ECE 183DA / MAE 162DA

Final Design Review

Team Search

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Executive Summary

One of the most important aspects of any business improvement is productivity, and innovative operator solutions present a unique opportunity for this. Taking steps toward emerging technology while customizing a solution to specific needs is one approach to a smarter solution. One specific innovation within this broad technological approach is robotics. Robotics are effective because of the need to control labor costs and shortages, improve timeliness, reduce waste, and elevate customer experience and employee morale. Healthcare is the largest employer in the U.S. and spending continues to rise with aging populations and pandemics. U.S. Healthcare is facing a labor shortage with a widening gap projected and one of the highest turnover rates of any industry. Within this space, one of the most cumbersome tasks is manual transport. Nurses are forced to walk long distances, carry heavy loads, deliver in requested time all while maintaining quality of service. This is clearly an area where an innovative approach could make a difference. Automation offers improved productivity and efficiency, improved service for users, reduction of injury, increased worker satisfaction, and reduces labor challenges through reallocation of staff. With a robotic solution, we could increase throughput and streamline the delivery workflow in order to achieve the improvements just mentioned.

Our automation method attempts to simplify navigation and individualize the robot's role. Our robot will autonomously line-follow to transport linens for nurses at chosen stop points. Our autonomous line-following robot is an easily integrative, non-invasive solution that can be tailored to any hospital. We considered things such as space restraints, efficiency, cost, and quality insurance through the use of feedback from nurses and healthcare systems. Our robot was designed to be adaptable, reliable, safe, cost-effective, and aesthetically pleasing. Our robot offers high navigation accuracy and uses advanced algorithmic techniques to keep nurses focused on their duties and not our robots.

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1 – Introduction and Overview

Have you ever found yourself being taken care of by a caring or inspirational nurse? Being attentive and professional in a hospital is highly demanding and no doubt one of the hardest working industries there is. They are not only expected to provide flawless medical service, but are also expected to provide a range of support aside from their medical duties. Registered Nurses encompass one of the largest segments of the US workforce -- being 3.8 million strong. Nurses are the eyes and ears of the hospital. They know which healthcare products work best, refine the processes for patient care, and identify excessive waste and other inefficiencies. By 2022, there will be far more registered nurse jobs available than any other profession, at more than 100,000 per year. With more than 500,000 seasoned RNs anticipated to retire by 2022, the U.S. Bureau of Labor Statistics projects the need for 1.1 million new RNs for expansion and replacement of retirees. And with the current effects of COVID-19 still playing out worldwide, nursing shortage projections only keep increasing. On top of the general shortage, nurses are often distracted by trivial tasks like mail delivery, transport of storage units, food, beds and many other items. This raises the question of how we can limit the number of people involved and how we can enhance the nursing industry without replacing these much-needed jobs.

Mobile autonomous robots are our solution to assisting nurses with their menial time-consuming tasks. Transporting linens is one such task nurses deal with, and our robots take care of this time burden by transporting linens for them. Previous attempts have been made to automate the transportation of common medical items; however, using these robotic systems is not the norm in hospitals, suggesting that the problem has not been solved satisfactorily. We modified previous solutions by simplifying the navigation and individualizing the robot's role. Our robot will autonomously line-follow using IR sensors, with lidar sensors for obstacle detection, to transport linens via trays housed inside the robot. The robot will interact only with nurses at chosen stop points. Our autonomous line-following robot is an easily integrative, non-invasive solution that can be tailored to the needs of any hospital, small or large. Our robot has high navigation accuracy and uses advanced algorithmic techniques to keep nurses focused on their duties, and not our robots. In terms of quantifiable specifications and with consumer desirables in mind, we take the next step in the following areas: ease and adaptability of installation and use, self-sufficiency of our algorithms, speed, and cost. We have validated our system with concrete results both mechanically and electrically and we have results showing excellent fitting and system performance. Naturally, we formulated our product with input from nurses and health care business opinions. We designed and reviewed our system with current nursing professionals from UCLA and Johns Hopkins University. We also incorporated feedback from the CEO of Dignity Health, one of the largest healthcare foundations in California, to ensure we constructed a viable market product.

2 – Problem Definition

2.1 – Problem Statement

We are motivated to explore a problem related to hospital operation broadly because hospital operation affects public health significantly. Specifically, the ongoing global pandemic, which has made hospitals the frontier of health crisis management is a motivating factor. As motivation for the more constrained problems we will attempt to address, we make the following observations:

- Hospitals are sites of high disease transmission rates [1].
- The population density of hospital staff is high.
- Person-to-person (PTP) and person-to-surface-to-person (PSP) contact is high.
- Medical staff frequently are occupied with nonmedical tasks.

These observations lead us to the following fundamental questions:

- Can we limit the number of people involved in hospital operations or ease their burdens?
- Can this be done with an engineered system?
- Will such a system's health benefits outweigh its other costs?

Thus, to direct our preliminary design, we formulate the problem as such:

> **Hospitals have thinly spread medical staff, frequent interpersonal contact, and high disease transmission rates.**

The context of this problem is clearly hospitals—more precisely, we claim it occurs in hospitals generally—this establishes the generality of the problem. We identify the stakeholders interested in the solution to this problem as hospitals as institutions and their owners, their patients, their staff, and the public, which is impacted by health conditions in hospitals. This problem's scope is large, so we will attempt to identify a region of the problem space to which we can design a solution.

2.2 – Context and Root Cause Analysis

From a very broad initial context, we first wanted to look at how menial tasks not related to creative problem solving or anything productive affected workers productivity. To give an idea of the severity, Otter.ai is a company built around increasing work productivity via transcribing and creating live captions for meetings in the workplace. They have conducted a lot of relevant research in this area, in just meetings alone, they found more than 35% of employees wasting 2-5 hours per day in meetings and on calls with no achievements to show [2]. Other striking stats include, 92% of employees find themselves multitasking during work and 49% of those admitted the work was completely unrelated [2]. From a more holistic overview, according to Gallup State's American workplace report, actively disengaged employees cost the U.S. as a whole

$483-$605 billion per year [5]. And from a narrower scope, 86% of employees reported they lost time each day on work-specific tasks unrelated to their core job [3].

The aspect of hospital operation we will focus on is the material supply chain. In an analysis of the Bispebjerg Hospital in Copenhagen, it was found that transportation tasks, including medicine transport, mail delivery, transports to storages, clothes transports, waste collection, etc. consumed 842.54 hours weekly with 27-28 dedicated personnel [2]. These materials are moved among several storage areas. Waste alone amounted to a weekly average of 21.12 metric tons of material which had to be collected and consolidated [2]. A summary from a study and a corresponding infographic can be seen in the figure below.

Task	*Personnel involved*	*Hours/Week*
Medicine Transport	Porter (2)	50,4
Mail Delivery	Hospital Employee (4)	107,1
Transports to Unit Storages	Porter (1)	27
Transports to Sterile Cabinets	Hospital Employee (2)	69
Food Transport	Porter (5)	98
Transports from central supply	Porter (2)	51,8
Empty beds	Porter (3-4)	113,4
Transport of clothes	Porter (4)	130
Waste Collection	Porter (4)	195,84

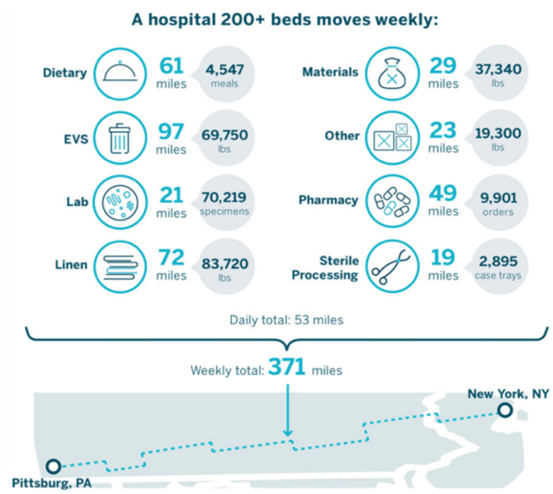


Figure 1: Summary of transportation tasks [1].

The authors of this study note that the “vast variety of materials” required in hospitals “often result in complex transportation systems and tangled flow[s] of materials” [2]. For these reasons, we believe we can target the material supply chain within the hospital and improve its efficiency and cleanliness with the application of a mechanical engineered system.

To reinforce and direct this conclusion, we perform a root cause analysis on the operation of the hospital material supply chain. The Ishikawa Diagram summarizing our results is presented in Figure 2.

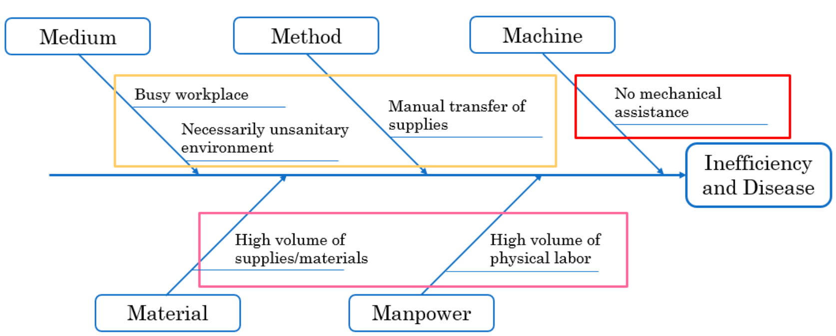


Figure 2: Ishikawa root cause diagram for nonmedical hospital operations

From the Medium and Method branches, we see a crowded and unsanitary workplace with manual handling of supplies. With the Material and Manpower branches, the workplace must involve a great number of individuals handling a large number of individual objects. Finally, with the Machine branch, this operation is enacted without mechanical assistance; specifically, there must be enough people to handle the whole supply chain, and these people must touch all the supplies that are brought through the hospital.

Since the lack of mechanical assistance is the crux of the population density and contact elements of the problem, we conclude that the Machine branch of the diagram bears the root cause: no mechanical assistance. We conclude that a mechanical system may address a significant part of this problem.

2.3 – Resources and Methods

Since the problem is consequential and carries health implications for millions [1], we expect there have been many analyses available for review. We have found, in addition to the Bispebjerg Hospital paper, a survey of robots in healthcare, including transportation robots [3], and several papers on mobile robot planning in hospitals [4-6]. We will also be making use of feedback from current nursing professionals and medical business personnel.

2.4 – Background and Scope

As is apparent in our references, path planning and routing will be important in the design of our system. We will need to study the existing supply chain in hospitals and amend it appropriately with one that makes primary use of a robotic system. The design of this robot also will require knowledge of load-bearing structures.

The authors of the Bispebjerg paper conclude that the most effective revision of the hospital supply chain is fundamental. Specifically, they call for a “central stock system” rather than the decentralized storage scheme that currently exists [2]. This would grant mobile robots the greatest effect on personnel reduction and allocation speed. We agree that this likely is the best scenario around which to design our system; further, we believe that rearrangements on this scale are achievable for hospitals and, coupled with the introduction of a series of mobile robots, would require far less disruption and cost than the installation of a hospital-wide ‘stationary’ delivery system (e.g. rail, tube, etc.).

Therefore, we will limit the scope of our solution to the design of a single class of mobile, load-carrying robot capable of following a preset path. This will substitute the complex human-powered supply chain that currently exists and will (1) reduce the number of people involved in hospital operation, (2) address a significant subset of the problem, and (3) confer more benefits than costs to the hospital, patients, and the public.

3 – Preliminary Analysis

3.1 – Requirements Definition

3.1.1 – Element Definition

Element definition is used to better define the aspects of our problem-solving artefact, its tasks, surrounding environment, and its effects.

Intended Practice / Other Practice: Assist hospital staff
Artifact: Mobile robot for carrying out menial tasks
Problem: [1] Nurses spend at least 10% of their time on tasks that can be done by someone or something else, person-to-person contact spreads disease
Technology: Navigation, obstacle sensing, driving, containers
Uses: Assist hospital staff, reduce the number of people in the hospital, reduce workload
Perception: Healthcare workers overworked in the pandemic on the news
Addresses: Work environment in the hospital
Environment: Hospital including staff/patients, infected and sterile environments, navigation infrastructure required for the robot
Function: Transportation of supplies, containment of supplies
Behavior: Driven movement, navigation, obstacle detection, supply containment, notification system, (irrelevant behavior) getting in the way
Structure: Wheelbase, support, wheels, sensors, receiver/interface, battery, lights, suspension, frame, containers
Intended Effects: Moving goods from one place to another, reduce the amount of hospital workers needed at once and reduce their interpersonal contact
Side Effects: Getting in the way, notification/obstacle noise, potential to cause unemployment

3.1.2 – Analysis

3.1.2.1 – Objective Tree Method

The aim of the Objective Tree Method is to clarify design objectives and sub-objectives of the solution artefact and the relationships between them. Discussing with the prospective clients and adding our own input, we came up with a list of objectives and sub-objectives. Then we separated the objectives into different levels and formed a hierarchy with the most general requirements at the top. The broadest objective for the artifact was to create a reliable, easy to use robot. From this main objective, sub-objectives would be reliability, ease of use, and good operating characteristics. The rest of the objectives could be categorized as sub-objectives of one of these three. The chart below was created with the lower objectives such as object detection being the means to achieving the higher objectives they are connected to: reliable operation.

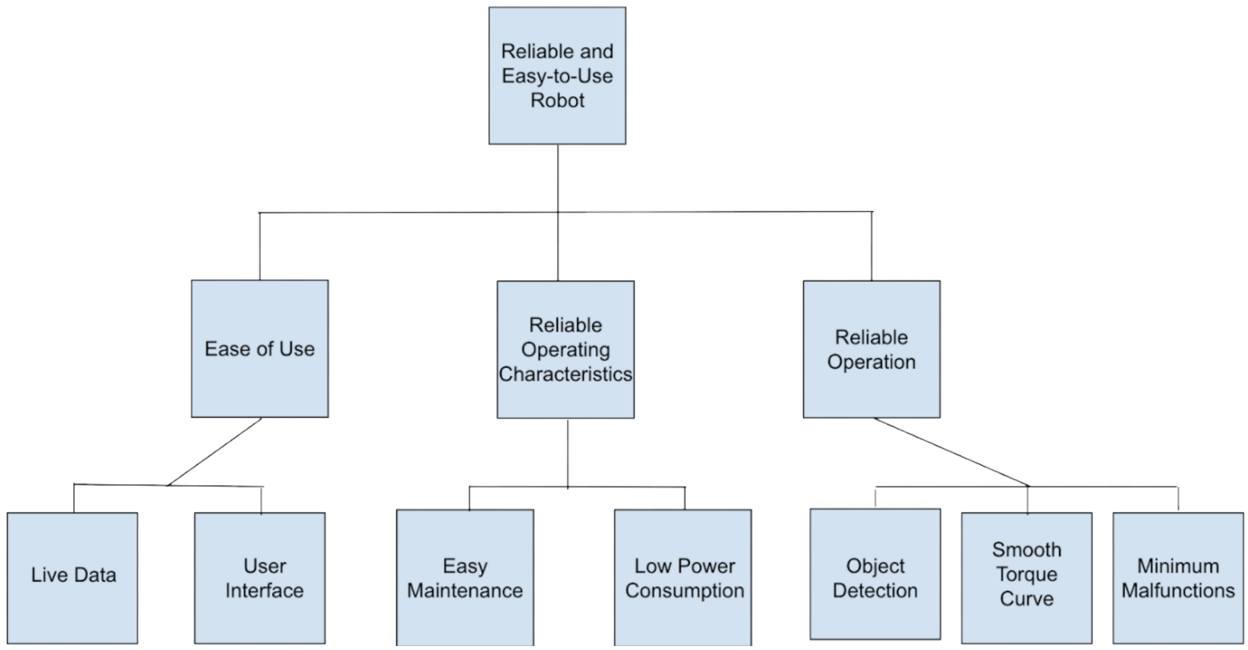


Figure 3: Objective Tree Method Diagram

3.1.2.2 – Performance Specification Method

The goal of the performance specification method is to give an accurate specification of the performance required of a design solution. At this early phase of the design process, mostly more general specifications were used to leave a sizable range of options for the final design. The performance attributes considered are those most necessary to the basic function of the robot and its environment. For values such as battery life and payload, a reasonable minimum value to satisfy basic requirements was chosen at this stage as an aid for the future. A longer battery life makes the robot a viable option to replace a human worker and a lighter robot means it can carry a heavier load for the same actuator output, meaning less powerful actuators can be used with a lighter robot. An operating speed up to average human walking speed, 3 miles per hour, is desired to maintain the flow of the environment. At the same time, the robot must not be too intrusive in the hospital environment especially given emergency cases. NFPA 101 Life Safety Code guidelines dictate new healthcare facilities have 2.4 meter wide corridors of which 1.8 meters must not be obstructed, but as much as 0.9 meters can be obstructed by a wheeled piece of equipment [7]. Given these values, a robot that fits within the hallway allowance space is desired to best keep it out of the way and maintain safety in an emergency. We chose to fit our robot within a 50cm by 50cm box so that it stays within the allowance in either upright orientation with leeway.

Table 1: Performance Specification Method Values

Hospital Robot Specifications	
Dimensions	Fits within 50(W) cm x 50(L) cm x 100(H) cm
Weight	Less than 75 lbs
Payload	Greater than 50 lbs, need not be more than 250 lbs
Battery Life	Greater than 8 hours
Operating Speed	Up to 3 miles per hour
Safety	ISO 10218-1

3.1.2.3 – Quality Function Deployment Method

The goal of the quality function deployment method is to set targets to be achieved for the engineering characteristics of a product, such that they satisfy customer requirements. To obtain a set of product attribute requirements we did not have the opportunity to consult with customers yet, so as a group we came up with our own set thinking from the point of view of a potential customer. Because of these initial circumstances the customer requirements are still likely to be a 'reinterpretation' by the design team at this stage. As a group we used points allocation to determine the percentage weights to attribute to each attribute. The most important attributes were reliability, simplicity, user-friendliness, safety, and long battery life.

Next, we evaluated what we viewed as competing products based on function against the set of important attributes created. The four products chosen were the TUG Drawer and TUG Exchange, made by Aethon, and the EVOcart 3 and EVOcart 5, made by Oppent. Then we took the attributes and created a set of engineering characteristics that are the means to the attributes to measure each competitor against. For example, longer battery life is most directly related to power consumption, weight, and payload as well as being related to material, downtime, acceleration, and working temperature. We used symbols to represent the strength of the relationship between each attribute and the engineering characteristics responsible for them. The correlation between different engineering characteristics is represented by symbols in the 'roof matrix' to demonstrate the relationships that exist between some of them. One example is that power consumption is directly related to the weight and payload of the robot. Using the competitor values, we came up with a set of target figures for our design to score on the chart.

