (defined later).
3. producing these agents in a cost-efficient manner with a low-price final product.

Decentralized swarms with no CPUs are often overlooked and overshadowed by their more common CPU-based, centralized counterparts (CCCs); CCCs hold a clear advantage in the complexity of tasks they can complete. Additionally, with modern encryption methods, they are secure to most common attacks. CCCs become ineffective when their cyber protection, communication, or required resources become unavailable. ASEC acts as a proof of concept for a rover-based, CPUless, decentralized swarm. To achieve these goals, the ASEC design group devised a solution that would require no CPU: taking inspiration from insect behavior and utilizing analog electronics. The project yielded successful results but certain areas, namely swarm communication, underperformed.

Our client, Dr. Borowczak, is a faculty member in Computer Science that specializes in cybersecurity. Decentralized swarms are particularly valuable to him because they are much more resilient to common attacks. Whereas an attack on the center of a centralized system can be devastating, a decentralized swarm can withstand individual attacks without compromising the rest of the system. The work performed by the ASEC team will aid Dr. Borowczak in understanding the challenges that face the physical implementation of decentralized swarms (DS). The applications of such a swarm are quite numerous. What is lost in processing capability by the non-inclusion of a CPU is gained in resilience. With less sensitive electronics and simpler communication channels, DS can be deployed to areas with punishing conditions such as space, irradiated environments, disaster zones, and conflict zones. While our specific design will not be implemented in any of these environments, the core principles of DS agent design can be carried over. Every component of the agents acts as a potential vector of attack and manipulation; thus, the ASEC team was careful to weigh design choices with potential future impacts.

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

CHAPTER 1: PROJECT OVERVIEW

As previously mentioned, there are two broad categories of swarms: centralized and decentralized. Both styles have their advantages, and there are clear cases when one class is preferred over another. Centralized systems tend to do well in computationally complex tasks, as ferrying complex information to a central system where it can be analyzed is often more realistic (Hu, 2018). However, it is not uncommon for centralized systems to become quite expensive with complex equipment and communication devices. Modern military aerial drones are a prime example of this concept. Many different agents are in operation at any given time. They collect information about their surroundings and relay it back to a central hub where it is processed either by humans or machines. From there, the central controller can direct the agents based on the collected information. Let's consider some of the implications in a system like this. First, there must be information channels between the agents and the central hub. This information channel becomes a target for attackers and a potential point of failure. If the channel is crippled, so is the swarm's effectiveness. This does not always mean the swarm is useless; many centralized swarm systems have built-in (built into the agent) protocols for how an agent should operate when contact with the controller is lost (for example, a drone may return to friendly airspace). It is pertinent to realize that information channels are not unique to centralized swarms. All swarms communicate in some regard; centralized systems tend to rely on these information channels more heavily. Secondly, If central control is compromised, so is the swarm. One of the biggest concerns with central systems is security, and it is from this worry that decentralized systems were spawned.

Decentralized systems solve some of the security risks presented by centralized systems by distributing control to multiple agents. This makes a crippling attack less likely because instead of only needing to attack the center, an attacker must take a sufficient number of agents offline for the swarm to lose effectiveness (Hu, 2018). The next apparent attack focuses on the most significant point of failure in decentralized homogenous swarms, CPUs. Most commercial CPUs utilize high-level object-oriented languages such as Python. This is particularly dangerous because an adversary would only need to find a way to communicate with an agent before traditional attacks could cripple it. Modern CPUs and the hardware that support them are built for streamlined communication and usually have at least one access port where new information can be shared (for example, updates to a board would require some path of high-level communication). As one can see, the CPU presents an inherent security risk to decentralized swarms, as it is built to handle relatively large computations.

The solution that we pursued, the removal of the CPU, is the next step in preventing tampering with agents. This solution is not without its own set of problems, however. Without a CPU, many tasks that an agent needs to undertake will be handled less efficiently. These inefficiencies can add up quickly and often lead to systems that cannot react dynamically to their environment, struggle to communicate, and sometimes wholly lock up (Gupta, 2016). This became one of ASEC's most prominent goals: finding a solution to the aforementioned problems or mitigating the issues when the ASEC team did not find solutions.

Certain species of ants and bees are often the go-to example of decentralized swarms. We decided to model our agents on this principle which started to shape some loose parameters. First, these insects need a way to communicate basic ideas to one another while handling all other functions internally, without the aid of a swarm. For example, ants do not need nearby ants to wander or climb. Insects rely on chemical triggers to communicate basic ideas such as threat, food, and clan denomination. The concept of using virtual pheromones is not new (Payton, 2001), but it is a highly effective and simple way to mimic the version found in nature. The virtual pheromone model was the first building block in the project. As mentioned in the project description, agents without complex electronics are better suited for extreme conditions(Srour, 1982); this is true for both complicated ICs and CPUS. These two concepts formed together the broad outline of the project. With basic functionality in mind, it was time to define the project and set clear goals. Our client, Dr. Borowczak, gave the ASEC team significant autonomy in choosing elements ourselves. With the aid of their client, the ASEC team was able to define preliminary deliverables:

1. At least three agents were to be manufactured.
2. Agents should withstand temperatures ranging from -40 to 40 C
3. Agents should be designed with modularity
4. Agents need to function as a swarm and “communicate” across a medium

The early deliverables shine a light on the scope of this project. The essential takeaways are about the swarm functionality and not necessarily the actual end objective of the rover. In this aspect, this project differs from many product-based designs. Ultimately, we needed a task for our rovers to perform. We wanted the task to mimic a potential application of a decentralized swarm. One application that had caught our interest in the past was lunar ice collection. This idea was boiled down to its simplest components, and out of it, we obtained our agent’s job. Our agents were to wander an enclosed environment searching for small magnets. Upon finding a magnet, an agent would alert the other nearby agents, who would then turn and head towards the source. In addition to the reasons chosen above, we chose this task because it was relatively simple to set up and test and allowed for a moderate display of agent functionality.

CHAPTER 2: PROJECT REQUIREMENTS

After speaking with our client, we developed an organizational structure for our project. Two team members were assigned to the physical fabrication, testing, and re-design of the chassis that would house all agent components. The other two team members would focus on developing and implementing the circuitry that drove the agent. For the mechatronics and swarm protocol portion of the project, the client advised avoiding artificial learning implementation. AI is not necessary or feasible to implement for the product. The objective is left up to us; however, it needs to be defined early on since it will go into the design of the product. To achieve our selected objective, the rover will randomly move about a demo space/environment to locate and achieve its goal. A vital aspect of this project is communication between agents. We researched multiple natural swarm communication methods, such as those found in beehives and ant colonies. These colonies use pheromones to communicate, which can be mimicked in several ways, including electromagnetic fields, ultrasonic sensors, and visible light avalanche circuits. Modeling our agent's behavior off of these systems is robust, as agents do not need to know their fellow agents' location to operate smoothly; however, without a verification system in place, adversaries can attack our system by planting fake agents that disrupt the flow. The use and implementation of analog sensors is the best approach to information collection. The client recommended this approach to keep things simple and avoid the complications of digital systems.

Another goal that the client presented was the size of the rover. The end goal is to make the chassis and rover as small as possible. An agreed-upon value of 4 inches by 4 inches was given as our target. This goal is not a part of the minimum viable product, but it gave us a starting point. The first working model we are making is slightly larger than this target size. If and when issues arise from making a rover this small, we will have to make adjustments and possibly increase our agents' size. Another client requirement dealt with the number of agents that will be in this swarm. The minimum number that is needed to achieve this goal is three agents. If time and resources allow, we would like to extend well beyond this minimum.

