ME 366J Mechanical Design Methodology: Final Report

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Chapter 1: Introduction

Robots provide the unique ability to perform human-like tasks in environmental conditions where humans should not or may not wish to operate. As technology continues to advance, with lower costs and higher complexity, robots are becoming ever more prevalent in various functions, from household cleaning to warfare. Robots for assisting fire-fighters have been proposed and developed for a wide number of roles but have yet to be fully embraced in the field. Fires often involve life-or-death scenarios, and firefighters are hesitant to use equipment to take their place rather than simply go in themselves. However, certain situations, in which it is clear that no human lives are in danger, may be benefitted by the use of robots rather than firefighters themselves.

For example, if it is known that a pet is trapped in a burning building, it is highly desired that the pet be rescued, but at minimal risk to firefighters' safety. A simple robot capable of navigating the environment and locating the pet could provide significant safety advantages over having a firefighter perform the same task.

Chapter 2: Project Proposal

The purpose of this project is to design, fabricate, and test a portable, remotely operated, ground vehicle suitable for search and rescue missions in a fire-fighting context. Firefighters are often called upon to rescue pets from burning buildings, and these operations pose significant challenges and dangers to firefighters. The specific purpose of our robot is to increase the safety of these operations by finding the pet and providing the location to the firefighters before they even enter the building.

Background Research

Prior Work/Other Robots

Reconnaissance robots are designed for situations unsafe or impractical for humans, such as in military or rescue operations. One example is the Micro Tactical Ground Robot (MTGR), a robot developed by Roboteam for explosive ordnance disposal and reconnaissance in a military environment (Robo-Team, 2016). It is equipped with a robotic arm and several cameras, and has been adopted for use outside of the military due to its capabilities by organizations such as the Austin Fire Department (Culver, 2017). However, its lack of high-temperature capabilities and water resistivity have limited further adoption for fire-rescue operations.

Another reconnaissance robot we researched is the Fire Fighting Robot, (FFR), developed by at the University of California San Diego (Chen, Warren, & Yang, 2013). This robot uses both red, green, and blue (RGB) color and thermal imaging cameras to create a 3-D temperature map of its location. The robot itself is unsuited for high-temperature environments, but provides a perfect example of the mapping capabilities possible with only a few cameras and a power control module.

The last reconnaissance robot we researched was the Recon Scout Throwbot developed by the U.S. Military and later made available to police and fire departments (Dillow, 2011). The name implies its primary feature - the ability to survive being physically thrown into its work environment, generally through a window, and then transmit visual feedback. The durability and simplicity of this robot is desirable, but unfortunately, the robot was not intended for high-temperature environments.

In addition to the aforementioned data gathering robots, other vehicles are designed to enter active fires and quench the flame. One example of is the Thermite 3.0 designed by Howe Technologies, a robot capable of delivering up to 600 gallons/minute of water to an active flame (Howe and Howe Tech, 2014). This vehicle is encased in A440 steel and aircraft grade aluminum providing it with structural integrity and protection.

A similar example is the Fire OX, developed by Lockheed Martin as an extension of the Squad Mission Support System (SMSS) (Lockheed Martin, n.d.). The SMSS is designed for use in Afghanistan as a semi-autonomous ground vehicle for delivering materials and supplies, and as such is designed to be all-terrain and capable of withstanding high temperatures and impact forces. To modify the vehicle for use with fire fighting, Lockheed Martin added a large water tank and pump system, to be able to navigate in, survive, and quench fires.

Necessary Subsystems

This project mandates that several distinct subsystems work in conjunction to ensure the robot's safety and mission completion. These subsystems are environmental protection, robotic control, and navigation. Together, these provide the ability to remotely search a room for any pets or victims safely, without damaging the robot or subjecting the hardware to dangerous scenarios.

Environmental / thermal protection. The primary challenge of this project is to design a robot that can survive long-term exposure to high-temperature conditions. Often times, fires can reach into the thousands of degrees, and the heat flux imposed on the robot pose as much a threat as it would a living being. As the subjugation of the robot to these temperatures is inevitable, it is necessary to design around this challenge, as well as design systems in order to minimize, or avoid increased exposure.

Today, most firefighters are equipped with protective suits made of kevlar and nomex (Du Pont, 2017). This combination provides protection from most dangers found in burning buildings. Like most polymers, nomex is fire resistant, and with the addition of kevlar, the combination becomes highly durable. The use of polymers and fabrics for thermal protection is not unique to firefighting purposes, and is additionally utilized as thermal shielding for space exploration robots, and other applications (Williams, 2015; Mid-Mountain Materials Incorporated, 2017). For more extreme applications, such as forging, where temperatures reach well above 1500°F, metals are often used, because they have melting temperatures far higher than other materials, like plastics (Robot Protection Systems, 2017).

Backdrafts, which occur when oxygen is reintroduced into a hot fuel rich room, are life-threatening. The re-ignition of fuel sources within a room results in increased temperatures within the room and quick pressure changes; this causes flames to jet into surrounding areas. These often prove fatal to unsuspecting responders, and will cause harm to the robot (Hall et al., 2017).

The robot will be under constant heat flux and will require subsystems to resist increases in temperatures. Most commercial electronic systems have a high temperature limit of 70°C to 85°C, thus requiring that the robot design have some method of cooling (Altera, 2017). There are several methods of cooling, subsumed into active and passive cooling. Passive cooling is accomplished by dissipating heat convectively through heat sinks or via the storage of the energy into a thermal mass.

Active cooling use mechanisms to circulate coolant, which draws thermal energy away from sensitive areas. Fans are commonly used to drawing heat from electrical components by flowing air across them or by working in conjunction with passive cooling methods. Liquid cooling works similarly - when liquids are circulated through the system, they draw heat and circulates it back into a reservoir for dissipation. Liquid cooling is two to ten times more effective than air at removing heat (Gobor, 2017). To effectively encourage heat transfer, the flow is optimally turbulent; laminar flow creates an insulating layer of fluid which reduces heat transfer. Due to agitation, turbulent flow can easily absorb heat, up to 1-5 times as much, as no insulating layer develops (Advantage, 2017).

Robotic control. Options for control systems of the vehicle are a microcontroller (i.e. Arduinos), or a single-board computer (i.e. Raspberry Pi). Arduinos are an electronics platform that provide a simple interface for communicating with and programming single-board microcontrollers (Arduino, 2017). This is done with the pre-manufactured Arduino boards, or by using the Arduino software on a bare Atmel chip loaded from a programming device (Sparkfun, 2014). These microcontrollers are loaded with a single binary program and begin running that program after about 8 seconds (Chris, 2008). They have direct control over the input output pins, and coupled with a wealth of Arduino's internal libraries lower the technical barrier of entry to accurately control and read from various hardware such as motor controllers and sensors.

Single-board computers (SBCs) are more expensive than Arduinos and provide a greater layer of abstraction to the hardware. Instead of a single binary executable, SBCs run an operating systems that controls various daemons, processes, and applications all at once. The processor constantly switches execution between all these tasks, and therefore provides limited control to the user over the execution of critical programs. Additionally, because of the operating system, the individual input/output pins are treated at a much higher level of abstraction, making it challenging to interface with hardware directly. Fortunately, some libraries such as RPI.GPIO remove that barrier for the Raspberry Pi (Hager, 2013), but the abstraction can still impact measurement accuracy (Windeler, 2008). Despite the added complexity of using a full computer for robotic control, there are added benefits. SBCs are typically much more powerful than bare microcontrollers. For example, the Raspberry Pi II has 3000x the FLOP rating of the ATmega64 (Gratton, 2014). This is also reflected in the increased power consumption of SBCs; however, given the power needed for other functions such as motor control the extra loss could be considered negligible. For the vision processing and streaming needed to send visual information about the environment to an external control unit, this extra performance is essential. Furthermore, the OS allows the usage of additional software platforms, such as OpenCV for vision control and Apache or NGINX to use as a web server (Apache, 2011; NGiNX, 2017; OpenCV, 2008).

As stated above, both these methods of control have some serious drawbacks. We can mitigate the downsides by playing to each of the devices strengths and using them in union. A complicated SBC can offload commands for robotic control to an external microcontroller over a serial connection. The microcontroller can then read the status of the sensors and drive the motor controller, while relaying data back to the SBC controller. The SBC can do more complicated tasks such as hosting a web server for control and handling data from a vision device. This would increase the complexity and potential for failure of the system, but is an effective way to mitigate the drawbacks of either a purely microcontroller or single-board computer control system.

Navigation. For navigating the search area, the robot must be equipped sensors to avoid obstacles and other objects in the room. Additionally, the vehicle must have a way to distinguish and identify the target. One way of determining the distance to objects in the room is with either infrared or ultrasonic distance sensors. They both operate by emitting a signal to the environment, measuring the time it takes for it to reflect back to the sensor, and then making a calculation on the travel time of the signal to find the approximate distance from the sensors. Ultrasonic sensors use the speed of sound in air which may cause an error in accuracy in high temperature environments if this is not accounted for. However, the infrared sensors have issues when in environments with several sources of infrared light. This is an issue when dealing with bright sunlight, or in an active fire or high temperature environment. Therefore the ultrasonic sensor should be used, with proper temperature corrections for the speed of a wave in air.

To identify the pet or person inside of the fire, an imaging device that will work in a smoke filled room is necessary. The imaging device needs to be able to detect temperature gradients in the room from a distance in order to see the difference in temperature between a warm body and the environment. One such device is a thermal camera which can be used as visual aid for navigation. While there are several such devices available, most except for a few very low resolution cameras are prohibitively expensive. Near-infrared imaging, while not as effective as thermal imaging, can still cut through thick smoke more significantly than visual light does (Infiniti Electro-Optic, n.d.) Additionally most low-grade consumer cameras detect near-infrared light, and can be coupled with infrared-passing and visual spectrum-blocking filters to only show that range of light.

Customer Needs

We determined the customer needs for this project from a variety of sources and separated these needs into four different categories: environment protection, physical constraints, capabilities and user interface. They are weighted 1 to 5; any needs of weight 5 was non-negotiable, 3 was important but not mandatorily required for the scope of this project, and 1 was helpful to have if time and monetary constraints allowed. Appendix A outlines the full list of customer needs we determined.

Environmental protection is broken into four distinct categories: heat resistance, heat endurance, water resistance and shock resistance. For heat resistance and heat endurance, the project requirements were clear, and we assigned both a weight of 5. From the firefighter interview, the robot will need water resistance for traversing pools of water on the floor and surviving decontamination (Culver, 2017). We gave this a weight of 3, as it is not directly a project requirement but still important for real-world situations. We determined the robot would need shock resistance to survive drops and falling debris--this is weighted 3.

For physical constraints, the three concerns were volume, weight, and cost. The project requirements for volume and cost were clear, and we gave both a weight of 5. For weight there is no listed requirement, thus we determined that the robot should be lightweight to simplify transport and deployment. It seems improbable that our design reach a weight limit, so we gave this requirement a weight of 2.

Capability requirements of the project formed the largest category of customer needs: pet identification, obstacle detection, obstacle traversal, localization, temperature avoidance, mapping, and oxygen sensing. The ability to identify a pet is the primary purpose of the project, so it is weighted 5. To move around a room and find a pet, the robot must be able to detect large obstacles and navigate around them; this is weighted 4. Obstacle traversal is distinct from obstacle detection as traversal deals with obstacles the robot can drive over, while detection covers obstacles the robot must drive around. Debris poses a significant hindrance to robotic movement, so it is weighted 3, as it is uncertain that the evaluation of our robot will involve floor debris (Culver, 2017). Localization is needed for the robot to communicate where the pet is, thus it is weighted 4, as the “visual” capabilities of the robot will allow the operator to know the pet’s location, without precise coordinates. Temperature avoidance, room/obstacle mapping, and oxygen sensing were all features that would be helpful to the firefighter but not necessary for locating the pet, and we gave all of these capabilities a weight of 3.

The user interface needs of the project were divided into remote control, ease-of-use, and controller durability. The remote control requirement consists of transmitting a feed of data to the operator and allowing the operator to control the robot from outside. As this requirement is crucial to the operation of the robot, it is weighted 5. Ease-of-use and controller durability are considered helpful to have but not mandatory for the scope of this project, and we gave them a weight of 3.

House of Quality Analysis

We completed the House of Quality analysis (Appendix B) using our customer attributes of environmental protection, physical constraint, abilities, user interface, and data acquisition and assigning our engineering metrics developed previously.

Most of the relationships that we developed were expected; having to withstand high temperature would depend on the material's thermal resistance and internal temperature, and the relationship between lightweight and small size with mass and volume. Long-lasting need would depend on the material's thermal resistance, internal temperature, and integrated heat flux which means that we must take into account the performance of battery life as well as the battery's performance at high temperatures for an extended period of time.

Engineering Requirements

In order to translate our customer needs into target metrics, we gathered information from a variety of sources. Our primary source was the stated design requirements, but we additionally took information from interviews and independent research. We then benchmarked these metrics against the published technical details of alternate commercial systems, and created estimates when such details were unavailable. Similarly to our customer needs, our engineering requirements were categorized into environment protection, physical constraints, capabilities, and user interface. Our metrics for size, high temperature endurance, and cost were assigned based on the values given as project specifications. Other specifications such as wireless signal strength and ingress protection were chosen based on readily available industry standards, and more information about these requirements and the justification behind choosing them can be found in the Engineering Requirements table in Appendix C.

Based on a thesis analyzing the weight that average workers can transport safely and securely, we determined the the maximum weight our robot should be is 51 lbs (Chapla, 2004). We then used this weight value to calculate the minimum impact energy our robot must be able to sustain. The 2012 International Building Code (IBC) mandates the height of the window sill should be 3 ft above the adjacent interior floor and if we assume the firefighter would not drop the robot from the exact height of the sill, thus we decided to assume a drop height of 4 ft. Using the conservation of energy formula we can derive a formula for the velocity our robot will reach right before impact, $v_{final} = \sqrt{2gh}$. Based on this formula we are able to determine the final velocity of our robot will be approximately 4.85 m/s. From there we could calculate the final energy to be $E_{final} = \frac{1}{2}mv_{final}^2$, therefore the minimum impact energy our robot must withstand is 270.48 J.

When compiling the requirements list we had to decide if our metrics were a demand or a wish. We assigned demands for specifications that we see as critical to this project. Alternatively, if we thought a specification was important but not completely necessary for the scope of our project, we assigned them to be a wish.

We also established how to verify our specifications have been met. For specifications such as size, weight, or the resolution/range of thermal cameras, the validation is as simple as ensuring that our design meets constraints or that purchased components meet our target metrics. For other specifications such as weight and cost we decided the best way to ensure we don’t go over these values is to compile a list of the individual components and compute the total cost and weight as we go. Lastly, there are the metrics where we will have to do testing either with SolidWorks simulations for metrics like internal temperature and duration at high temperatures, or with physical testing. The latter, includes metrics such as decibel rating of the location beacon, signal strength of a wireless access point, and ingress protection which need to be tested with the fully realized prototype.

Problem Statement

We are to design and fabricate a robot that can remotely identify incapacitated pets within a burning structure and alert first responders to their location. The robot must be able to operate in extreme temperature conditions mimicking that of a burning structure. It must also be able to navigate its way through the structure and relay information back to the pilot concerning the environment and potential dangers. The cost of our robot must be under $250 and the volume must not exceed 0.096 m^3.

Chapter 3: Design Review

Introduction

After completing our research for the project proposal, and referencing and updating our gantt chart and task list (Appendix A and B, respectively,) we sought to expand upon our core idea of a fire rescue robot. This was accomplished by going through three essential phases; concept generation, design screening, and low resolution prototyping. To generate several designs, we initially divided the problem statement into several different subproblems and identified the systems necessary to solve them. The relationship between these systems was then visualized as a functional diagram, detailing the flow of energy, materials, and information. By using several brainstorming strategies methods, we then created several different designs for each of these core systems. We also performed additional research to identify the state of the art of the subsystems, and existing solutions to these problems. From these idea generation methods, we selected the most practical designs for each subsystem and combined them using a morph matrix to form six variations of a fire rescue robot.

With these fleshed out concepts for the robot, we compared and contrasted each design using a Pugh chart. We selected the metrics for comparison based off of our prior work done identifying customer needs, in addition to quantifying the performance of the individual subsystems. From this design screening we chose one leading concept that we felt comfortable with designing and manufacturing. This concept was shaped into a low resolution prototype in order to assess the merits of its physical design, and to identify problems or additional aspects we need to consider for the manufacture of the fully functional prototype. With this prototype in hand we identified subsystems that need additional experimentation and functional design before the final prototype could be made.

Concept Generation

Function Modeling

To help generate function-based solutions we needed to identify which functions our robot needed to perform. First, we created a black box diagram (Appendix C) with the main function being: provide pet location. As shown in the diagram, the energy input will be heat flux that the robot will operate in and detect from the environment. The energy out will be mechanical movement, light, noise, and heat. There will be fluid in and out of the system with an active cooling configuration, otherwise, there will be no material flow. Information coming into the system will be heat that is detected by the robot and user input that comes from the controller. Information going out of the system will be image and data which are relayed to the user, and light and noise which are output for the firefighters.

Next, we created a function tree (Appendix D) that breaks up our main function into subfunctions which, when all accomplished, accomplishes the main function. This helped us to identify the main subsystems of our robot which are: environmental protection, robotic control, and navigation.

Finally, we created a function diagram (Appendix E) that maps the flows between subfunctions showing how each subfunction interacts with the others.

Critical Subsystems

The critical subsystems that we identified for concept generation techniques were movement, communication, and environmental protection. We recognized movement as a critical subsystem because the robot ideally needs to effectively navigate the burning building in order to locate the pet. There will be obstacles and debris that the robot would need to avoid or travel over without getting disabled. Communication is a critical subsystem because there needs to be some form of communication to the user, who is outside of the room, and the firefighters once the pet has been located. And environmental protection is a critical subsystem because the robot will be in an environment with high heat and lots of water, each of which could damage electrical components if not accounted for.

To address these critical subsystem problems, we performed the following concept generation methods to create solutions.

Brainstorming with Mind Mapping

Our brainstorming with mind mapping results are shown in Appendix F. For environmental protection, we organized our solutions in subgroups of kinetic shock, thermal protection, moisture protection, and protection from debris. Some of the notable results include water-cooling for thermal protection, bumpers for kinetic shock, and shell for moisture and debris protection. We felt that these solutions were the most practical and relatively easy to implement.

For our movement brainstorm with mind mapping, we recognized that land locomotion was the most reasonable method of travel. Our notable solutions are using wheels or tread with the addition of using flipper arms to overcome obstacles or difficult terrain.

The two most important subsystems of our communication mindmapping were sensors and control. This is because sensors will communicate information to the user and control would be the method of communicating that information. Some of the notable results were ultrasonic and O_2 sensors. An ultrasonic sensor would be useful to detect objects without using heat in a heat rich environment, and the O_2 sensor would be vital to alert firefighters of the oxygen levels in the room to identify potentially dangerous conditions.

6-3-5

The 6-3-5 concept generation technique involves 6 individuals producing 3 ideas for 2 different subsystems and then editing and improving the other team members ideas as you switch your papers in a complete circle. Our results for our 6-3-5 are located in Appendix G. We received help from a biology major, in order to gain a multidisciplinary design perspective and foster a wider range of idea generation. This directly led to some biologically inspired designs, including sweating (surface evaporative cooling) and a coolant circulatory system based off the human bloodstream (a “heart” for pumping and “lungs” for heat transfer).

We focused on the two sub-functions of movement and thermal protection for the 6-3-5. We wanted to generate concepts for the movement of our robot, because it is one of the main functions of the robot that will be necessary to perform our task and one of the broadest subfunctions. Most of our group members came up with a design with treads, because we believe that this would be an easy technique to manufacture, control, and that prevent things from getting caught around the axle. Another common concept amongst our ideas was the addition of flippers to allow the robot to more easily navigate over debris or to climb stairs. There were also some more unique ideas for how our robot should maneuver around, such as hundreds of little legs that simultaneously bend like a centipede, a sphere robot, and one that acts like a slug vacuuming up a low friction fluid and propulsion from fans. We had some pretty good insights based on the team member’s observations of each other’s designs, such as pointing out design flaws and pointing out solutions to them. These observations included moving design elements within the sketches like flipper locations, or pointing out the necessity for additional components such as motors, shocks, pistons, etc. We decided that going forward a design with tank treads and flipper arms was our strongest design that would be effective at navigating most obstacles we will occur and that could be manufactured with reasonable ease. The other sub-function we decided to tackle was the thermal protection technique we would employ. This is an important sub-function because if the components overheat, they will not be able to perform as required and the robot will lose functionality. Here we saw a variety of techniques to hinder the robot from overheating, especially as mentioned above with the biology member in our group. Some of which were impractical like sweating, vasodilation, or the use of a fire extinguisher. There were also several repeated concepts throughout our group, such as the use of insulated material, water cooling, fans, and heatsinks. After evaluating all our ideas we decided that a combination of our latter concepts would be the best bet moving forward. Such as an insulated material shell with a water cooling system and a heat sink.

Patent Search

We performed a patent search to identify other state of the art ideas for solving some of the subtasks we were dealing with. The patents found dealt mainly with the all-terrain drive mechanism, object detection capabilities, and communication modules. While these are patented ideas and therefore can’t be used in our design they still provide a good basis for brainstorming additional ideas.

Patent US 7011171B1 (Appendix H.i) details an all-terrain drive system for a robot that can be used to navigate over obstacles and climb stairs. The vehicle's drive system in enclosed in two clam shells that can rotate independently with respect to a large tail boom. The tail boom moves to stabilize the center of gravity, while the two clam shells move to scale obstacles. The simplicity of the design was very attractive, and provided us with the idea to further investigate the use of a counterweight mechanism to stabilize our robot and help traverse obstacles.

Patent 8644991 (Appendix H.ii) outlines the use of flippers on a robot to help it traverse over obstacles or across holes in the ground by shifting the center of gravity. Although the flippers used in this patent have their own tracks, untracked flippers can still perform the same center-of-gravity changes, albeit to less effect. Such a design would vastly help with our terrain traversal ability for minimal additional cost and complexity.