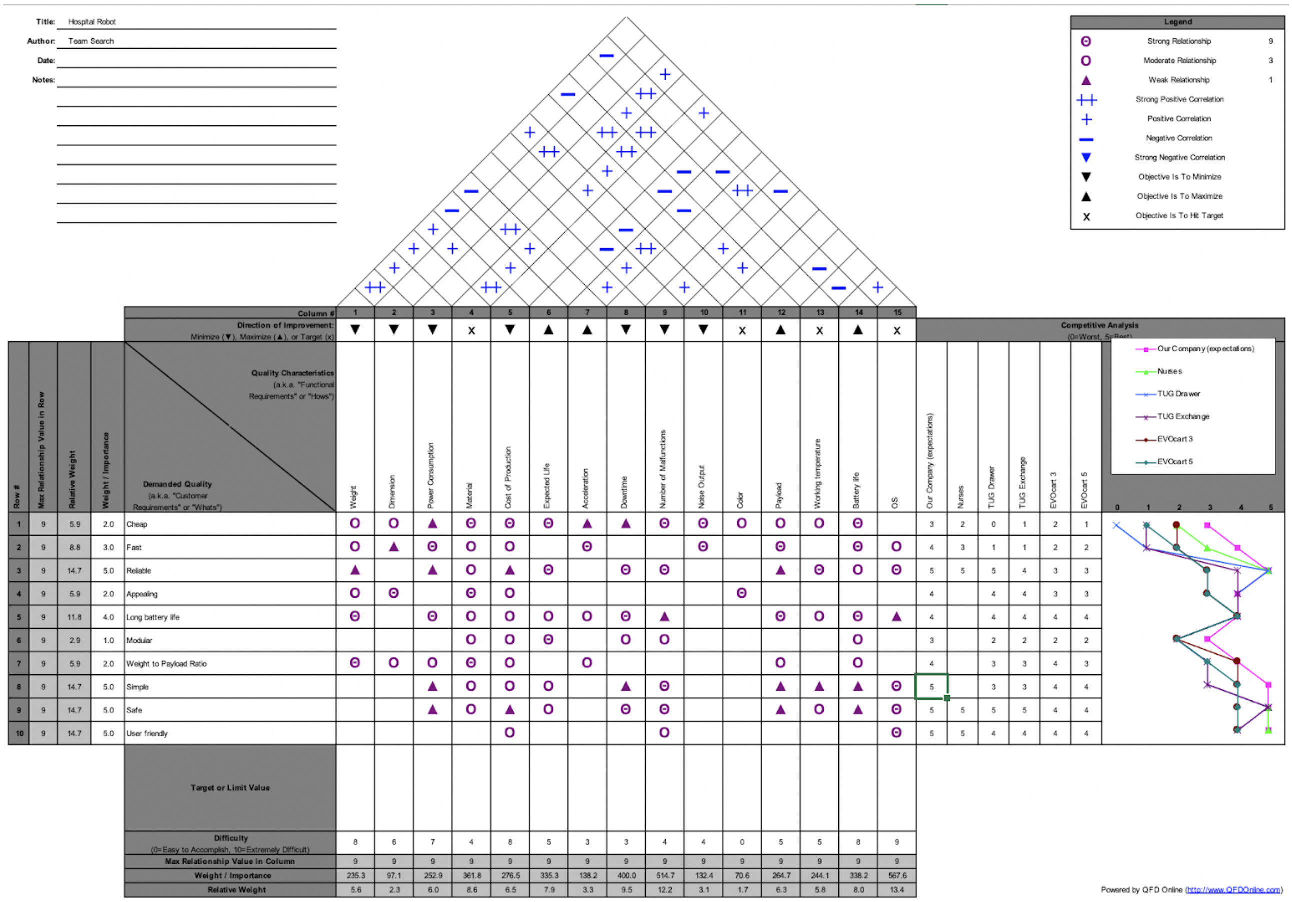


Figure 4: House of Quality

3.2 – System Design – Block Diagram (Function analysis method)

3.2.1 – Block Diagram Definition

The preliminary block diagram of the artifact is shown in Figure 4. It consists of three blocks that are Power, Controller, and Chassis.

The power subsystem is responsible for power delivery from the battery to the other subsystems as well as recharging the battery. The input of the power subsystem is electricity from the external power source. The outputs are electricity stored in the battery and heat generated due to inductance.

The controller subsystem takes the data from the user or sensors and then calculates its next move by using various algorithms. The inputs of the controller subsystem are signal commands from the end and raw image data from the sensors. The outputs are various instructions that control the current of the actuators.

The chassis is where all the basic components of the mechanism work together. The inputs of this subsystem are current that actuates the motors and external forces that are applied to the chassis. The outputs are both wheel speeds, heat from the electronics and friction, and displacement of an object.

The mathematically characterized requirements of the subsystem specifications are listed in the requirements definition.

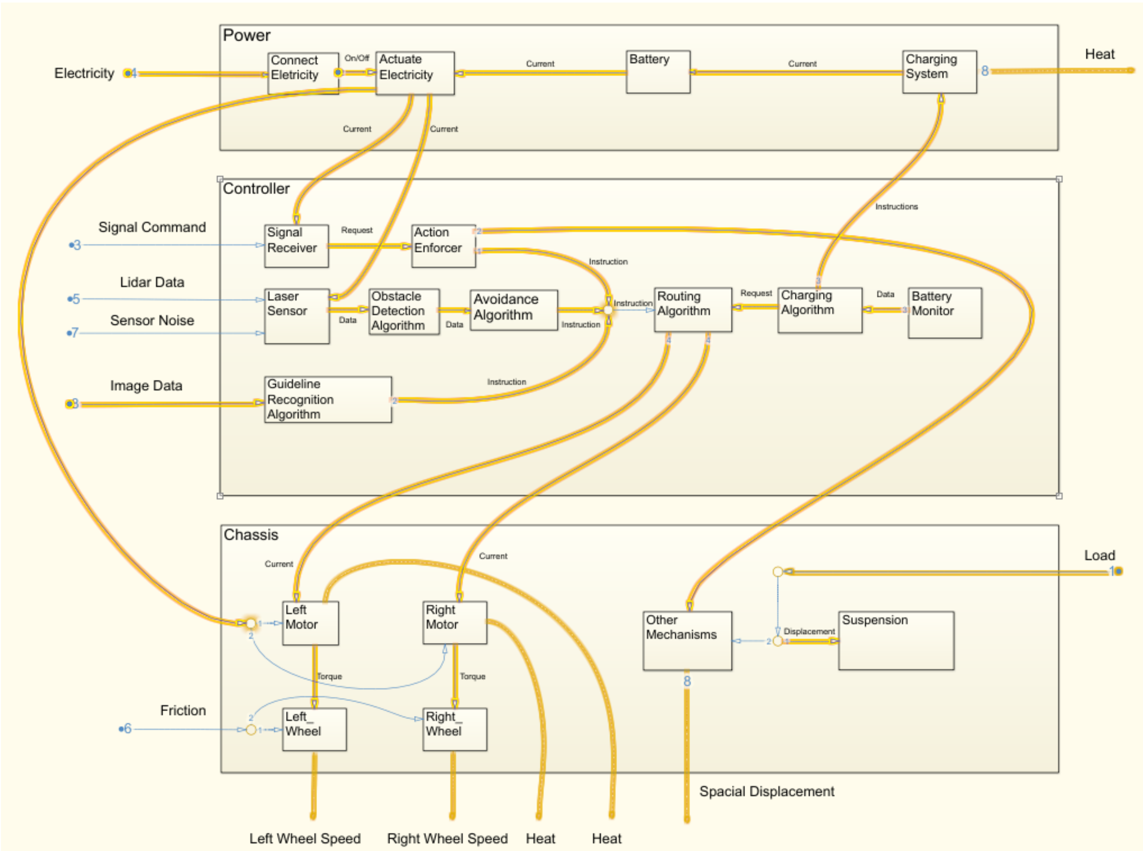


Figure 5: Block Diagram

3.2.2 – Subsystem Breakdown

Inside the power system there are switches that control the flow of current, a battery that serves as the power reservoir, and also the charging system that will make sure the battery stays fully charged.

Inside the controller subsystem there are sensors that will convert the raw data to useful information for the routing algorithm to determine an optimal path to the next location with the assistance of an obstacle avoidance algorithm. The controller will also monitor the battery level and send commands to the central controller to guide the robot to the charging station.
DC motors will be used for active motion with a PID controller from the controller subsystem. Areas where motion occurs are wheels and self-disinfecting mechanisms. Passive motion such as the suspension will also be taken into account in the design.

3.3 – Development of Design Candidates and Selection

3.3.1 – Creative Methods

At this point, we have established the problem we are trying to address and the general scope of our solution, but now we are going to be discussing how we exactly reached our formal design candidates. We began with creative methods, in particular brainstorming and synectics.
For brainstorming, it is first important to note we choose to build around a technology in a bottom-up fashion. The technology we chose was line-following. We felt this was a proper algorithmic challenge given our knowledge and technology that was universal enough to be effective. We then thought about plausible spaces where we could apply this system. Could we put them in restaurants or use them in the food industry, could we put them in hospitals or use them in the health industry, could we put them in public spaces such as libraries, could we use them in the sports world, and so forth. This process led us to the three best spaces: restaurants where the robot could act as food servers, hospitals where we could use the robots for medical delivery, and libraries where robots could serve as automated librarians.

After establishing each of these solution spaces, it was then a question of how our robot would make the biggest impact and from a high-level overview, where it best serves as a solution to our problem. In order to tackle this, we used the research from the problem explication section on how much time workers are really spending on menial tasks in these fields. This led to our choice of the hospital as a solution space. We found it interesting that some of the most trivial tasks took the longest. For example, waste collection and transportation of clothes/linen were the two most time-consuming tasks. If we built a robot capable of transporting either or both of these, we could save more hours per week than any of our other solution spaces.

3.3.2 – Creative Methods II

For synectics, we began first with the problem. Hospitals have frequent personal contact, thinly spread medical staff, and potential for high disease transmission. With benefiting nurses in mind, our goal became alleviating daily time-consuming tasks. To think of ways to address these issues, we used analogies to draw comparisons and think about our impact. The obvious analogy is just general time spent on activities not productive during an average workday. There are numerous studies and surveys showing that vast majorities of the working day are spent on menial tasks not related to creative problem solving or anything productive and these were summarized in the problem explication as well. The problem then becomes, how do we free up more of this time and alleviate stress and other factors to increase productivity for the responsibilities with high significance. Robots clearly offer a unique, technological solution where we simply eliminate the possibility of human distraction and also the laborious tasks themselves. In our case, these robots have the potential to free up nurses and other staff to have more time for patients and other more important tasks, while also helping reduce unsanitary interaction.

3.3.3 – Creative Methods III

Lastly, we felt it was important to get some opinions and thoughts from nurses as they are our primary audience. To do so, we researched currently existing feelings towards robots in the healthcare industry and talked to a few nurses currently working in the field about their thoughts on the idea of robotic transportation helpers. In terms of existing robotics in the healthcare world, a lot of the feedback was mixed. Many felt robots were helpful, saved time/energy, were fun to work with and were completing thankless jobs that people felt were better to be done by a robot simply because of that. On the other hand, however, many noted that they were kind of a pain. Nurses and healthcare workers complained about the robots breaking or running into problems frequently (which then falls on them to fix), and also noted they felt the loss of some of these jobs was not worth the investment. This trend seemed to carry through to most of our discussions with current nurses. We then talked to a few nurses from the University of Johns Hopkins and UCLA. They both agreed that the cost of transporting material and waste was an overhead cost, so having technology to handle that efficiently, could be of benefit for nurses, as more money could be put towards other areas and nurses in general would have more time for patient care. They both noted that the fatigue of doing some of these tasks was a real problem and they both talked about just how much walking per day is done manually by nurses in transportation of various things. On the other hand, both did question the reliability and consistency of robots for these tasks in addition to a lot of questions on the integration of these robotic systems. They noted that there are constant decisions that need to be made based on situational circumstances and incoming information. They both concurred that the potential for this technology was really promising and that they would both be in favor of working in conjunction with them.

3.3.4 – Morphological Chart

Then we moved to rational methods where we took a more formally oriented approach. One way to accomplish this was with a morphological chart.

	Solutions ->			
Sub Functions	**1**	**2**	**3**	**4**
Holding Object	Safe	Drawers	Cart	Trays (shelves)
Transportation Method	Autonomous Line-Following	Wall-Mounted Rails	Roof-Mounted Rails	
Accessibility	Patient Interaction	Nurse Interaction	Interaction of Both	No Human Interaction
Ground Interface	Wheels	Treads	Mounted Rails	
Path Sensors	IR	Ultrasonic	Lidar	Camera
Obstacle Sensors	IR	Ultrasonic	Lidar	Camera

Table 2: Morphological chart—design choices highlighted in yellow [4].

The columns represent different solution ideas, and the rows represent sub functions we need our robot to accomplish. This chart was slightly revised from our original winter quarter chart following a few design clarifications that we were originally unsure of. We initially created it too generally and thus could not effectively judge the sub-functions in the following weighted objectives chart.

The first sub-function we considered was how to hold the object. We included all possibilities in this chart ranging from security based like a safe, to drawers, to more open solutions like a tray. For the transportation of linens, we determined that it's not a sensitive enough material to need a safe, and drawers would simply add more time for the nurses to remove the linens.

We then needed to consider the impact of these robots on space inside the hospital, so we considered different transportation methods. The best solution we found and approved was placing lines on the floor of the hospital up against the side wall confining it to guideline-based hallway space.

Next was accessibility, the fundamental question of how and who our robots were going to interact with. This impacts interface, display and a lot of other aspects, so this was an important area to discuss different solutions. Would we want the robot to only interact with patients, only with nurses, both or require no human interaction at all. This raised the question of our targeted audience, who we were trying to help the most, which was nurses. It also affects our sanitation, if we interact with patients, we definitely increase our chance of disease spreading, if we only interact with nurses, we have a much lower chance of spreading. The last couple of functions are mechanical and algorithmic design choices for the robot.

How exactly is our robot going to move (ground interface) and how are we going to implement the line following algorithm (different sensors). Mounted rails pose a major construction project for the hospital which is not ideal, and wheels are preferable to treads for line-following, as they have more potential to block the line. We determined that IR path sensors would be advantageous so that different line types could be used to designate different speed zones within the hospital to increase the safety of the robot. Camera sensors were deemed to be overly complex for both the task and our knowledge. Lidar sensors were chosen for obstacle detection since the robot will be travelling in a contained environment along the wall, where obstacles will be directly in front or behind it picked up by the lidar. Overall, this was a useful way to explore how exactly we could best design our robot to best solve our problem.

3.3.5 – Competitors and an Introduction to Design Objectives

This will be discussed more in Section 4, but we will introduce our main competitor here as we used this in initial research to formulate our system and design objectives for the subsequent weighted objective chart. Our main competitor is TUG, an autonomous mobile robot made also specifically for hospitals by Aethon, a robotic company based in Pittsburgh who launched the company in 2004 as a way for healthcare administrators to cut costs, save on nurse turnover and limit injury risk. Here is a quantifiable specifications comparison to gain an idea of the systems.

Specification	TUG	OUR
Sensors	Sonar/infrared/laser	Lidar/IR
Battery	10 hours with intermittent charging	6.5 hours on one charge
Dimensions	58.9x113.5 cm	50x100 cm
Drive system	4WD	Front 2WD
Navigation Method	Internal map and real time lidar	Line following
Charging	Navigates to charging station	Navigates to charging station

Where we take the next step…

Specification	TUG	OUR
Initial setup	Required mapping with emptied out hospital	Simple line installation
Operating weight	220 Ilbs	<75 Ilbs
Technology drawback	Requires algorithmic monitor	Entirely self-sufficient
Max speed	1.7 mph	3 mph
Cost	$105,000	$23,665
Max torque	26 oz-in	240 oz-in

Table 3: Overview of competitor specifications and our solution.

3.3.6 – Weighted Objectives Chart

With this established, we used a weighted objective chart to quantitatively compare our sub-function solutions to our main competitors to prove our marketability. Please note that this was made prior to quantifiable measurements for the objectives and thus the weights are based on our opinion, we later compare again in Section 7 using quantitative measurements.

		Our Robot		**Our Main Competitor (TUG)**	
Objectives	**Weight**	**Score**	**Utility (Score x weight)**	**Score**	**Utility (Score x weight)**
Navigation Reliability	5	5	5 x 5 = 25	4	5 x 4 = 20
Cost	5	5	5 x 5 = 25	2	5 x 2 = 10
Safety	5	4	5 x 4 = 20	3	5 x 3 = 15
Speed	3	3	3 x 3 = 9	2	3 x 2 = 6
Aesthetics	4	4	4 x 4 = 16	4	4 x 4 = 16
Total			**95**		**67**

Table 4: Weighted objectives chart. Note everything is scored out of 5 [6].

After considering all the sub functions from our previous chart, we scored our two main ideas. The main objectives are then listed on the left, including navigation reliability, cost, safety, speed and aesthetics. Then all objectives were assigned a weight out of 5 based on the importance of setting our robot apart. We felt reliability, cost and safety were our most important objectives as we need our robot to accomplish its given task with the highest success rate possible that is safe for medical personnel and patients (otherwise we could fail to solve our problem at a fundamental level). For the two candidates, each objective was given a score out of 5 and a subsequent utility score that combines the score and objective weight. Clearly, our robot ranks better, which is exactly what we'd hope for. In section 7 we will quantifiably rescore this with our final system.

4 – Design specifications

4.1.1 - Adaptability

One of our most important design requirements as per consumer feedback and our analysis of what could set us apart was adaptability. In the U.S., hospitals can be differentiated by a variety of factors such as functionality, size, ownership and specialization. Thus, we sought to create a solution that was as universal as possible in order to help nurses in any given area. The most relevant to our transportation of linens was size. Size is primarily defined by the number of hospital beds and is usually categorized as small, medium or large based on geographic region classifications such as rural, urban nonteaching and urban teaching. A rural hospital with 25 beds and about 350 staff members is going to have different needs than a state-of-the-art urban hospital with 500+ beds and 3,500 staff members. So, in order to combat these types of details, we wanted to make sure our integration system was as easy and seamless as possible. Our main competitor's integration involves an internal mapping process, wifi, central system management, which requires user interface inputs and this can be a lot for an isolated hospital where the average intake of patients per day is only about 7. We have thus designed a minimal, non-invasive setup with a largely simplified investment that can be tailored to any type of hospital as mentioned. The simplicity of our line following navigation makes it easy for hospitals to specify where they want the robot with nothing more than a line and subsequent flooring protection layer (details addressed in cost section). Additionally, our robot requires no wifi nor central management and we make use of an extremely minimal interface to make us as self-sufficient as possible to ensure nurses are indeed getting more time with patients and not more time fixing robots.