One of the most critical aspects of any design is defining the minimum viable product, and this project is no exception. In our client discussions, there has been a heavy emphasis on the design process and refining a minimum viable product. Our client has elected to take an evolving approach due to this project's novel nature, and he fully expects us to re-evaluate and update the minimum viable product as the project continues.

Our client conversations are not strictly limited to technical detail. Most notably, we were introduced to the concept of "failing fast." With an ambitious project, failure in some capacity is guaranteed, and not just once either; the critical part of failing is learning from the loss, identifying what caused the breakdown, and recovering in the shortest amount of time. A senior design project's beauty becomes apparent when one looks at it through the lens of failure. We have had projects in other classes and, indeed, at times, failed and learned from our mistakes. What sets this project apart is the unparalleled control given to us. I suspect our group is among the most autonomous groups, given our client/team relationship. There is a significant difference between messing up a part of a pre-made modular project that most ME classes elect to give and messing up a research-based framework that we designed from nearly the ground up. In our opinion, this experience, and the failures that will come with it, will be some of the most important lessons we take away from our degree.

CHAPTER 3: ENGINEERING DESIGN AND ANALYSIS

The chassis design that we went with is the rocker-bogie design. The rocker-bogie suspension system will provide us with the most mobility. The rocker-bogie suspension system will also allow us to keep the weight of the agent distributed evenly across all of the wheels over extreme terrains. Our agent will have a total of six motors with six wheels. The assembly of the final agent can be seen in **Figure 1.**

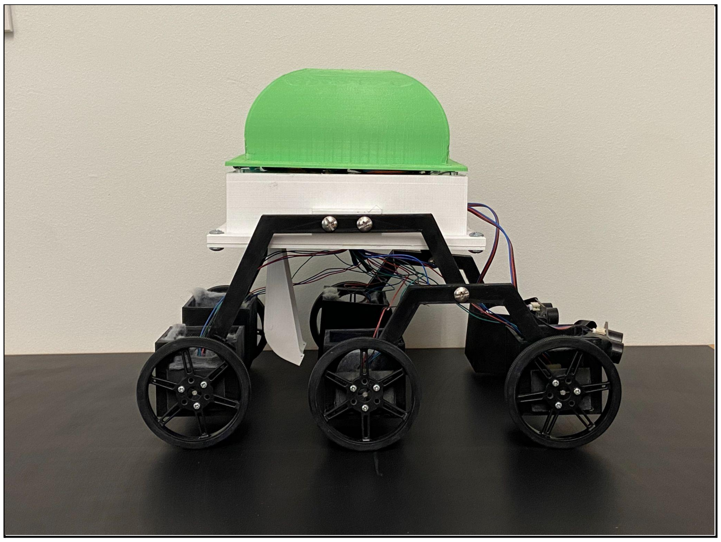

Figure 1. The completed final prototype of our agent.

Our agent also has a capture arm that is below the electronics bay. The capture arm includes another motor, a shaft, and a nylon rope. The agent will use this arm to retrieve the object that these agents are looking for. The circuitry is more complex with regard to our project. As a reminder: traditionally, in a project such as this one, a commercially available processing unit, such as an Arduino or Raspberry Pi, would be implemented to control the logic and decision-making capabilities of the agents. While this method has its advantages, the inherent risk associated with a processing unit's security is one of the main facets of our project; thus, our agents do not contain any centralized commercially available processing units and instead rely on basic analog voltages that are fed into the system from external sensors.

There were two critical components concerning the electrical portion of the project: the swarm protocol and the physical implementation of the circuitry - mechatronics. The swarm protocol is the overarching ruleset that the circuitry must obey. The protocol consisted of four components.

1. Navigation: The agent will wander in a straight line when no other conditions are met.
2. Obstacle Avoidance: The agent will pause its forward motion to rotate if it encounters an obstacle.
3. Beacon Reception: The agent will turn to face an active beacon before continuing forward towards it.
4. Objective Collection: The agent will slow down, drop its scoop (stretch goal), and deploy its onboard beacon upon detection of an objective.

These four elements listed are in ascending order of importance, meaning that the larger number (1,2,3,4) will override the smaller number; this allows a cascading effect, where the agent will execute the most pertinent portions of its mission when necessary and then fall back into its default state once triggers have passed.

To achieve the modularity deliverable, each of the four elements listed above was developed independently. Constructing the circuitry in this way allows for an easy part swap if the agent's goals change. One does not need to rebuild the entire circuit if only the objective changes.
Preliminary research confirmed that an analog system was the best way to accomplish our deliverables. Small chips, like operational amplifiers and relays, were used in conjunction with a variety of sensors. The following sensors were used.

1. Analog Ultrasonic Sensors: Used in obstacle avoidance
2. Hall Effect Sensors: Used to identify the objectives (magnets)
3. Auditory Buzzers: Used as the deployable onboard beacons
4. Analog Microphone: Used to listen for beacons

Analog ultrasonic sensors provided a way for the agent to detect obstacles from a minimum distance of 5 ~ 10 cm. The ASEC team selected the ultrasonic sensor due to its maximum detection range of 500 cm. The sensor operates at 3.3 ~ 5.5 Volts DC, and can operate in temperature from -10 ℃ ~ 70 ℃. Hall effect sensors were chosen as a simple way to detect the magnetic fields given off by our objectives. From research, hall effect sensors provided a useful method to effectively measure magnetic fields within an acceptable range for our agents. Additionally, hall effect sensors can easily transit data back to the circuits using analog variable voltage, which was desirable. The buzzer and microphone were both operable in the 3.3 ~ 12 V range, which made them acceptable choices. The shortcomings of some of these components will be detailed later in this paper.

The other electrical components included operational amplifiers, solid-state relays, 555 timers, and a stepper motor driver module (DRV8825 Stepper Motor Driver Module) to interface with our stepper motor engines. Lastly, resistors, fuses, capacitors, diodes, and regulators supplemented and completed the circuit. Op Amps provided a simple way to compare voltages using their well-known properties and were an essential part of our design. Analog voltages coming from the sensors could be compared and influence the state of relays, which affected the rover's movement. If the desired output voltage was met, the opp amps would then produce a true or false saturation voltage of approximately 5 volts to trigger a response. This response is controlled by solid-state relays. S.S. relays provided an easy and effective way to trigger circuits. Solid-state relays typically have a lower failure rate when compared to mechanical relays, which makes them a better choice. Additionally, solid state devices use less power. The ASEC team implemented ne555p timers into the engineering design because the DRV8825 driver module required a square voltage wave to drive stepper motor magnetic timing. With the ne555p timer, simulating this square wave was easily accomplished and, in return, allowed us to control our stepper motor speed and torque. DRV8825 Stepper Motor Driver Module provided a way to control and power our stepper motors for the agents to move around. It additionally offered an easy method to control stepper speed, torque, and direction. With the selection of both sensor and IC circuit components complete, the next step was to implement these components into a functional working circuit.