Morph matrix

We completed the morph matrix (Appendix I) by populating the concept designs with solutions from our brainstorming with mind mapping and 6-3-5 concept generation techniques as well as prior art in the form of patent searching. Movement, environmental protection, and communication subfunction concepts were generated by these techniques. Important guidelines for our choices were simplicity and feasibility.

We formed overall concepts by first selecting the drivetrain we wanted to try and varying other subfunction solutions. Thermal protection was another important subfunction where we looked at varying and adding concept solutions together to form an overall concept. We did this because a single thermal concept solution is unlikely to provide enough protection in the high temperature environment the robot will operate in. And lastly, we focused on environmental sensing as a critical subfunction for solution concepts. As with thermal, we often added concepts together so that we would have more information about the environment the robot is operating in.

By completing the morph matrix we found that overall solutions one and five are the least viable solution designs. This is because solution one uses a full-fledged processor for the control system which is unnecessary for the tasks we are asked to perform, while solution five uses shock absorbers which is too complex of a solution to a non-critical subfunction.

Results

In the morph matrix a we created 6 main solutions to solve the fire rescue problem. These solutions differed mainly in the methods of control, environmental protection, and object detection. Each solution is described along with its pros and cons below.

The vehicle in the first solution uses 6 wheels that are slightly offset to give more traction and stability. The use of flipper arms on the front help it navigate rough terrain. Two near IR cameras are used in stereo to provide a 3D map of the room, with all processing done on it's powerful x86 processor. Thermal protection is achieved through the use of a composite material shell, water cooling, and compressed air for extreme high internal temperatures. A dedicated controlled is used to control it, communicating over wifi to the robot. This design benefits by generating a extremely useful 3D map of the room on robot and has several modes of effective heat transfer. However, these modes individually are not as effective, and the on board processing greatly increases the cost of the design.

The robot for concept 2 maneuvers around with linked treads and two additional flipper arms that will allow the robot to climb stairs and navigate over obstacles. It also has a rotating feature with all the sensors mounted on it, this will allow it to easily and quickly assess the room without much movement required. On the inside of the robot there is a refrigerant cooling system, in which the refrigerant is pumped through a compressor to a condenser that cools the water with a fan, it is then fed into pipes that lead to a heat sink with the components mounted in a dry bag atop it, then the water is fed through an expansion valve and into an evaporator that is fed back into the condenser. All the data is transmitted from a single-board computer over Bluetooth to a native app open on a laptop or phone. The benefits of this robot are the high performance cooling systems and the rugged drive train. The downsides are the lack of high bandwidth streaming over bluetooth and the complexity of designing the refrigerant system.

The vehicle for concept 3 moves using two wheels and a caster. To detect the environment it uses a thermal camera and a thermometer attached to an amature. It uses water cooling and heat sinks to cool internal components. Tactile push-button bumpers register whenever it runs into an object. The environmental data is transferred over a fixed tether to a dedicated controller. The entire robot is controlled by a microcontroller. The benefits of this design are affordability and simplistic design. The downsides are the dangers of using a fixed tether and the low precision control with using two wheels and a caster.

The design for solution 4 uses a linked tread system to maneuver, providing effective all terrain drive. It is thermally protected by a water cooling system augmented with a composite shell. The robot has flipper arms to help it interact with the environment and move objects. It detects the environment through an oxygen sensors and thermometer fixed to the robot, with two near IR cameras in stereo. Data processing is done remotely to conserve power, and is used to detect objects in addition to several ultrasonic sensors. The robot is controlled with a single board computer, which hosts a web application that can be accessed over wifi. The benefits of this system include advanced object detection and environmental sensing, along with a rugged drive system. The downsides include complexity of the 3d imaging and the risk of using a water cooling system.

The robot for solution 5 drives using 4 wheels and a motor. The environmental detection consists of a oxygen sensor, thermal camera, and thermometer mounted directly to the front of the robot. It uses shock absorbers to protect the electronics from impacts. The thermal cooling consists of a heat sink with fans and a composite shell. A microcontroller drives the robot and hosts a simple web app that can be accessed over wifi. Object detection is achieved with an IR distance sensor. The benefits of this design include low cost of the microcontroller and simplicity of the heating system. The downsides are the low resolution of distance sensor and potential ineffectiveness of the thermal protection system.

The design for concept 6 uses 6 wheels and two motors to drive. The thermal protection system consists of a composite shell with compressed air cooling and fans to circulate the air. The environmental detection is achieved by using an oxygen sensor and thermometer mounted to a fixed armature. Objects are detected with both tactile bumpers and IR distance sensors. The vehicle is controlled with a microcontroller streaming data over radio to a dedicated controller. The benefits of this design include lack of complex electronics and ease of use of the sensors. The downsides include no vision or remote thermal data, making pet detection potentially very difficult.

Pugh Chart

To construct the Pugh Charts we first created several metrics by which we could sufficiently judge the quality of each design. Based upon several of the predefined guidelines for the project, as well as several key design features, a total of 10 metrics were used for the Pugh

Chart. These metrics were: modes of heat transfer, water resistance, shock resistance, volume, cost, environmental sensing, obstacle avoidance and detection, environmental interaction, and battery lifetime.

After defining the metrics by which the different concepts would be analyzed, it was important to determine how each of these metrics could be compared between the concepts. For instance, by researching common items that would be used to create the robot (e.g. motors, sprockets, etc.) it was possible to calculate potential power consumption, volume, and cost. Other comparisons made in the pugh chart would be determined by inferring each concept's strength for a particular metric. For example, both shock resistance and modes of heat transfer are metrics that would be inferred based upon the members of Team Deux's knowledge of heat transfer, as well as the number of systems which function to reduce kinetic shock, (i.e. shock absorbers).

With the metrics defined, it was then necessary to begin comparing the different concepts. To compare the different concepts we created three different pugh charts, each with a different datum (i.e. a different concept as the baseline). The three concepts that were used as a datum for the pugh charts were Concept 1, Concept 4, and Concept 5. Concept 1 was chosen because it had the most complete thermal protection system. Concept 4 was chosen because because of its multiple sensors. Finally, Concept 5 was chosen due to what we believed would be one of the more complex drive systems.

From the pugh charts 3 different sets of results were generated, which can be seen in Appendix L. From the first pugh chart (Concept 4 as the datum), it was found that Concepts 1, 2, and 6 would be potentially better designs. From the second pugh charts it was found that only Concept 5 had a positive rating when compared to Concept 1; Concept 3 also had was shown to be equally good design. From the third pugh chart it was found that only Concept 6 had a positive rating compared to Concept 5. Concept 4 also proved to be similar to concept 5.

Low Resolution Prototype

We next created a low resolution prototype of solution 4 from the morph matrix, using primarily cardboard and paper to simulate the various components of the robot. The drivetrain assembly was created to match the design quite closely, including stand-ins for the motors driving the front wheels and idling rear wheels. The flippers were additionally included and have full 360 degree articulation, but the linked track design was simulated by a single-piece track in order to simplify the construction process. Size stand-ins for the sensor suite, power distribution board, single-board computer, and battery were also included in the low resolution prototype. The water-cooling system proved too complex to include at this stage, and a single piece representing a fan and heat exchanger was included instead. Finally, the top of the prototype was left open in order to facilitate access and best display the internal layout.

This prototype proved quite helpful for several reasons. Primarily, the prototype helped us determine the optimal way to arrange the internal layout of robot and ensure that the interior volume was adequate for containing all of the necessary components. The layout consisted of the following, from front to back: sensor suite, front drive motors, circuit boards, battery, rear idler mounts, and heat exchanger. All of the components fit very well within the space, with sufficient room leftover to wiring and working fluid pipes for the water cooling system. Additionally, the prototype helped us to verify that the current drivetrain setup is viable, with two drive motors in the front and two idler wheels in the back. Maintaining track tension proved difficult but manageable using only four wheels total, but considering the materials and precision involved, the prototype proved that such a system could work with proper materials and construction. Finally, the addition of flippers to the prototype helped demonstrate their ability to assist the robot in climbing over large obstacles.

Next Steps

These various concept generation methods were very helpful to gauge the feasibility of different solutions and visualize how the various subsystems could be combined into a full system. After selecting a few leading concepts we proceed to flesh out each of these designs and begin creating functional prototypes of each subsystem. With the low-resolution prototype in mind we also began to construct the base of the robot which would contain these various subsystems.

Chapter 4: Final Design

Leading Concepts and Tasks:

Following from the morph matrix in our design review, we produced a number of leading concepts to choose from when determining how to next proceed. The leading concept we chose for the low resolution prototype can be seen in Appendix J, Solution 4; the low resolution prototype can be seen in Appendix N. The main characteristics of its design are treads and flipper arms for increased mobility, as well as a water cooling system for providing thermal control. The central box contains all of the electronic components in a sealed, insulated environment, to provide passive thermal control.

In order to validate this design, we developed a variety of thermal and physical experiments to demonstrate the robot's ability to survive heat and move effectively. Our oven test involved varying several different aspects of the design (thickness of insulation, presence of a reflective outer coating, and presence of water reservoir cooling). Both simulations and hand calculations were performed to validate the results from the experiments . Mobility concerns were to be analyzed by simply attempting to drive the robot over a variety of obstacles. We set aside time to complete all of these tasks well ahead of the final deadline. However, unforeseen issues soon arose related to the complexity of the design, from designing the coaxial shaft for the flipper to even obtaining the treads themselves within our budgetary requirements. Additionally, we realized that an active cooling system was likely unnecessary, and began to reassess whether our current leading concept deserved its place.

While continuing to perform tests, we shifted our focus to another one of the leading concepts produced during our design review. This design consists of two front drive wheels and a rear castor wheel, all external to a central box that holds the electronics, with passive cooling provided by the outer frame and some insulation. Thermal testing proceeded as planned, due to the many shared design aspects between the old and new leading concepts. More specifically, because both designs consisted of equivalently sized central boxes for the electronics with double walled insulation, test results from the old concept were completely applicable to the new concept. Our gantt chart and task list remained the same, with the same thermal and mobility requirements to be tested.

FMEA On Leading Concept

We performed a failure modes and effects analysis (FMEA) on our leading concept to determine any potential weaknesses of our design (Appendix U). The core areas of focus were our electronics board, sensors, drivetrain elements, and thermal protection elements. Given the conditions that the robot would have to operate in, we came to the conclusion that the main causes of failure would be a result of the high temperature and the resulting stresses of operation on various components throughout the robot.

One of the suggested revisions was to use a high temperature rated rubber material for the tread and replacing the strip of rubber for a timing belt. The reason we made these suggestions were that the rubber will be on the exterior of the machine and exposed to a high temperature environment where the possibility of reaching the melting temperature was possible. Also, we failed to come up with a feasible way to bond the rubber strip to itself to create the tread, therefore, we decided that switching to a timing belt could reduce failure.

Based on the high risk potential numbers (RPN) due to the tread system, as well as not having permission to lathe wooden pulleys to run the treads on, we decided to redesign the drive system to feature two wheels and a castor instead. We wanted to reduce the complexity of the drive system to reduce the likeliness of failure while also making sure that manufacturing would not be an issue.

Simulation

For the simulation we created a simplified CAD model (Pictured in Appendix O Section i), which was similar to the actually box we used during our oven tests. This was because our original design was highly complex and caused problems when trying to mesh or run studies. This actually was beneficial because our new design was actually pretty similar to the box we choose. We modeled two different layouts, one using the 1" Cork and the other with the ½" cork. Simplifying the model also allowed us to be able to use a coarser mesh because there were no small features, which allowed the study to run much quicker. We used a thermal study within solidworks to perform the temperatures the robot would reach during the 10 minutes it is required to be in the oven. In order to accurately simulate this we had to make our thermal study be transient instead of steady state, because the robots temperature is changing over a period of time. To simulate the robot being placed in the oven we had to apply certain temperature constraints to our study. Such as we assumed the initial temperature of all of the components would be at room temperature, approximately 25°C. And then we applied a temperature of 90°C to the external faces of the box. In order to for the study to be accurate we also had to edit the materials and define the thermal conductivity values of the cork and plywood. The results for each of the study is given in Appendix O (sections ii &iii), where the contour plots are given for the chassis after the 10 minute period in the 90°C oven . We also plotted the temperature of the inside of the box as well as for the temperature between the wood shell and the cork vs time for both 1” and ½” cork over the 10 minute period.

Validation

We performed heat transfer calculations (Appendix T), to ensure that the internal temperature would not reach the critical temperature of 80℃ and also to validate the results of the simulation. To do this we used our robot as the system and assumed that the main mode of heat transfer would be natural convection to the plywood shell, with an ambient temperature of 90℃, and conduction between the plywood and the cork. We made an assumption that the internal temperature of the air would reach the internal cork temperature simultaneously, and that the plywood provides minimal resistance so that we could disregard the heat storage of the plywood.

Since the robot will need to be functional after ten minutes in the oven, the internal compartment must not reach the critical temperature in less than ten minutes. We found that it would take our robot 1.9 hours to reach the critical temperature of 80℃ using 1 inch cork insulation.

We then solved for the interior cork temperature after ten minutes and found that it would reach 32.6℃. Our simulation showed that the internal temperature would reach 35℃ in ten minutes which gives us a percent error of 6.86%.

DOE

For our thermal design of experiment (DOE), we experimented with the insulation thickness (X1 variable), with or without water packs (X2 variable), and with or without an aluminum foil wrapping on the outside of the thermal shell (X3 variable) (Appendix Q). The physical tests that we performed for X1 used high and low values of the insulation thickness. The first thickness that was tested was 0.5in, the experimental low value, and 1in for the high value. The water packs had high and low values which corresponded to whether the water packs were inserted into the test box. High and low values for the aluminum foil similarly corresponded to whether or not the test box was covered in aluminum foil. We decided to test variations of the first two variables because we thought their adjustment would contribute the largest change in measured internal temperature. In each of these oven tests we chose to measure two points, one on the interior of the robot inside the cork and one in between the external shell of the robot and the cork insulation. The first point measures the temperature of area with the internal electronics while the second measures where the external sensors will be housed. The various tests we did are tabulated in (Appendix Q), along with the plots of temperature of the two measured points over time for the 4 tests run. The main and interaction effects for theses two variables was also plotted.

From the individual experiments we saw that regardless of the cork thickness both the inside and outside of the insulation increased temperature at a similar rate. However, using ice packs significantly lowered the internal temperature and delayed the rate of temperature increase. These individual experiments also showed that even setting both variables low would be sufficient for this project keeping the temperature at around 60 degrees, which is lower than the maximum operating temperature of the battery and electronic components. Regardless, we still sought to minimize the two measured temperatures.

From these plots we can see the impact the variable changes had on the two variables measured. For the interior data point we can see from the main effects that both X1 and X2 should be maximized to reduce the temperature. These two variables also have no interaction for the interior data point as shown by the parallel lines on the interaction plots. However the data for the point outside the cork insulation is counter-intuitive. Separately it shows little change between the X1 and X2 main effects (around 2-4 degrees), but the main effect plot shows a large amount of interaction at that point, and shows that to minimize the temperature at that point X1 has to be set low. This is counterintuitive, and likely due to experimental noise. The area of the box where the exterior point was measured warped as the experiments progressed due to repeated exposure to high temperature. Additionally the thinner cork had more space in that area causing a small air-gap that provided extra insulation that will not be there in the final design. For these reasons we chose to disregard this aspect of the experimental data and instead maximize X1 and X2, and therefore use 1 inch cork and ice-packs in our final design.

Simulation vs Experiment

The Simulation actually matched remarkably well with the experimental data we collected from the oven tests. I collected the data from the solidworks transient study and graphed them next to the data we collected from the actual experiment (Appendix R). The 1” cork data for inside the cork was almost spot on for both of the test we collected, the only real difference was during the first test we had put the box in the oven when it was still a little hot and therefore the temperature values are a little higher in the beginning of that test but it evened out and followed the trend after about 200 sec. The outside temperature (temperature between the wood and cork) was not as accurate as the internal temperature for the 1” cork. However, all the experiments follow the same trendline, I believe the solidworks data is lower because the box we used in the real oven experiment was not completely closed in the corners because they were just quickly stapled together, allowing for more hot air to easily enter the container.

The ½” cork data was not as accurate as the 1” temperature readings. The outside temperatures follow the same trend with the Solidworks model being lower than the actual values. However, the internal values don’t seem to match up as well, with the solidworks values being higher than the actual, this may be because we had done the oven test with the ice packs right before this allowing the internal temperature to start lower than room temperature yet the outside still be hotter than we predicted.

Design For Manufacturing and Assembly

When beginning to manufacture our prototype, we encountered a variety of manufacturing and assembly problems that led to redesigns, our original design is provided in Appendix W. The primary problems we encountered involved our old leading concept with treads. We had decided to create our own treads from rubber strip material in order to save on costs, but were not able to develop a robust and reliable means of connecting the two ends together to form a continuous tread. The designs were either deemed insufficient for providing tension or overly complex otherwise. Additionally, we experienced manufacturing and assembly constraints regarding the traveler wheels for the treads. We hoped to create the traveler wheels by using a wood lathe to reduce the diameter of the inner section of the wheels, with the outer section providing sidewalls to keep the tread in place. However, we were unable to find a wood lathe to accomplish this task and realized that we would need to produce each wheel by sandwiching lasercut sheets, a time prohibitive design considering that the design required eight wheels total.

Altogether, these basic issues regarding manufacturing and assembly led to our choosing the new leading concept with two drive wheels and a rear castor wheel (Appendix X). We fleshed out this concept with the same manufacturing and assembly constraints in mind. We designed the robot frame and wheels to be entirely made from lasercut wood that was easily obtainable in the maker studio. The laser cutter provided us with very high construction accuracy and a low manufacturing time when compared to traditional methods. Puzzle-piece like matching between perpendicular components was used in order to ensure regularity when piecing the walls together, and a combination of glue and L-brackets were used to fully seal and secure the various frame connections. The motor mounts with complex geometry were 3-D printed with ABS in order to vastly lower their production time while sacrificing little in terms of strength and durability. We also used good manufacturing techniques while 3D printing such as filleting all the edges and maintaining constant thickness with an arch structure. Standard sized ¼" bolts were used throughout the design wherever they would fit in order to minimize the number of tools required for assembly. A hinged lid was added so that the interior was easily accessible for component placement and swapping. With these considerations in place, assembly of the final prototyped proceeded significantly more smoothly.

FMEA On Final Design

We then performed the FMEA analysis on the preliminary final design (Appendix V). The results of this analysis showed the potential for the thermal shell to fail. We suggested a remedy of using two types of bonding materials to make the thermal shell more durable as well as cut-out tabs to connect the shell together. We then used epoxy on the edges to keep the tabs together and used L-brackets to fasten the sides to each other to make it more durable. This reduced our RPN from 240 to 60 out of 1000.

Another suggestion that we made was to eliminate the active water-cooling system and replace it with water packs that can be frozen beforehand. This reduces the chance of water leaking from our system and damaging critical electrical components. This reduced our RPN from 90 to 20 out of 1000.

Final Drawing

For the final design we chose to simplify some of the aspects of our leading concept to reduce the failure modes and manufacturing complexity. This also allowed us to reduce the cost of several of the subsystems thereby significantly reduce the cost of the robot. Below we briefly describe each subsystem and the various changes to it.

The movement subsystem was changed from using a pair of treads under tension to two large drive wheels and a castor. The wheels were laser cut from 4 layers of ¼ inch plywood and are each attached to a shaft using JB Weld epoxy and specialty aluminium hubs. These wheels are also large enough to provide 2 inches of clearance, allowing the robot to have extra maneuverability by climbing over small obstacles. Each shaft is connected to a shaft coupler and is driven by a motor with a built-in gearbox, with a maximum speed of 300 RPM. We also added in 2 small bushings to reduce the friction between the shaft and the wooden wall.

Our controls subsystem had to be changed due to the estimated insufficient performance of a near IR camera in dense smoke. Without the near IR camera we didn't have any devices with a high enough resolution to accurately do the 3D mapping as intended. This reduced the need for a complex computing solution on the robot, and changed the control requirements to only reading data from sensors and driving the motors. This reduced complexity allowed us to remove the single board computer, one of the more expensive parts of the budget, and replace it with a much more inexpensive microcontroller, the Lolin ESP8266. This microcontroller is equipped with a WiFi chip, allowing it to act as a access point for a local network. In addition, with various libraries available from the Arduino IDE, the microcontroller can server HTML data and host a WebSocket server. We then constructed a web application using HTML and Javascript that the controller could serve to each client connected on it's network. This web application establishes a connection to the WebSocket server running on the microcontroller allowing real-time asynchronous communication between the client and the robot. From the web application the client can view the output from the thermal and ultrasonic sensors in addition to sending commands for movement and other devices. These movement commands are captured by the Arduino code and send to a L298N motor controller. The motor controller is able to read in these signals and uses them to set the direction and speed of each motor. Additionally this motor controller acts as our power distribution board by converting the 12 volts in from the battery system to 5 volts, which is used to power motor controller and sensors. We chose to use a small sealed lead acid battery to power the robot due to it's high current capacity and regulated 12 volt output. To communicate the location of the pet to the fire-fighters we added a sounding device, in this case a loud car horn that can be triggered remotely through the web interface.

For the thermal protection we decided to use 1" thick cork as our main source of thermal protection. We decided on the cork because it had surprisingly good insulative properties and it was also relatively inexpensive and easy to work with. We also decided to add unfrozen ice packs in random places wherever we believe we need a little extra thermal protection, such as near the motors or electronics. We also decided for our shell to be made out of wood because for the temperatures were testing at wood is also a good insulator. After our oven experiments and solidworks thermal studies we discussed in the sections above, we determined that our thermal protection system was more than enough to keep our internal components in their operating temperature ranges.

With all the components described above, our total budget is about $191. This is significantly less than the provided budget of $250, and it mainly due to our thermal and control system being driven with mostly inexpensive components. A full bill of materials can be found in Appendix S.