4.1.2 – Reliability

In order to create a minimal and simplistic solution for nurses as required by our adaptability, we needed to create a system with highly proven accuracy to make sure our claims about keeping nurses focused on patient time as opposed to robot time were quantifiable. We began with the mechanical elements of the robot to ensure the integrity of our system. To do this we used structural loading FoS, suspension, cooling, tolerance check, etc., all of which are discussed in the analysis section. With this in place, we were then able to focus on the reliability of our navigation algorithms. Through the use of controller evaluation, trajectory analysis and simulation, we were able to ensure the robot follows the line accurately without fail in a wide range of test cases through multiple simulations such as Webots, MATLAB, Simulink, and SolidWorks, again which will be discussed in detail below. We also took advantage of user input from both nurses and health care business representatives. We designed our system with Nurse feedback from current Nursing professionals at UCLA, Johns Hopkins University, and pitched/incorporated feedback from the Chief Executive Officer of Dignity Health Foundation.

4.1.3 – Safety

Another main design component was safety. This is a very important area because of the intensity of our environment. Hospitals have strict guidelines and obviously place a large emphasis on patient and staff safety. With this in mind, we sought to follow the International Organization for Standardization (ISO) for robots and their systems integration in addition to following CDC and hospital building codes and guidelines. Some of the ISO standards we tried to adhere to include cableless teaching pendants, human robot collaboration, emergency guard systems, and data-based diagnostics for improvement initiatives and failure modes.

First, ISO standard includes requirements for unique identification of cableless devices — so only one cableless pendant can be used per robot to prevent unintended operation of another robot that may result in a hazard to personnel. Our system does not require a pendant at all as we have hardcoded our algorithms through the controller which was tested to ensure reliability upon immediate integration. In terms of human-robot collaboration, if an operator must interface with the robot (in our cases Nurses interacting with the robot) traditional safety controls require help to confirm that the robot is in a safe state or position, which typically means safely limiting its motion, or bringing it to a full stop and removing its energy source. We have designed our robot according to safe speed requirements and designed our interface to be as easy for nurses to use as possible. We have also worked hard to ensure the safety of our system through the use of an emergency guard system. This again was an important side effect of our environment and we had to make sure we addressed these scenarios. To handle this, we combined an algorithmic approach including the use of complex obstacle detection systems for different scenarios with the robotic system design as a whole to minimize hazard risk. Our path following system and defined coordinate space offers a unique safety insurance for our robot. And lastly, data provided by advanced automated safety systems contributes to continuous improvement initiatives by measuring a robot system's faults and failures on a statistical and historical basis. We throughout the quarter used our simulation to ensure not only that our robot would work as designed when in proper conditions but would also function accordingly when faced with unfamiliar scenarios.

4.1.4 – Cost

In order for our robots to best serve their purpose, they need to additionally be affordable so that the people are not afraid to invest. As talked about with our emphasis on easy and adaptable system integrations for different hospitals, there is the other portion which is cost. Although patient care is the priority of hospitals everywhere, it is important to remember that they are also businesses and as with any product, it is crucial to consider cost-effectiveness. This is also heavily reliant on our competitors as well. We felt one of the main areas we could again set ourselves apart was cost. We have designed our robot with this in mind and we believe with our minimal line installation and robot cost that we can be marketable to any hospital and encourage investment to cut cost in the long run. Healthcare spending continues to rise with aging population. Efficiency and costs are a top priority – yet wages are driving up costs. So by re-allocating nurse’s time, we are improving productivity, limiting injury risk, and increasing worker satisfaction. Our goal was to enhance the nurse workforce as opposed to replacing jobs and with our low cost, we feel we can achieve this.

4.1.5 – Aesthetics

Lastly, we felt it was important to remember that this is a newer technology that very few people are used to in a vulnerable environment and so in addition to functionality, we needed to ensure our robots were not only futuristic but welcoming at the same time. Among the many factors that can determine a robot's acceptability, such as purpose or safety, its physical appearance can instantly affect how users perceive it. Therefore, we felt it was of high importance that the robot be designed in such a way that its skills and functions are quickly and easily communicated to avoid ambiguities and concerns while at the same time impressing viewers. Through the use of multiple iterations and user feedback, we feel we have worked to achieve a sellable and original aesthetic.

5 – System design

Figure 7: Rendering of our robot [1].

5.1 - Mechanical engineering design

5.1.1 - Frame Design

We start the design by determining a suitable frame size for the robot. According to the Life Safety Code Chapter 18[7], "A new hospital corridor must provide a minimum width of 8 feet (2440 mm) under Chapter 18...Where dispensers are installed in a corridor, the corridor shall have a minimum width of 6 ft (1830 mm)." The above code implies that our robot should operate within a distance of 0.6m to one side of the wall, which suggests that it is conservative for our robot to have an overall dimension that should not exceed 0.5m in width. This dimension is very important in that not only it will affect the height of the robot to be stable but also it will yield the kinematic results from our mathematical formulation. We also refer to the dimensions of our competitor's robot to confirm that our previous assumptions are reasonable.

Next, the materials used to construct the frame combined with the geometry of the structure must be able to endure the static and dynamic loads as well as the reacting moment associated with the actuators.

The frame is made out of 10x10x1.5mm and 20x20x2mm 6061 alloy aluminum square tubings as opposed to the originally proposed PP copolymer. The total length of square tubings used to construct the frame is 4140mm. The corners are reinforced with gussets and the rest of the junctions will be welded in place since the robot is unlikely to experience any lateral load.

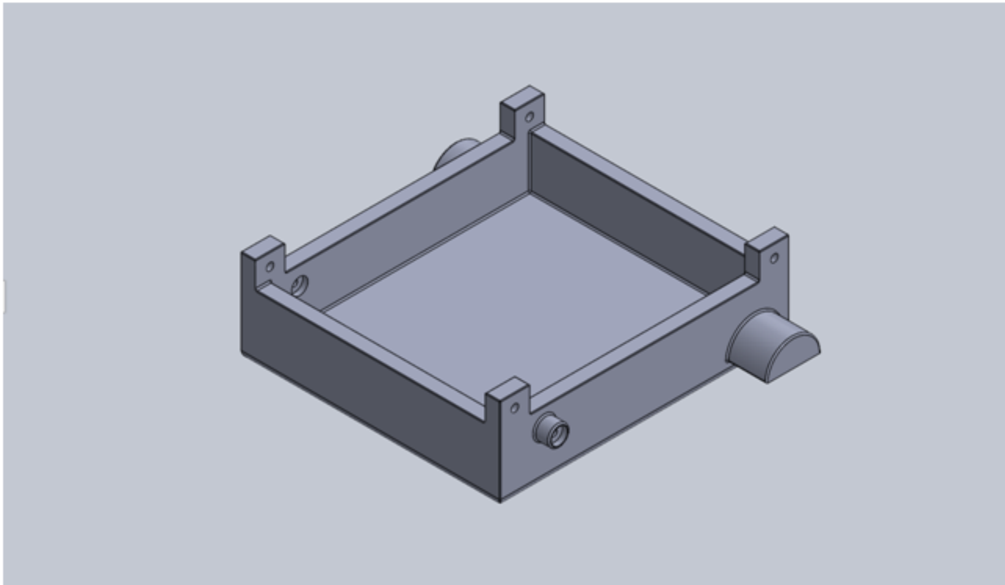


Figure 8: Copolymer Unibody Prototype

Figure 9: Tubular Frame Chassis

The advantages of using square tubings over polymers are the following:

1. The frame is much easier and more cost-effective to construct with stock tubings compared to the copolymer. Even though the cost of raw materials is higher for 6061 aluminum stock tubings, roughly $10 per meter, the quantity needed is much less compared to using copolymer. The need of creating a mold for plastic forming can impose another $3000 into the cost.

2. 6061 alloy aluminum is much stronger than most polymers. Its tensile strength is 124084000 N/m^2 and its yield strength is 55148500N/m^2 while the PP copolymer only has a tensile strength of 27600000N/m^2.

3.Precision parts such as bearings can be fitted into machined billet blocks rather than held inside polymers that will deform over time.

5.1.2 - Drivetrain

We intend the robot to move no faster than a nurse so that the nurse will not lose track of the robot and the robot will impose less danger to the surroundings. According to the Centers for Disease Control and Prevention (CDC), the range for moderate-intensity activity is 1 to 1.8 meters per second (m/s). A moderate pace is 1 to 1.6 m/s, while a brisk pace is 1.6 to 1.8 m/s. In addition, our competitor TUG autonomous robot has a top speed of 0.76 m/s (Figure 10). Thus, we have decided that the top speed of our robot being 1.34 m/s is reasonable.

Figure 10: TUG Autonomous Mobile Robot Speed.

As for choosing a proper actuator for our drivetrain, it needs to be simple and reliable. To ensure the robot has a small footprint, the drivetrain needs to have minimum moving parts to accommodate for power in a limited space. By minimizing the number to just several core components it allows us to quickly identify the weak points of the mechanism and make the robot easy to maintain. The actuator must provide adequate torque to drive the robot to its maximum speed in a relatively short period of time while it is capable of operating at high RPM if the wheels are small. For an actuator to meet both torque and speed requirements it is apparent to us that a gearmotor is the perfect candidate.

The size of the driving wheels determines the RPM output of the actuators in that the robot can achieve the same linear velocity with bigger wheels at relatively lower RPM. However, if the wheels are too large, they will not only interfere with the top shelf but also elevate the center of gravity of the robot, which is undesirable. The material of the wheels needs to have great traction to the floor and be able to withhold the weight of the robot.

By connecting the wheel shaft directly to the motor shaft, we will reduce the powertrain loss due to heat and minimize part wear. The wheel shaft and motor shaft are held in place coaxially with a coupler. The keys ensure that the torque will be transferred from the motor shaft to the wheel and they will be rotating in sync. The set screws are not designed to prevent "shaft walk" during rotation, thus the wheel shaft has grooves on both sides of the wheel bearings to receive c-clips that will keep both the bearings and shaft in check. The wheel bearings are to reduce friction and support the wheel shaft.

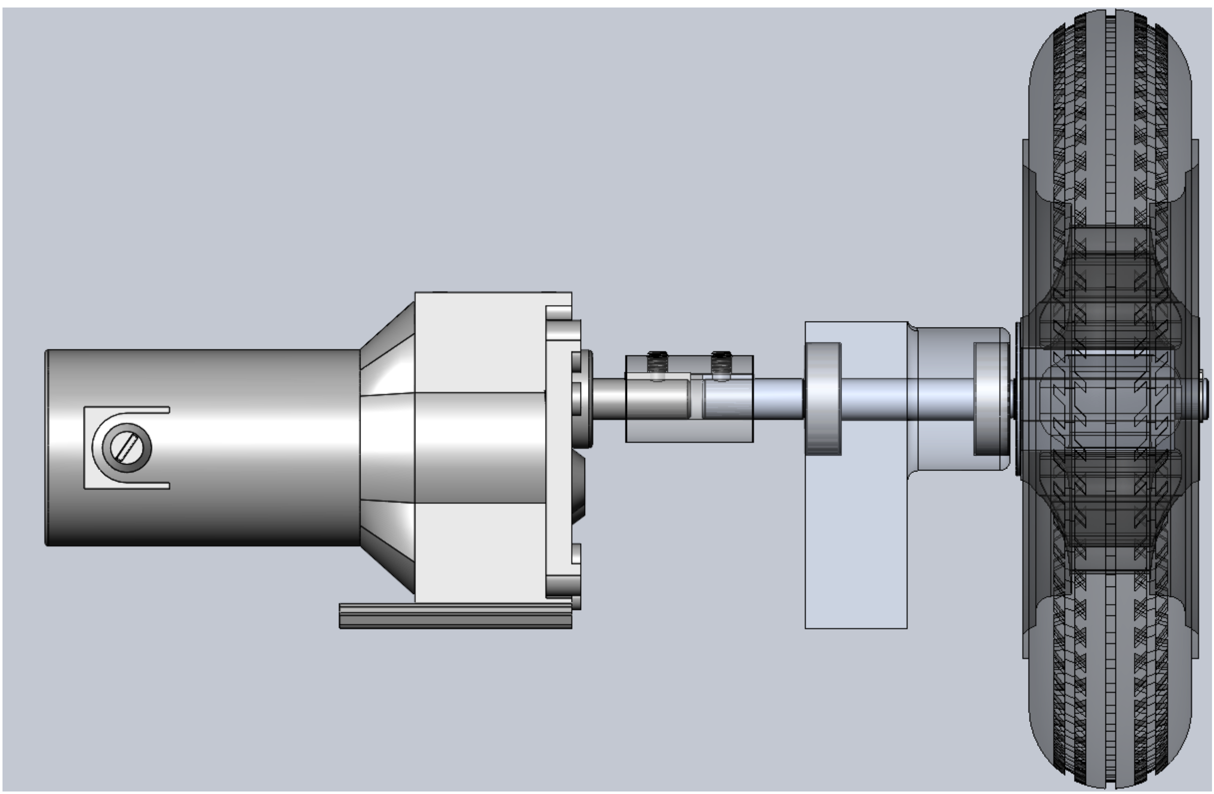


Figure 11: Drivetrain Components

The chosen actuator for our robot is Crouzet Gearmotor 808050Y15.31Z.

Specifications			
		17 Watts	**17 Watts**
Type		80 805 0	80 805 0
Voltage		12 V	24 V
Standard speed (rpm)		2600 rpm	2600 rpm
Output speed (rpm)	**Ratios (i)**		
616	4.22	**80 805 0X04.22Z** ●	**80 805 0Y04.22Z** ●
385	6.75	**80 805 0X06.75Z** ●	**80 805 0Y06.75Z** ●
339.5	7.66	**80 805 0X07.66Z** ●	**80 805 0Y07.66Z** ●
212	12.25	**80 805 0X12.25Z** ●	**80 805 0Y12.25Z** ●
170	15.31	**80 805 0X15.31Z** ●	**80 805 0Y15.31Z** ●
106	24.5	**80 805 0X024.5Z** ●	**80 805 0Y024.5Z** ●
68	38.28	**80 805 0X38.28Z** ●	**80 805 0Y38.28Z** ●
53	49	**80 805 0X00049Z** ●	**80 805 0Y00049Z** ●
42.5	61.25	**80 805 0X61.25Z** ●	**80 805 0Y61.25Z** ●
21	122.5	**80 805 0X122.5Z** ●	**80 805 0Y122.5Z** ●
10.5	245	**80 805 0X00245Z** ●	**80 805 0Y00245Z** ●
General characteristics			
Motor		82 800 0	82 800 0
Gearbox		81 035 0	81 035 0
Maximum permitted torque from gearmotor under continuous conditions (N.m)		5	5
Axial load (dynamic) daN		6	6
Radial load (dynamic) daN		6	6
Max. output (W)		16.3	17
Nominal output (W)		15.7	15.6
Gearbox case temperature rise (°C)		44	40
Weight (g)		920	920

Figure 12: Actuator Data Sheet

The actuator operates on 24V because it is a very common voltage to use among our competitors in that it is safe and can provide enough electrical power compared to lower voltage-rated motors. It can provide sufficient torque to break the initial rotational resistance and has a maximum RPM that will enable our robot to reach its top speed, that way we do not need to design a separate gear reduction mechanism to trade torque for speed or vise versa, thus reducing the complicity of the drive train and minimizing part wear.

The distance from the center of the motor shaft to the base of the robot is 44.80mm, if we choose a 152.40mm wheel that would give us 10.18mm of ground clearance (Figure 13) to accommodate deflection due to impact load and to make enough room for color sensors that will be attached to the bottom of the robot. Any wheel size that's less than 152.40mm diameter will result in insufficient ground clearance and anything bigger will result in an unnecessary increase in height of the center of mass to prevent the wheel from hitting the storage structure, or otherwise if the wheels are to be put outside the structure that will violate the dimension requirement.

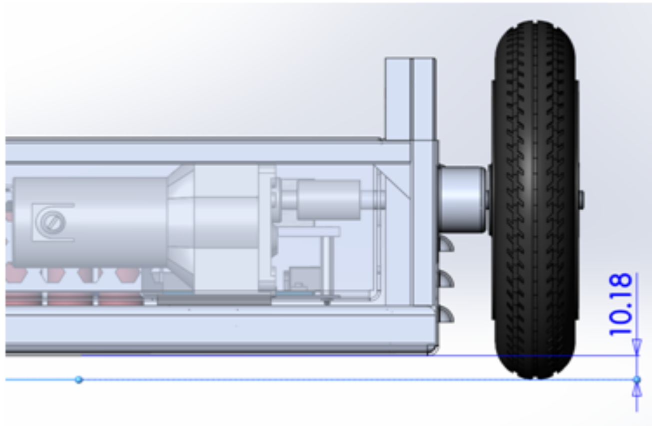


Figure 13: Wheel Ground Clearance

With all of the above considered, we decided to choose the 152.40mm(6”) rubber caster wheel shown below.