For the movement circuit, all four ic components were implemented to process the data from the ultrasonic sensor and respond based on obstacles that the agent encounters. First, we would have to determine the desired output voltage from the ultrasonic sensors and set up our opp amp to compare and look for this voltage. This meant that the use of a comparator setup was ideal for the op amp. From research and previous engineering coursework, the following circuit schematic and equation was implemented to determine the ideal set up with resistors:

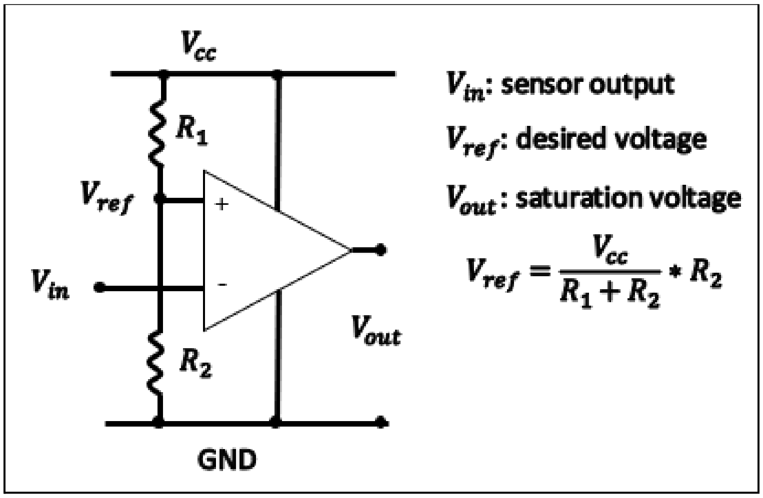

Figure 2. Circuit diagram for non-inverting comparator opp amp set-up.

With an idea of how to implement the opp amp, focusing on implementing the S.S. relay is the next key step in the circuit. Ideally, when the opp amp determines when an obstacle is directly in front, based on sensor input, a saturation voltage will be emitted, which will trigger a response using the S.S. relay. Additionally, using data sheets from the S.S. relay manufacturer, we can determine where the saturation voltage out of the op amp will connect to the relay. Information from the manufacturer as well as recommended pin connection is provided below:

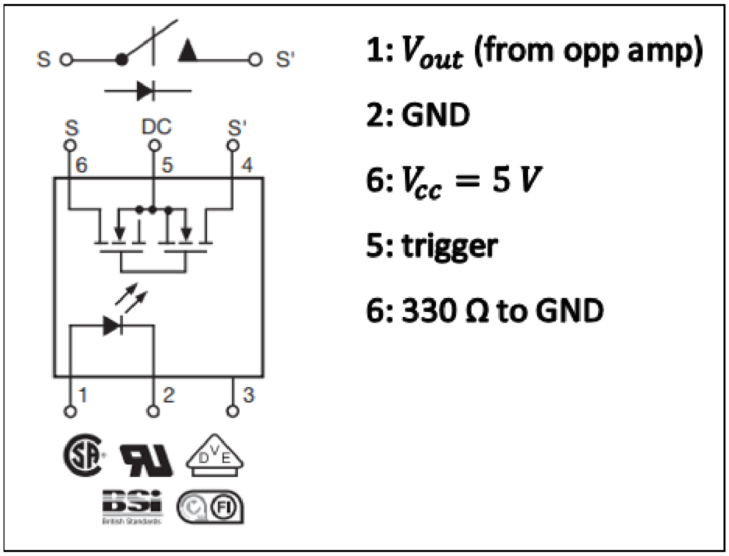

Figure 3. Circuit diagram with pinouts for S.S. relay.

The trigger off of the relay will be used to control the direction of the stepper motors. Using the DRV8825 Stepper Motor Driver Module, when voltage is supplied to the direction lead (DIR) this will put the motors rotating clockwise and when voltage is not supplied then it will go counterclockwise. This will control the direction and turning abilities of the agent when it meets an obstacle. Manufacturer pin diagram is displayed below:

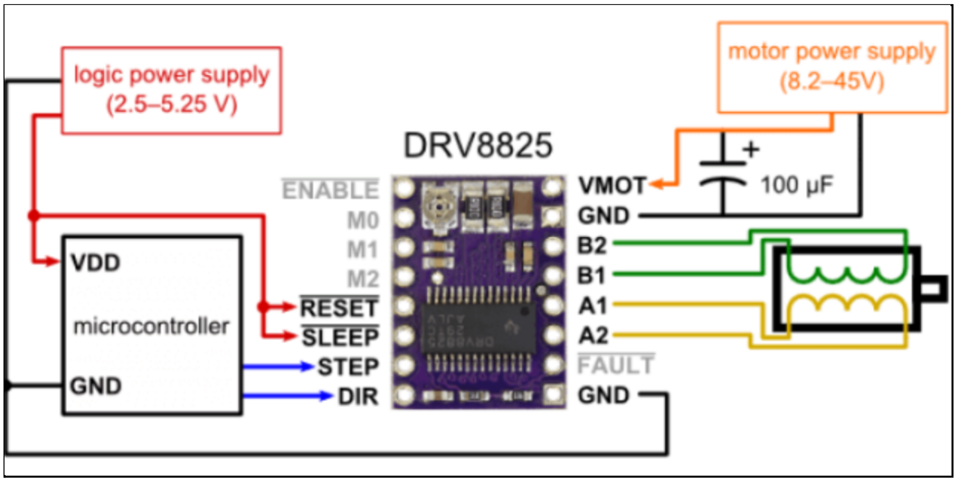

Figure 4. The pin diagram for our motor drivers.

(Note: microcontroller is not implemented: DIR controlled by S.S. relay and STEP controlled by ne555p)

The ne555p timer in the circuit, as mentioned before, is used to drive the magnetic timing of the DRV8825 driver module. To produce optimal torque for our motors, it was decided that the slowest speed was needed for the motors which means slow magnetic timing. To produce this, a 10 msec period timing was used per rotation for the motors. The ne555p timer needs to produce a square wave with a 10 msec period, and using data sheets provided from the manufacturer, the following equations and circuit schematic were used to determine the correct set-up to achieve 10 msec:

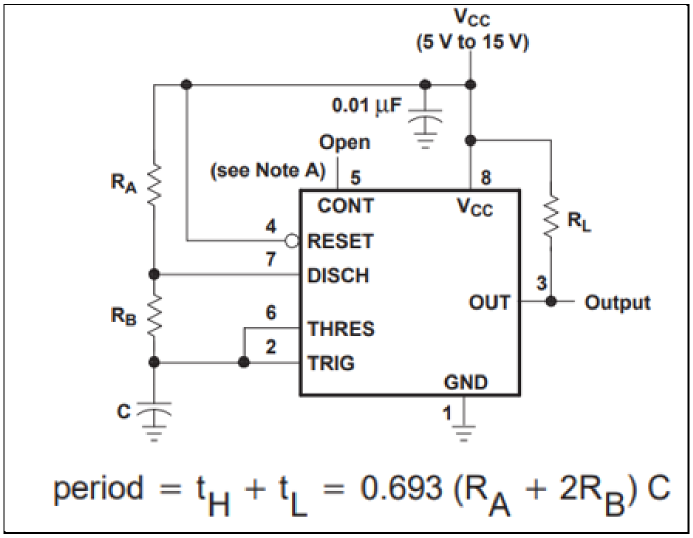

Figure 5. The ne555p timer circuit diagram.