Customer Needs Revisited

In Chapter 2, *Task Clarification*, we outlined what we believed to be the critical needs that a customer would want given the design guidelines that we were given. We characterized these needs into 4 distinct categories: vehicular capabilities, environmental protection, physical constraints, and user interface. As specified in the in the section *Customer Needs,* in Chapter 2, these different needs were then weighted one to five; from wishful thinking to non-negotiable.

In review, we met all of the needs that we determined to be non-negotiable, several moderately weighted needs, and some of the wishful needs. In some instances we far exceed the expectations that we had set for ourselves, and in others we determined, during the design process, that some of the ideas that we had been aspiring to implement were not as possible to attempt given other factors. The full list of the customer needs can be viewed in *Appendix A*.

When we established our list of the robot's capability needs we identified only one non-negotiable: the ability to identify a pet that was simulated by a heating pad. The final design of our robot is fully capable of accomplishing this task. Fitted with a thermal sensor, and an ultrasonic sensor the robot is able to identify the heating pad in a room full of objects. Several other notable needs that we listed were: the ability to detect large obstacles and navigate around them (3), detect small obstacles and traverse them (3), the ability to sense the temperature (1), and the presence of oxygen in the room (1). These are notable as during the design process it was these four other customer needs where, at some point, there was an attempt to integrate into the design.

For some of the needs listed above, we were able to add some functionality to accomplish some of the desired need. For instance, our robot is capable to detect large obstacles using the ultrasonic sensor, but it is unable navigate itself around them autonomously. However, during the development of the design, we decided that the ultrasonic sensor should be mounted higher on the robot in order to better sense large objects that might be standing higher off the floor, like a table. Thus, our robot does not have the ability to detect small objects as effectively. Due to the implementation of larger wheels and larger ground clearance, the robot can more easily traverse small obstacles, such as clothing.

The ability to sense the internal and external condition of the robot was never destined to be a high priority, it was strongly considered for implementation as it would be a simple addition to the robot and would not require significant design adjustments. The leading concept from our pugh chart was a robot that utilized both of these sensors. After the oven experiment, and observing the effectiveness of the thermal protection, the design it was determined that having a thermocouple within the robot would not be necessary. The addition of a thermocouple on the outside of the robot was also deemed to be not necessary. Similarly, during the design process the desire to implement an oxygen sensor slowly waned; its cost being too sizeable and its implementation being significantly more complex than anything else that was attempted on the robot. Given more time, since we are so under-budget, we would have liked to implement both of these sensors on the exterior of the robot. We felt that providing additional information beyond the oxygen and temperature data to first responders would be something worth exploring in future designs of the robot.

The environmental protection needs that established were: heat resistance, heat endurance, water and dust resistance, and shock resistance. Of the four customer needs, only heat resistance and endurance were considered to be non-negotiable; the latter two being weighed as threes.

When we created these needs we decided that having a robot that would be durable and deployable in many different environments would be important. We also thought that the robot should be able to survive accidental exposure to certain elements (i.e. water) or some sort of human error (i.e. being dropped). Since the guidelines of the project outlined that the robot needed to be able to function after being exposed to a temperature of 90°C, the robot needed to be not only resistant but durable when exposed to high temperatures. In our design we addressed this need with the implementation of cork lining as well as a thermal mass, in the form of water packs. As seen in the section *Thermal Experiment*, and the data that was collected from the experiment shown in Appendix P, the thermal protection system was more than capable of limiting the internal temperature of the robot below 40°C.

In order for the robot to be shock resistant we ensured that the sides of the robot would be securely fastened together using l-brackets with nuts and bolts, JB weld, and wood glue depending upon the location of the pieces; sometimes multiple of these were used in a single place (i.e. the walls of the robot). Unfortunately, we were not able to do a drop test, as by the time the robot was completed it was too close to the robot showcase to risk determining if the robot would be able to survive a four foot drop, which is the average height of a window. Looking at the design, we are concerned that the robot may experiences significant stresses where the caster mount meets the shell of the robot; we believe that if there were to be any part of the frame to experience a fracture it would be in this area.

As for water and dust resistance, it was initially intended that the robot would be able to survive being exposed to water, indirectly, sprayed into the building from a fire hose, and that it would be able to protect internal components from ash, and airborne debris. The final design does protect form some water and air debris, but exposure to any sizeable quantity would result in damage of the internal components, as it was too expensive to invest in a method to make the shell water-tight, particularly around the motors and around the roof. There are just too many cracks in the shell to resist a sizeable quantity of water. Internally, as discussed previously in the section *Final Design*, there is a secondary shell of cork which acts to insulate the components as well as protect from water and airborne debris. However, to make room for components like motors and sensors, there needed to be holes drilled into both the cork and the outer shell; this made it near impossible to make it effectively water resistant.

Most of the physical needs of the robot were given as criteria for the design: the size, and total price of all components used on the robot. We also designated an additional need, which was that the robot needed to be able to be easily carried and deployed and thus the weight needed to be low.

All of these needs had some sort of dependence upon each other, and during the design process we tried to minimize the size so that we could limit the amount of material we needed to purchase. Initially we had planned on using steel for the shell, which would be stronger and more resistance to heat, but the cost of building the robot out of metal was going to be significantly more expensive than using wood. Because of this we easily met all of the physical needs: noticeably undersized, a fraction of the proposed weight limit, and significantly under budget.

The user interface needs we broke into two subcategories: user interaction directly with the robot, and user interaction with the controller. The most significant needs: real-time transmission and remote control through walls were both met. By wirelessly connecting to the robot we are able to stream data from the robot the the user through the web app, and send instructions back to the robot in a different area. Fast deployment was also considered throughout the design process, and due to the robots small size we believe that we met this need.

As mentioned during the review of our environmental protection needs, shock resistance was considered during the design of the robot. Being able to deploy the robot through a window was a need that we initially considered but we were not able to follow through on. As we were never able to force testing on the robot we are unaware if the robot would survive the drop from a window. Given more time, we would like to have done tests to assess the durability of different parts under stress.

Chapter 5: Conclusion

We are confident in the robot that we have created; it will be able to meet complete the tasks that it had been created to do. The drivetrain will be able to allow the robot to quickly maneuver around small objects and debris on the floor. The design allows for two inches of ground clearance so both small common household objects, like books and clothing, and the fire debris can be easily driven over without causing the drive mechanism to stall or catch on the hazard.

An ultrasonic sensor provides enough information to the operator that they will be able to navigate around large obstacles that could impede the robots ability to find the objective. Our thermal sensor has also shown to be more than capable when determining the differences between a person and the background.

The synthesis of these sensors with the control system is the most critical system of the robot. Working concurrently they effectively relay information back to the operator, and allow him or her to make quick and responsive decisions. The user interface and controls are simple to use and does not require much operating time in order to learn the intricacies of the system, meaning that new operators can quickly be trained to drive the robot.

The robot is also very light, and relatively cheap. Its lack of weight means it can be carried without much issue, and allow for rapid deployment. It's relatively small price means that should it be damaged during a rescue attempt, a replacement robot can be purchased without great expense.

While the design is rugged and will be able to complete the challenge at hand, there are several improvements and small changes that could be made to the design to improve its effectiveness and address additional consumer needs before the robot would go into production. These changes include adjustments to materials, size, sensors, and programming.

Due to cost concerns we decided to construct the robot out of wood. Wood is a strong and durable material, but most importantly it is cheap compared to other structural materials, like steel. The wood that we used for the working model had a tendency to splinter and we were concerned that significant stress could cause it to easily fracture during operation. Therefore, if this project were to be continued into the future, we would quickly change from the wood to a metal.

The design would need to become more intricate as the sheet metal used for shell would need to be welded together to properly join the sides effectively. This would also help to make the outer shell more watertight than it is now. The welded frame would be much more resilient to stresses than the wood frame that is now in operation.

The shift of materials to a metal would increase the costs significantly. To minimize this it is possible to shrink the shell of the robot. The current design is currently larger than is needed, and we have discussed that we could decrease the outer dimensions of the robot without significantly affecting the functionality of the robot. The change in size would also help to increase the portability and ease of storage of the robot when it is being carried or when it is not in use.

As mentioned in the in the Chapter 4 section *Customer Needs Revisited*, in future iterations of the robot, we would like include additional sensors onto the robot. The added functionality of these sensor would prove to be invaluable when the robot is being used in a real world scenario. As mentioned the inclusion of a temperature, outside of the robot, and an oxygen sensor would provide important information about the environment within the area that the robot had been deployed. We would also have liked to include extra ultrasonic sensors on the sides of the robot so that the robot could get a better view of its surroundings.

With these extra sensors we would also like to improve the code which the robot is running. Given more time to complete this project, and before production, we would have liked to employ environmental mapping, so that the operator can map conditions within the building. The ultrasonic sensors would allow the robot to generate a three dimensional layout of the room, recording and remembering data already collected and relaying that information to the operator to be shared with first responders. Using the thermal camera and the thermocouple mounted on the shell of the robot, we would map temperatures throughout the room; comparing the thermal camera temperature to that found by the thermocouple. By designating high temperature areas, first responders can be aware of hazardous areas before entering the area.

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Appendix A:

Customer Needs List

- Environmental Protection:
  - Heat Resistance: Not flammable, capable of surviving heat spikes - 5
  - Heat Endurance: Capable of operating under 90°C conditions for 10 minutes - 5
  - Water and Dust Resistance: Ingress Protection Rating of 65 - 3
  - Shock Resistance: Survive drops from 4 feet and small debris impact - 3
- Physical Constraints:
  - Size: <40 cm Width, <40 cm Height, <60 cm Length - 5
  - Weight: <51 lbs - 2
  - Cost: <$250 - 5
- Capabilities:
  - Identify a pet simulated by a heating pad - 5
  - Detect large obstacles and navigate around them - 3
  - Detect small obstacles and traverse them - 3
  - Determine exact location within room (both robot and pet) - 2
  - Determine relative location with respect to objects in room (both robot and pet)- 2
  - Map the obstacles in the room - 1
  - Map the temperature in the room - 1
  - Sense the presence of oxygen in the room - 1
- User Interface:
  - Real-time transmission of data to operator - 4
  - Remote control through walls - 5
  - Water and drop resistant controller - 2
  - Can be operated with gloved hands - 1
  - Fast deployment - 3
  - Able to be deployed through a window - 2

Appendix B
House of Quality

			How													Now
			Maximum operating temp	Ingress protection rating	Impact Energy withstanded	Mass	Volume	Range of thermal imaging	Location resolution of sensors	Decibels of location alarm	Lumens of location alarm	Internal Temperature	Signal Strength	Duration @ high temp	Price	
		Direction of Improvement	↑	↑	↑	↓	↓	↑	↑	↑	↑	↓	↑	↑	↓	
		Units	°C	IP	J	lbs	cm^3	ΔC	cm	dB	Lm	°C	dBm	min	$	
5	What / Enviro Protection	Heat Resistance	■									■				
3	What / Enviro Protection	Water Resistance		■												
3	What / Enviro Protection	Shock Resistance			■											
4	What / Enviro Protection	Heat Endurance	■									■		■		
2	What / Physical Constraint	Weight				■	▒									
5	What / Physical Constraint	Volume					■									
5	What / Physical Constraint	Cost													■	
5	What / Capabilities	Pet Identification						■	■							
4	What / Capabilities	Obstacle Detection							■							
5	What / Capabilities	Localization							■							
2	What / User Inerface	Ease of Use														
5	What / User Inerface	Remote Transmission/Control							■				■			
2	What / User Inerface	Controller Durability		■												
5	What / Data Aquisition	Ease of Location								■	■					
4	What / Data Aquisition	Ability to stream outside fire										▒	■			
		MGTR robot	60	65		19	24,279									
		Recon Scout Throwbot				1.2	4,598								12,636	
		Thermal RGB Mapping for Firefighting		10		11		0.05								
		Thermite					6.6E+06									
		Door Ease Target Exiting Device								95				1,260		
		Target		IP65	270.5	51	96,000	60		100	60	80	-85	10	$250	

Appendix C
Requirements List

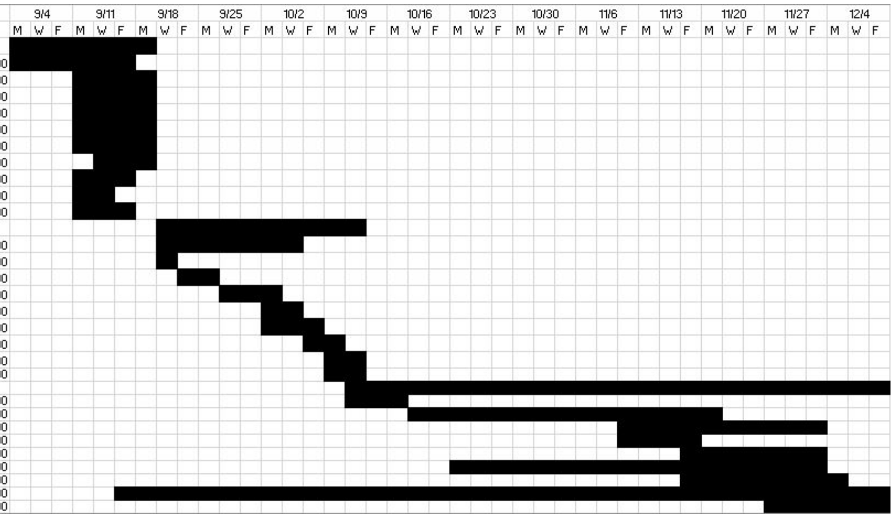
Date	Demand or Wish	Specification	Verification/Validation	Justification	Source
9/15	Demand	weighs ≤ 51 lbs	Maintain a list of the masses of all the material we are going to use on our robot	According to a thesis written by Piyush G. Chapla the maximum weight to ideally be handled should not be more than 51 lbs	(Chapla, 2004)
9/15	Demand	Internal temperature of the robot must be ≤ 80°C (i.e. the area of our robot holding the electronic components & battery)	Insert an internal thermal couple by sensitive components and perform a SolidWorks simulation to ensure design meets specification	Based solely off the specs for the raspberry pi and its temperature constraints. (Note: in the future may have to update if another component has a lower maximum operating temperature)	(Altera, 2017)
9/15	Demand	Cost ≤ $250	We will have to budget and make sure that we can afford all of the components we want on our robot	This is the value dictated in the assignment specifications	
9/15	Demand	Volume ≤0.096 m^3 (40Wx40Hx60L)	Ensuring our design meets these dimensions	These are the values dictated in the assignment specifications	
9/15	Demand	Ability to withstand 90°C for 10 min	Make sure we meet the thermal resistivity values and internal temperature values necessary to continue working after being exposed	This is the condition dictated in the assignment specifications	

			to oven.		
9/15	Wish	Ingress Protection Rating of IP 65	Spray prototype with 6.3 mm water jets and verify that no water enters the electronic housing	From Culver's interview, stated issue with several robotics is they can't be hosed off after a mission	(CSA, n.d.)
9/15	Demand	Thermal Imaging Range > 60 Celsius	Specification of the sensors in use	Temperature of a person or animal is around 37 degrees, and to be sensed in a 90 degree environment, the thermal imaging range must be > 60 degrees Celsius	(Web M.D., n.d.)
9/15	Wish	Resolution of thermal imaging < 7 Celsius	Specification of the sensors in use	Normal visualization tools for heat gradient have ~9 separate colors to signify values. To fully indicate the range specified above the resolution of each color would need to be less than 7 degrees	(Stempor, n.d.)
9/15	Wish	Decibels of location alarm > 100 dB	Measurement of decibels output by prototype from fixed distances and from behind objects	NFPA 72 recommends alarms to be 15 dB over ambient noise, and average firefighter equipment is around 85 dB	(Root, Schwennker, Autenrieth, Sandfort, Lipsey, & Brazile, 2013; NFPA, n.d.)
9/15	Wish	Lumens of location alarm > 60 lm	Specification of the sensors in use	From a forum posting from several fire fighters stating the flash-lights the use in smoke-filled environment, and comparing the average	(MonkeyBoab, n.d.)

				lumens rating of those flash-lights	
9/15	Demand	Signal Strength of Communication module > -85 dBm	Testing signal strength of hardware through various insulations and materials	Several industry tools define poor network quality as any signal strength below -85 dB	(O'Connor, 2013)
9/18	Wish	Withstand ≥ 270.5 J of energy when dropped	Run drop test Solidworks simulation of our design to make sure the impact energy is not exceeded	We calculated the minimum impact energy our robot can sustain by solving conservation of energy formulas using the max. weight of robot from the avg. height of windows.	(Inter-national Code Council, 2012)

Appendix D
Gantt Chart

	Assignee(s)	Start Date	Due Date	% Complete
Project Proposal		9/4	9/19	
Background Information		9/4	9/15	100
Materials	Isaac			100
Control Systems	Joseph			100
IR/Vision	Alex			100
Other/Similar Robots	Robert	9/11	9/18	100
Customer Needs		9/11	9/19	100
House of Quality	Alex	9/13	9/19	100
Requirements List	Isaac		9/19	100
Problem Statement	Isaac		9/19	100
Gantt Chart	Isaac	9/11	9/19	100
Project Design Review		9/20	10/12	
Develop Concepts		9/20	10/4	100
Create Functional Model		9/20	9/20	100
Address Critical Subproblems		9/22	9/25	100
Identify Additional Solutions		9/27	10/2	100
Create Morph Matrix		10/2	10/4	100
Generate Layouts		10/2	10/6	100
Screen Designs		10/6	10/9	100
Pugh Chart		10/9	10/11	100
Create Low Resolution Prototypes		10/9	10/12	100
Final Report		10/12	12/7	
Down-select from Leading Concepts		10/9	10/16	100
FMEA on Critical Subsytems		10/18	11/18	100
Conduct Experiments		11/10	12/1	100
Thermal experiments		11/10	11/17	100
Drivetrain experiments		11/17	12/1	100
Refine from FMEA and Experiments		10/23	12/1	100
Build and Assemble Final Prototype		11/17	12/4	100
Write Final Report		9/15	12/4	100
Prepare Final Presentation		11/27	12/4	100



Appendix E
Task List

Task	Responsibility
BACKGROUND RESEARCH	
Research Materials to use for construction of robot	Isaac
-Research materials with high thermal resistivity	Isaac
-Research Thermal Protection Systems	Isaac
Research Control Systems for robot	Joseph
-Compare microcontrollers	Joseph
Research IR/Vision sensors for robot	Alex
-Research pros and cons of IR and UV camera systems	Alex
Research Other/Similar robots	Robert
-Research firefighting robots	Robert
-Research reconnaissance robots	Robert
-Research general robots	Robert
Gather Customer Needs from Project Statement and Customer	Isaac, Joseph, Alex, Robert, Zeke
-Read Project Statement	Isaac, Joseph, Alex, Robert, Zeke
-Conduct interview with firefighter	Isaac, joseph, Alex, Robert, Zeke
Perform House of Quality analysis	Isaac, Joseph, Alex, Robert, Zeke
-Create engineering metrics for customer needs	Alex
-Create relationships between needs and metrics	Joseph
-Summarize HoQ analysis in Project Proposal Report	Alex
Write out Requirements List	Isaac, Joseph, Alex
-Provide justification/verification for requirements	Alex, Joseph
Write Problem Statement	Isaac
Create Gantt Chart	Isaac
-Create Task List	Isaac, Robert
PROJECT DESIGN	Isaac, Joseph, Alex, Robert, Zeke
Develop Concepts	Isaac, Joseph, Alex, Robert, Zeke
-Create Functional Model	Isaac, Joseph, Alex, Robert, Zeke
-Develope list of Subproblems	Isaac, Joseph, Alex, Robert, Zeke
-Address Critical Subproblems	Isaac, Joseph, Alex, Robert, Zeke
-Mindmapping	Isaac, Joseph, Alex, Robert, Zeke

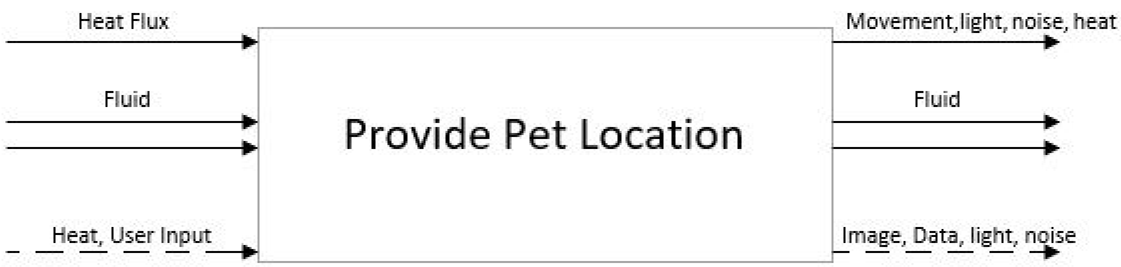
-6 - 3 - 5	Isaac, Joseph, Alex, Robert, Zeke, Brian
-TRIZ	Isaac, Joseph, Alex, Robert, Zeke
-Design by Analogy	Isaac, Joseph, Alex, Robert, Zeke
-Identify Additional Solutions	Joseph, Zeke
-Research Solutions to Subproblems	Joseph, Zeke
-Create Morph Matrix	Isaac, Joseph, Alex, Robert, Zeke
-Using Functional Decomposition, Identify Categories for Morph Matrix	Isaac, Joseph, Alex, Robert
-Use Categories to Populate Morph Matrix	Isaac, Joseph, Alex, Robert
-Mix-and-Match Solutions to Generate a Concept	Isaac, Joseph, Alex, Robert, Zeke
-Generate Layouts	Isaac, Joseph, Alex, Robert, Zeke
-Perform Another Round of Idea Generation	Isaac, Joseph, Alex, Robert, Zeke
-6 - 3 - 5	Isaac, Joseph, Alex, Robert, Zeke
-Create Layouts for Overall Vehicle System	Isaac, Joseph, Alex
Screen Designs	Isaac, Joseph, Alex, Robert, Zeke
-Create Pugh Chart	Isaac, Joseph
-Using Requirement List Create a Comprehensive Set of Criteria for Pugh Chart	Isaac, Joseph
-Back-of-the-Envelope Estimation	Alex, Robert
-Develop First Budget	Joseph, Robert
-Create 3 Concepts	Isaac, Joseph, Alex, Robert, Zeke
-Develop Concept 1	Isaac, Joseph, Alex, Robert, Zeke
-Develop Concept 2	Isaac, Joseph, Alex, Robert, Zeke
-Develop Concept 3	Isaac, Joseph, Alex, Robert, Zeke
Create Low Resolution Prototype of Solution 4	Zeke
-Create Concept 1	Isaac, Joseph, Alex, Robert, Zeke
-Create Concept 2	Isaac, Joseph, Alex, Robert, Zeke
-Create Concept 3	Isaac, Joseph, Alex, Robert, Zeke
-Get Feedback from Potential Users	Isaac, Joseph, Alex, Robert, Zeke
-Update Leading Concept	Isaac, Joseph, Alex, Robert, Zeke
Concept Analysis	Isaac, Joseph, Alex, Robert, Zeke
-Describe Additional Modeling	Isaac, Joseph, Alex, Robert, Zeke
-Describe Necessary Experimental Efforts	Isaac, Joseph, Alex, Robert, Zeke
-Validate Leading Design	Isaac, Joseph, Alex, Robert, Zeke