Hamilton
6" Diam x 2" Wide, Hard Rubber Caster Wheel - 650 Lb. Capacity, 2-1/4" Hub Length, 3/4" Axle Diam, Straight Roller Bearing
MSC Part #: 52128162 Mfr Part #: W-620-EH-3/4 | Write the first review

Price $36.19 Add to Cart

Specs Reviews Recommendations

Specs

Wheel Material	Hard Rubber
Wheel Diameter (Inch)	6
Wheel Diameter (Decimal Inch)	6
Wheel Width (Inch)	2
Axle Size (Inch)	3/4
Axle Size (Decimal Inch)	0.7500
Load Capacity (Lb.)	650
Bearing Type	Straight Roller
Hub Length (Inch)	2-1/4
Additional Information	Abrasion Resistant; Floor Protection; High Temp. (130 F); Moisture Resistant; Rolling Ease

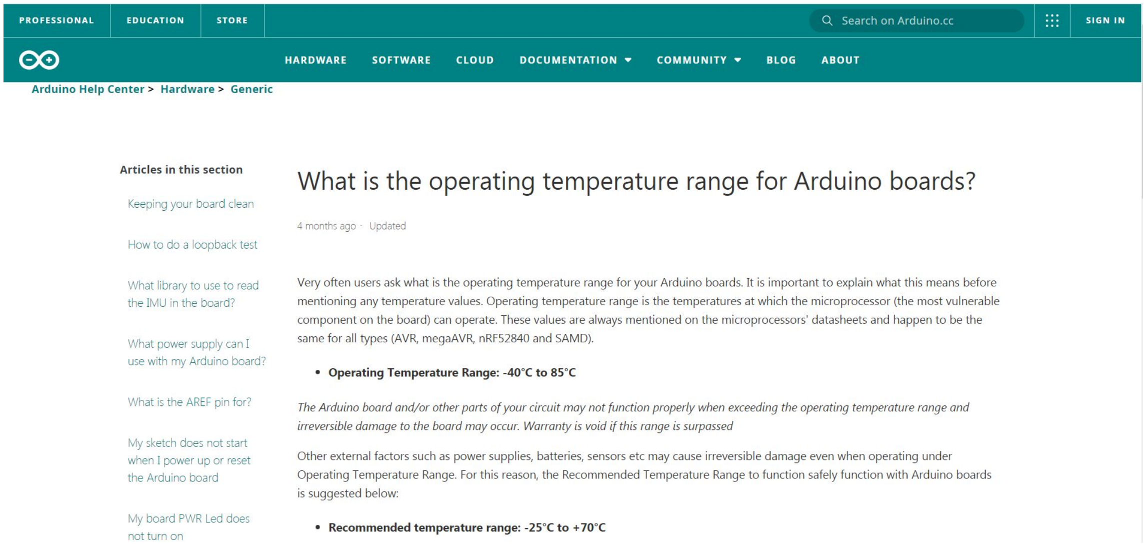
HAMILTON.

MSC Part #:	52128162
Mfr Part #:	W-620-EH-3/4
Country of Origin: Country of Origin is subject to change	China

Figure 14: 6” Wheel Data Sheet

5.1.3 - Thermal

Our hospital robot must be safe. One aspect of being safe is to keep the electronics cool to prevent parts damage caused by overheating. Each electrical component has different maximum operating temperatures according to the datasheets from the manufacturer, but it is safe to set the upper-temperature limit to be 70°C. A sufficient cooling solution should be deployed to keep the internal temperature under the limit. Since the robot is battery-powered we have to take the precaution of battery safety because there have been accidents in robotics competitions where the batteries exploded upon removal due to overheating and lack of proper protection. Moreover, the enclosure should be free of dust and water in case of overheating or water damage.



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- How to do a loopback test
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- What power supply can I use with my Arduino board?
- What is the AREF pin for?
- My sketch does not start when I power up or reset the Arduino board
- My board PWR Led does not turn on

What is the operating temperature range for Arduino boards?

4 months ago · Updated

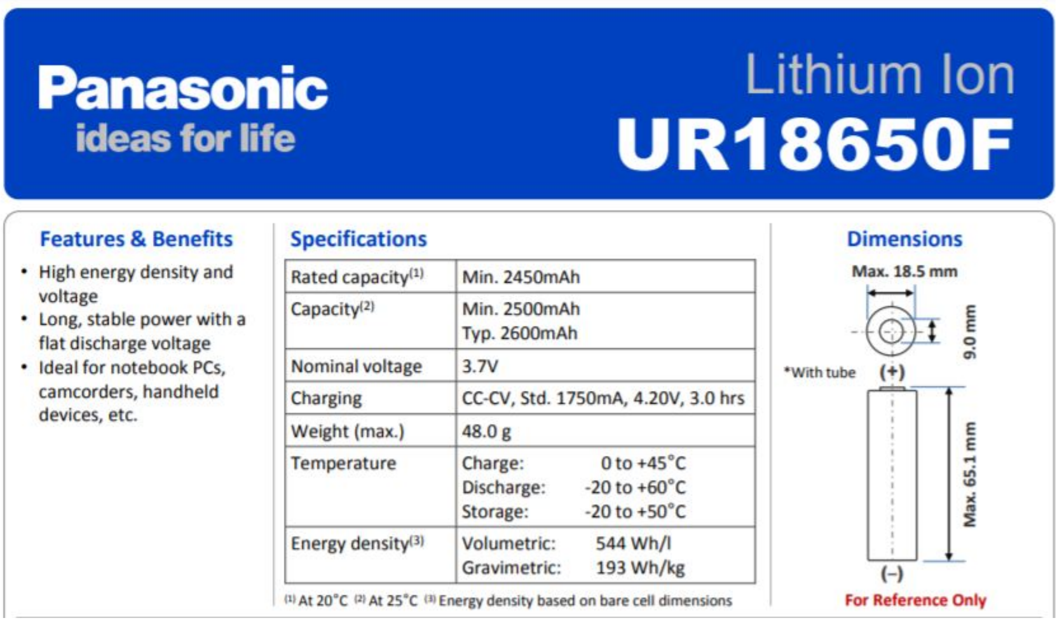
Very often users ask what is the operating temperature range for your Arduino boards. It is important to explain what this means before mentioning any temperature values. Operating temperature range is the temperatures at which the microprocessor (the most vulnerable component on the board) can operate. These values are always mentioned on the microprocessors' datasheets and happen to be the same for all types (AVR, megaAVR, nRF52840 and SAMD).

- **Operating Temperature Range: -40°C to 85°C**

The Arduino board and/or other parts of your circuit may not function properly when exceeding the operating temperature range and irreversible damage to the board may occur. Warranty is void if this range is surpassed

Other external factors such as power supplies, batteries, sensors etc may cause irreversible damage even when operating under Operating Temperature Range. For this reason, the Recommended Temperature Range to function safely function with Arduino boards is suggested below:

- **Recommended temperature range: -25°C to +70°C**



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Lithium Ion
UR18650F

Features & Benefits

- High energy density and voltage
- Long, stable power with a flat discharge voltage
- Ideal for notebook PCs, camcorders, handheld devices, etc.

Specifications

Rated capacity(1)	Min. 2450mAh
Capacity(2)	Min. 2500mAh Typ. 2600mAh
Nominal voltage	3.7V
Charging	CC-CV, Std. 1750mA, 4.20V, 3.0 hrs
Weight (max.)	48.0 g
Temperature	Charge: 0 to +45°C Discharge: -20 to +60°C Storage: -20 to +50°C
Energy density(3)	Volumetric: 544 Wh/l Gravimetric: 193 Wh/kg

(1) At 20°C (2) At 25°C (3) Energy density based on bare cell dimensions

Dimensions

For Reference Only

Figure 15: Recommended Temperature range for Arduino uno and 18650 Battery Data Sheet

MEAN WELL

100W Single Output Switching Power Supply

LRS-100 series

■ Features

- Universal AC input / Full range
- Withstand 300VAC surge input for 5 second
- Protections: Short circuit / Overload / Over voltage
- Cooling by free air convection
- Miniature size and 1U low profile
- Compliance to IEC/EN 60335-1(PD3) and IEC/EN61558-1, 2-16 for household appliances
- Operating altitude up to 5000 meters (Note.7)
- Withstand 5G vibration test
- LED indicator for power on
- No load power consumption<0.3W
- Over voltage category III
- 100% full load burn-in test
- High operating temperature up to 70℃
- High efficiency, long life and high reliability
- 3 years warranty

■ Applications

- Industrial automation machinery
- Industrial control system
- Mechanical and electrical equipment
- Electronic instruments, equipments or apparatus
- Household appliances

Figure 16: Power Supply Datasheet

The main components of the enclosure are an inner shell, an outer shell, and a cover. The inner shell is made out of 18-gauge 6061 aluminum sheet metal, it is the host for all the electrical components, including motors, sensors, batteries, controllers, drivers, and the power supply. These components are subject to cooling by convection from four 60mm x 60mm fans on the sides. The fan grills are wire shapes because studies show that they allow the moist air to go through. The batteries are secured with a perforated metal brace. The outer shell is mainly for aesthetics but with louvers for exhaust hot air. The cover has perforated holes for the fans to draw air from the top, this design helps filter out dust while eliminating the chance of letting water into the system if there is water on the floor or someone accidentally splashed water on the robot. The holes are directly on top of the batteries and motors, so they are the first to be cooled by incoming air. Underneath the cover, there is an air filter that will block dust up to 40 microns.

Figure 17: Inner Shell

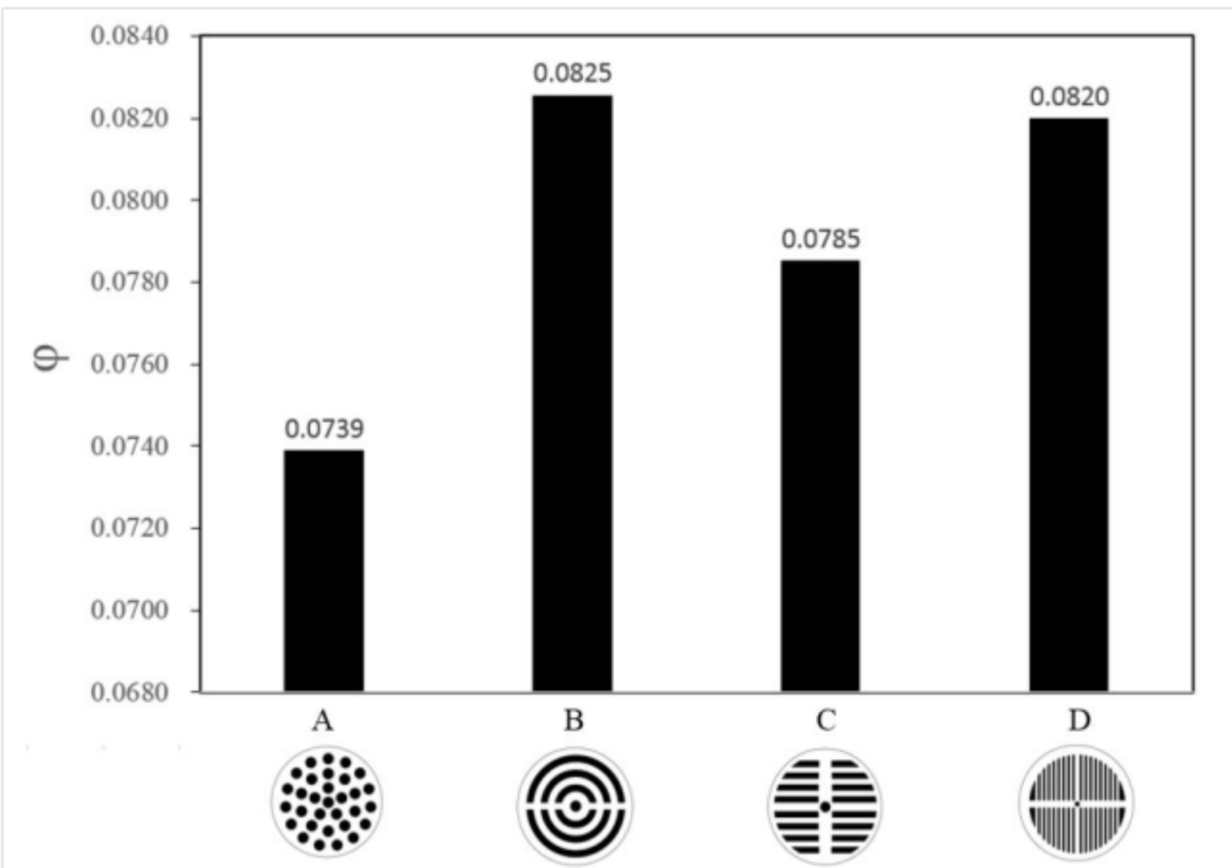


Figure 18: Variation of Mass Flow Rate Coefficient of Motor Cooling fan With Inlet Vent Shape

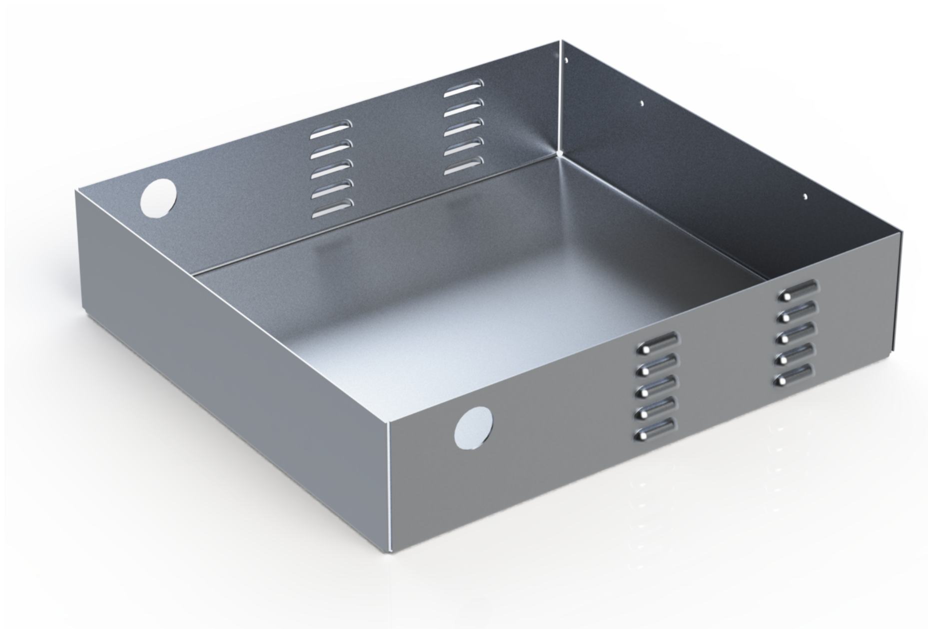


Figure 19: Outer Shell

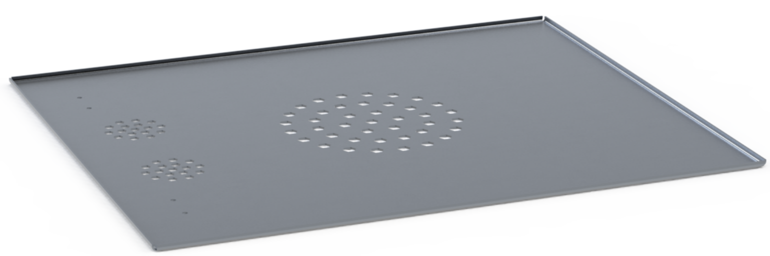


Figure 20: Enclosure Cover

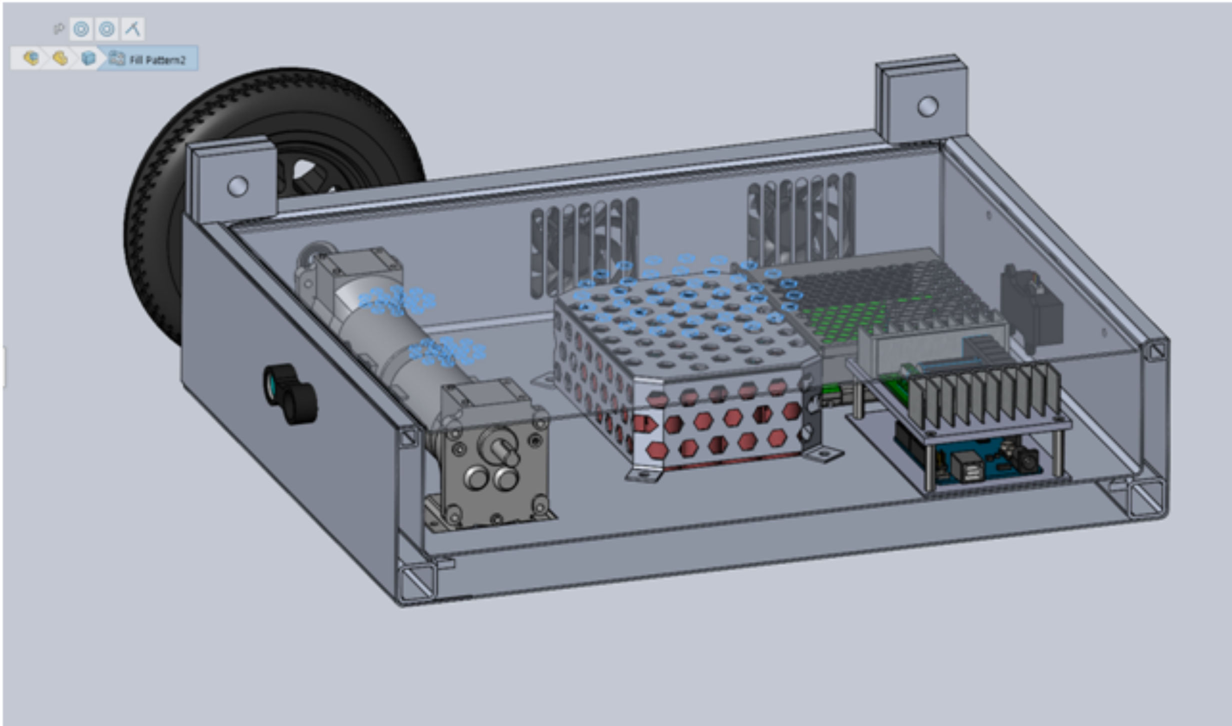


Figure 21: Electronic Components Arrangements Inside the Enclosure

5.1.4 - Suspension

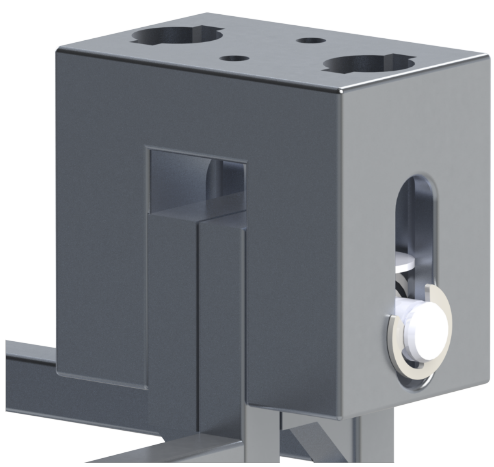


Figure 22: Suspension block subassembly.