Implementing all of the circuit components above, the following circuit schematic was produced below:

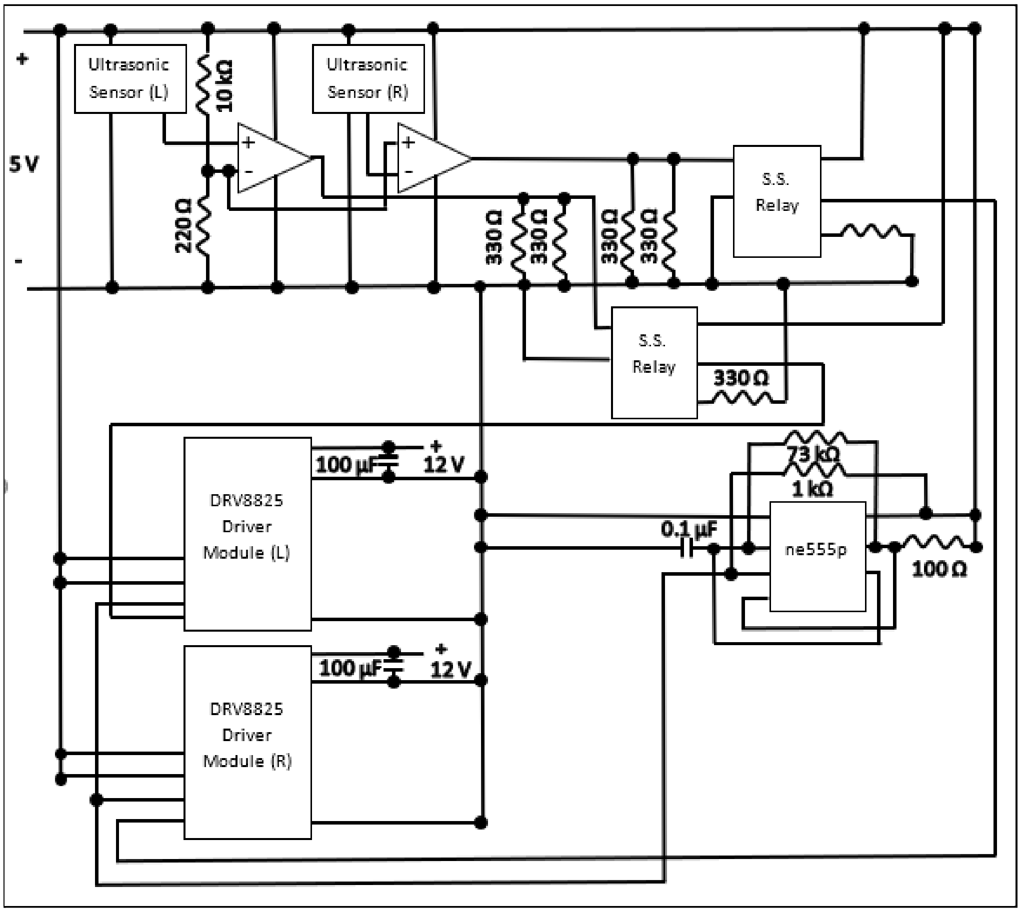

Figure 6. Circuit diagram for movement circuit implementing all ic components and sensors.

The circuitry for the beacon detection and objective detection circuits can be seen below, in figure 7. The design incorporates two microphones that output analog voltages. The mounting geometry of the two microphones is such that one is fixed in the direction of travel (front) and another is fixed upwards, perpendicular to the direction of travel (top). Under normal conditions, these microphones output similar voltages, and a small resistance is felt on the other end of the S.S. relay. When a buzzer is sounded, the top microphone will receive a slightly greater signal in most directions except when the agent is pointed nearly at the source. The comparator op-amp will increase resistance in half the wheels until the agent is facing in the appropriate direction, at which time the resistance will fall, causing the agent to rotate, then proceed. An added benefit to this system, having microphones control the turn rate, is that background noise will consequently cause small random jitters in half of the wheels. These small random jitters help the agent unstick itself from tight quarters. These microphones were the sources of most of our experimental troubles, as the quality of the cheap microphones was not consistent and, even with tuning, failed to output consistent results.

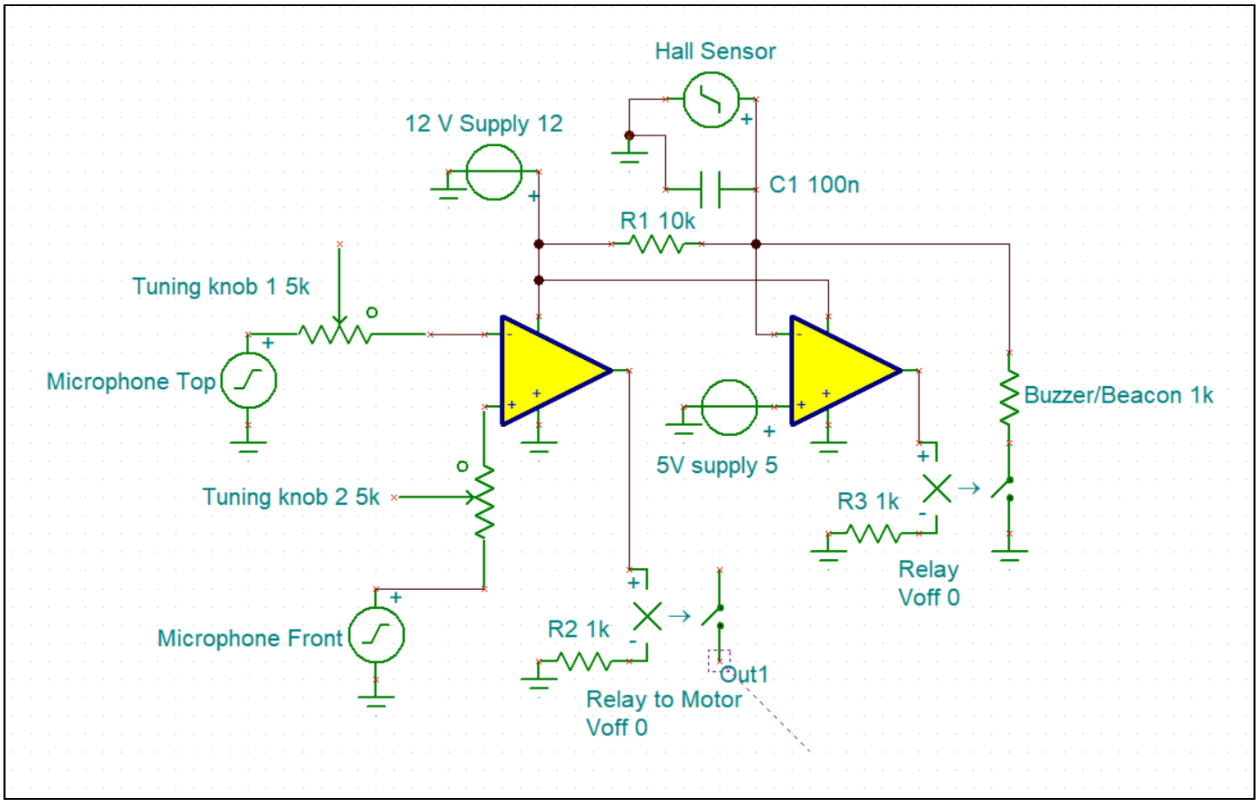

Figure 7. Circuit diagram for beacon and objective detection, implementing all ic components and sensors.

CHAPTER 4: PROJECT FABRICATION

Our chassis is made out of PLA. PLA is readily available in the Makerspace lab and reliable with regards to printing. Once we were able to finalize our design, we would schedule print times within the Makerspace. The cost of the printing varies with each part that we print. Certain prints take longer due to the size and structure of them. This longer print time will then lead to a higher costing part. The print time for all parts of our agent is around 90 hours. This time could be cut down if we had access to larger printers and would be able to have access to the printers at all times of the day. After everything was printed, we just had to assemble the pieces together, and this took around 10 hours. Once these agents were all ready the circuitry could then be installed.