FINAL REPORT	Isaac, Joseph, Alex, Robert, Zeke
Concept Review	Isaac, Joseph, Alex, Robert, Zeke
-Describe Required Tasks for Development of a Prototype	Isaac, Joseph, Alex, Robert, Zeke
-Create Development Gantt Chart	Joseph, Alex
-Meet with TA about Plan	Isaac, Joseph, Alex, Robert, Zeke
FMEA	Robert
-Create FMEA for Leading Concept	Robert
-Highlight Areas that Need Further Experimentation	Robert
Conduct Experiments	Isaac, Joseph, Alex, Robert, Zeke
-Develop CAD for Thermal Protection System	Alex
-Acquire Materials for Construction of Prototype	Isaac, Joseph, Alex
-Build Functional Prototype of Thermal Protection System	Isaac, Alex
-Create Models	Alex, Robert
-Create Thermal Model	Alex
-Create Stresses Model	Alex
-Design Test for Thermal Protection System	Joseph, Alex
-Develop Experiment Procedure	Joseph
-Procure Materials and Equipment Needed for Experiment	Joseph
-Test Thermal Protection System	Isaac, Joseph, Alex, Robert, Zeke
-Create Prototype for Drive Train	Isaac, Joseph, Alex, Robert, Zeke
-Develop CAD Model for Drive Train	Isaac, Alex
-Acquire Materials for Construction	Isaac, Joseph, Alex
-Build Functional Prototype	Isaac, Joseph, Alex, Robert
-Test Drive Assembly	Isaac, Joseph, Alex, Robert, Zeke
-Address Problems and Redesign	Isaac, Joseph, Alex, Robert, Zeke
Robot Design Projections	Isaac, Joseph, Alex, Robert, Zeke
-Provide Preliminary Drawings for Complete Design	Isaac, Alex
-Finish CAD of Robot	Isaac, Alex
-Compile a Bill of Materials	Joseph, Robert
-Determine Project Budget	Joseph, Robert
Design and Manufacturing Analysis	Isaac
-Document Rules and Guidelines for the Manufacturing Process	Isaac, Joseph, Alex, Robert, Zeke
-Analyze and Document Assembly Process	Zeke

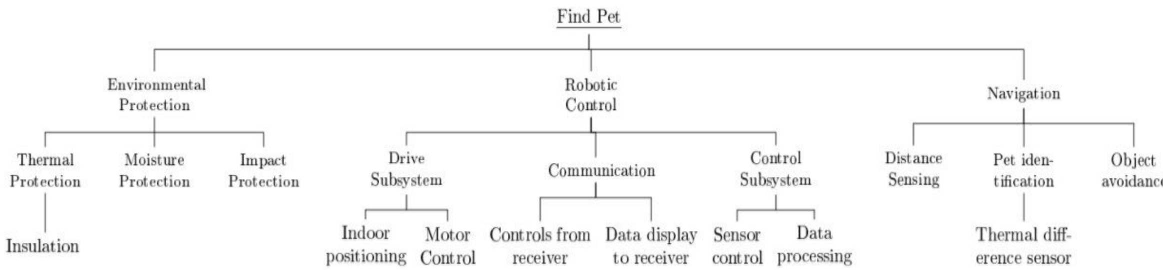
-Identify Means to Simplify Assembly Process	Alex
Perform FMEA on Final Design	Robert
-Document Remaining Opportunities for Lowering Risk of Failure	Robert
-Improve Final Design based upon Finding	Alex
Finalize Design	Isaac, Joseph, Alex, Robert, Zeke
-Finalize CAD of Robot	Alex
-Finalize Bill of Materials	Joseph
-Finalize Budget	Joseph
-Create Final Drawings of Robot	Alex
Build and Assemble Final Prototype	Isaac, Joseph, Alex, Robert, Zeke
-Procure Raw Materials and Non-Self-Manufactured Parts	Isaac, Joseph, Alex, Robert, Zeke
-Manufacture Parts	Isaac, Joseph, Alex, Robert, Zeke
-Assembly of Final Design	Isaac, Joseph, Alex, Robert, Zeke
Write Final Report	Isaac, Joseph, Alex, Robert, Zeke
Prepare Final Presentation	Isaac, Joseph, Alex, Robert, Zeke
-Create Powerpoint	Isaac, Joseph, Alex, Robert, Zeke

Appendix C

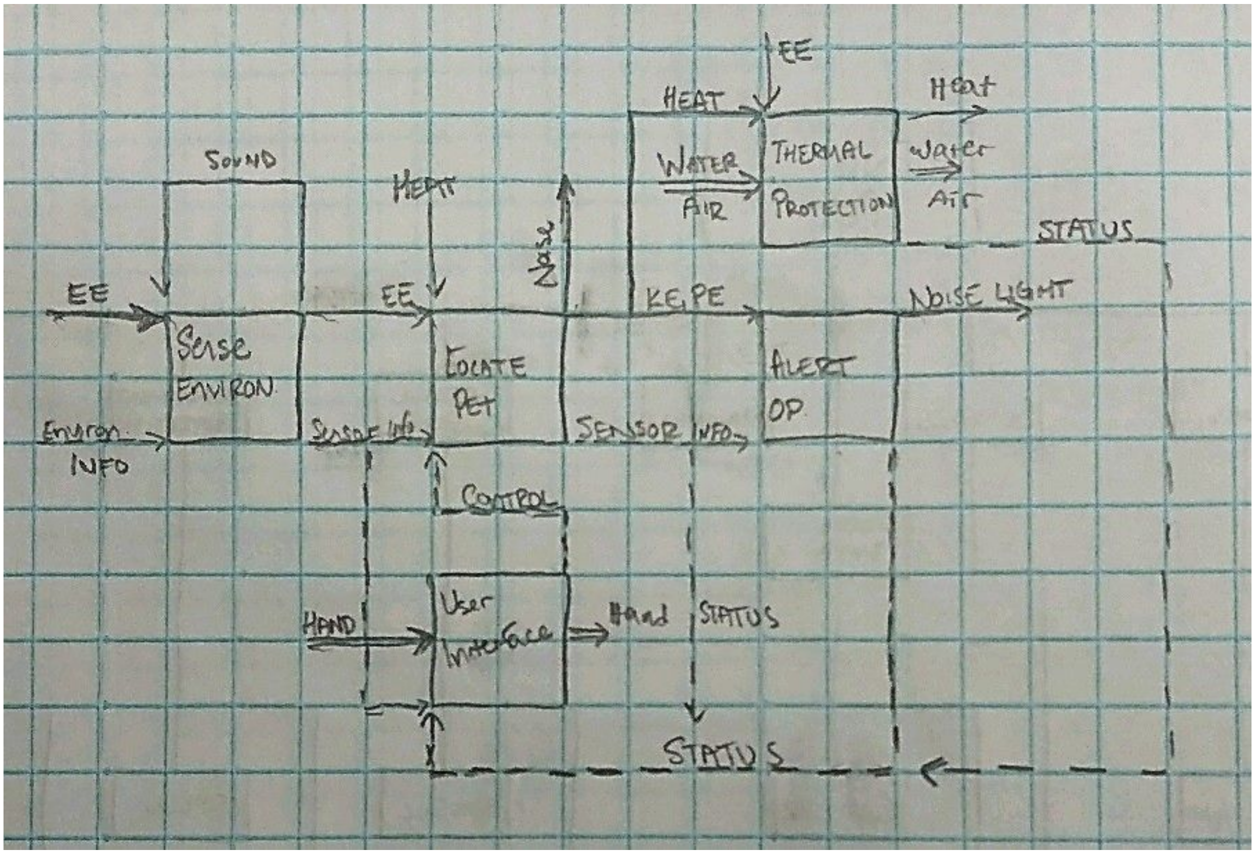
Black Box Diagram



Appendix D
Function Tree

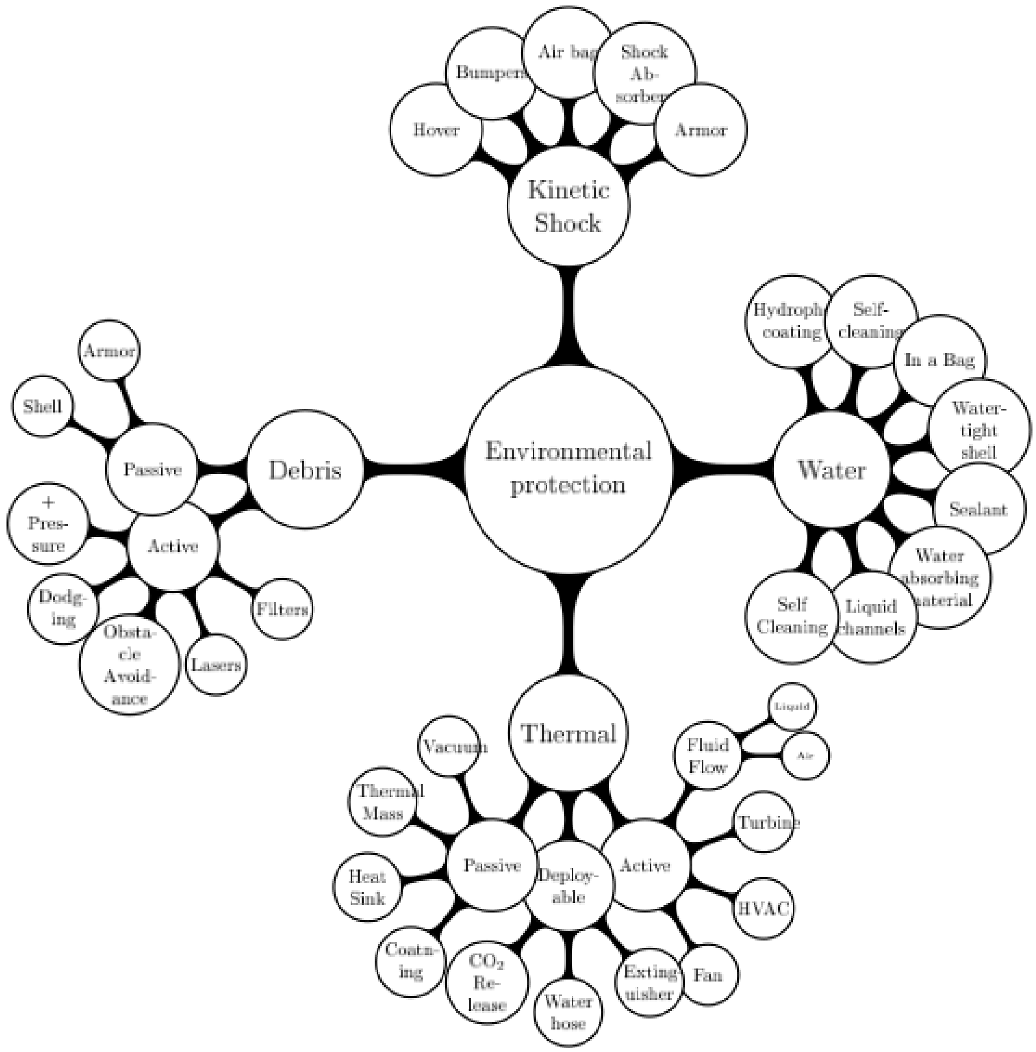


Appendix E
Function Diagram

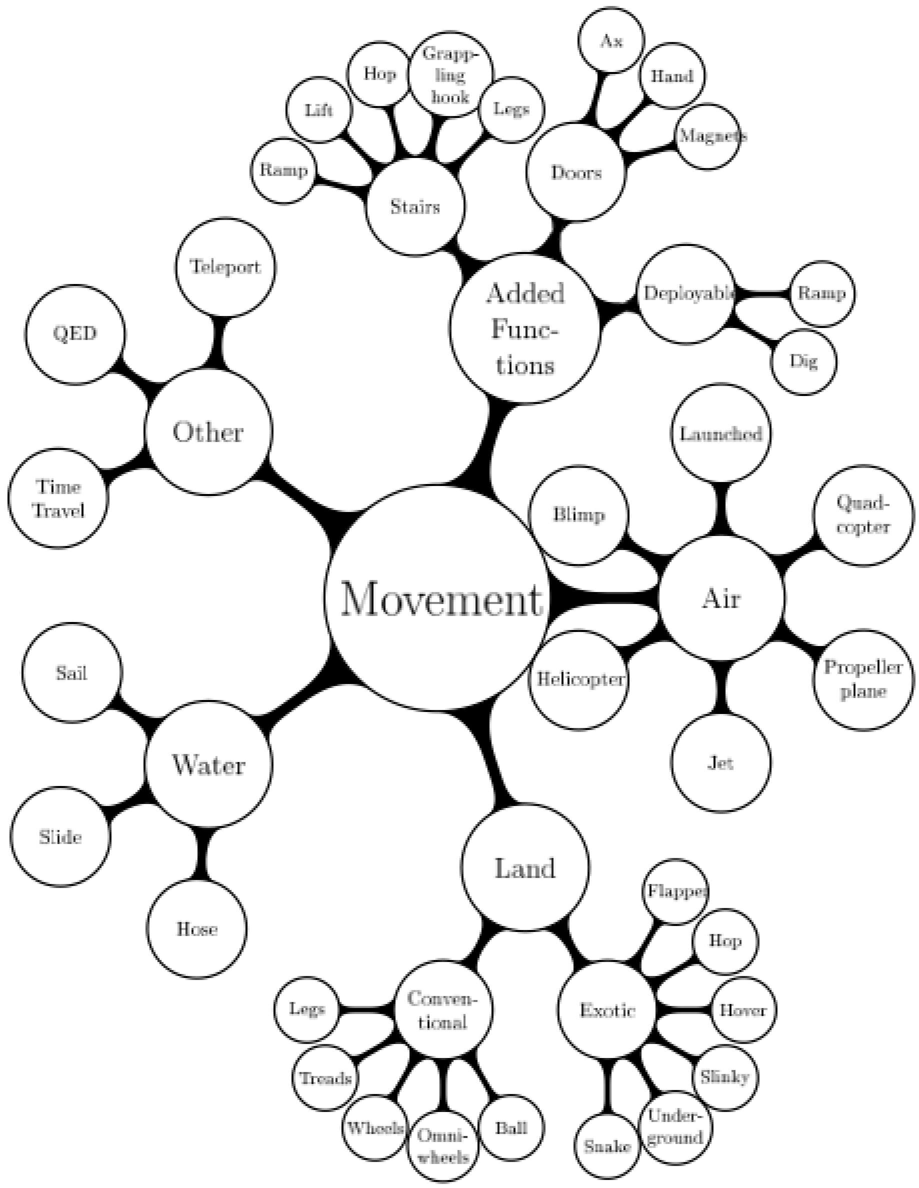


Appendix F
Mind Mapping

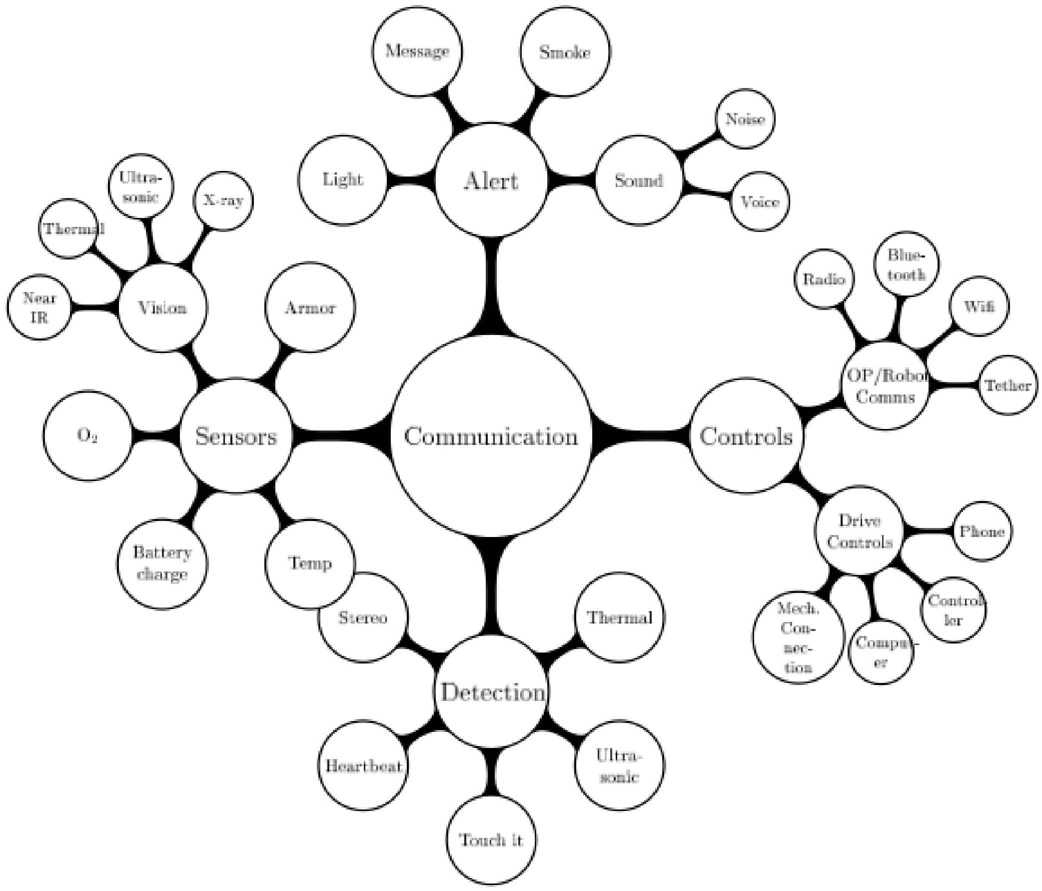
i) Environmental Protection



ii) Movement


Movement
Added Functions
Stairs
Ramp
Lift
Hop
Grappling hook
Legs
Doors
Ax
Hand
Magnets
Deployable
Ramp
Dig
Other
Teleport
QED
Time Travel
Air
Blimp
Launched
Quadcopter
Propeller plane
Jet
Helicopter
Water
Sail
Slide
Hose
Land
Conventional
Legs
Treads
Wheels
Omniwheels
Ball
Exotic
Flapper
Hop
Hover
Slinky
Underground
Snake

iii)Communication

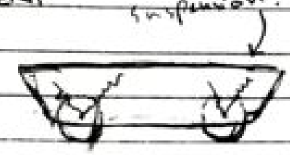


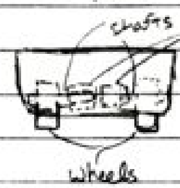
Appendix G
6-3-5
Probably just gonna attach actual copies too hard

MOVEMENT

do we need some sort of means to keep the wheels aligned with the motors if using axle suspension?

1.





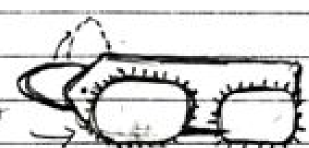
tires instead of suspension? (springs are a pain)

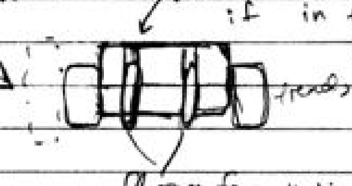
I like it. Very simple

Entire drive train/axel needs to be suspended,
Is lateral movement possible? I like [illegible] - rigid linear suspension

2.

probably best if outside body so 360° freedom - I agree
would 1 be enough if in the center? (but stable [illegible])

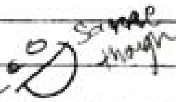




What are the flappers for?
flappers are for climbing over obstacles
But what do they do? Add extra friction maybe. Are they static or pliable?
I'm guessing they can pivot some and pull robot over obstacles

3.

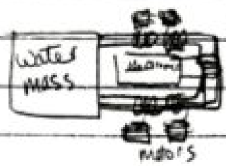
How does it move? ⇐ This



I like treads. ✓✓
If tread design, around wheels, slow, etc. Flap is real flaws!
If long & strong enough, could "flip" over stairs & obstacles
L tumbler

Thermal Protection

1.



- do we need that many motors?

Hmm?

or oil?

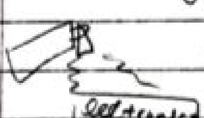
- simple and effective. I like it. Maybe ICE/WATER?
- How does water cool? Fixed cooling capacity
  - L leaks

2.

Maybe, what material? Looks like its used for explosives

- worth looking into a simulation to see if adequate
- Insulation is good, but material selection will make/break. Composite Sandwiching?
- have to make sure doesn't act like an oven if the components produce own heat plus some temp. rise from outside.

3. fire extinguisher   But what will turn on the extinguisher?



- motor for actuating extinguisher.
- might as well have a larger one for the fire too?
- Doesn't protect sensors or anything outside platform
- could have a pressurized pump that pushes the button to extinguish or some sort of computerized valve.

3

4

5

6

7

8

9

10

11

12

Appendix H
Prior Art

i)Patent US 7011171B1

US007011171B1

(12) **United States Patent**
Poulter

(10) **Patent No.: US 7,011,171 B1**
(45) **Date of Patent: Mar. 14, 2006**

(54) **RUGGED TERRAIN ROBOT**

(76) Inventor: **Andrew R. Poulter**, 7467 W. Nichols Pl., Littleton, CO (US) 80128

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 216 days.