The suspension amounts to four suspension blocks bolted to the underside of the storage frame and resting on eight suspension springs. The blocks are free to travel in the vertical direction with respect to the chassis below. Each spring has a constant of 30.2047 kN/m, which gives the storage unit a resonant frequency more than twice the expected disturbance band (i.e. > 2*5 Hz.). The analysis behind the spring choice is discussed in section 6.

The blocks and springs sit on a shaft in a bearing that passes through the chassis frame, as seen in Figure 22.

The suspension brackets can be machined conventionally; the bearings, pins, clips, and washers can be obtained from a supplier like McMaster-Carr.

5.1.4 - Storage

Figure 23: Storage unit subassembly.

The storage unit is based on a frame of hollow Aluminum 6061 beams (25x25x2.5mm) inside a thin plastic housing. The beams are welded to a base of the same material with a thickness of 10 mm. This frame rests on a thin Aluminum 6061 base plate that physically separates the storage zone from the robot chassis and provides an additional layer of safety against explosive electrical malfunctions.

The frame has three levels for shelf installation, in the form of welded-on mounts. The shelves are thin stainless-steel sheets (2.5 mm). Both the storage frame and the shelves possess factors of safety above 5 when loaded to excess (more than 30 lbs of linens per shelf). The front of the storage unit has open spaces through which to place or remove linens. A more complete discussion of the static analysis of the frame is presented in section 6.

The gaps between the shelves leave enough room for an appropriate amount, of linens and make organization of requested room supplies simple. Operators may insert and remove materials without worrying about the stability of the storage unit, and the flat, open storage spaces make the unit easy to examine and to clean.

The aluminum beams may be obtained from a supplier and cut to size; the frame bottom can be machined conventionally; the bottom plate can be made from sheet metal with holes drilled; the shelves may be found at a supplier or cut from sheet stock. The shelf mounts must be welded onto the beams.

5.1.5 - Aesthetic housing

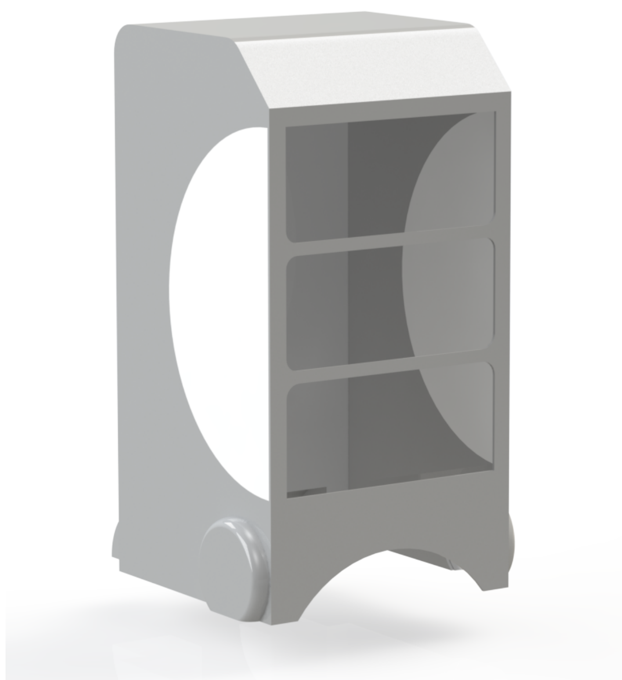


Figure 24: Outer housing.

We wanted to make the robot more appealing to customers, users, and observers. To address this, we modified the outer plastic housing with an improved design. The housing is a 5 mm sheet of PP copolymer with two hemispheric acrylic sheets. Its total mass is 7.7 kg. The lower main body is separate from the top and hangs on the frame. There is enough space left around the outer shell not to interfere with cooling of the interior of the chassis.

We expect to use vacuum thermoforming to produce the two large PP copolymer parts. The negative space can be cut away after forming. The smaller parts (wheel and swivel caps) may be manufactured this way or with a small injection mold. The front grate can be cut from a sheet of plastic or molded.

5.2 - Electrical and computer engineering design

5.2.1 - Controller

Description of subsystem: The controller electrical subsystem consists of the controller and controller algorithm, and the IR and LIDAR sensors.

5.2.1.a - Robot sensing - IR

We decided to use an infrared LED to emit IR light toward the ground, which then would be reflected back onto the photodiode if the light is transmitted onto a white surface. We then decided our line would be white with one IR photodiode and infrared LED on each side of the line, with black surrounding the sides of the path. When the left side's LED shines light onto the line (due to the robot moving off course to the right) for instance, the left side's photodiode will pick up IR light and in response, we will slow down the left wheel of the robot to correct the robot's course.

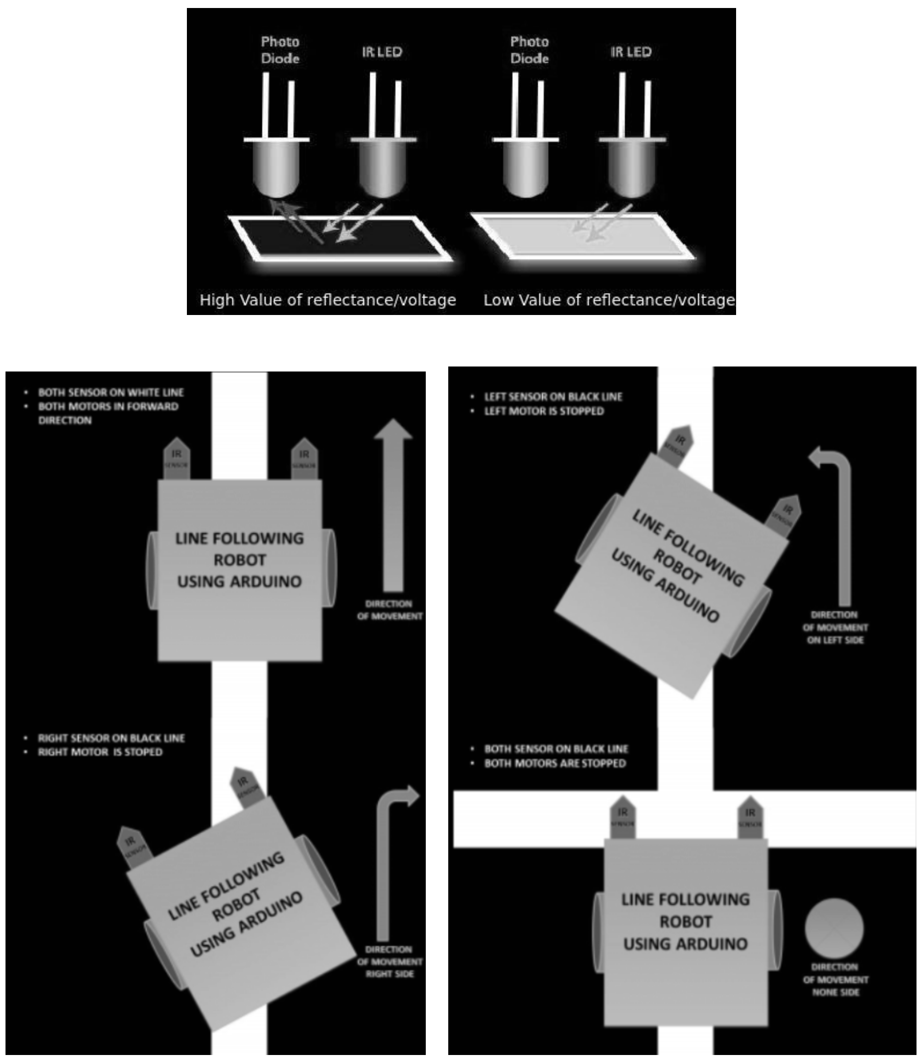


Figure 25: Line following and IR basics.

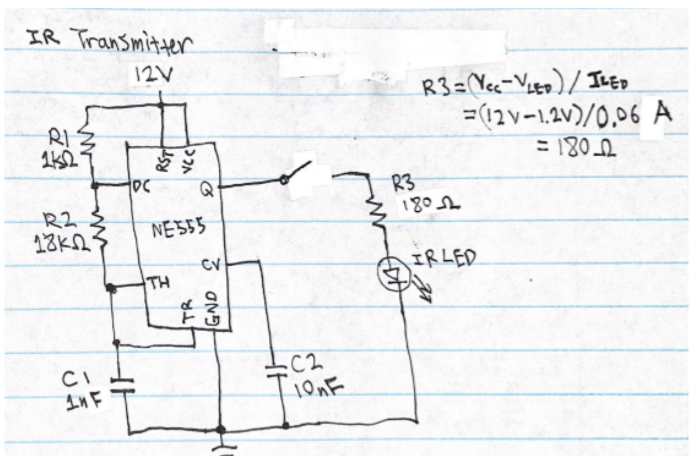
So, for our required elements, we needed the following circuit components:

- Transmitter circuit
    - Infrared LED (LTE-4206)
    - NE555 IC
    - Resistors (1kOhm, 18kOhm, 180Ohm)
    - Capacitors (1nF, 10nF)
    - Voltage source (12V)

- Receiver circuit
    - IR photodiode (TSOP1738)
    - Resistor (10kOhm)
    - Voltage source (5V)
    - Controller (Arduino Uno)

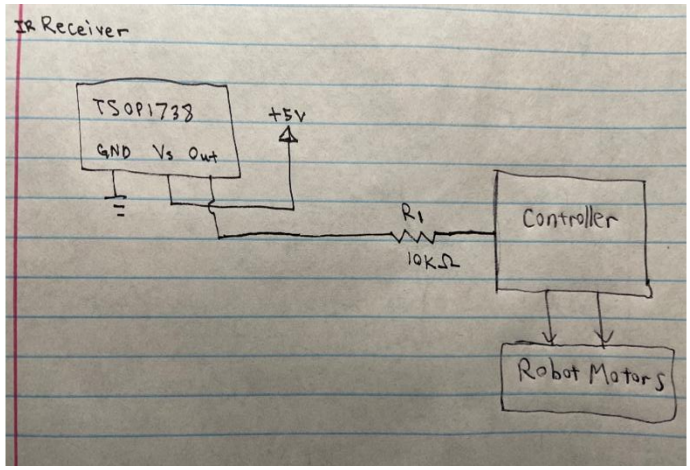
For the IR circuit design:

- Transmitter circuit



    - The NE555 will be "in Astable Multivibrator mode. In this mode, the 555 IC will work as a free running oscillator and generates an approximate 38 KHz square wave" fed into the IR LED input (ElectronicsHub). The 38 KHz square wave is required for our photodiode, as its part number (17**38**) indicates a 38KHz band-pass filter applied by the photodiode according to the datasheet.
    - We use the LTE-4206 IR LED that has a 60mA continuous forward current rating and 1.2V forward voltage rating, so we need a 180Ohm resistor in series with the LED.
    - NE555 RST pin "should be connected to VCC to prevent electrical noise accidentally causing a reset" if not used (ApogeeWeb).
    - NE555 CV pin "should be connected to a 10 nF decoupling capacitor (between this pin and GND) to ensure electrical noise doesn't affect the internal voltage divider" if not used (ApogeeWeb).
    - TH and TR pins are connected to each other and so the 555 will self trigger and act as a free running multivibrator (ElectronicsHub, ElectroSome).

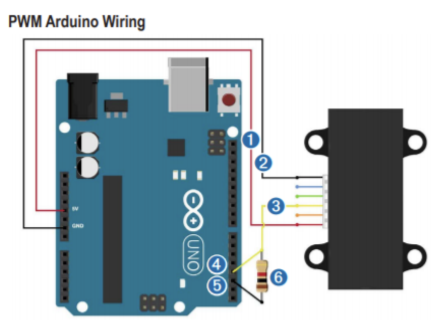
- Receiver circuit



    - TSOP1738 output goes low upon IR detection, and is fed into the controller.

5.2.1b - Robot sensing - LIDAR

The Garmin Lidar Lite v3 sensor we chose has a measurement range of 40 meters, and below is the circuit diagram provided for integrating the Lidar sensor with our Arduino controller. According to the sensor's datasheet, "Pulling the mode control pin low will trigger a single measurement, and the device will respond by driving the line high with a pulse width proportional to the measured distance at 10 µs/cm," and if the "mode control pin is held low, the [distance measurement] process will repeat indefinitely, producing a variable frequency output proportional to distance." We can obtain the output signal, measure the frequency, and stop our robot 1.5 meters before hitting an obstacle with the following conversion of distance to pulse width: 150 cm * 10 µs/cm = 1500µs pulse width.



Item	Description	Notes
1	5 Vdc power (+) connection	Red wire The sensor operates at 4.75 through 5.5 Vdc, with a max. of 6 Vdc.
2	Power ground (-) connection	Black Wire
3	Mode-control connection	Yellow wire
4	Monitor pin on microcontroller	Connect one side of the resistor to the mode-control connection on the device, and to a monitoring pin on your microcontroller.
5	Trigger pin on microcontroller	Connect the other side of the resistor to the trigger pin on your microcontroller.
6	1kΩ resistor	

Figure 26: Lidar PWM mode - Arduino Diagram and Specifications.

5.2.1c - Robot movement

We decided to use 2-wheel differential drive as opposed to independent steering because of the simplicity of our environment and because power performance converges for larger radius turns. Additionally, we decided on front wheel drive because the ball transfers we used are point contacts to the ground and thus don’t contribute to the direction.

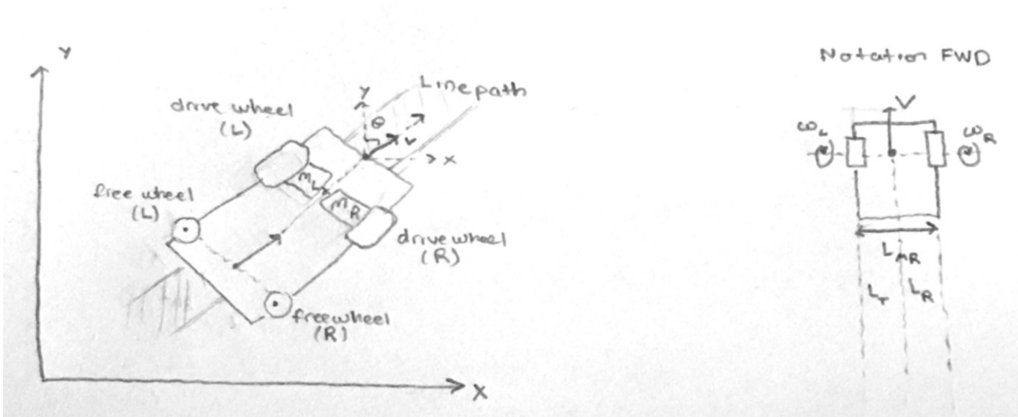


Figure 27: Kinematic diagrams.

Linear velocities for both of the front driven wheels v_L and v_R can be calculated refer to the wheel radius R and angular velocity each wheel and,

$$v_r = \omega_R R$$
$$v_L = \omega_L R$$

A linear velocity v for the mobile robot calculated by average of the angular velocity of right and left driven wheel. It called by direct kinematic model of TWD linear velocity,

$$v = \frac{v_r + v_L}{2}$$
$$v = \frac{(\omega_R + \omega_L)R}{2}$$

Component of linear velocities $\dot{x}$ *and* $\dot{y}$ and derived from the coordinate system consist of x and y position,

$$\dot{x} = v\ sin\theta$$
$$\dot{y} = v\ cos\theta$$

Substitution of linear velocity (4) to the component velocities (5) and (6) imply that function of angular velocities to be,

$$\dot{x} = \frac{(\omega_R + \omega_L)R}{2}\ sin\theta$$
$$\dot{y} = \frac{(\omega_R + \omega_L)R}{2}\ cos\theta$$

As for the orientation, we can define L_L *and* L_R to be the length from the track line to the left and right wheels respectively and L_{MR} to be the length between the TWD,

$$\theta = \frac{L_R - L_L}{L_{MR}}$$

For a high-level overview of our obstacle detection sensor formulation, we first must note that our robot will move at up to 3 miles per hour. Therefore, we will incorporate readings from our LIDAR sensor into our microcontroller code, we decided to stop the movement of the robot if there is an obstacle within 1.5 meters of the path.

We decided to formalize our design in terms of block diagrams and binary diagrams. First, we created our high-level path algorithm diagram. This is the overall look at our system, not including the PID and obstacle detection subsystems.

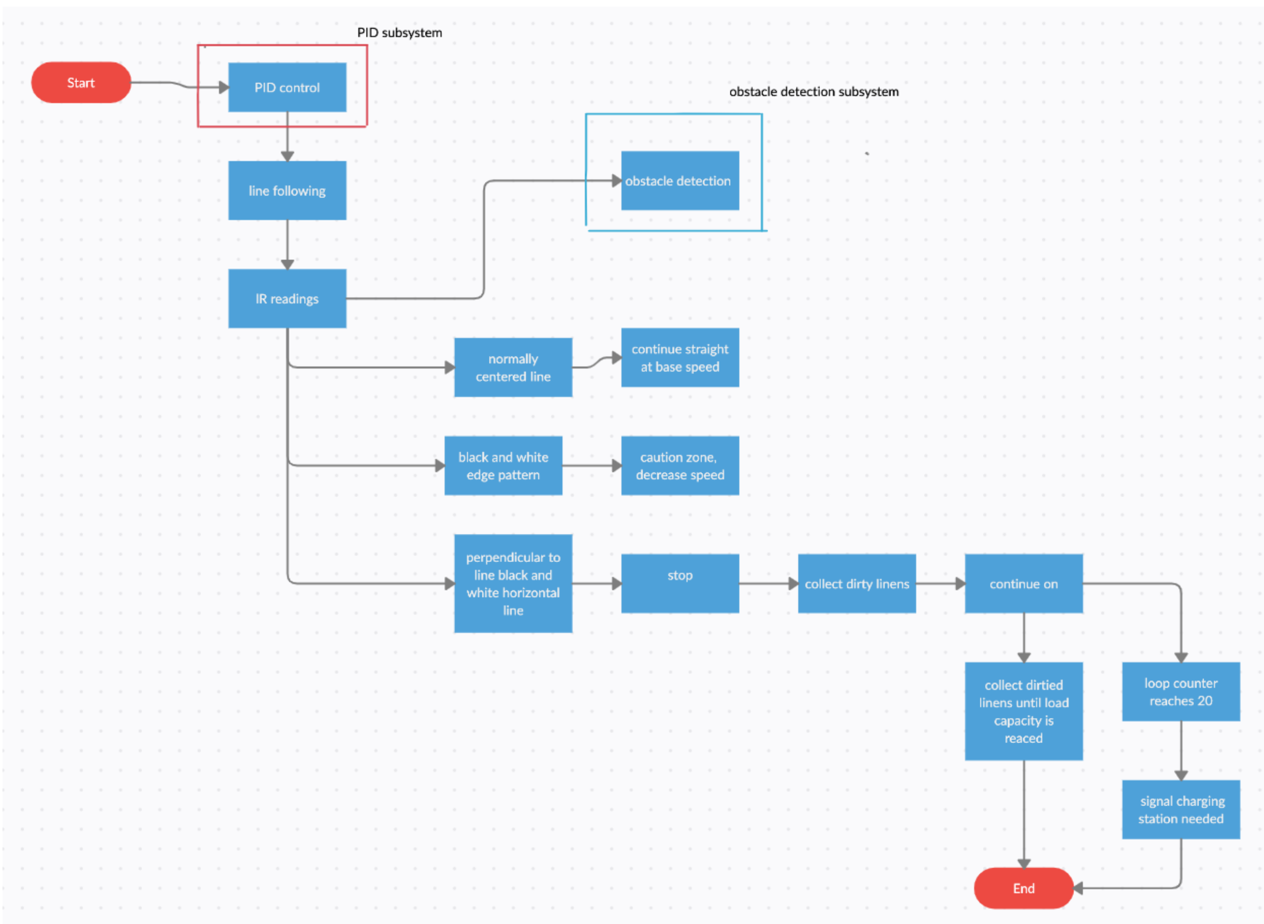


Figure 28: High level system block diagram.