As discussed previously, the electronics/mechatronics are constructed circuits that do (1) not use a CPU and (2) will achieve the SWARM Protocol for the rovers. To achieve this and SWARM Protocol, it was decided last semester that four circuits will be designed and consist of movement/obstacle avoidance, objective locating, beacon locating, and home return. These circuits are modular so that they can be interchangeable based on certain tasks we want our rover to achieve.

For fabrication of the circuits, it was decided to use perma-perf boards and perf boards and solder the ic components to them. To accomplish this various components such header pins and ic chip holders were soldered into the board to prevent damaging of certain ic components during soldering. Once these were soldered into the board, we could easily replace any damaged parts without having to remove any soldering. Header pins also allowed for ease of connection across various other modular circuits and sensors.

Another important circuit component that was implemented during fabrication was a 5-volt regulator. Since the agent used a 12-volt source to run the stepper motors, there had to be a 5-volt source for the logic ic components. Using a 5-volt regulator and proper grounding allowed for a 5 and 12-volt hotline for our agent to run both the motors and logic circuits. Using the circuit schematics presented during the design and analysis of the project, the following circuits were constructed and fabricated:

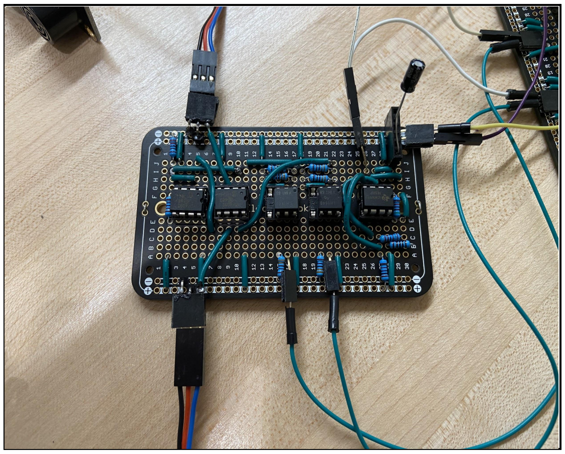

Figure 8. The Movement logic circuit (board 1) with opp amps, S.S. relays, and ne555p timer.

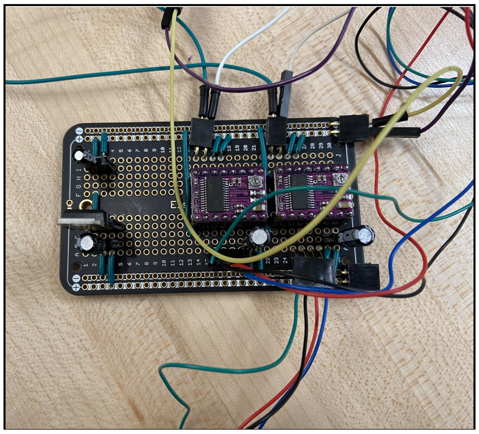

Figure 9. The movement logic circuit (board 2) with 5 volt regulator, and DRV8825 driver module.

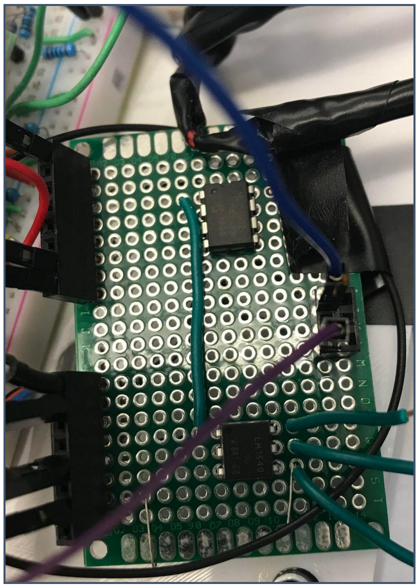

Figure 10. The primary PCB controlling the beacon and objective location circuits

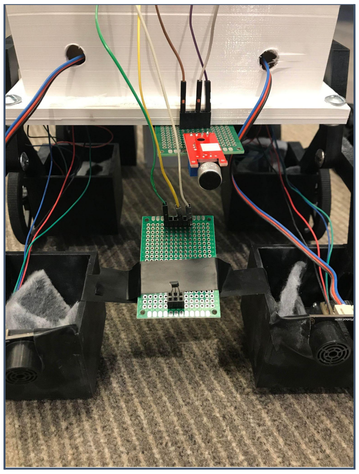

Figure 11. A front view of a completed agent with temporary sensor mounts using electrical tape

CHAPTER 5: TESTING PLAN

The first section that we tested is engineering tests. These tests helped us determine if the rover is operable in extreme environments and determine the rover's reliability across various domains. Each test was used to analyze a mechanical feature that is in our agent. Testing the strength of our agent is a crucial engineering test. We wanted to be able to see the limits that our chassis can endure. The first part of the strength test was the speed test. This test determined the speeds our agent can travel at before it starts to fail. For this test, we increased the speed of our motors until a failure occurred. The second part of the test was a drop test (FEA simulation). This simulation was conducted in SOLIDWORKS to produce a factor of design at specific heights. By looking at this factor of design, we were able to determine the heights our agent can fall from without breaking. Since only one prototype was fully completed, we decided to simulate this experiment rather than physically test it. Following this test, we moved onto more engineering tests to find the limits of our agent.

Another engineering test we conducted was the duration test. For this testing, we used the Atmospheric Science department environmental chamber, which is capable of dropping temperature to our desired temperature of -40C. During this test, we recorded the duration that the agent ran. The environmental chamber currently does not have the capability to go up to the desired 40C, so we were not able to confirm our test for the upper extreme of temperature ranges. This test was designed to determine if the rover is operable in these extreme environments and determine the rover's reliability across severe temperature ranges. Each test was only performed once due to the availability of the environmental chambers.

The last engineering test that we conducted is the maneuverability test. We had the agent traverse over various obstacles and inclines to determine its potential maneuverability for this testing. One part of this test was an incline test where the agent would attempt to climb a ramp at various degrees to determine the max slope the agent can climb. These tests were conducted three times to determine the average incline the agents can achieve. We also placed objects in front of the agent to determine the max object the rover can overcome. Each of these obstacle tests was performed three times to determine the average object height the rover can get over.

For usability testing (tests that observe functionality), three tests were conducted.

1. Obstacle Detection: This test tested the agent's range that obstacles could be detected.
2. Objective Detection: This test establishes a 3D model of where the agent can recognize objectives.
3. Beacon Detection: This tested the agent's ability to respond to a beacon signal given by another agent.

Obstacle detection testing begins by test and recording the distance at which the ultrasonic sensors would detect an obstacle at approach angles from 0°-90° at 10° intervals and 45° in the middle. From these results, we can best determine the optimal mounting angle of the ultrasonic sensor to the agent and how effective the agent can avoid obstacles from the approach of low angles. Objective testing was performed in a similar manner. In spherical coordinates, objectives were placed a radial or angular axial distance away from the agent and moved until a 90% detection success margin was found. Beacon detection testing was performed by placing the agent in the center of a room and playing the beacon buzzer at 15-degree intervals at a radial distance of 1 m away. The ASEC team monitored the response of the agents, and over ten trials determined the success rate.