(21) Appl. No.: **10/680,446**

(22) Filed: **Oct. 7, 2003**

Related U.S. Application Data

(60) Provisional application No. 60/416,973, filed on Oct. 8, 2002.

(51) **Int. Cl.**
B62D 51/00 (2006.01)

(52) **U.S. Cl.** **180/8.2**; 180/65.1; 280/5.32

(58) **Field of Classification Search** .... 180/8.1, 180/8.2, 8.3, 8.4, 8.5, 8.6, 65.1, 908; 280/5.2, 280/5.26, 5.32, DIG. 10, 763.1, 764.4; 901/1
See application file for complete search history.

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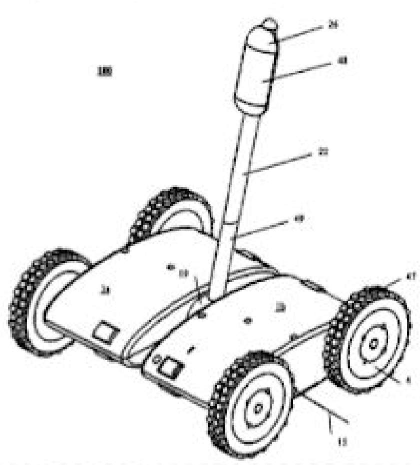
(Continued)

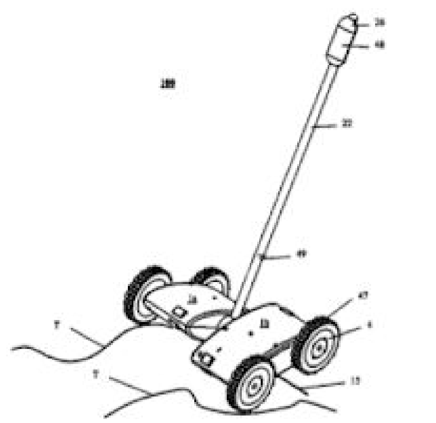
Primary Examiner—Christopher Ellis
Assistant Examiner—Brian Swenson
(74) *Attorney, Agent, or Firm*—Rick Martin; Patent Law Offices of Rick Martin, P.C.

(57) **ABSTRACT**

A rugged terrain robot (RTR) apparatus can function as a reconnaissance robot to optimize safety of search or rescue personnel. Remote control places the RTR in either a rolling mode or in a stair-climbing mode. Remote feedback is provided by an on-board RTR camera and microphone. The RTR consists of two clamshell sections and a tail boom section. The RTR uses polymorphic locomotion of the clamshells for efficient maneuverability in traversing rugged terrain when in a "rolling" mode and is switched remotely into a stair-climbing mode (or extreme terrain) using end-over-end clamshell motion with a tail boom assist to climb stairways. The RTR can carry various communication devices, sensors and payloads for use by police, firemen, soldiers, rescue or other applications to optimize safety when direct entry by a human may not desirable until an area is reconnoitered. The RTR is remote controllable and easily transported to a reconnaissance area.

29 Claims, 22 Drawing Sheets





ii) Patent US 8644991B2

US008644991B2

(12) **United States Patent**
Ohm et al.

(10) **Patent No.: US 8,644,991 B2**
(45) **Date of Patent: Feb. 4, 2014**

(54) **MANEUVERING ROBOTIC VEHICLES**

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(73) Assignee: **iRobot Corporation**, Bedford, MA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 1499 days.

(21) Appl. No.: **11/842,881**

(22) Filed: **Aug. 21, 2007**

(65) **Prior Publication Data**

US 2008/0183332 A1 Jul. 31, 2008

Related U.S. Application Data

(60) Provisional application No. 60/828,611, filed on Oct. 6, 2006.

(51) **Int. Cl.**
B62D 55/075 (2006.01)

(52) **U.S. Cl.**
USPC **700/250**; 700/245; 180/9.3; 180/9.32; 901/1; 901/48; 280/5.22

(58) **Field of Classification Search**
USPC 700/245, 250; 180/6.7, 8.1–10; 901/1, 901/2, 48; 280/5.2–5.3, 6.15; 318/568.12
See application file for complete search history.

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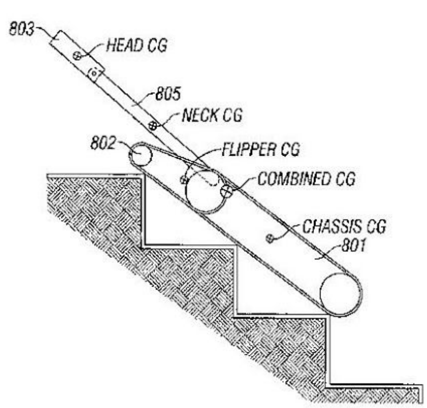
(57) **ABSTRACT**

Configurations are provided for vehicular robots or other vehicles to provide shifting of their centers of gravity for enhanced obstacle navigation. A robot chassis with pivotable driven flippers has a pivotable neck and sensor head mounted toward the front of the chassis. The neck is pivoted forward to shift the vehicle combined center of gravity (combined CG) forward for various climbing and navigation tasks. The flippers may also be selectively moved to reposition the center of gravity. Various weight distributions allow different CG shifting capabilities.

24 Claims, 13 Drawing Sheets



Appendix I
Morph Matrix

Solution 1: Subfunctions	Concepts					
	1	2	3	4	5	6
Thermal Protection	**Water Cooling**	Refridgerants	**Composite Materials**	**Compressed Air**	**Heat Sink**	Fans
Moisture Protection	**water tight shell**	Sealant	hydrophobic coating	all components in a dry bag	water channels	
Impact Protection/ enviornment interaction	shocks absorbers	bumpers	tires	no sharp corners	**Flippers arms**	**armature**
Movement	Linked Treads	Rubber Treads	4 wheels, 2 motors	2 wheels, 1 caster, 2 motors	**6 wheels, 2 motors**	6 wheels, 6 motors, rocker bogie
Data display to receiver*	cheap smartphone	Native app	Web display	**dedicated display**		
Sensor Mounting	Can rotate	**Positioned on armature**	Fixed			
Data processing*	Remote/Cloud	**On bot - x86 full processor**	Off bot	Local controller		
Environment Sensing	**Near IR Imaging**	Mid IR/Thermal Imaging	**O2 Sensor**	**Thermometer**	Pressure sensor	
Communications	Bluetooth	**wifi**	radio	tether		
Object avoidance	**Ultrasonic**	Tactile Bumpers	IR Distance sensing			
Control system	Microcontroller	Single board Computer	**Full-fledged processor**			

Solution 2: Subfunctions	Concepts					
	1	2	3	4	5	6
Thermal Protection	Water Cooling	**Refridgerants**	Composite Materials	Compressed Air	Heat Sink	Fans
Moisture Protection	water tight shell	Sealant	hydrophobic coating	**all components in a dry bag**	water channels	
Impact Protection/ enviornment interaction	shocks absorbers	bumpers	tires	no sharp corners	**Flippers arms**	armature
Movement	**Linked Treads**	Rubber Treads	4 wheels, 2 motors	2 wheels, 1 caster, 2 motors	6 wheels, 2 motors	6 wheels, 6 motors, rocker bogie
Data display to receiver*	cheap smartphone	**Native app**	Web display	dedicated display		
Sensor Mounting	**Can rotate**	Positioned on armature	Fixed			
Data processing*	Remote/Cloud	On bot - x86 full processor	Off bot	**Local controller**		
Environment Sensing	Near IR Imaging	**Mid IR/Thermal Imaging**	O2 Sensor	Thermometer	Pressure sensor	
Communications	**Bluetooth**	wifi	radio	tether		
Object avoidance	**Ultrasonic**	Tactile Bumpers	IR Distance sensing			
Control system	Microcontroller	**Single board Computer**	Full-fledged processor			

Solution 3: Subfunctions	Concepts					
	1	2	3	4	5	6
Thermal Protection	**Water Cooling**	Refridgerants	Composite Materials	Compressed Air	**Heat Sink**	**Fans**
Moisture Protection	**water tight shell**	Sealant	hydrophobic coating	all components in a dry bag	water channels	
Impact Protection/ enviornment interaction	shocks absorbers	bumpers	tires	**no sharp corners**	Flippers arms	**armature**
Movement	Linked Treads	Rubber Treads	4 wheels, 2 motors	**2 wheels, 1 caster, 2 motors**	6 wheels, 2 motors	6 wheels, 6 motors, rocker bogie
Data display to receiver*	cheap smartphone	Native app	Web display	**dedicated display**		
Sensor Mounting	Can rotate	**Positioned on armature**	Fixed			
Data processing*	Remote/Cloud	On bot	Off bot	**Local controller**		
Environment Sensing	Near IR Imaging	**Mid IR/Thermal Imaging**	O2 Sensor	**Thermometer**	Pressure sensor	
Communications	Bluetooth	wifi	radio	**tether**		
Object avoidance	Ultrasonic	**Tactile Bumpers**	IR Distance sensing			
Control system	**Microcontroller**	Single board Computer	Full-fledged processor			

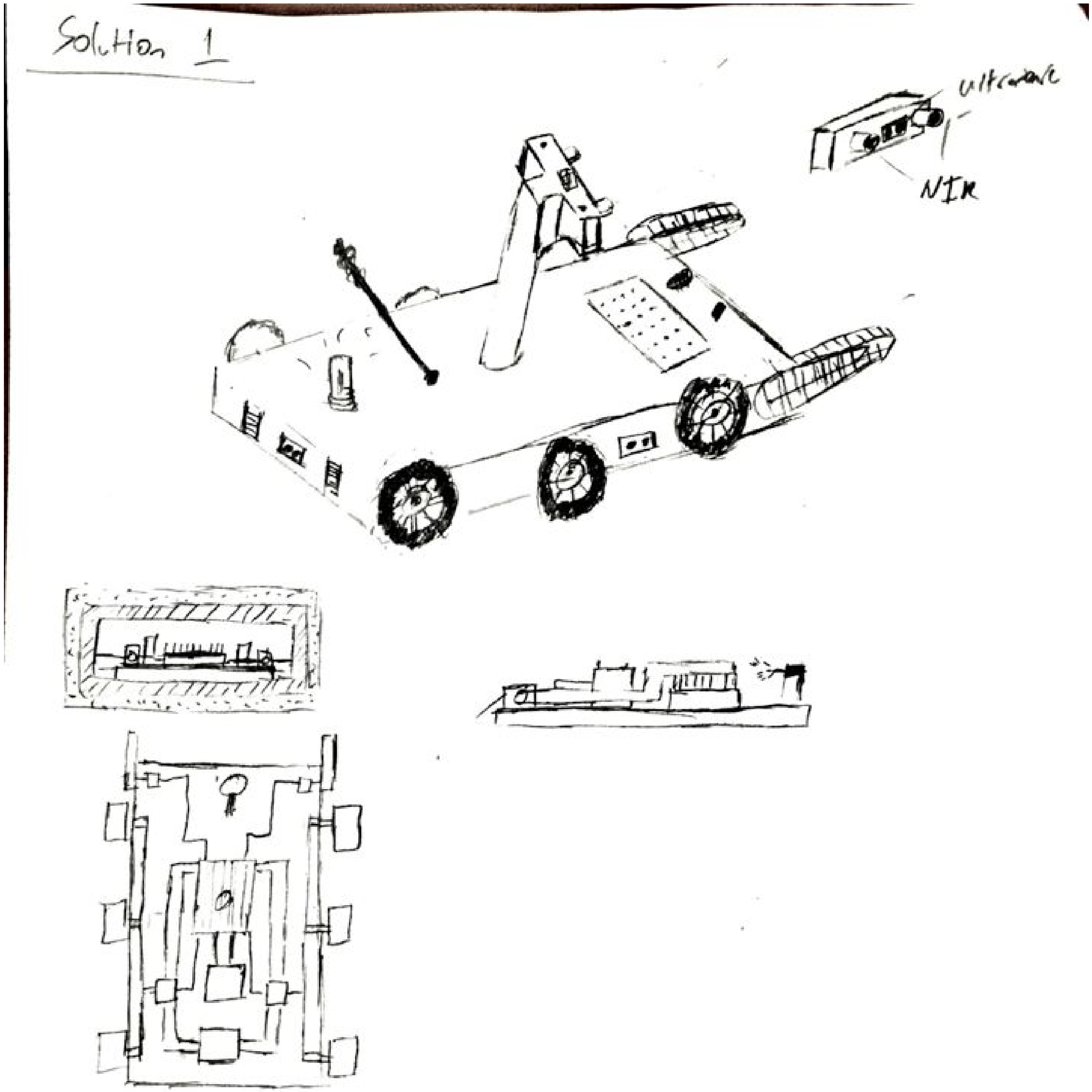
Solution 4: Subfunctions	Concepts					
		2	3	4	5	6
Thermal Protection	**Water Cooling**	Refridgerants	**Composite Materials**	Compressed Air	Heat Sink	Fans
Moisture Protection	water tight shell	**Sealant**	hydrophobic coating	all components in a dry bag	water channels	
Impact Protection/ enviornment interaction	shocks absorbers	bumpers	tires	**no sharp corners**	**Flippers arms**	armature
Movement	**Linked Treads**	Rubber Treads	4 wheels, 2 motors	2 wheels, 1 caster, 2 motors	6 wheels, 2 motors	6 wheels, 6 motors, rocker bogie
Data display to receiver*	cheap smartphone	Native app	**Web display**	dedicated display		
Sensor Mounting	Can rotate	Positioned on armature	**Fixed**			
Data processing*	**Remote/Cloud**	On bot	Off bot	Local controller		
Environment Sensing	**Near IR Imaging**	Mid IR/Thermal Imaging	**O2 Sensor**	**Thermometer**	Pressure sensor	
Communications	Bluetooth	**wifi**	radio	tether		
Object avoidance	**Ultrasonic**	Tactile Bumpers	IR Distance sensing			
Control system	Microcontroller	**Single board Computer**	Full-fledged processor			

Solution 5: Subfunctions	Concepts					
	1	2	3	4	5	6
Thermal Protection	Water Cooling	Refridgerants	**Composite Materials**	Compressed Air	**Heat Sink**	**Fans**
Moisture Protection	water tight shell	**Sealant**	hydrophobic coating	all components in a dry bag	water channels	
Impact Protection/ enviornment interaction	**shocks absorbers**	bumpers	tires	**no sharp corners**	Flippers arms	armature
Movement	Linked Treads	Rubber Treads	**4 wheels, 2 motors**	2 wheels, 1 caster, 2 motors	6 wheels, 2 motors	6 wheels, 6 motors, rocker bogie
Data display to receiver*	cheap smartphone	Native app	Web display	dedicated display		
Sensor Mounting	Can rotate	Positioned on armature	**Fixed**			
Data processing*	Remote/Cloud	**On bot**	Off bot	Local controller		
Environment Sensing	Near IR Imaging	**Mid IR/Thermal Imaging**	**O2 Sensor**	**Thermometer**	Pressure sensor	
Communications	Bluetooth	**wifi**	radio	tether		
Object avoidance	Ultrasonic	Tactile Bumpers	**IR Distance sensing**			
Control system	**Microcontroller**	Single board Computer	Full-fledged processor			

Solution 6: Subfunctions	Concepts					
	1	2	3	4	5	6
Thermal Protection	Water Cooling	Refridgerants	**Composite Materials**	**Compressed Air**	Heat Sink	**Fans**
Moisture Protection	water tight shell	**Sealant**	hydrophobic coating	all components in a dry bag	water channels	
Impact Protection/ enviornment interaction	shocks absorbers	bumpers	tires	**no sharp corners**	Flippers arms	**armature**
Movement	Linked Treads	Rubber Treads	4 wheels, 2 motors	2 wheels, 1 caster, 2 motors	**6 wheels, 2 motors**	6 wheels, 6 motors, rocker bogie
Data display to receiver*	cheap smartphone	Native app	Web display	**dedicated display**		
Sensor Mounting	Can rotate	**Positioned on armature**	**Fixed**			
Data processing*	Remote/Cloud	On bot	Off bot	**Local controller**		
Environment Sensing	Near IR Imaging	Mid IR/Thermal Imaging	**O2 Sensor**	**Thermometer**	Pressure sensor	
Communications	Bluetooth	wifi	**radio**	tether		
Object avoidance	Ultrasonic	**Tactile Bumpers**	**IR Distance sensing**			
Control system	**Microcontroller**	Single board Computer	Full-fledged processor			

Appendix J
6 Concept Sketches

i) Solution 1



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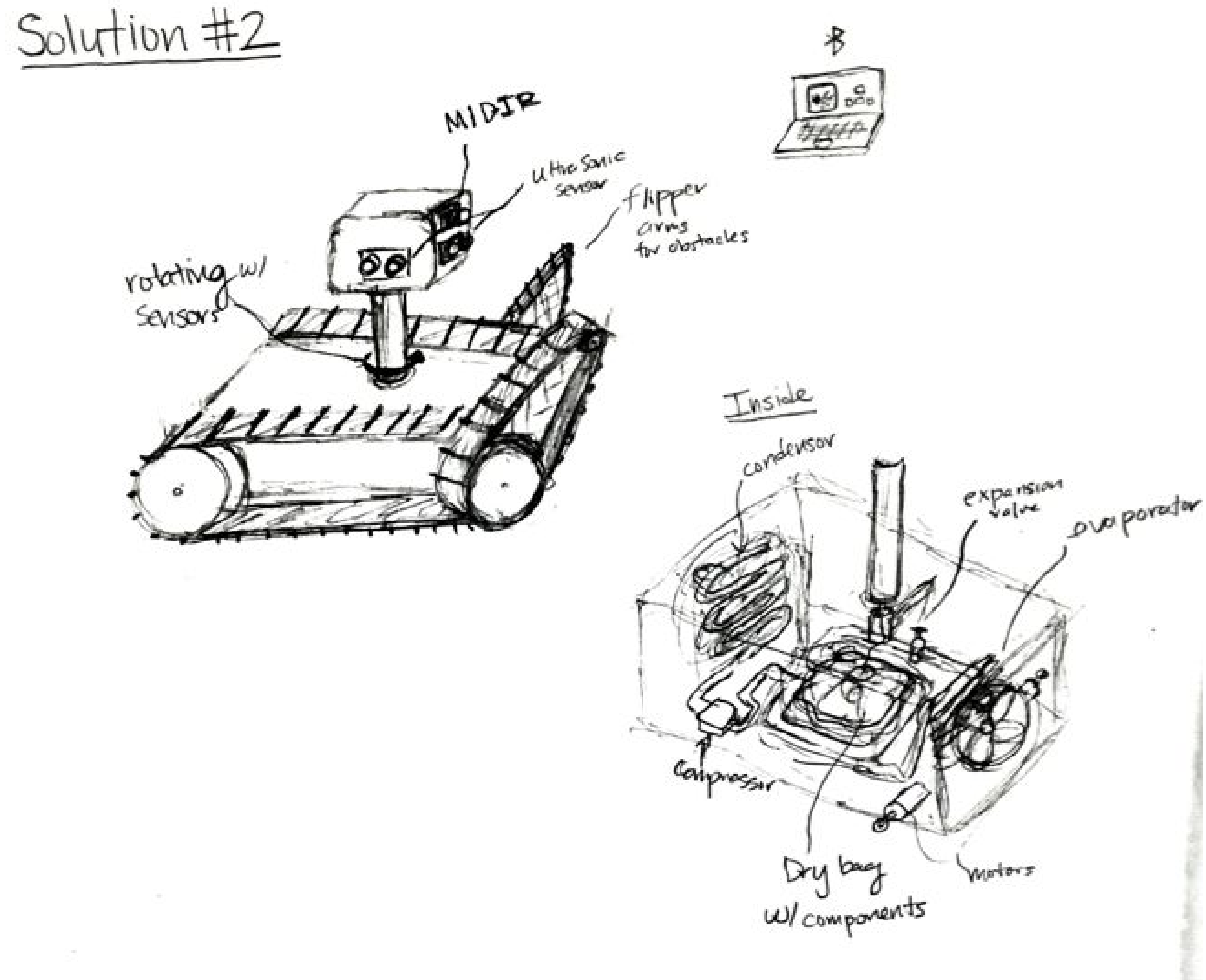
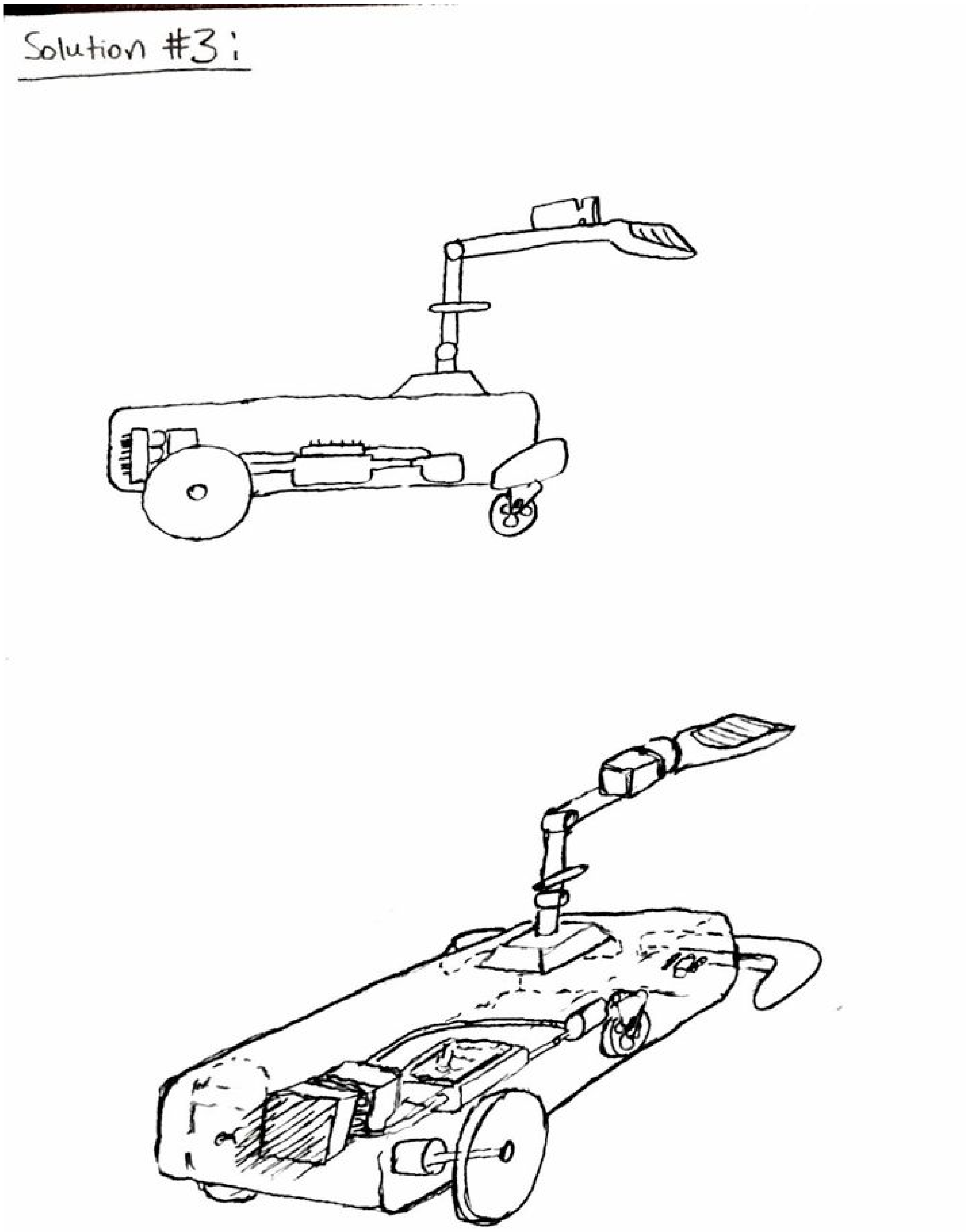