For the obstacle detection subsystem, we created binary charts for both emergency and non-emergency cases as follows. We came up with a variety of cases where an obstacle in the stochastic environment that is a hospital floor could block our robot from moving on its designated path. The robot could have an obstacle in front, or it could have an obstacle behind in which case it will stop moving and wait for the obstacle to disappear, issuing an alert if it's waiting too long. If the robot is stopped in front of a doorway, we will have it attempt to move out of the doorway on its own. Any of these conditions being fulfilled or a combination of these conditions on the left of the diagram makes our robot enter a variety of states, in which the robot will have a unique response to the situation.

State Chart

Robot in slow zone (i.e. blocking doorway)	0	1	0	1	0	1	0	1
Obstacle in front	0	0	1	1	0	0	1	1
Obstacle behind	0	0	0	0	1	1	1	1
Action Taken	follow line	follow line slowly	stop until obstacle in front gone	move back	follow line	follow line slowly	stop until obstacle in front gone	stop until obstacle in back or front gone

Table 5: Emergency obstacle detection subsystem.

For our controller, we used a path following PID algorithm similar to our analytical python simulation, but this time do not base our error on angular velocity alone. Although this worked well for reaching targets at defined points on a grid where less direct paths were used (lots of angular shifts), our webots navigation is more realistically. Here is the general system diagram to describe the overall layout of the controller along with the function definitions.

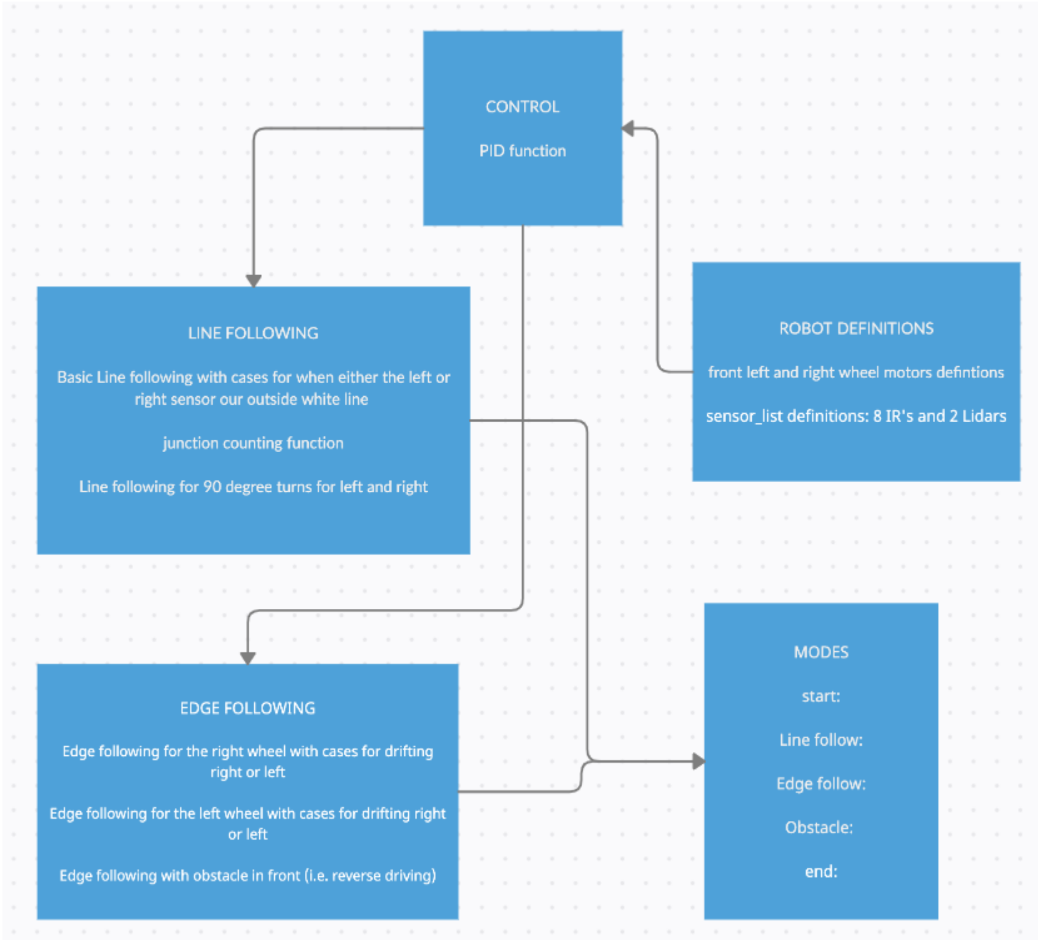


Figure 29: Webots controller block diagram.

5.2.1d - Controller Algorithm

Our controller begins with the simple robot structure definitions like the motor and sensor lists. This is followed by the error definitions and PID function. Then while the simulation is running, depending on the track and corresponding sensor readings, we will either navigate according to line following or edge following. Each reads in live sensor values and sets the correct motor speed for each of the drive wheels. Then we run the main loop where depending on particular sensor readings and obstacles, we execute one of the modes from the diagram above. There are modes for starting, line following when there are no obstacles and the IR values indicate a white line with black outer track, edge following when the left and right IR sensors pick up different contrasting values (black and white on opposite sides, not black on both sides), obstacle modes and stopping conditions.

Here is a closer look at the PID algorithm,

```
PID algorithm
     define I, D, P, kp, ki, kd
     Set the Proportional component equal to the error
     set the integral component equal to error + I
     set the derivative component equal to the error - the last_error
     set the last error equal to the current error
     define the balance = (kp*p)+(ki*i)+(kd*d)
     set rectify equal to balance
     for each correction scenario (i.e. to the left/right wheel to the
     left, left/right wheel to the right)
          rectify
     set the motor_speed
     return balance
```

For the PID tuning process, we followed an approach based on our sensor setup. We had two arrays of 8 sensors at the front and back of the robot and we considered them separately here. The general process was,

- Start with kP given kD and kI equal to zero
- First determine initial kP
  - Each Sensor returns a value between 0 and 1000
  - For an array of 8 sensors, this means total we would return a max value of 1000*(num of sensors-1)
    - Thus our range is [0, 7000]
    - Our goal is to follow exactly in the center which corresponds to Max value/2 = 3500
    - Thus our Goal is to be around a value 3500 for each of the sensor arrays at all times
  - If we consider the worst case scenario when we drift off the line to the left or rightmost sensor, the kp*error will reach 100%
  - Using this worst case, 100/goal = kp = 0.025
- We then chose I with D set to zero
  - We simply increase kI until the system oscillated quickly enough
- Finally we choose D
  - increase kD until the system minimized oscillation
  - ended up being 3x kp

In terms of worlds, we again wanted to take advantage of webots's more realistic displays in addition to functional testing, so we created multiple worlds (tracks) encompassing different aspects of our navigation.

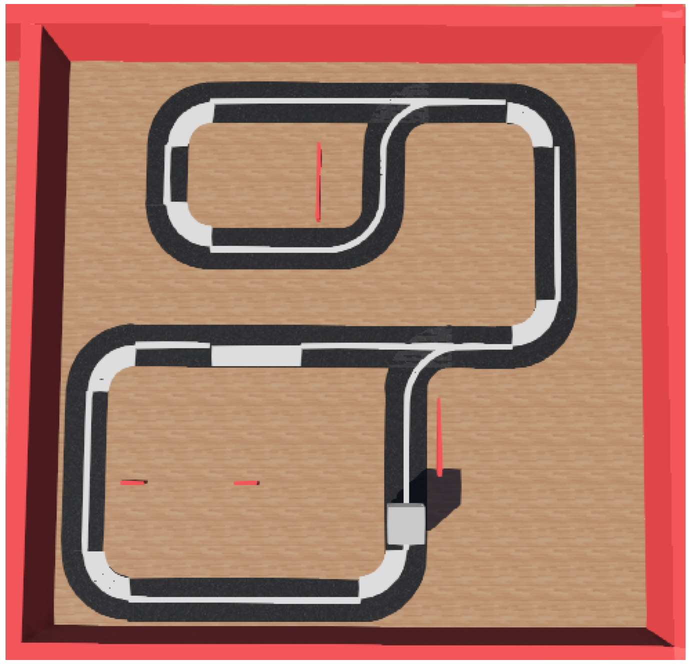


Figure 30: Webots rendering.

We additionally accomplished live-time object detection for this simulation. Our robot stops before hitting an obstacle placed in front of it in real-time and continues once the obstacle moves away. We included terminal messages in the console that reflect the process as seen below.

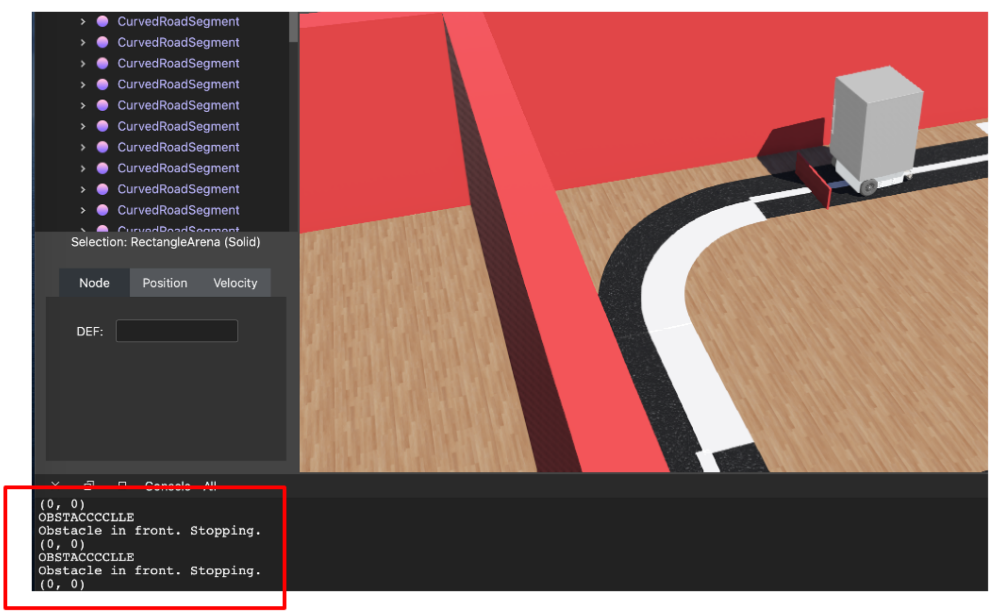


Figure 31: Live time obstacle detection for simulation.

One other important function of our controller was ensuring proper junction handling. It is first important to note that because of our wall following design, the possible junction cases are limited. In other words, because the right of our robot is always a wall, we could never have more than 1 junction. With that established, we used junctions in more ways than one. We first defined a cross junction function to allow us to later count each time we cross a junction which is important for us. Then in the line following function, we use the left half of the IR sensors to read a line coming in perpendicular to the straight line we are on and subsequently slow our speed in response to handling. We display the reading of the junction and corresponding speed change in the terminal.

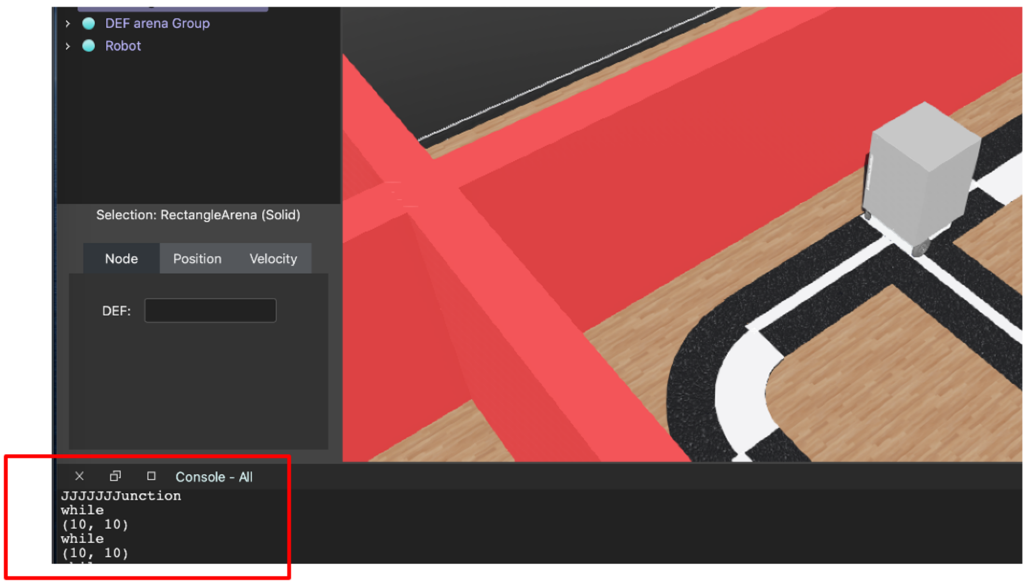


Figure 32: Live time junction detection for simulation.

The other reason junctions are important to our system is for battery life. Because webots does not really have any effective way to monitor battery during simulation, we have decided to use our junction counter as a tracker for our battery. Based on the time it takes to complete a full loop cycle and the loop counter (based on the junction counter), we navigate to a charging station at 16 cycles. We based that figure on the urban non-student size hospital, it would need to be recalculated based on the size of the hospital, but it is a very quick and simple redefinition.

$$battery\ life\ B = 6.5\ hours$$

Then the avg speed given 65% line following and 35% edge following which we fill is approximately indicative of how much each of these would most likely fill the floor.

$$avg\ speed\ S = 0.65(3) + 0.35(1.5)/2 = 1.237\ mph$$

The avg distance for the loop around the hospital floor is,

$$avg\ distance\ D = 0.495\ miles$$

So, the time per loop is,

$$t = D/S = 0.495/1.237 = 0.400\ hours$$

Meaning we can cross,

$$6.5/0.400 = 16\ junctions$$

5.2.2 - Drivetrain

Description of subsystem: The drivetrain electrical subsystem consists of the motors used to drive the robot and the battery used to power the motors.

The Panasonic NCR18650B battery will be used to power our Sabertooth 2x25 motor driver, and the 2x25's 5V and ground connections can be used to power the Arduino controller. Switch 3 on the Sabertooth should be set to the down position as specified in the Sabertooth datasheet, in order to prevent damage to lithium battery packs due to being in a severely discharged state.

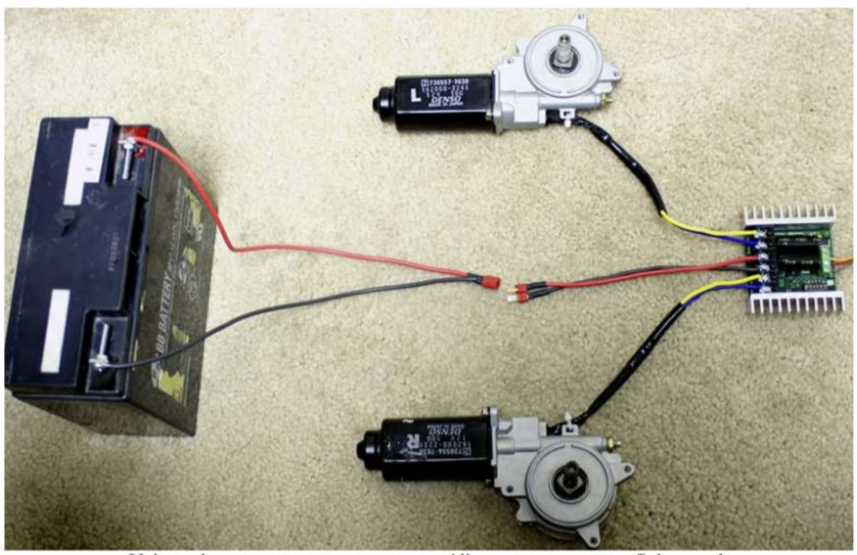
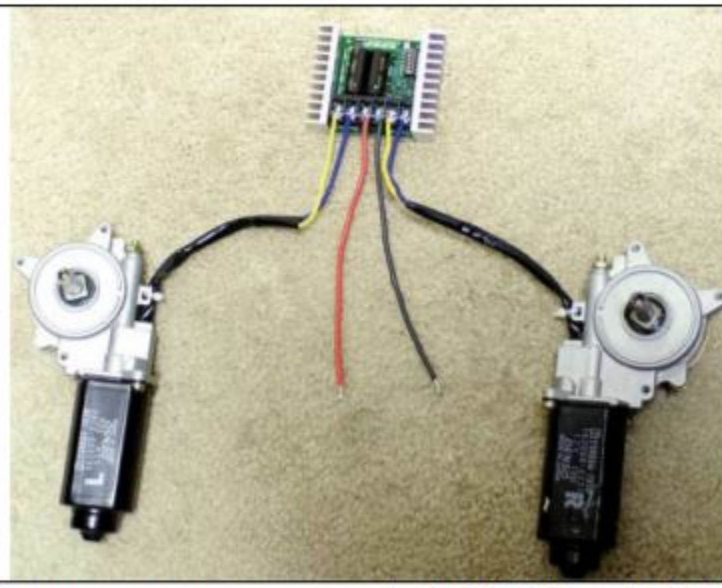


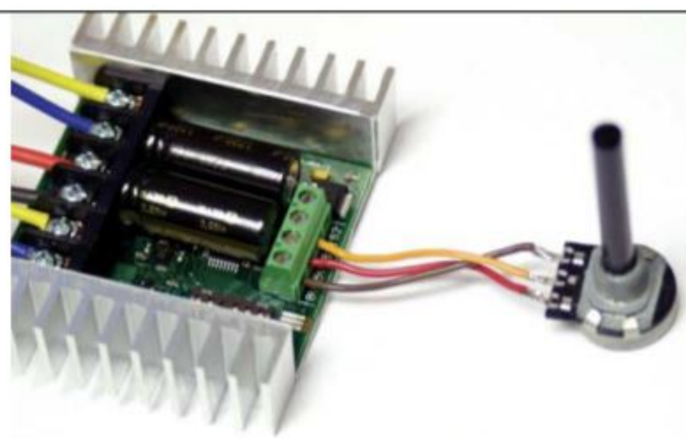
Figure 33: Connections diagram.