CHAPTER 6: PROJECT PERFORMANCE

The first section that we have tested and will be testing is engineering tests. These tests are designed to determine if the rover is operable in extreme environments and assess its reliability across various domains. Each test will be used to analyze a mechanical feature in our agent. The first engineering test which we have conducted is the strength test. The strength test was broken up into two different parts. The first part is a speed test to test our chassis’ strength at various speeds. We conducted this part with our old rocker-bogie arms that were 3/16 of an inch thick. At the lowest rate of our motors, the arms were not stable and experiencing too high of deflections. We changed the thickness to 3/8 of an in thick to solve this issue. This change made our agent more stable and prevented these deflections. The second part of the strength test was the SOLIDWORKS drop test. This test allowed us to see how our agent would react to being dropped at a variety of different heights. The results of our simulations can be found in **Table 1**.

Table 1. SOLIDWORKS Drop Test results for our agent.

Drop Height	The Factor of Design (Front Arms hit First)
5 ft	>100
10 ft	>100
15 ft	60
20 ft	10

The following engineering test that we conducted is the maneuverability of our agent. Our agent traversed various obstacles and inclines for this testing to determine its potential maneuverability. Another part of this test was an incline test, where the agent will attempt a ramp at various degrees to determine the max slope the agent can climb. The results of our agents' maneuverability can be found in **Tables 2 & 3**.

Table 2. The results of our obstacle testing.

Height	Trial 1	Trial 2	Trial 3
.75"	Successful	Successful	Successful
1.5"	Not Successful	Not Successful	Not Successful

Table 3. The results of our slope testing.

Angle [Degrees]	Trial 1	Trial 2	Trial 3
5	Successful	Successful	Successful
10	Not Successful	Successful	Not Successful
15	Not Successful	Not Successful	Not Successful

The results of these two tests were not what we were wanting, but we have recommendations that would help further groups to overcome this challenge.

The last engineering test is the duration test. The duration testing was completed at -40C; however, due to the limited time for the chamber, we will only be able to run this test once. In order to evaluate the test results, we used the control run time at room temperature and compared it to the run time at -40C. The results for this test can be found in **Table 4.**

Table 4. The results from our duration testing.

Temperature [C]	Total Run Time [mins]	Percent Lost [%]
-40	25	1.96
21 (Room)	25.5	0

The 3 main focuses for usability testing was (1) obstacle detection, (2) objective detection, and (3) beacon detection testing. From this testing plan, the following results are represented in **Table 5** from the objective detection testing. Analysing the results, it was established that the lower the angle of approach to an obstacle the agent is (ie, off to the side rather than in front). This also meant that to optimize optical avoidance, it is best advised to mount the ultrasonic sensors at an angle, rather than in front to better detect obstacles from the side at approach.

Table 5: Results from obstacle detection testing.

Angle of Approach	Left Sensor	Right Sensor
90°	3"	3"
80°	3"	3"
70°	2-7/8"	2-15/16"
60°	2-3/4"	2-3/4"
50°	2-3/8"	2-1/2"
45°	2"	2-1/8"
40°	1-1/4"	1-1/8"
30°	7/8"	7/8"
20°	1/4"	1/8"
10°	1/8"	1/8"

Table 6. Results from objective detection testing

	Radial (cm)	Horizontal Angular (degrees)	Vertical Angular (degrees).
90% Reliability	0 → 3	-30 → 30	-15 → 20
0 → 3	0 → 60	-30 → 30	-50 → 70

Table 7. Results from beacon detection testing

Angle	% Success	Angle	% Success	Angle	% Success
0	30	120	30	240	10
15	30	135	10	255	0
30	50	150	10	270	20
45	60	165	0	285	30
60	60	180	10	300	40
75	30	195	10	315	50
90	30	210	10	330	30
105	10	225	20	345	30

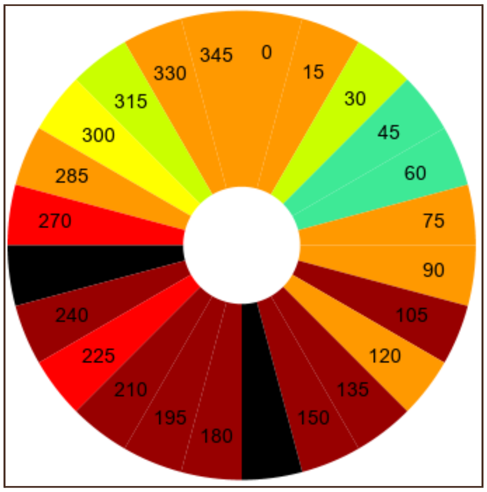

Figure 12. Visual representation of Table 7

CHAPTER 7: PROJECT MANAGEMENT PLAN

Table 8. The work breakdown structure outline.

Task #	Task	Length (Days)	Dependent on...
1 (Start of Sept 1)	Concept Development	40	
2	Initial Design of Chassis	31	1
3	Initial Design of Electronics	31	1
4	Initial Design Collaboration	14	2,3
5	Create Parts List	7	2,3
6	Detailed Design of Chassis	90	4
7	Detailed Design of Electronics	90	4
8	Detailed Design Collaboration	14	6,7
9	Project Manufacturing	120	5,4
10 (End of May 8)	Testing and Refinement	45	9,8

As written above in **Table 8**, this project has three main phases. Phase 1, the initial design review, has concluded, but during this phase, we met with our client and set goals and expectations. We talked about the minimum viable product and what this design process would look like in large part. It was during this phase that the shape and scope of the project came together, and it was where we divided our team into sub-groups.

Phase two, which we have just entered, begins with compiling a preliminary parts list and starting to design in detail the project's entirety. This phase, which lasts for upwards of 90 days, will see the trial and error that comes with constructing and simulating our project. It will be during this stage that the most significant flaws in our designs become apparent, and radical changes may be needed if unforeseen obstacles arise; however, if phase one was completed correctly, we should already have an idea of the challenges that lie in front of us, and no significant re-designs are expected.

Phase three, or the refinement phase, will begin once all of this project's pieces have been laid. At the end of phase two, we are expected to have at least one functioning agent, but it is during phase three that we will take our functioning design and begin optimizing it. We will improve the size and reliability of our agents. Depending on when we reach phase three, we can even extend the project's scope if time allows. During phase three, our product's live-action demos can take place, and we will be ready to start submitting papers to academic sources.

CHAPTER 8: PROJECT SAFETY

Our project is low risk in nature; however, there are still safety issues that need to be addressed. These issues can be broken into two different sections like the majority of our project. The first part is the safety issues with the chassis. The chassis is made out of PLA, and it can fracture if it is put under too much stress. If the PLA did fracture, the broken pieces would be sharp and could become airborne. In testing our chassis, we are exposing it to extreme temperatures. This range of temperatures could create burns if proper handling is not used. To mitigate these two issues, we will always wear PPE (safety glasses & gloves). While we are testing the temperature range of our agent, we will have a supervisor from atmospheric science watch over the lab.

On the electronic side of our project, we have issues that need to be addressed as well. When dealing with electronics, there is always a risk of overheating. If overheating does occur, it could lead to a potential fire. With overheating occurring, there is also a risk of getting burned if the circuits are handled wrong. To mitigate both of these, we will have an emergency shut-off switch and be aware of the closest fire extinguisher when working on circuits. Another safety risk that can occur is electrical shock. This shock can happen if the circuits are handled wrong as well. To mitigate this risk we will make sure the power is completely discounted and always be aware of how we are handling the circuits. Our first priority of this project is to ensure that everyone is safe while building and testing our agents. By using all of these mitigation strategies, we should lower our risk even lower in this project.