iii) Solution 3



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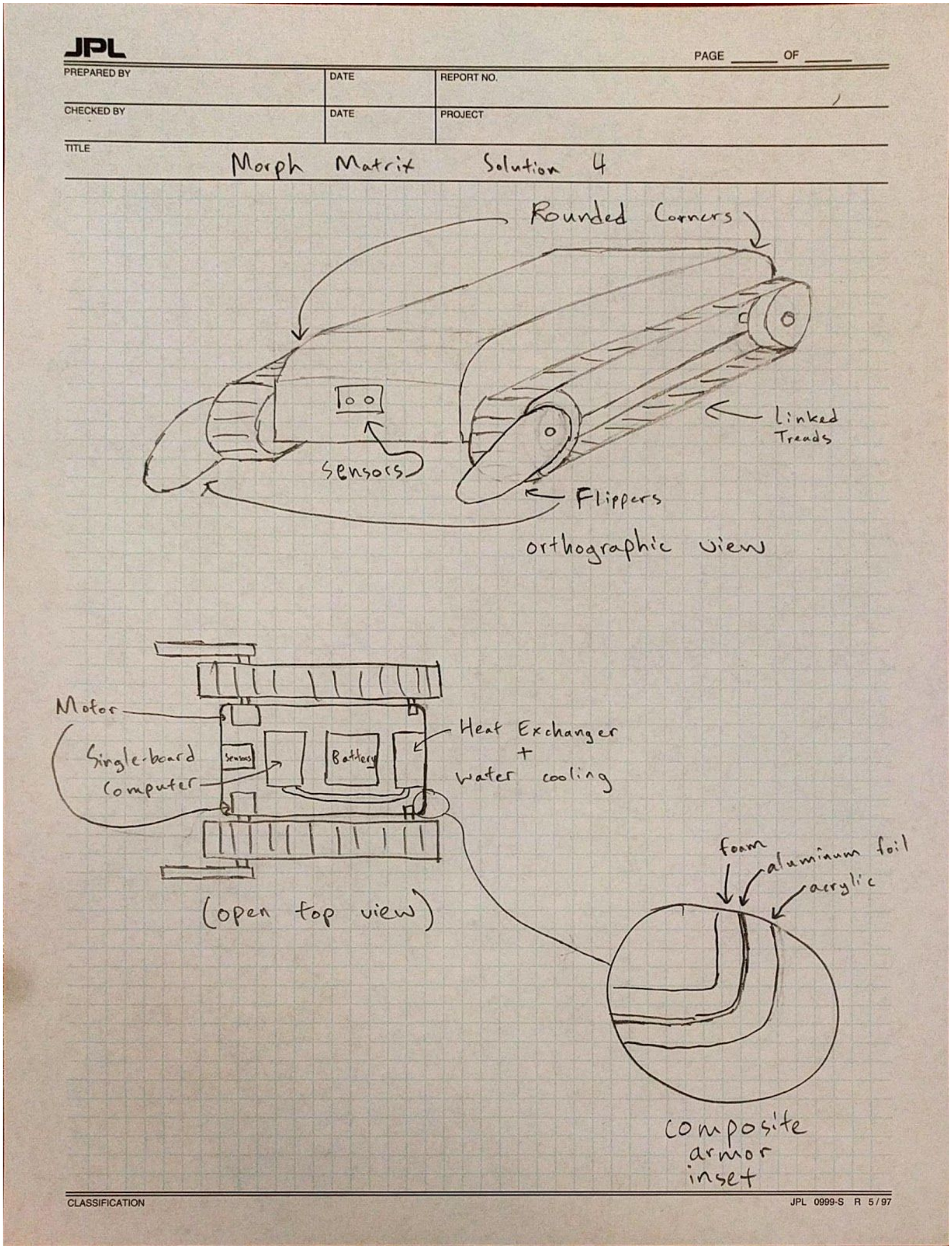
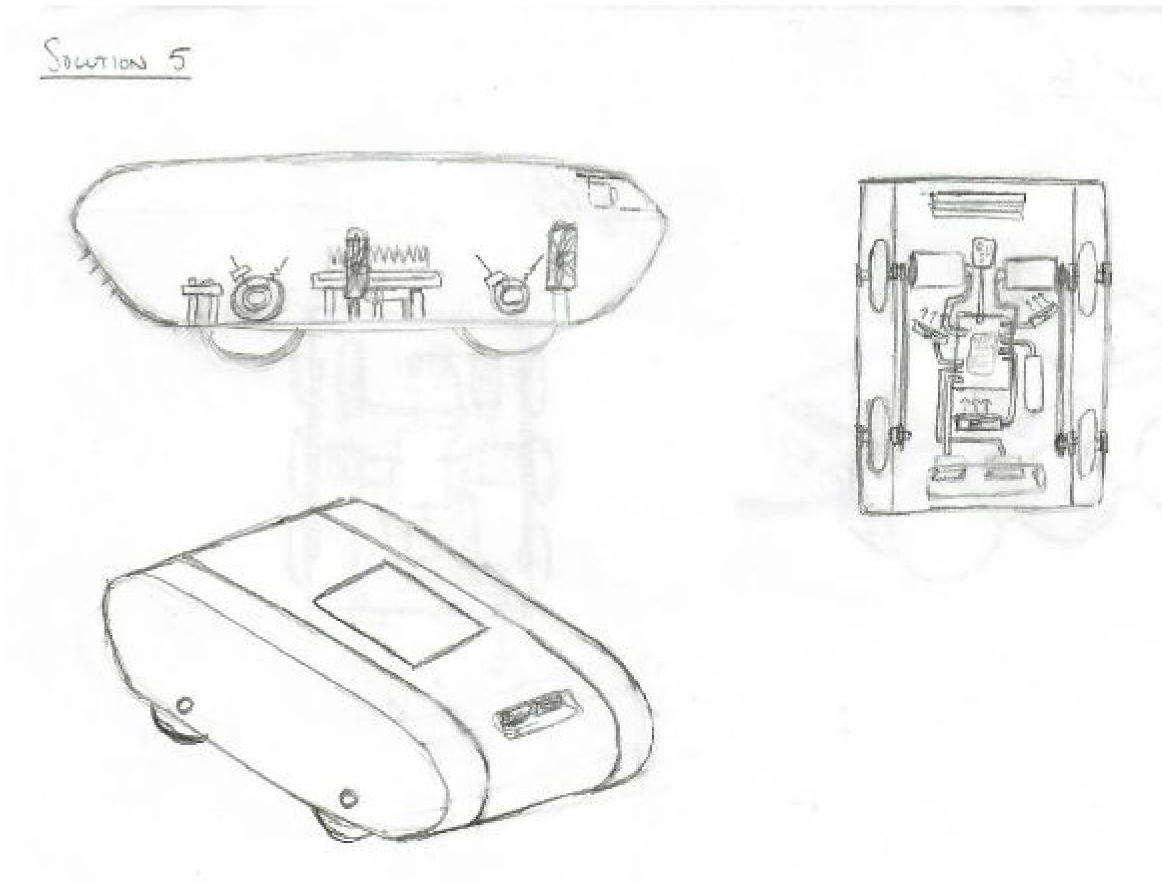


v) Solution 5



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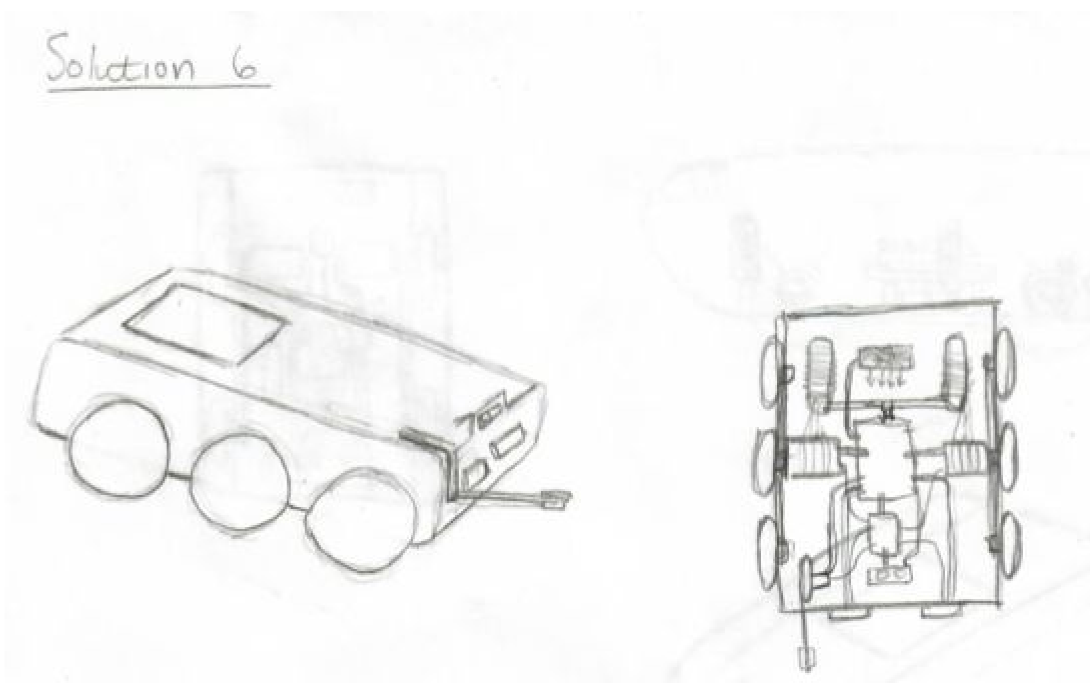


Appendix L
Back-of-the-Envelope Calculations

	Size	Cost (USD)	Power Consumption (W)	1			
				number	Item cost	Item Volume	Total Power
Wheels	28.27	4	0	6	24	169.62	0
Motors	25.49	20	162.24	2	40	50.98	324.48
Sprockets	1.327	8	0	2	16	2.654	0
Shaft	4.71238898	5.69	0	1	5.69	4.71238898	0
Ultrasonic	0.82382055	4	0.075	4	16	3.2952822	0.3
Near IR	20.27	6.5	2.5	2	13	40.54	5
Mid IR	0.2	22.16	0.015	0	0	0	0
Single Board Computer	1.775	9	1	0	0	0	0
Microcontroller	0.035	5	0.125	0	0	0	0
02 Sensor	0.2945243113	15	0.11	1	15	0.2945243113	0.11
Thermometer	0.0078125	3	0.0006875	1	3	0.0078125	0.0006875
Heat flux sensor	0.0012	1.75	0.0522	0	0	0	0
Batteries	5.36	40	0	1	40	5.36	0
Motor controller	0.635	2	0	1	2	0.635	0
x86 processor	4.47	140	7	1	140	4.47	7
PD board	0.32	5	0	1	5	0.32	0
Fans	0.976	12	2	0	0	0	0
pneumatic tanks	5.5	20	0	1	20	5.5	0
Coolant Pump	1.817	7	4.8	1	7	1.817	4.8
Dedicated controller	12	25	0.25	1	25	12	0.25
Radio Communication	0.223	2.19	0.04	0	0	0	0
Totals					371.69	302.206008	341.9406875

	2				3			
	number	Item cost	Item Volume	Total Power	number	Item cost	Item Volume	Total Power
Wheels	8	32	226.16	0	3	12	84.81	0
Motors	3	60	76.47	486.72	2	40	50.98	324.48
Sprockets	3	24	3.981	0	2	16	2.654	0
Shaft	1	5.69	4.71238898	0	1	5.69	4.71238898	0
Ultrasonic	4	16	3.2952822	0.3	0	0	0	0
Near IR	0	0	0	0	0	0	0	0
Mid IR	1	22.16	0.2	0.015	1	22.16	0.2	0.015
Single Board Computer	1	9	1.775	1	0	0	0	0
Microcontroller	0	0	0	0	1	5	0.035	0.125
02 Sensor	0	0	0	0	0	0	0	0
Thermometer	0	0	0	0	1	3	0.0078125	0.0006875
Heat flux sensor	0	0	0	0	0	0	0	0
Batteries	1	40	5.36	0	1	40	5.36	0
Motor controller	1	2	0.635	0	1	2	0.635	0
x86 processor	0	0	0	0	0	0	0	0
PD board	1	5	0.32	0	1	5	0.32	0
Fans	2	24	1.952	4	2	24	1.952	4
pneumatic tanks	0	0	0	0	0	0	0	0
Coolant Pump	2	14	3.634	9.6	1	7	1.817	4.8
Dedicated controller	0	0	0	0	1	25	12	0.25
Radio Communication	2	4.38	0.446	0.08	0	0	0	0
Totals		258.23	328.9406712	501.715		206.85	165.4832015	333.6706875

	4				5			
	number	Item cost	Item Volume	Total Power	number	Item cost	Item Volume	Total Power
Wheels	8	32	226.16	0	4	16	113.08	0
Motors	2	40	50.98	324.48	2	40	50.98	324.48
Sprockets	2	16	2.654	0	2	16	2.654	0
Shaft	1	5.69	4.71238898	0	1	5.69	4.71238898	0
Ultrasonic	4	16	3.2952822	0.3	0	0	0	0
Near IR	2	13	40.54	5	0	0	0	0
Mid IR	0	0	0	0	1	22.16	0.2	0.015
Single Board Computer	1	9	1.775	1	0	0	0	0
Microcontroller	0	0	0	0	1	5	0.035	0.125
02 Sensor	1	15	0.2945243113	0.11	1	15	0.2945243113	0.11
Thermometer	1	3	0.0078125	0.0006875	1	3	0.0078125	0.0006875
Heat flux sensor	0	0	0	0	0	0	0	0
Batteries	1	40	5.36	0	1	40	5.36	0
Motor controller	1	2	0.635	0	1	2	0.635	0
x86 processor	0	0	0	0	0	0	0	0
PD board	1	5	0.32	0	1	5	0.32	0
Fans	0	0	0	0	3	36	2.928	6
pneumatic tanks	0	0	0	0	0	0	0	0
Coolant Pump	1	7	1.817	4.8	0	0	0	0
Dedicated controller	0	0	0	0	0	0	0	0
Radio Communication	0	0	0	0	0	0	0	0
Totals		203.69	338.551008	335.6906875		205.85	181.2067258	330.7306875

	6			
	number	Item cost	Item Volume	Total Power
Wheels	6	24	169.62	0
Motors	2	40	50.98	324.48
Sprockets	2	16	2.654	0
Shaft	1	5.69	4.71238898	0
Ultrasonic	0	0	0	0
Near IR	0	0	0	0
Mid IR	0	0	0	0
Single Board Computer	0	0	0	0
Microcontroller	1	5	0.035	0.125
02 Sensor	1	15	0.2945243113	0.11
Thermometer	1	3	0.0078125	0.0006875
Heat flux sensor	0	0	0	0
Batteries	0	0	0	0
Motor controller	1	2	0.635	0
x86 processor	0	0	0	0
PD board	1	5	0.32	0
Fans	1	12	0.976	2
pneumatic tanks	1	20	5.5	0
Coolant Pump	0	0	0	0
Dedicated controller	1	25	12	0.25
Radio Communication	1	2.19	0.223	0.04
Totals		174.88	247.9577258	327.0056875

Appendix M
Pugh Charts

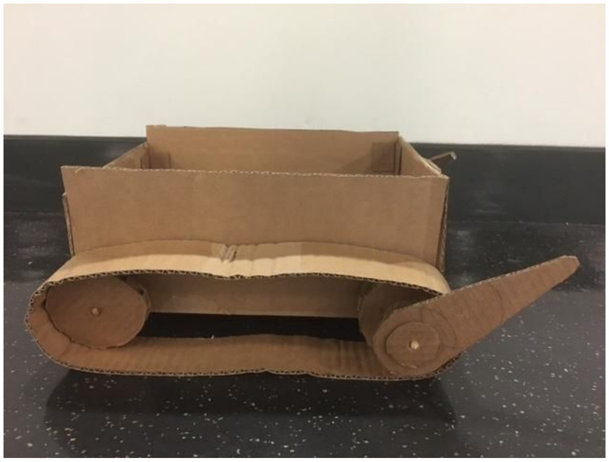
Pugh Chart #1							
Criteria	Def (if needed?)	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5	Solution 6
Modes of Heat Transfer	inference	1	1	-1	0	-1	-1
Water Resistance	research/calc	1	1	1	0	0	0
Shock Resistance	inference	-1	-1	0	0	1	0
Volume	calc	1	1	1	0	1	1
Cost	calc	-1	1	-1	0	-1	1
Environmental sensing		0	-1	-1	0	1	-1
Obstacle Detection/avoidance		0	0	-1	0	-1	1
Environmental Interaction		1	0	0	0	-1	0
Battery lifetime	calc	-1	-1	1	0	1	1
	Total	1	1	-1	0	0	2

Pugh Chart #2							
Criteria	Def (if needed?)	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5	Solution 6
Modes of Heat Transfer	inference	0	1	-1	-1	-1	-1
Water Resistance	research/calc	0	0	0	-1	-1	-1
Shock Resistance	inference	0	0	1	1	1	1
Volume	calc	0	-1	1	-1	1	1
Cost	calc	0	1	1	1	1	1
Environmental sensing		0	-1	-1	0	1	-1
Obstacle Detection/avoidance		0	0	-1	0	-1	-1
Environmental Interaction		0	-1	-1	-1	-1	-1
Battery lifetime	calc	0	-1	1	1	1	1
	Total	0	-2	0	-1	2	-1

Pugh Chart #3							
Criteria	Def (if needed?)	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5	Solution 6
Modes of Heat Transfer	inference	1	1	1	1	0	1
Water Resistance	research/calc	1	1	1	0	0	0
Shock Resistance	inference	-1	-1	-1	-1	0	-1
Volume	calc	-1	-1	1	-1	0	-1
Cost	calc	-1	-1	-1	1	0	1
Environmental sensing		-1	-1	-1	-1	0	-1
Obstacle Detection/avoidance		1	1	-1	1	0	1
Environmental Interaction		1	1	1	1	0	1
Battery lifetime	calc	-1	-1	-1	-1	0	1
	Total	-1	-1	-1	0	0	2