Two Crouzet Gearmotor 808050Y15.31Z motors will be attached to terminals M1A/M1B and M2A/M2B on the Sabertooth 2x25 motor driver.



The motors connect to terminals M1A/B and M2A/B

Our Arduino controller will control the motor driver by sending analog voltage signals to terminals S1 and S2 on the Sabertooth 2x25, using these terminals to control the speed and direction of the Crouzet motors. According to the Sabertooth datasheet, “an analog voltage of 2.5V corresponds to no movement. Signals above 2.5V will command a forward motion and signals below 2.5V will command a backwards motion.” The Sabertooth will be setup with “switches 1 and 2 [set] to the UP position” to indicate analog input from the Arduino controller.



The input signals connect to terminal S1 and/or S2

The datasheet also suggests for switch 4 to be “in the DOWN position, [where] independent mode is selected [and] the signal fed to the S1 input directly controls Motor 1 (M1A and M1B) and the signal fed to S2 controls Motor 2.” In order to soften “control around the zero speed point,” we will set “switch 5 [to] the DOWN position, [where] the response to input signals will be exponential. This ... is useful for control of vehicles with fast top speeds or fast max turning rates.” Finally, switch 6 will be set to the DOWN position, where “Microcontroller mode is enabled instead of standard R/C mode,” which makes controlling the robot extremely convenient with a microcontroller as “the Sabertooth will continue to drive the motor according to the last command until another command is given.” Safety concerns are not an issue as the moment our robot leaves the line track, it is programmed to immediately stop and end its movement algorithm, being unable to return to any other movement states until the robot is power cycled.

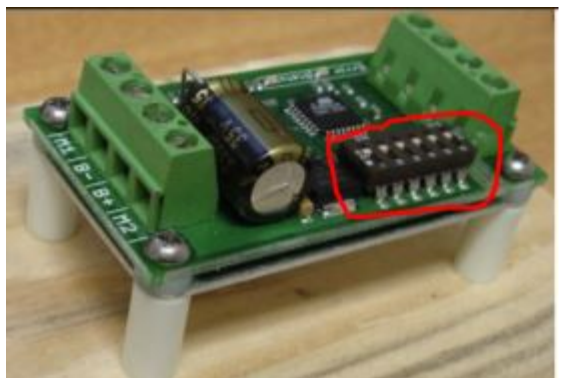


Figure 34: Sabertooth.

6 - Analysis

6.1 - Mechanical engineering analyses

6.1.1 - Motor capabilities

The maximum torque that is required to break the initial rolling resistance is determined by the coefficient of friction of the bearing that the shaft passes through and the load on the races. Our robot will have 2 front driving wheels with 2 bearings on each wheel shaft and 2 back swivel wheels. Under the maximum load with self-weight, each bearing will endure 277.83 lbs of force and the coefficient of friction of a ball bearing is 0.0015 (Figure 35), assuming linearity of the combined effects of friction from all 2 bearings on 1 shaft we get the torque that is needed to move the robot is 0.79N•M.

Bearing Type	Coefficient of friction - μ
Deep Groove Ball Bearing	.0015
Angular Contact Bearing	.0020
Cylindrical Roller Bearing, Cage	.0010
Cylindrical Roller Bearing, Full Comp.	.0020
Tapered Roller Bearing	.0020
Spherical Roller Bearing	.0020
Ball Thrust Bearing	.0015
Cylindrical Roller Thrust Bearing	.0050
Tapered Roller Thrust Brg. Cage	.0020
Tapered Roller Thrust Brg. Full Comp	.0050

Figure 35: Variation of Bearing Coefficient of Friction.

Figure 36. shows the torque needed to overcome bearing friction in Solidworks. This result is very close to the theoretical value that we have calculated above.

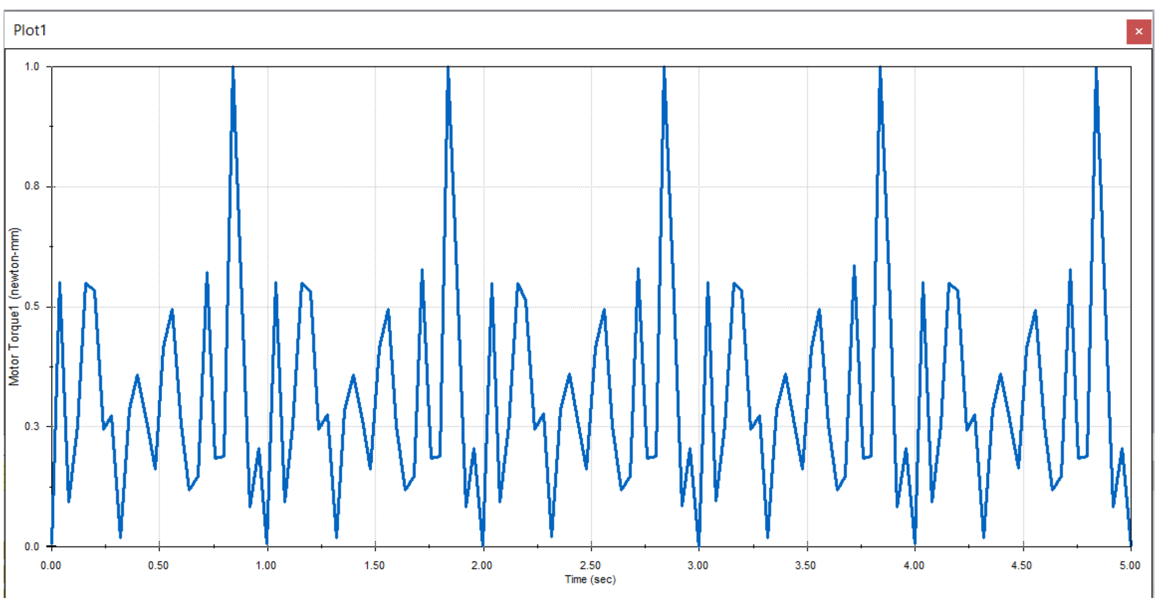


Figure 36: Motor Torque Plot Under Bearing Friction.

Now that we have made sure the robot is able to move from rest, we have to also consider the slip conditions. We know that the rubber wheels have a coefficient of static friction of 0.7 and the stall torque can be estimated to be twice the rated maximum torque under continuous operation, which is 10N•M.

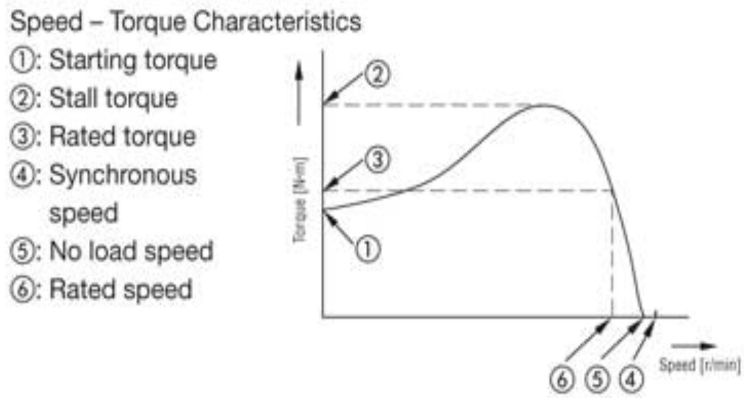


Figure 37: Motor Speed-Torque Characteristics.

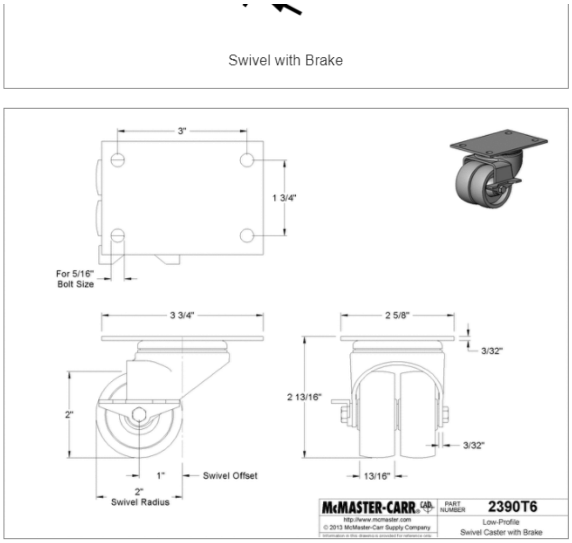
$$Known : Coefficient \quad of \quad static \quad friction \quad \mu_s = 0.7, \tau_{rated} = 5N \cdot M$$
$$Maximum \quad friction \quad f_{max} = \frac{m_{max} \cdot g}{4} \cdot \mu_s = 194.5N$$
$$\tau_{friction} = f_{max} \cdot R = 14.8N \cdot M$$
$$\tau_{stall} \approx 2 \cdot \tau_{rated} = 10N \cdot M < \tau_{friction}$$
$$\therefore Wheel \quad will \quad not \quad slip$$

Next, we need to analyze the kinematics of the robot, more specifically the maximum torque output that is required to accelerate the robot to its maximum velocity in a short period of time. Through Webots simulations we have great success in accelerating the robot to 1.314m/s under 1.1 seconds without slip. The theoretical maximum torque needed is 1.7N•M, which is easily achievable by our actuator.

$$Known : \quad V_{max} = 3mph = 1.341m/s, \quad R = 3" = 0.0762m, \quad m_{max} = 250lb = 113.4kg$$

$$V_{max} = \omega_{max} \cdot R \rightarrow \omega_{max} = 17.6rad/s$$
$$Non-slip \quad angular \quad acceleration : \alpha = 16rad/s$$
$$t = \frac{\omega_{max}}{\alpha} = 1.1s$$
$$V_{max} = a_{max} \cdot t \rightarrow a = 0.406m/s^2$$
$$2f = m_{max} \cdot a_{max} \rightarrow f = 23N$$
$$\tau_{max} = f \cdot R = 1.7N \cdot m$$

A 152.4mm(6 inches) rubber wheel has a maximum load capacity of 2889.38N, according to the chart provided by MSC Industrial Supply Company, and each of the back swivel wheels has the load capacity of 800.14N(Figure 38.), thus the common limiter is the swivel wheels. Considering the robot's structure is designed to withhold a maximum static load of 1111.30N with an impact load of 1778.08N, thus the rubber wheels will have a factor of safety of 6.5.



Mount Type	Plate
Wheel	
Diameter	2"
Width	13/16"
Number of	2
Mount Height	2 13/16"
Capacity per Caster	180 lbs.
Hardness Rating	Firm
Hardness	Durometer 90A
Mounting Plate	
Length	3 3/4"
Width	2 1/2"
Mounting Holes	
Center-to-Center Length	3"
Center-to-Center Width	1 3/4"
For Screw Size	5/16"
Mounting Fasteners Included	No
Wheel/Tread Material	Rubber
Tread Shape	Flat
Nonmarking Wheels	Yes
Wheel Color	Gray

Figure 38: Swivel Wheel Data Sheet.

We also did a static analysis on the shaft to make sure there is no permanent deformation or risk of premature failure due to torque exerted on the shaft. The analysis is conducted where the spokes are fixed on one end and a 10N•M of torque is evenly applied around the other end. The highest stress,1.223e+07 N/m^2 occurs at the slots where grooves are cut to receive the c-clips, the von Mises stress is well below the yield strength of 6061 aluminum alloy that is 53515e+07N/m^2.

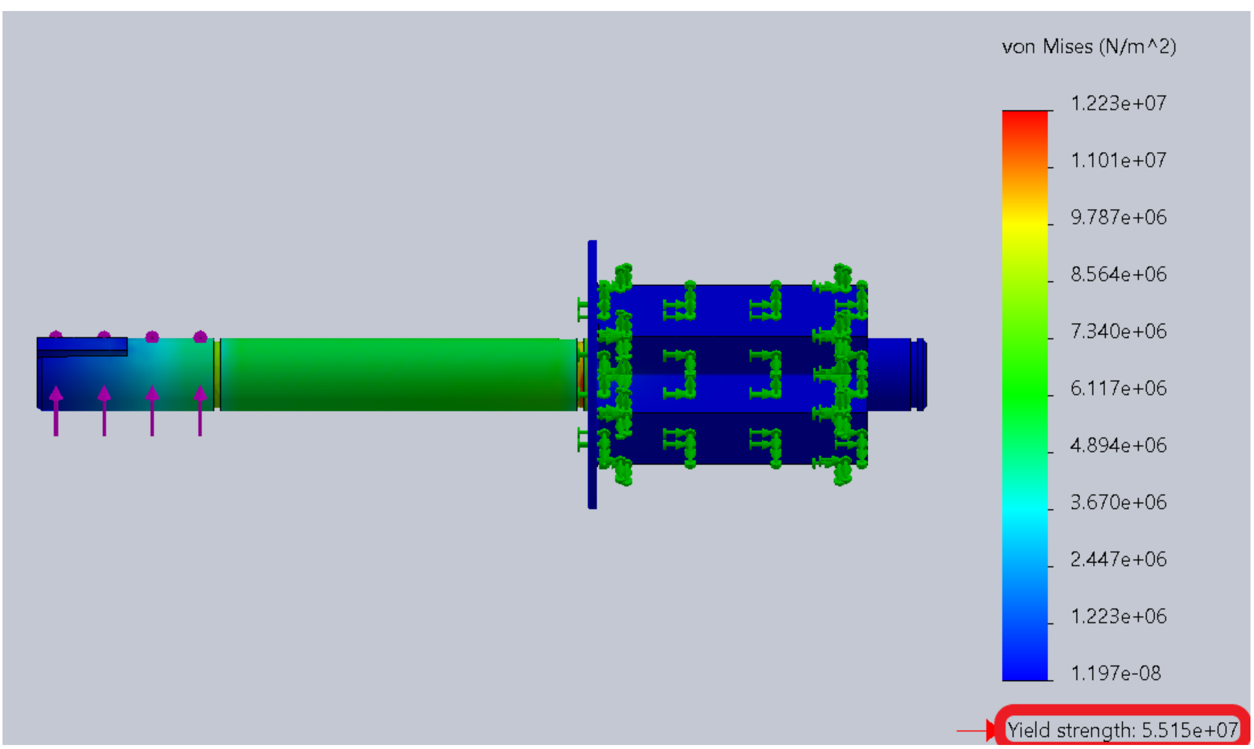


Figure 39: Wheel Shaft Static Analysis Subjected to 10N•M of torque.

6.1.2 - Static analysis of storage frame

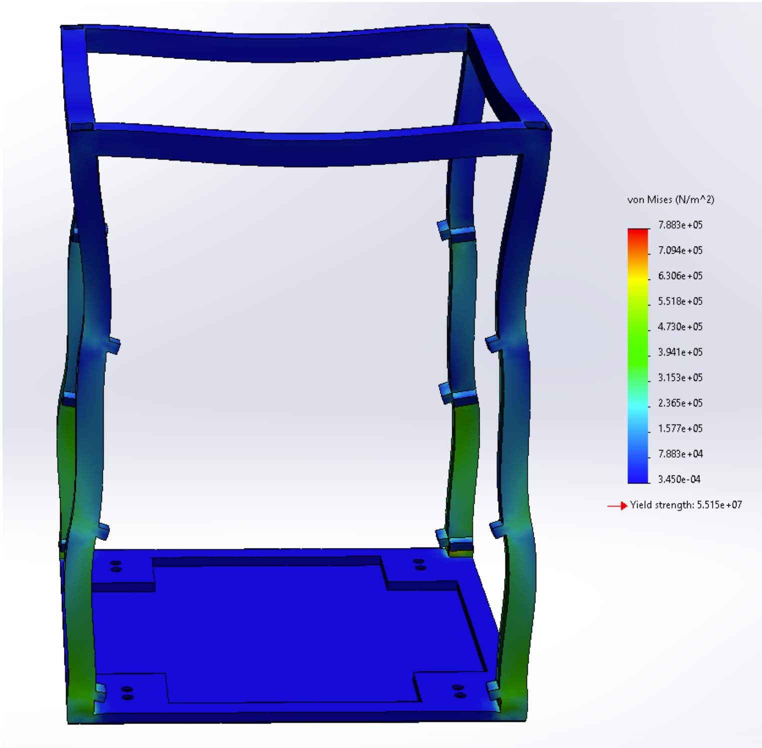


Figure 40: Static FEA of storage frame.

The nature of our stored materials, linens, made for loose requirements for a functional storage structure. For this reason, we decided to use a simple rectangular frame with solid Aluminum 6061 beams. To evaluate this choice, we performed FEA using SolidWorks with excess loading and gravity and found a factor of safety of 9.5. Since we wanted to reduce weight as much as possible, we considered using hollow beams, which retain most of the beam stiffness. An example is shown below for the case of a prismatic square beam of side length a:

$$S = EI \rightarrow I_x = \int_{-\frac{1}{2}a}^{\frac{1}{2}a} \int_{-\frac{1}{2}a}^{\frac{1}{2}a} y^2 dydx = \frac{1}{12}a^4.$$

If a square area of side length b is removed from the beam (b < a), we have

$$I'_x = \int_{-\frac{1}{2}a}^{\frac{1}{2}a} \int_{-\frac{1}{2}a}^{\frac{1}{2}a} y^2 dydx - \int_{-\frac{1}{2}b}^{\frac{1}{2}b} \int_{-\frac{1}{2}b}^{\frac{1}{2}b} y^2 dydx = \frac{1}{12}(a^4 - b^4).$$

And the ratio of the new moment of area to the original is given by

$$\frac{I'_x}{I_x} = \frac{a^4 - b^4}{a^4} = 1 - (\frac{b}{a})^4,$$

Which remains greater than 0.75 for a b/a < 0.707. More than 70% of the inside length of the beam can be removed—half the cross-sectional area—while maintaining 75% of the beam stiffness.