In addition to the more traditional physical safety concerns listed above, we feel it is important to mention broader concerns associated with this project. Any autonomous system comes with its own series of unique problems that stem from the fact that there is little to no human intervention once the system is released. In our case, especially where there is no central processing unit, the risk of mal performance increases. In other instances in which CPUs are present, it is standard practice to implement checks to ensure that the system is functioning well within its expected perimeters. For example, at standard intervals, the system can record metadata and analyze it with a table of expected values, or it can communicate via the internet and check its data with the expected values housed on a larger database. In our case, and in the cases of other projects like it, we do not have the luxury of such processing. This raises the question: how does our system protect itself from becoming a potential vector of malice?

The first step in answering this question is to analyze some of the potential vectors of attacking this system. Our agents were modeled off of pheromone using insects; therefore, one of the most straightforward vectors of attack would be the one that evolution produced in some predators to prey on and confuse insects like ants: mimicking pheromones. Our agents do not use chemicals; they use various signals. To detect objects, they use reflected ultrasonic frequencies. To look for their objectives, the agents are currently using Hall Effect sensors. To communicate that they found an object of importance, they use standard RF transmission. An adversary could mimic any of these and fill the environment with false flags, reducing the agent's effectiveness, or they could strategically place these false flags in dangerous areas causing potential harm to the agents as well as humans. Imagine if, in a space application, an adversary were to place small patches of millimeter-thin ice above critical wires outside of a Lunar base. If the adversary also removed the boundaries it is entirely feasible that the agents could wander to the wires, and complete their task by drilling the ice, but in the process, cut power to a critical subsystem of the base causing untold damage.

Perhaps an attacker does not target the pheromone system but instead targets the design of the agents. The agents are supposed to return to where they started once their collection pouch is full. What if an attacker placed dangerous chemicals or diseases in the bounded area where the agents roamed, and they unknowingly carried the harm back to humans by themselves? This example, and the one above, should showcase that although an autonomous system such as the one we are designing is saved from many traditional cyberattacks that require interfering with processing, they are not immune to attacks altogether. Even autonomous systems can be targeted. Our project is too small in scale and too limited in scope for these safety concerns to be addressed by us; however, if we were developing this system for an actual client outside of the safety net of senior design, the safety concerns listed above would be of the utmost importance, and therefore, we consider this section very relevant.

CHAPTER 9: PROJECT BUDGET

Dr. Mike Borowczak and the Cedar Lab provided us with a generous budget of $5,000. This budget was very achievable once we started to inventory the parts that we would need. As you can see in **Table 9**, the breakdown of the project budget and what areas required the most money. After ordering all the parts and taking in the manufacturing cost we have a total cost of $1,357.75. This total cost is split between three agents, so the cost per agent is $453. This cost will be lower because the running total includes multiple chassis designs and electronics were mass ordered to save time in the initial prototype stage. Our total project cost does not include manpower hours that would also have to be taken into consideration. For manufacturing the agent will take 100 man hours to produce the chassis and 60 hours to complete the electronics.

Table 9. Budget breakdown of the project.

Name	Item Total	Running total
Wheels & Extras	$89.64	$89.64
Motor Assembly	$424.45	$514.09
Chassis Manufacturing	$218.26	$732.35

Sensors	$91.46	$823.81
Material Protection	$52.65	$876.46
Electronics	$205.41	$1,081.87
Batteries	$275.88	$1,357.75

CHAPTER 10: CONCLUSIONS

In order to look at how well our project succeeds we can look at the project requirements. The project requirements that we established at the beginning of the semester can be found below in **Table 10.** The green in the table represents the requirements that we have met. The blue are the requirements are in progress.

Table 10. Project goals that we can compare to and the end of the year.

Project Requirement	**Desirable Magnitude (include units)**	**Priority (high, med., low)**
Size Restriction	15 x 15 [in]	High
Modular Ability	1 [Attachment]	Low
No Cpu	-	High
Agent Quantity	3 [Agents]	High
Swarm Communication	-	High
Objective Identification	0.5 [Meters]	High
Random Movement	Movements per time	Medium
Extreme Environment	-40 to 50 [C]	Medium

The first requirement that we can compare is the size restriction. This requirement was a high priority, and we were able to accomplish it. Our current agent is 8 inches by 8 inches. The following requirement was for the agent to have a modular arm. We were also able to accomplish this with our arm underneath our agent. A requirement that was one of our most important ones was that this agent would have No CPU. We have found ways to get around the CPU within our circuitry and be purely analog. The following two requirements, Agent Quantity & Swarm Communication, are being worked on currently and are partially complete. The agents have been produced; however, the swarm circuitry has not been installed on the agents. Objective Identification has been completed and the distance in which our sensors could read was achieved. We have been able to include random movements in our agent by using one wheel to work randomly, and lastly, we haven't been able to test the upper temperature extremes.

Based on our current project's success, there are recommendations that would help improve our agent. The first recommendation would be to change the motors for our agent. The existing motors provide 1.6Ncm of torque. This amount of torque allows our agent to operate, but it limits the environment that our agent can operate in. As you can see in **Tables 2 & 3**, the agent has difficulty climbing or going over any obstacle. New motors would provide more torque and allow our agent to function in a more extreme environment. We were able to create a static diagram to determine the needed torque to climb objects of 3.5 inches in height. This diagram can be seen in **Figure 13**.

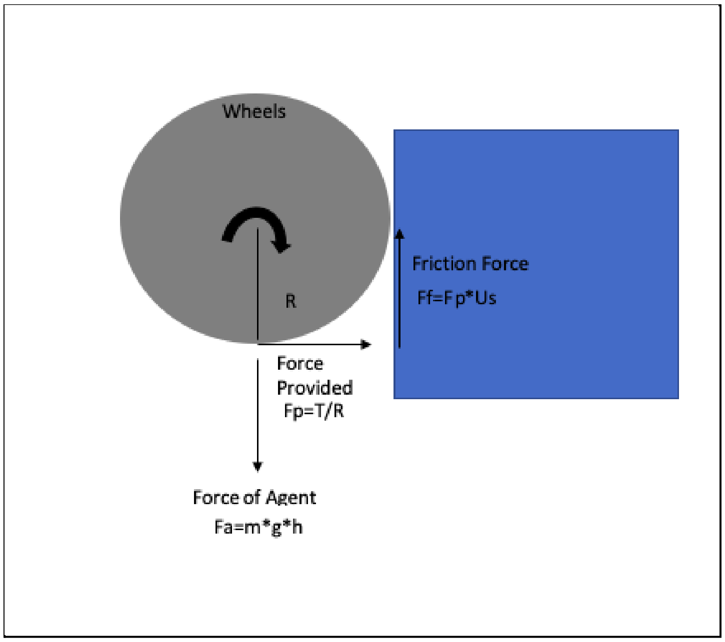

Figure 13. The FBD of our agents' wheel climbing an object.

In order to solve this we summed the forces in the vertical direction to determine the force needed. After the force is calculated, we can find the motor torque with the radius and force needed. By making these calculations we determined that the necessary torque per motor would be 4.8 N cm.

From this project we have also learned many lessons from design to testing. The first lesson that we have learned is with the circuitry. Our beginning goal was to be able to create an agent without a CPU. We were not sure how this was going to look or if we were even going to be able to achieve this goal. From working together we were able to achieve this goal by just using analog circuitry. Along with dealing with circuits we have learned how to safely deal with them when they can overheat or have other issues. Another lesson that we have learned came from the production of our agent. We were unfamiliar with 3D printing and how we were going to complete our project. Through many hours of training and dealing with the makerspace we have become more knowledgeable in printing. The refinement of our design and prototyping has allowed us to master the set up and actual printing of our chassis. One aspect that we would change from this project though is that we wish we would've ordered our own PLA. From ordering our own PLA we would’ve been able to print in one solid color and bypass the billing system within the makerspace. The last lesson we learned is our communication with outside parties. From communicating with our sponsor to communicating with other professors for testing, we have been able to improve our communication skills. Communication is one of the most important skills to have and this project has prepared us for our next step in life.