Appendix N
Low Resolution Prototype

Side View



Top View

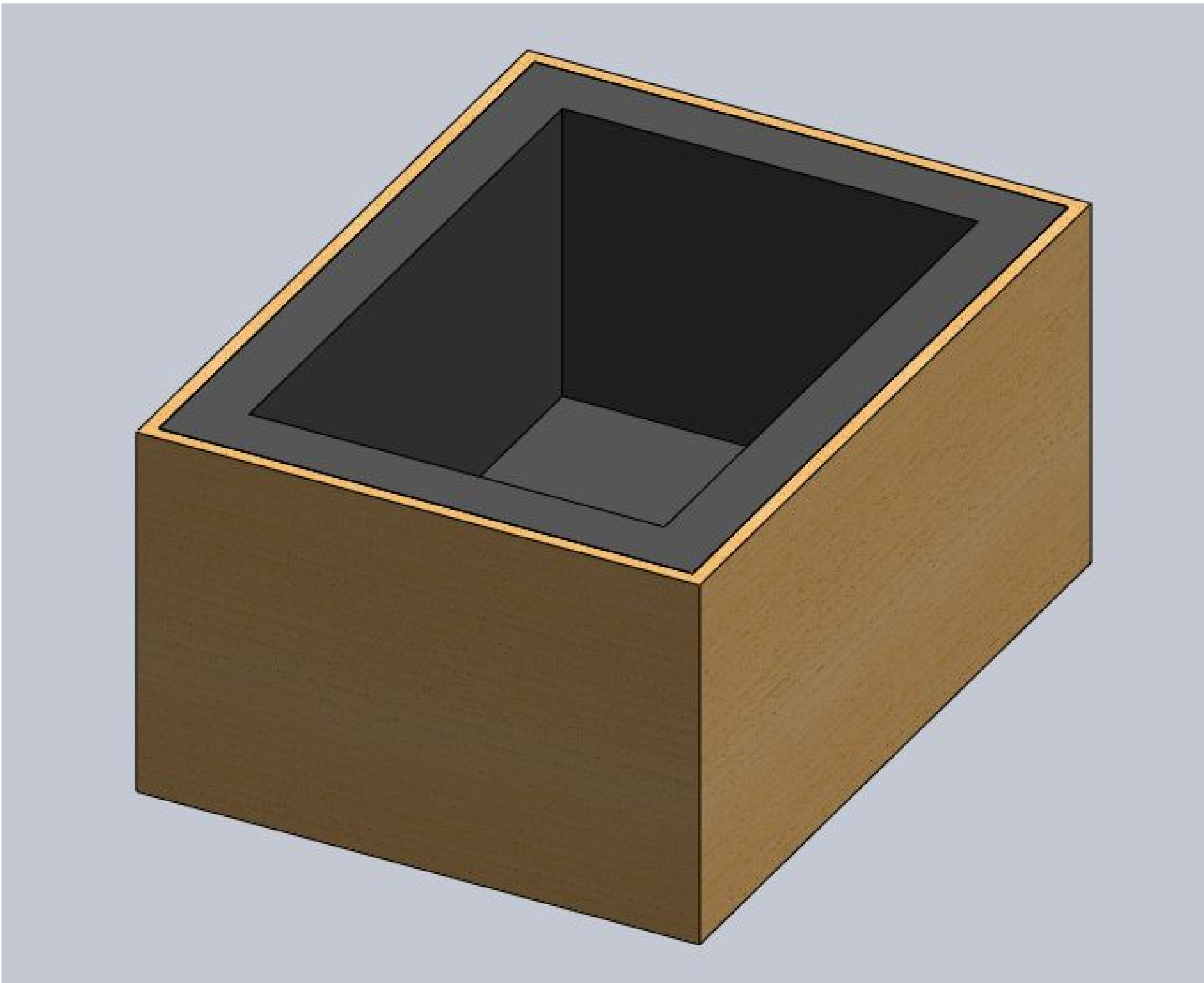
Front View

Back View

Appendix O

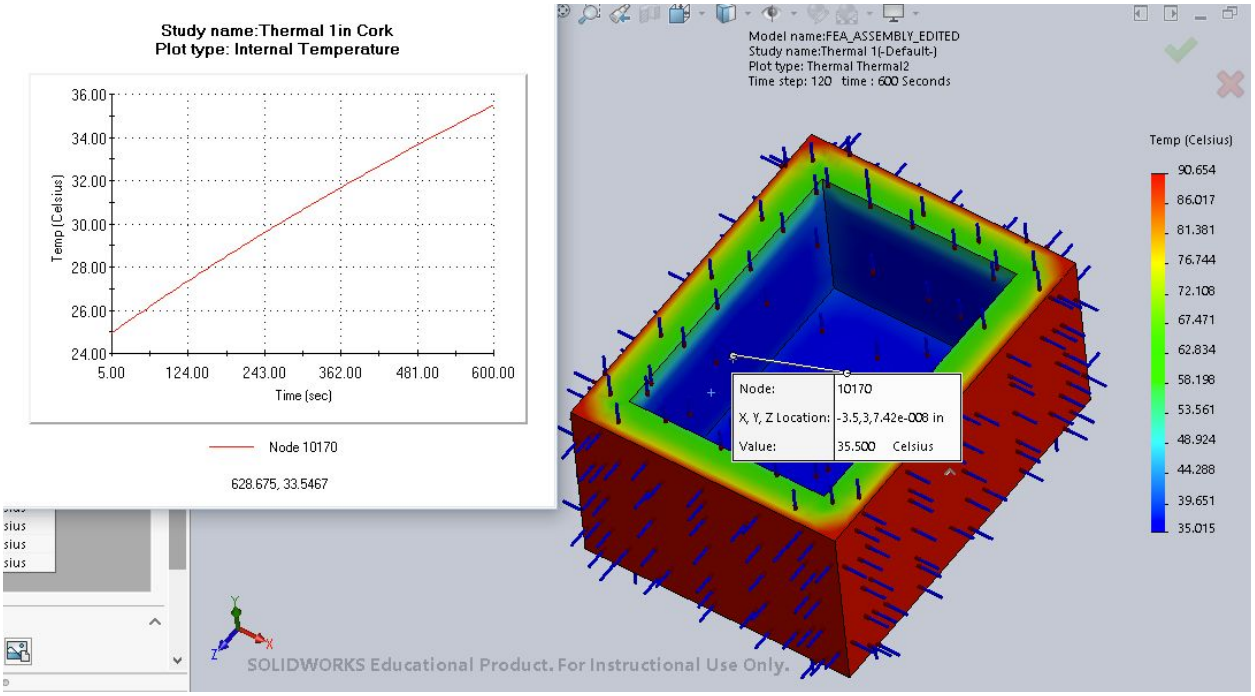
Solidworks Thermal Simulation

i) Simplified Solidworks model

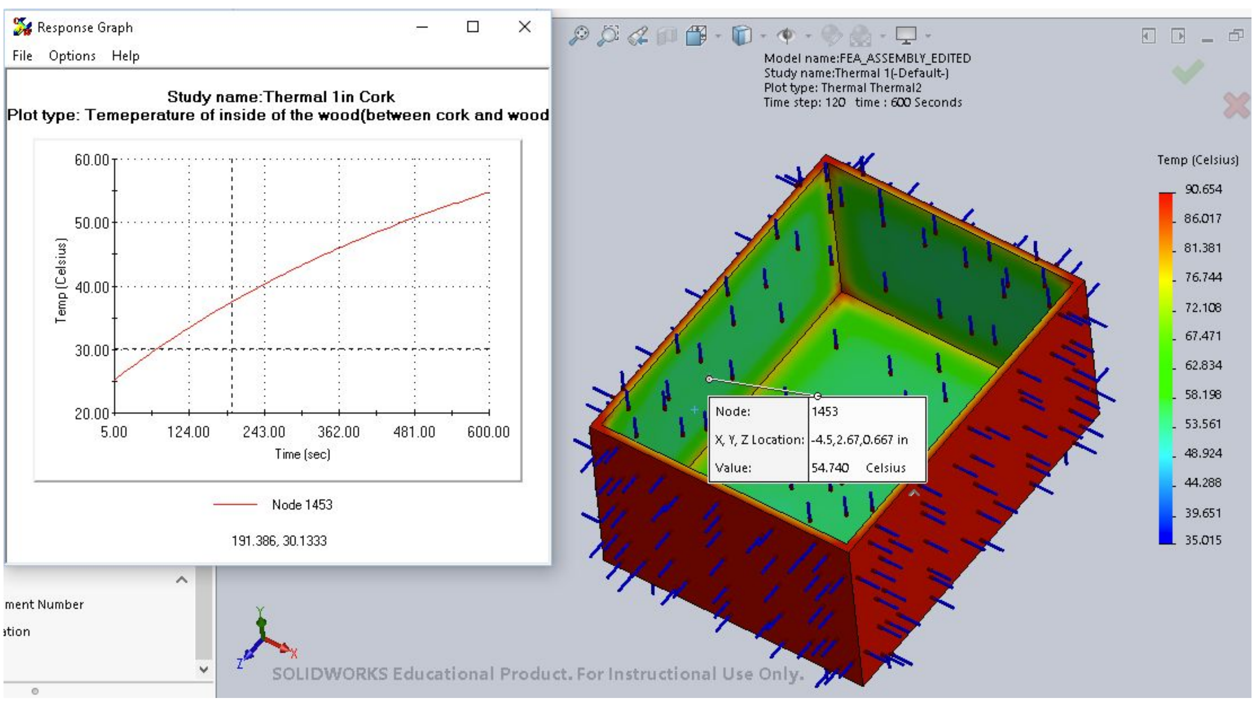


ii) 1” Cork Solidworks Thermal Study

a)Internal Temperature (1”)

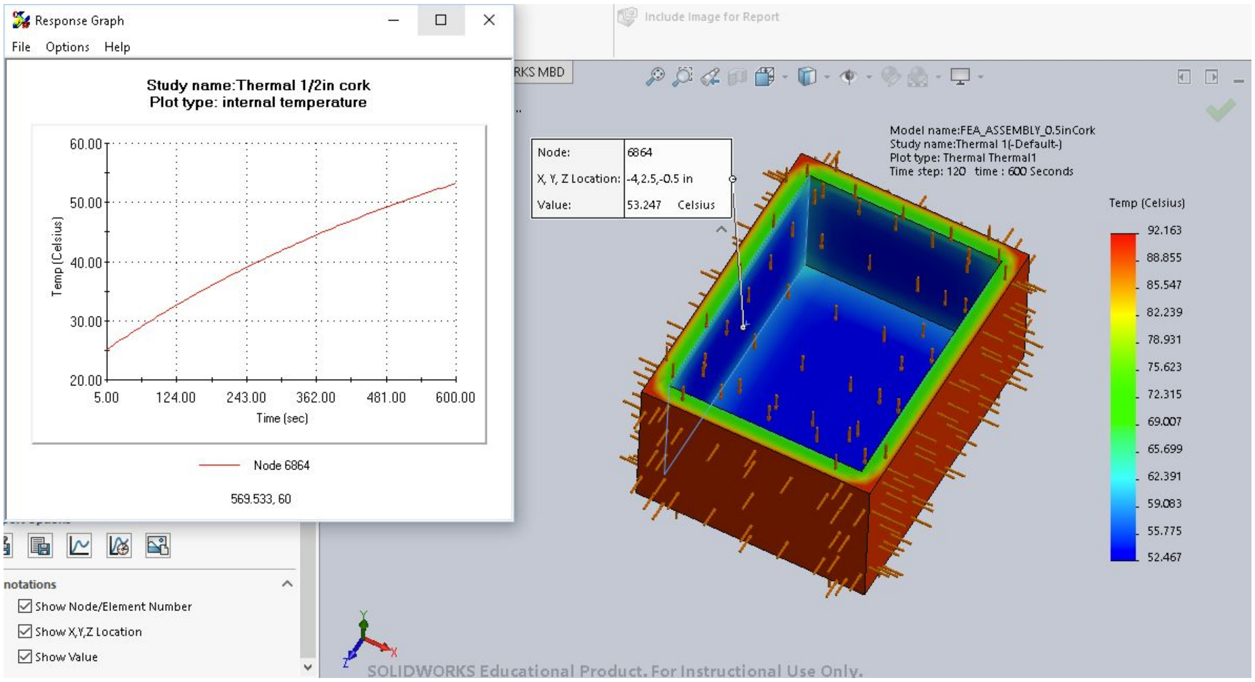


b) Temperature between Wood and Cork (1”)

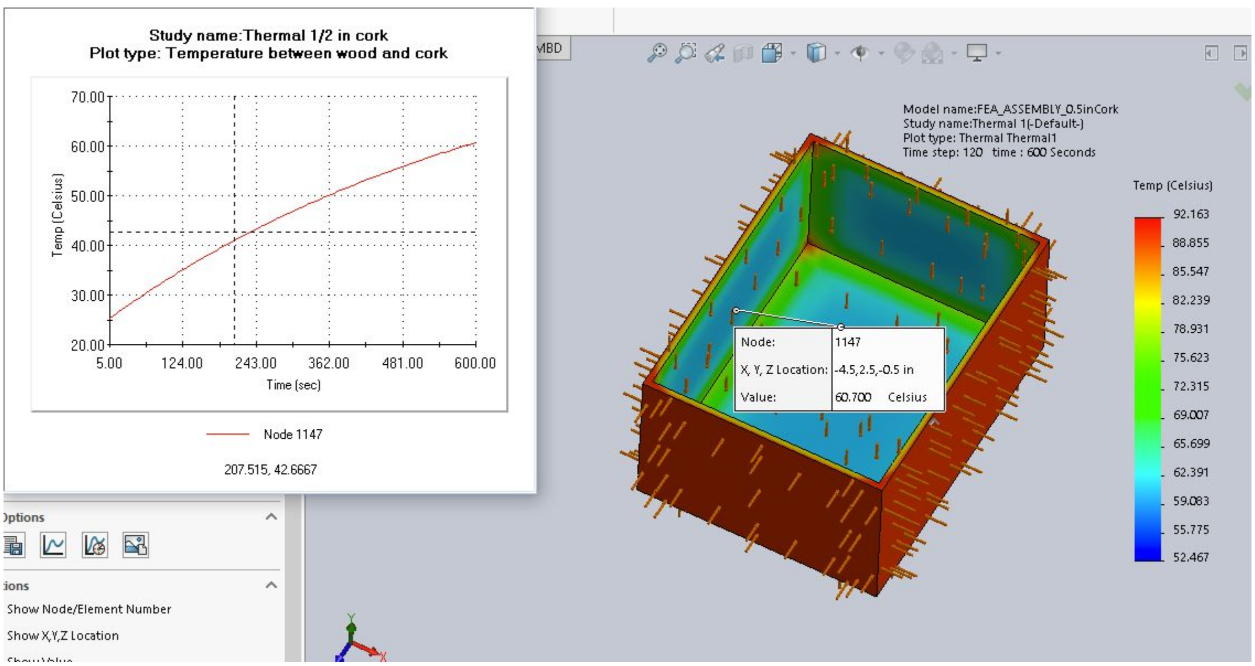


iii) ½" Cork Solidworks Thermal Study

a) Internal Temperature (½')



b) Temperature between Wood and Cork (½")

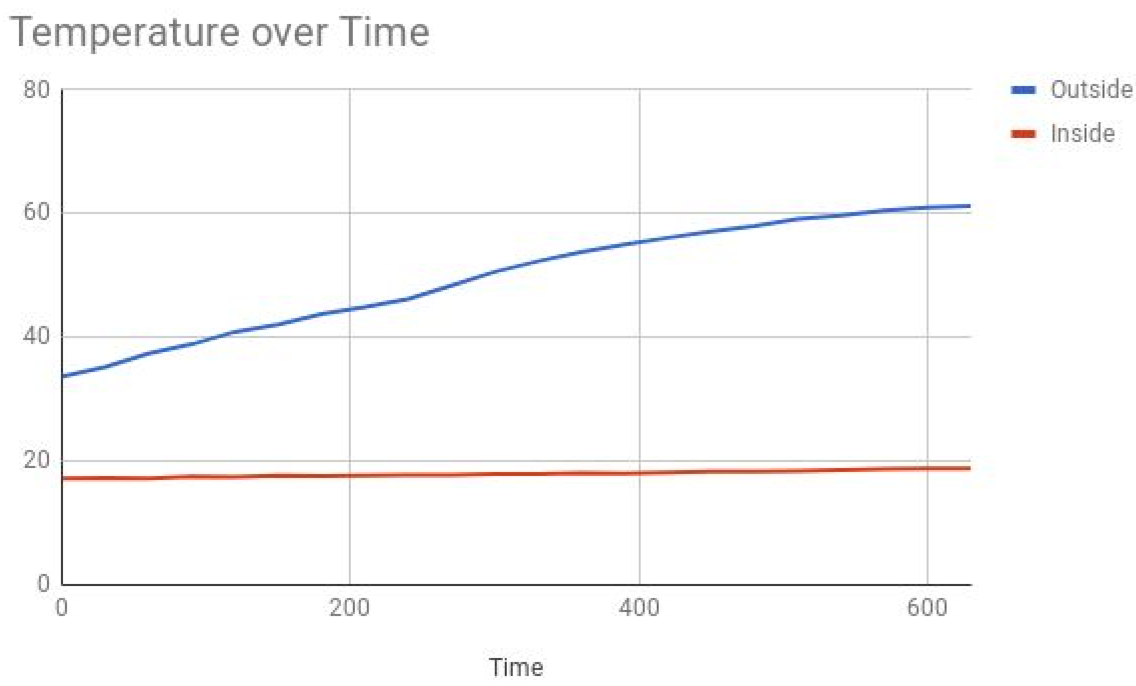


Appendix P

Experimental Results

1 inch cork and ice packs

Time	Outside	Inside
0	33.7	17.2
30	35.2	17.3
60	37.4	17.2
90	38.9	17.5
120	40.9	17.4
150	42.1	17.7
180	43.8	17.6
210	44.9	17.7
240	46.2	17.8
270	48.4	17.8
300	50.6	17.9
330	52.3	17.9
360	53.8	18.1
390	55	18
420	56.1	18.2
450	57.1	18.3
480	58	18.3
510	59.1	18.4
540	59.7	18.6
570	60.5	18.7
600	61	18.8
630	61.2	18.8



1 inch cork no ice 1packs

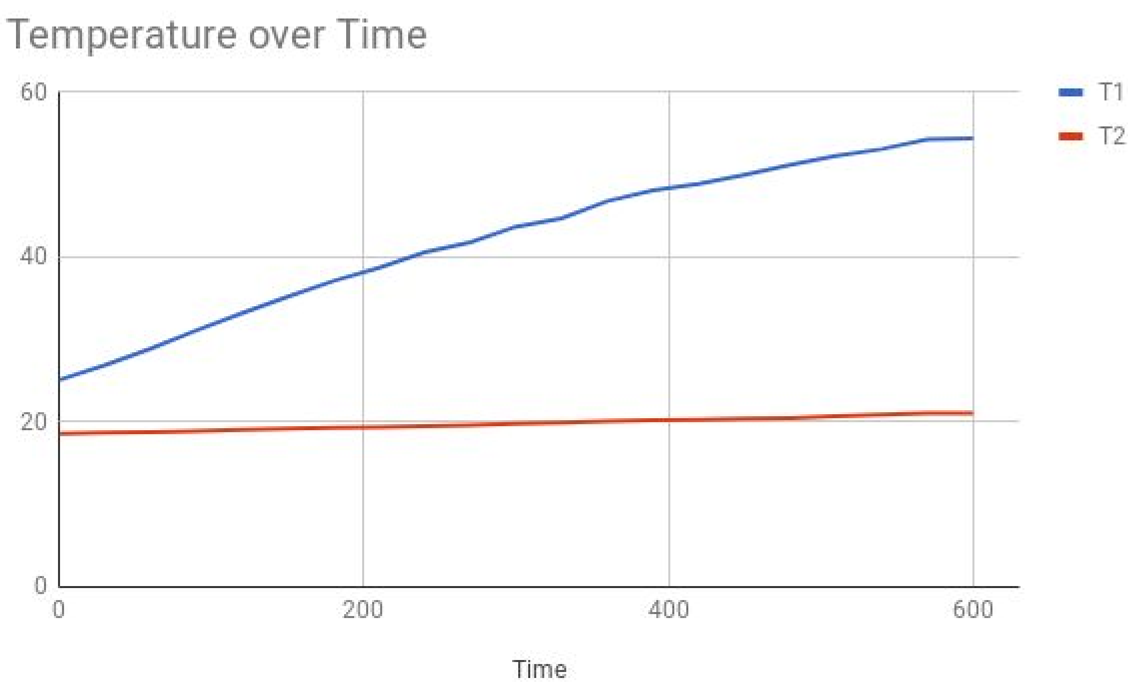
Time	Outside	Inside
0	29.1	32.6
30	33.8	29.5
60	34.9	29.7
90	36.6	30.2
120	38.2	30.2
150	40.1	30.7
180	41.8	30.9
210	45.1	31.2
240	46.7	31.6
270	48.1	32.5
300	49.1	32.9
330	50.5	33.4
360	52	33.9
390	53	34.2
420	54	34.7
450	55.1	35.3

480	56.1	35.7
510	57	36.3
540	57.7	36.9
570	58.6	37.4
600	59.2	37.8

½ inch cork with ice packs

Time	T1	T2
0	25.1	18.6
30	26.9	18.7
60	28.9	18.8
90	31.1	18.9
120	33.2	19.1
150	35.2	19.2
180	37.1	19.3
210	38.7	19.4
240	40.6	19.5
270	41.8	19.6
300	43.7	19.8

330	44.7	19.9
360	46.8	20.1
390	48.1	20.2
420	48.9	20.3
450	50	20.4
480	51.2	20.5
510	52.3	20.7
540	53.1	20.9
570	54.3	21.1
600	54.4	21.1



½ inch cork without ice packs

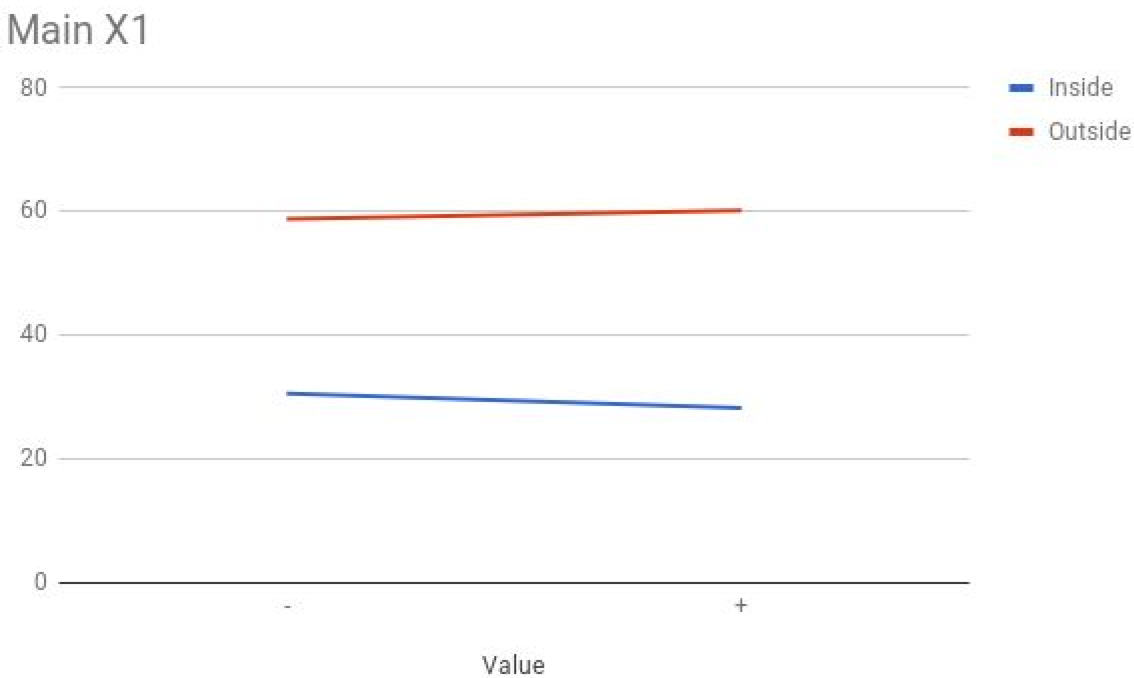
Time	Outside	Inside
0	29.1	21.1
30	31.2	23.2
60	35.7	23.7
90	38.3	24.1