CHAPTER 11: REFERENCES

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APPENDIX 1 – GLOBAL, SOCIETAL, AND POLITICAL ISSUES

In our project there are two issues that would benefit from our product. The first issue that our project could help deal with is overpopulation. The population of the Earth is growing at rapid rates. There are close to 7.6 billion people on the Earth. The demand for this population is also increasing as each year passes. There are fresh water shortages for nearly 2.7 billion people (“Water Scarcity”). These people struggle to find fresh water at some point during the year. The supply of fresh water is going to keep decreasing as the population increases and the supply keeps getting depleted. Another issue we are seeing is food shortage due to the ever-increasing population. There are areas in the country that do not get a consistent supply of food. This will lead to even further issues such as malnutrition and disease. The last impact that overpopulation has is the increase in energy demand. The EIA projects that there will be a 50% increase in world energy by 2050 (Kahan). This will lead to more pollutants in our air and in our rivers. With these issues we can see the carrying capacity of the world is starting to reach its limits.

Another issue that the world is seeing right now is issues with peace and security. The conflict in the world is rising at an alarming rate. Terrorism is on the rise throughout the world and it leads fear, insecurity, violence, and death. Along with terrorism the security of people is at risk as well. Security can be seen as society's technology security and how the risk of getting hacked is always growing, however security can also be viewed as to be protected from military and non-military threats. Both of these issues lead to people getting hurt and nations falling short of being able to provide a safe environment. Our project will be able to improve these two issues in different ways, but it would be a start for societies to use the technology that we are creating.

The issue of overpopulation can be improved by our project, but in an indirect way. People say that the only way we are going to get away from the issues of overpopulation is by moving civilization to other places besides the Earth. The closest place where civilization could move to is the moon. In order for people to live on the moon there needs to be water. Water will be able to be used to create food and sustain these colonies. Our project would help find water and allow people to go capture it. Instead of having people go out every day looking for water you could send our agents out and they would locate it for them. This strategy would cut down on the search time and lead to more water being discovered on the surface of the moon. Now the moon has an extreme environment, but luckily our agents should be able to withstand these harsh conditions. By having our agents on the moon, it will be a step forwards to colonizing somewhere else besides the earth. If colonization happens somewhere else then it will help with overpopulation and all of the issues that are associated with it will decrease. Our project will not be a direct solution to this issue, but it will potentially lead to a larger action to solve overpopulation.

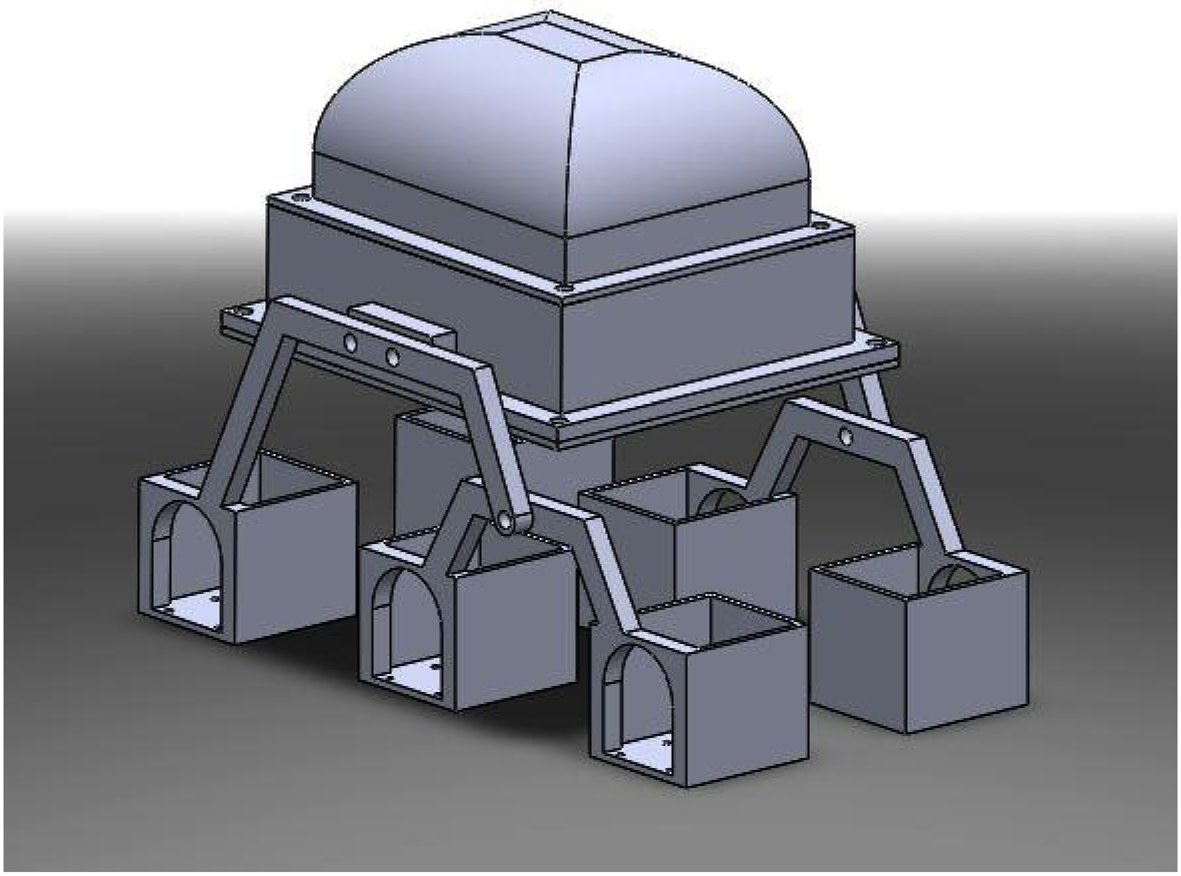
The next issue that our project will impact is peace and security. In the paragraph above I talk about how peace and security can lead to other issues like terrorism. Our project could directly help reduce terrorism. The agents that we are designing are very small and could be used in military operations to help prevent terrorism. These agents can have different uses, but one of them could be used for surveillance and it would make it so a human would not be put into harm. The other part of this larger issue is security. The agents that we are designing will also help with this issue. The robotic parts of our agent will not have a CPU and will be completely analog. This robotic design will make it so no one will be able to hack it and it should be completely secure. Now the actual agent may not contribute, but the electronic makeup will. The security of our electronics can be taken and applied to different areas. It can lead to less hackers getting into sensitive information and it can be used in military applications as well. Countries can use this technology to provide their people with a safe environment from foreign threats. The agents will contribute to trying to improve peace and security around the world by providing us with surveillance or by using its technology to keep us secure. Both of these issues need to be resolved and by looking at our project we can see that by using its technology, societies can take a step into the right direction

APPENDIX 2 – PROJECT DOCUMENTATION FOR CLIENT

Final Report Presentation -

https://docs.google.com/presentation/d/e/2PACX-1vRYC0QhISvgLJbOSK3eC6svdLVygqFyL6BbWH71wtPSnE8_a1EsOUBbxxmXGo4eX9aRzdtg9AnYHgnV/pub?start=false&loop=false&delayms=10000

SOLIDWORKS Model -



Circuit Diagrams - Included in Report

Physical Agents - Delivered to Client