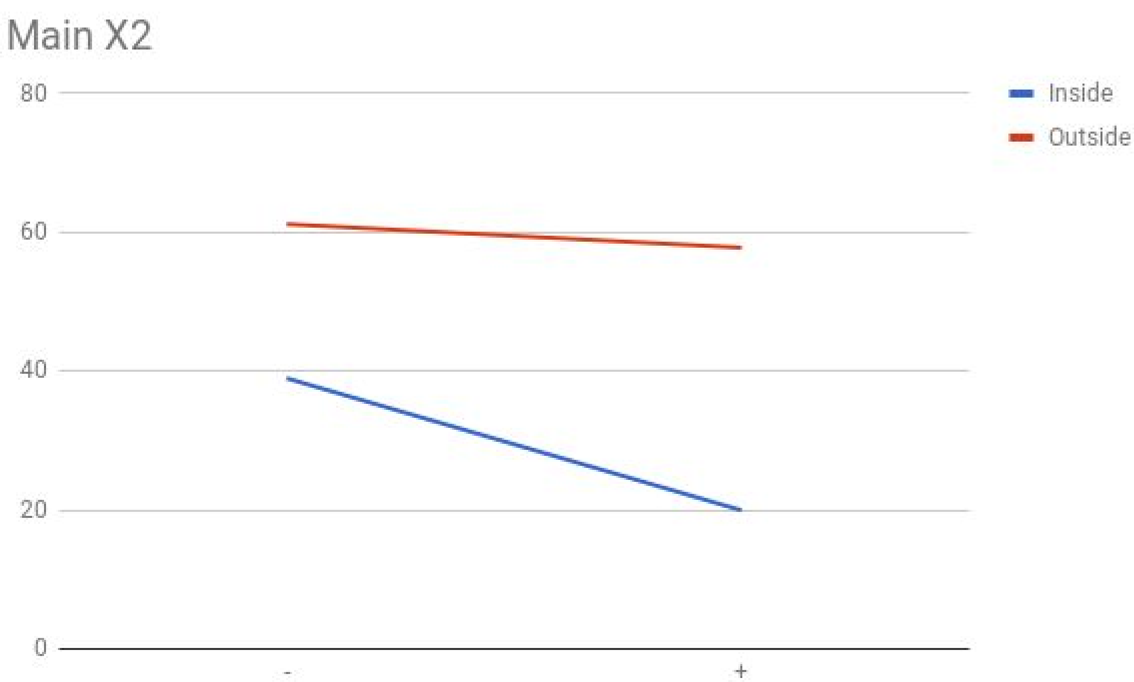
120	41.4	24.6
150	43.6	25.3
180	45.9	26
210	48.2	26.9
240	50.5	27.7
270	52.4	28.8
300	53.7	29.8
330	54.9	30.1
360	56.2	31.4
390	57.2	32.6
420	58.3	33.6
450	59.5	35
480	60.1	35.8
510	60.8	36.6
540	61.7	37.7
570	62.8	38.8
600	63.2	40.1

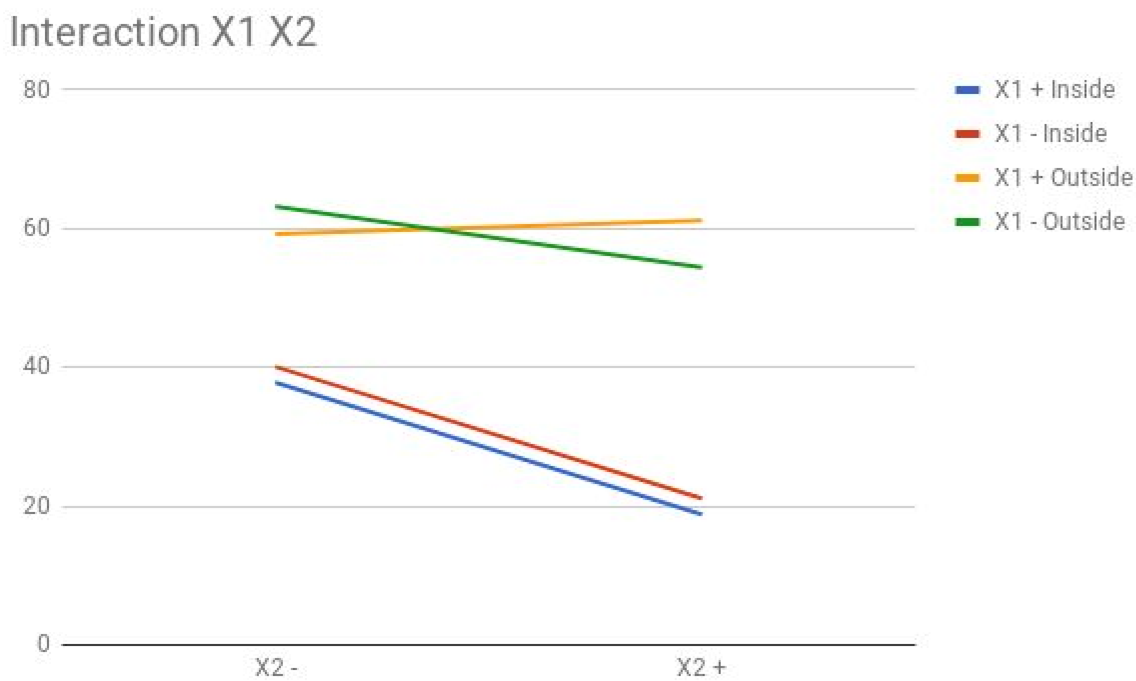
Appendix Q

DOE Results

X1 (Cork Thickness)	X2 (Water Packs)	X3	Value Inside	Value Outside
+	+	0	18.8	61.2
+	-	0	37.8	59.2
-	+	0	21.1	54.4
-	-	0	40.1	63.2
	Main X1		Main X2	
Value	Inside	Outside	Inside	Outside
-	30.6	58.8	38.95	61.2
+	28.3	60.2	19.95	57.8
Interaction				
Value	X1 + Inside	X1 - Inside	X1 + Outside	X1 - Outside
X2 -	37.8	40.1	59.2	63.2
X2 +	18.8	21.1	61.2	54.4


Main X1
80
60
40
20
0
-
+
Value
Inside
Outside


Main X2
80
60
40
20
0
-
+
Inside
Outside

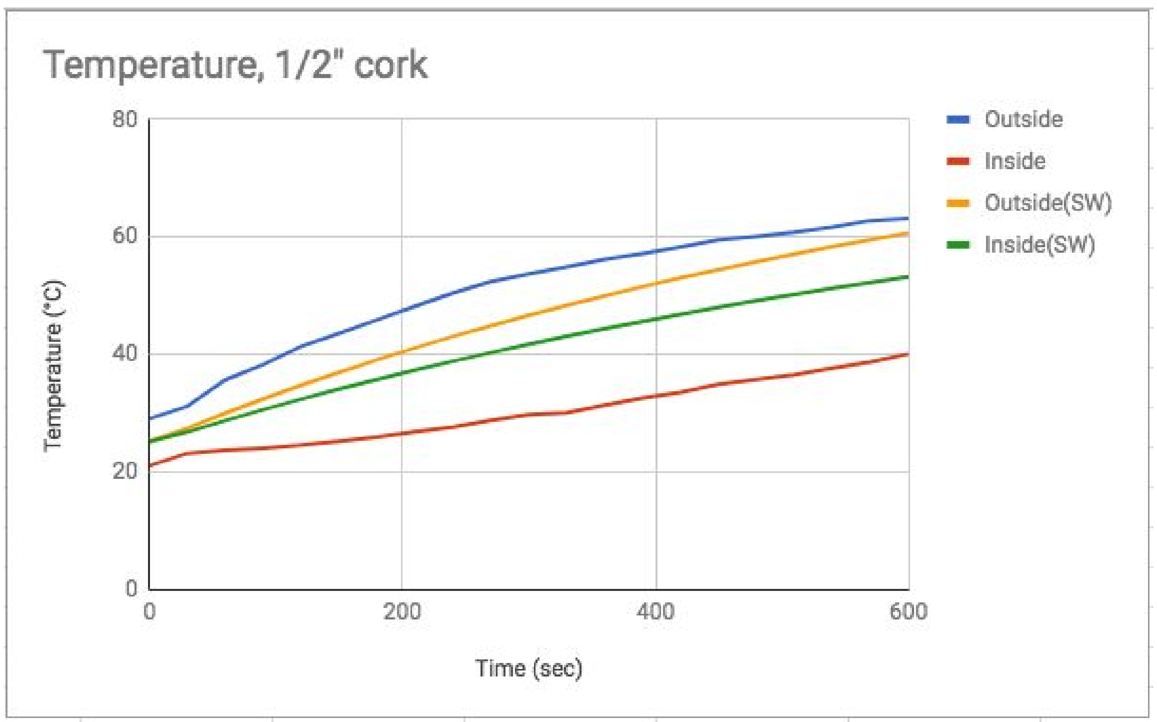

Interaction X1 X2
80
60
40
20
0
X2 -
X2 +
X1 + Inside
X1 - Inside
X1 + Outside
X1 - Outside

Appendix R

Compare Simulation and Experiment

i) 1" Cork Experimental Temperature Vs Simulated Temperature

ii) ½" Cork Experimental Temperature Vs Simulated Temperature



Appendix S
Bill of Materials/Budget

BOM		Amount	Cost per piece	
Sub system				
Thermal				
	Cork - 0.5 in	0.25	7.3	1.825
	Cork - 1 in	0.5	16.45	8.225
	Ice Packs	2	2.9	5.8
Movement				
	Motor mounts	2	0	0
	Motors	2	12.99	25.98
	Castor	1	9.03	9.03
	Hinges	2	1.235	2.47
	Brackets	16	0.4375	7
	Epoxy	0.3333333333	5.68	1.893333333
	Wheel hubs	2	6.945	13.89
	Shafts	1	1.5	1.5
	Wood	3.5	2	7
	Wood glue	0.13	2.98	0.3725
	Coupler	2	2.81	5.62
	Bushings	2	0.79	1.58
	All screws/nuts			0
Control				
	Thermal sensor	1	39.95	39.95
	Ultrasonic Sensor	1	1.732	1.732
	Level shifter	1	3	3
	Horn	1	8.91	8.91
	MOSFET	1	1.1	1.1
	Battery	1	18.21	18.21
	Motor driver	1	6.89	6.89
	Wires	1	0	0
	Connectors	1	3.5	3.5
	Microcontroller	1	6	6

	Protoboard	1	9.5925	9.5925
TOTAL				191.0703333

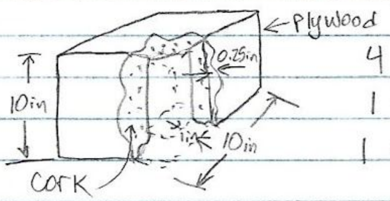
Appendix T
Heat Transfer Calculations

Heat Transfer Calculations for Experiment:

- Oven test, $T_\infty = 40°C = 363K$; $T_c(0) = 22°C = 295 K$, $T_c = 80°$

$T_f = \frac{363+298}{2} = 330.5K$

- Main modes of heat transfer: Natural convection to Plywood, Conduction to Cork; Natural Convection to Air.



4 verticle cold plates
1 top side of a cold plate
1 bottom side of a cold plate

Assumptions:

1.) Simplification of robot geometry will have neglegible effects on heat transfer.
2.) Interior air will reach interior cork temperature simultaneously
3.) Plywood provides minimal thermal resistance.

Experimental Parameters:

$K_P = 0.12 \frac{W}{m \cdot K}$; $K_c = 0.0415 \frac{W}{m \cdot K}$; $L_{c,P} = \frac{(.254_m)^2}{4(.254m)} = 0.0635m$, $\rho_c = 0.23 \frac{10^3 kg}{m^3}$

$L_{cork} = 0.0254m$; $A_P = 0.0645m^2$; $A_C = 0.058m^2$; $L_P = 0.00635m$, $V_c = 6A_c \cdot 1in$

Properties of Air @ 330.5K :

$\frac{330.5-300}{350-300} = \frac{\nu - 15.89}{20.92-15.89} \Rightarrow \nu = 18.96 \times 10^{-6}$

$\frac{330.5-300}{350-300} = \frac{P_r - .707}{.7-.707} \Rightarrow P_r = .703$

$\frac{330.5-300}{350-300} = \frac{\alpha - 22.5}{29.9-22.5} \Rightarrow \alpha = 27.01 \times 10^{-6}$

$\beta = \frac{1}{T} = 0.00275$

$Ra_L = \frac{9.8(0.00275)(363-298)(0.0635)^3}{(18.96 \times 10^{-6})(27.01 \times 10^{-6})} = 8.758 \times 10^5$

Heat Transfer Coefficients:

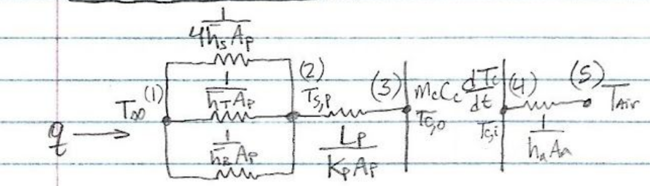
$$\overline{Nu}_L = \frac{\bar{h}L_c}{k} \Rightarrow \bar{h} = \frac{\overline{Nu}_L k}{L_c}$$

Top : $\overline{Nu}_L = 0.27 Ra_L^{1/4} = 0.27(8.758\times10^5)^{1/4} = 8.260 \Rightarrow \bar{h}_T = \frac{8.26(.12)}{.0635} = 15.61 \frac{W}{m^2\cdot K}$

Bottom : $\overline{Nu}_L = 0.58 Ra_L^{1/4} = 16.52 \Rightarrow \bar{h}_B = \frac{16.52(.12)}{.0635} = 31.22 \frac{W}{m^2 K}$

Sides : $\overline{Nu}_L = 0.68 + \frac{0.67 Ra_L^{1/4}}{[1+(0.492/Pr)^{9/16}]^{4/9}} = 14.99 \Rightarrow \bar{h}_s = \frac{14.99(.12)}{0.0635} = 28.33 \frac{W}{m^2\cdot K}$

Thermal Circuit:



$$q_{1\to3} = \frac{T_\infty - T_{c,o}}{R_{1\to3}}$$

$$R_{1\to3} = \frac{1}{A_P}\left(\frac{L_P}{K_P} + \frac{1}{4\bar{h}_s + \bar{h}_T + \bar{h}_B}\right)$$

$$R_{1\to3} = \frac{1}{0.0645 m^2}\left(\frac{0.00635 m}{0.12} + \frac{1}{4(28.33)+15.61+31.22}\right) = 0.917 \frac{K}{W}$$

Energy Balance on Cork:

$$M_c C_c \frac{dT_c}{dt} = q_{1\to3} - h_{NC} A\,(T_c(t) - T_{int}(t))$$

$$\frac{T_c(t) - T_\infty}{T_c(0) - T_\infty} = \exp\left[-\frac{t}{R_{1\to3} M_c C_c}\right]$$

$$t|_{80^\circ C} = -M_c C_c R_{1\to3} \ln\left(\frac{T_c - T_\infty}{T_c(0) - T_\infty}\right) = -\rho_c V_c C_c R_{1\to3} \ln\left(\frac{T_c - T_\infty}{T_c(0) - T_\infty}\right)$$

$$t|_{80^\circ C} = -(0.23\times10^3 \tfrac{kg}{m^3})(0.00884 m^3)(1.9 \tfrac{kJ}{kg\cdot K})\left|\tfrac{1000 J}{kJ}\right|(0.917 \tfrac{K}{W})\ln\left(\frac{80-90}{22-90}\right)$$

$$t|_{80^\circ C} = 6{,}790.6 s = 113 min = 1.9 hr$$

Temperature After 10 min:

$$T_c(600) = (22-90)\exp\left[-\frac{600}{0.917(3863.68)}\right] + 363 = 305.6 K = 32.6^\circ C$$

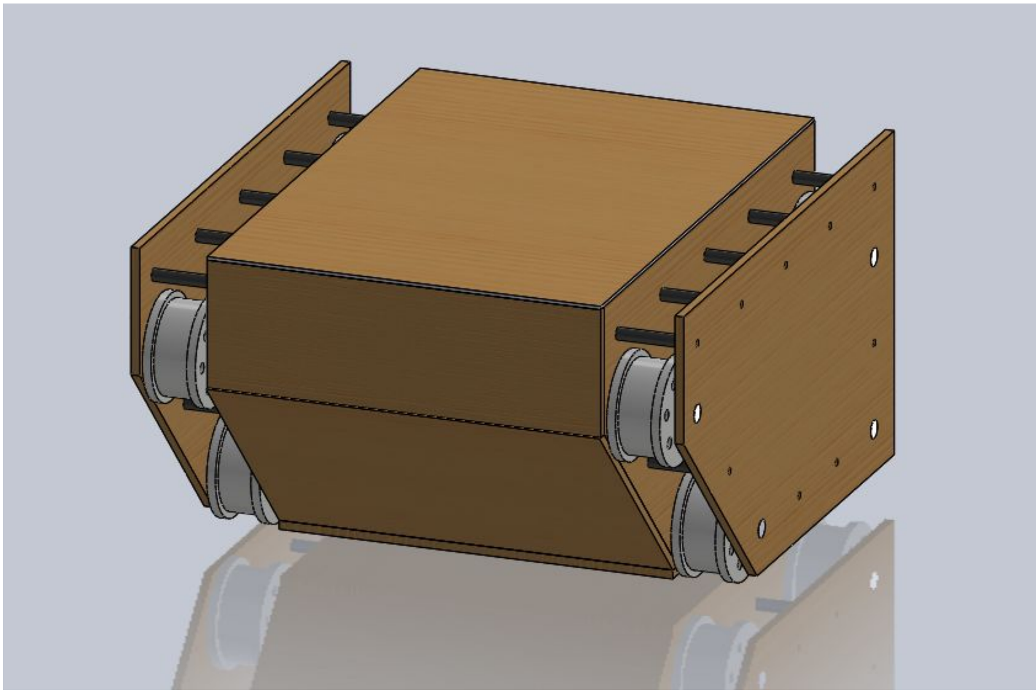
Appendix U
FMEA on Leading Concept

FMEA for: Leading Concept														
Team Deux														
				Current Situation						Improved Situation				
Failure Location/ Component/	Failure Mode	Failure Effec	Failure Caus	Current Detection Steps	S	O	D	RPN	Suggested Remedial Measures	Revision	S	O	D	RPN
Electronics board	Metalmigration	Loss of power	High heat	Simulation/ experiments/	9	3	3	81						0
	Thermal fatigue	Loss of power	Fluctuating temperatures	Simulation/ experiments	9	2	2	36						0
	Short circuit	Loss of power/l	Exposure to water	Experiments	10	3	3	90						0
Sensors	Loss of connect	Loss ofcommu	Badconnection	Experiments	10	1	4	40						0
	Overheating	Loss of sensor	High heat	Experiments	9	3	3	81						0
Gearbox	Plasticyielding	Loss of drive	High stress	Yielding calculations	9	2	2	36						0
Drive Shafts	Yielding	Loss of drive	High stress	Yielding calculations	10	1	2	20						0
Tread	Rubber melts	Loss of drive	High heat	Experiments	10	4	2	80	Use different rubber	Use high heat rated rubber	10	1	2	20
	Rubberdisconne	Loss of drive	High stress	Experiments	10	5	2	100	Use loop of rubber	Use drive belt	10	1	1	10
Flipper Arms	Become tangled	Impaired drive	Debris	Experiments	8	3	2	48						0
Battery	Dead battery	Loss of power	Defect/ not charged	Experiments	10	1	2	20						0
Water Resevoir	Leaks	Loss of therma	Poor construction	Experiments	10	2	1	20						0
Pump	Plasticyielding o	Loss of therma	Poor construction	Experiments	9	2	1	18						0
Standoffs	Yielding	Loss of drive	High stress	Yielding calculations	9	3	2	54						0
Sprockets	Become disconn	Loss of drive	High stress	Experiments	10	1	2	20						0
	Plastic Yielding	Loss of drive	High stress	Yielding calculations	9	2	2	36						0

Appendix V
FMEA on Preliminary Final Design

FMEA for: Preliminary Final Design														
Team Deux														
				Current Situation						**Improved Situation**				
Location/ Component/	**Failure Mode**	**Failure Effect**	**Failure Cause**	**Detection Steps**	**S**	**O**	**D**	**RPN**	**Remedial Measures**	**Revision**	**S**	**O**	**D**	**RPN**
Electronics board	Metalmigration	Loss of power	High heat	experiments/	9	3	3	81						0
	Thermal fatigue	Loss of power	Fluctuating temperatures	Simulation/ experiments	9	2	2	36						0
	Short circuit	Loss of power/ fire	Exposure to water	Experiments	10	3	3	90	Remove water pump system	Use sealed water packs	10	1	2	20
Sensors	Loss of connecti	Loss of communication	Bad connection	Experiments	10	1	4	40						0
	Overheating	Loss of sensor	High heat	Experiments	9	3	3	81						0
Gearbox	Plasticyielding	Loss of drive	High stress	calculations	9	2	2	36						0
Drive Shafts	Yielding	Loss of drive	High stress	calculations	10	1	2	20						0
Wheel adapter	Plasticyielding	Loss of drive	High stress	calculations	9	2	2	36						0
Wheels	Warping	Impaired drive	High heat	Experiments	7	3	1	21						
Thermal Shell	Piecesdisconnec	Loss of thermal protection	Warping due to heat	Experiments	10	8	3	240	Use two types of bonding material	Use L-brackets and epoxy	10	2	3	60
Battery	Dead battery	Loss of power	Defect/ not charged	Experiments	10	1	2	20						0

Appendix W
Original CAD Drawing



Appendix X
Final CAD Drawing