If the hollow moment is combined with a weight-per-unit length calculation, we can obtain a function for the ratio of moment to weight:

$$I_{x'}/w' = \frac{1}{12}(a^4 - b^4)/\rho g(a^2 - b^2) = \frac{a^4 - b^4}{12\rho g(a^2 - b^2)}\,\frac{m^4}{Nm^{-1}},$$

which strictly increases for $0 < b < a$. This contributes to the increase in the factor of safety we observed.

With the new frame, we obtained a significant weight reduction and a new factor of safety of 12, a result of lessened gravitational loading on the lightened frame.

The final change to the frame, adding shelf mounts to both inner sides of the beams, increased the factor of safety to unusually high levels (more than 50), because of the moment application across a diagonal axis of the square beam cross section rather than the bisector.

6.1.3 - Static analysis of chassis frame

Figure 41. shows a static analysis of the frame with loads in various locations with a total static loading of 3202.70N(FoS of 1.3) on the frame and 108.50NM of bending moment at the base of the motors. The maximum deflection is under 0.75mm, which shows that our robot will perform quite well under normal loads.

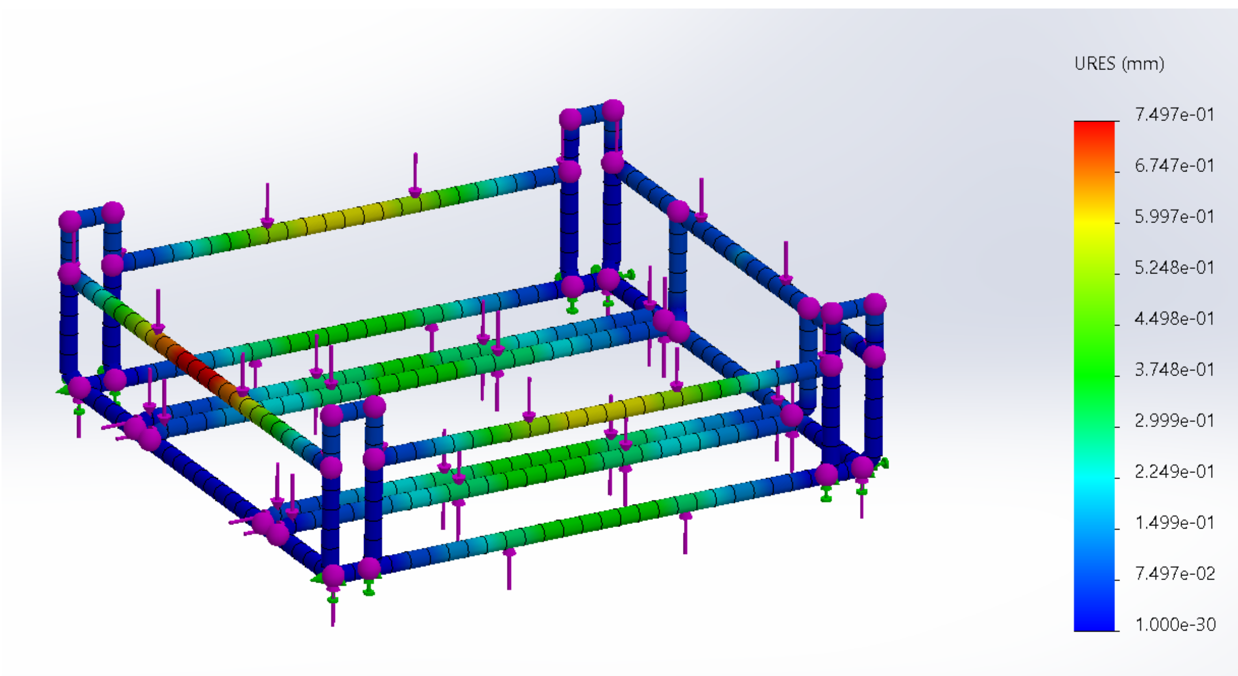


Figure 41: Frame Structure Static Load Analysis.

6.1.4 - Cooling performance analysis

Here we set up a flow simulation on a simplified model of the robot. The ambient temperature is set to be 20°C and the fans are set to operate at 1800 RPM. We used the heat generation rate from the data sheets provided by manufacturers for conducting the simulation.

We would like to see the cooling performance with just one inlet in the front while the robot is moving at its average speed**.**

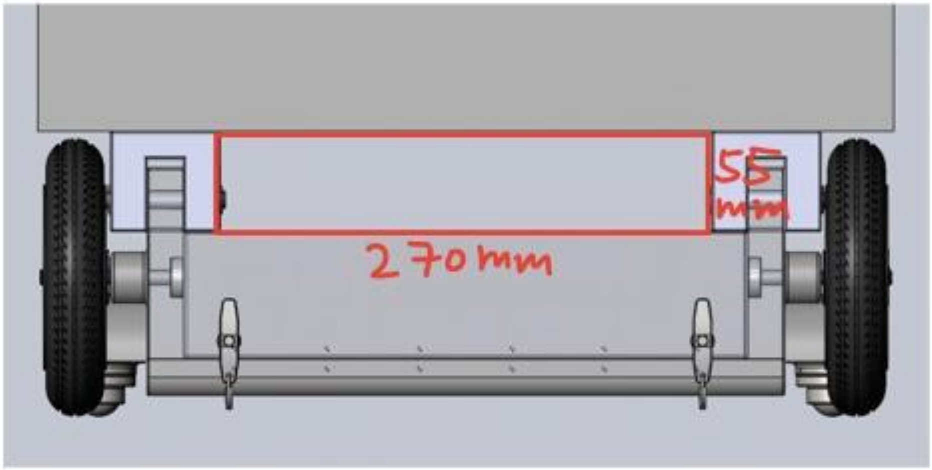


Figure 42: Air Intake Opening.

$$V = 2mph = 0.894m/s$$

$$\nu @ 300K, 1atm = 0.847m^3/kg$$

$$A = 0.27m \cdot 0.055m = 0.01485m^2$$

$$\dot{m} = \frac{AV}{\nu} = \frac{(0.01485m^2) \cdot (0.894m/s)}{0.847m^3/kg} = 0.0157kg/s$$

Under those conditions the mass flow rate of air that is going into the enclosure is 0.0157kg/s. We use that value for the simulation in Solidworks and the result(Figure 43.) shows the temperature spectrum of the internal airflow is around 50℃, which is well within the temperature range for safe operation.

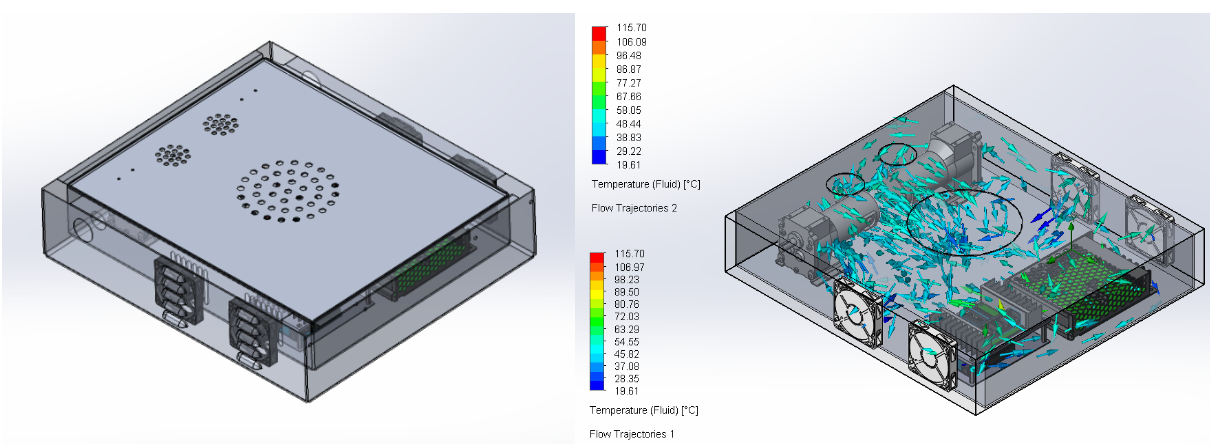


Figure 43: Air Flow Temperature Distribution inside the Enclosure.

We have also conducted a particle tracing simulation in SolidWorks with dust particles of 50 microns in diameter and see how they behave inside the robot.

Here we can see from SolidWorks simulation and excel data, 30 dust particles (colored in blue) out of 50 samples will eventually reside in the robot.

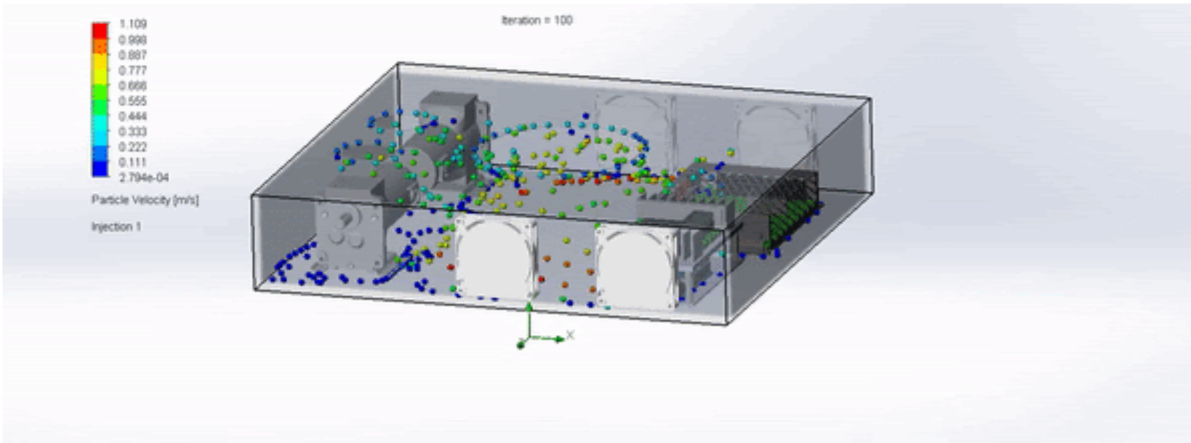


Figure 44: Dust Accumulation Simulation.

Save to ASCII	Length [mr	Residen	Fate
Injection 1			
#34 (133.167 mm; 240.023 mm; 345.841 r	188.44384	1.493	Interpolation failed
#3 (-27.323 mm; 240.023 mm; 229.189 m	104.70214	1.343	Maximum steps in cell
#4 (-32.274 mm; 240.023 mm; 244.686 m	251.40092	20.245	Maximum steps in cell
#5 (-28.821 mm; 240.023 mm; 258.070 m	152.52619	12.301	Maximum steps in cell
#6 (-17.620 mm; 240.023 mm; 268.386 m	236.76958	14.636	Maximum steps in cell
#7 (-2.013 mm; 240.023 mm; 270.533 mr	203.28796	6.569	Maximum steps in cell
#8 (11.266 mm; 240.023 mm; 261.573 mm	231.71185	6.962	Maximum steps in cell
#9 (16.429 mm; 240.023 mm; 244.320 mr	219.25297	6.502	Maximum steps in cell
#12 (-10.168 mm; 240.023 mm; 295.429 m	273.14485	15.372	Maximum steps in cell
#13 (2.723 mm; 240.023 mm; 299.307 mr	148.73278	0.767	Maximum steps in cell
#14 (13.858 mm; 240.023 mm; 313.779 m	278.90524	5.691	Maximum steps in cell
#18 (-26.469 mm; 240.023 mm; 340.724 r	226.44528	21.329	Maximum steps in cell
#19 (-32.083 mm; 240.023 mm; 324.853 r	257.823	22.926	Maximum steps in cell
#20 (-30.638 mm; 240.023 mm; 310.841 r	126.79204	9.738	Maximum steps in cell
#21 (-23.459 mm; 240.023 mm; 301.280 r	160.49315	11.954	Maximum steps in cell
#26 (67.751 mm; 240.023 mm; 259.863 m	161.24399	4.775	Maximum steps in cell
#27 (63.668 mm; 240.023 mm; 274.558 r	139.72868	5.983	Maximum steps in cell
#28 (64.807 mm; 240.023 mm; 295.151 m	128.87756	3.469	Maximum steps in cell
#29 (71.600 mm; 240.023 mm; 313.637 m	214.61056	9.178	Maximum steps in cell
#30 (78.092 mm; 240.023 mm; 324.211 m	177.94541	2.17	Maximum steps in cell
#35 (150.744 mm; 240.023 mm; 343.242	182.21014	6.999	Maximum steps in cell
#36 (164.224 mm; 240.023 mm; 337.021 r	164.3781	4.632	Maximum steps in cell
#37 (175.978 mm; 240.023 mm; 327.910 r	163.4998	4.641	Maximum steps in cell
#38 (182.900 mm; 240.023 mm; 315.271 r	134.96106	0.782	Maximum steps in cell
#39 (190.111 mm; 240.023 mm; 299.829 m	242.48836	9.071	Maximum steps in cell
#40 (190.977 mm; 240.023 mm; 283.819 r	336.34142	29.192	Maximum steps in cell
#41 (187.779 mm; 240.023 mm; 265.909 r	109.13396	5.785	Maximum steps in cell
#42 (181.787 mm; 240.023 mm; 250.777 r	236.10047	17.171	Maximum steps in cell
#43 (175.307 mm; 240.023 mm; 243.312 r	201.92847	7.539	Maximum steps in cell
#44 (168.827 mm; 240.023 mm; 235.847	178.2312	3.848	Maximum steps in cell
#47 (133.079 mm; 240.023 mm; 220.727	204.75453	2.123	Maximum steps in cell
#1 (-18.229 mm; 240.023 mm; 222.147 mr	218.71985	2.03	Opening
#2 (-5.761 mm; 240.023 mm; 221.932 mm	199.18034	0.298	Opening
#10 (10.983 mm; 240.023 mm; 229.464 m	208.03359	0.718	Opening
#11 (1.564 mm; 240.023 mm; 222.375 mm	195.28473	0.507	Opening
#15 (15.286 mm; 240.023 mm; 331.570 m	269.76042	1.345	Opening
#16 (4.334 mm; 240.023 mm; 344.035 mr	270.79528	1.243	Opening
#17 (-12.642 mm; 240.023 mm; 347.248 r	209.62603	0.339	Opening
#22 (97.757 mm; 240.023 mm; 224.909 r	140.90272	0.22	Opening
#23 (88.251 mm; 240.023 mm; 230.966 m	142.33758	0.222	Opening
#24 (80.738 mm; 240.023 mm; 238.497 r	167.43517	1.405	Opening
#25 (74.072 mm; 240.023 mm; 246.610 m	188.34028	3.722	Opening
#31 (88.280 mm; 240.023 mm; 332.929 m	146.01611	0.349	Opening
#32 (98.845 mm; 240.023 mm; 340.908 r	139.05458	0.221	Opening
#33 (116.123 mm; 240.023 mm; 345.606 r	142.47041	0.368	Opening
#45 (157.883 mm; 240.023 mm; 228.609	155.25062	0.296	Opening
#46 (146.182 mm; 240.023 mm; 222.850 r	155.49223	0.31	Opening
#48 (122.214 mm; 240.023 mm; 220.046 r	171.16571	1.105	Opening
#49 (111.572 mm; 240.023 mm; 220.719 m	141.59791	0.243	Opening

Figure 45: Dust Accumulation Data Sheet.

However, the air filter we choose is capable of filtering particles that are less than 40 microns. Therefore, we can conclude that the robot will not have much dust inside once an air filter is in place.

6.1.5 - Dynamic analysis of suspension

The storage frame is mounted on a set of suspension blocks with a total of eight springs. These springs must support the weight of the storage unit with sufficiently small compression length and also avoid propagating disturbance impulses with resonant motion. These requirements ensure the robot will traverse the hospital smoothly and without excessive vibration.

To meet these requirements, we planned to model the storage mounting as a second-order system with mass and spring. This would allow us to use the relation $F = -kx$ to find the minimum required spring constant and the expression $\omega_n = \sqrt{k/m}$ to select a constant that would not be excited by disturbances. To verify these assumptions, we used SolidWorks dynamic analysis to find the vertical resonant mode of the suspension and storage assembly.

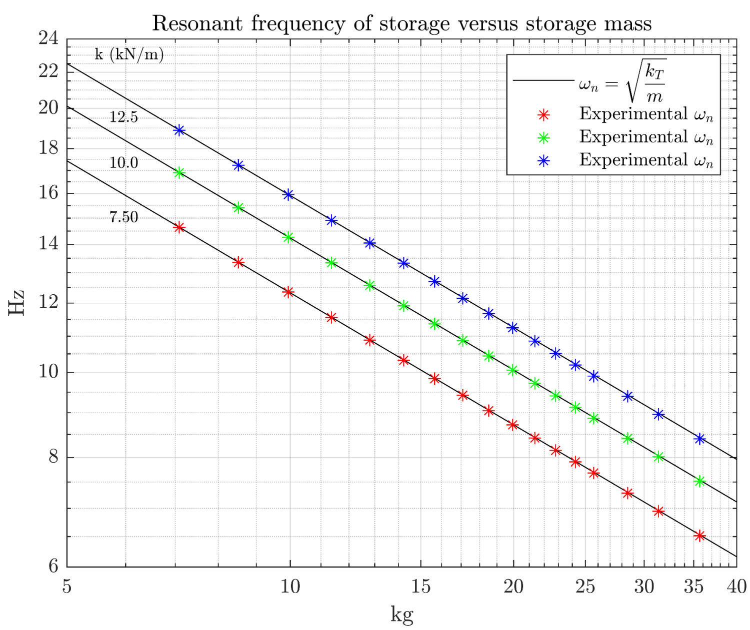


Figure 46: Vertical resonant mode of storage unit on suspension for variable mass and spring constant.

Figure 45 shows the results of the analysis. The deviation of the resonant frequency from the analytical model is extremely small; therefore, we can safely assume the model is appropriate for this situation and select springs accordingly.

6.1.6 - Tipping

With an upright design for the robot, tipping is a concern. The simplest realization of tipping requirements is energy-based:

$$E_{tip} = mg\Delta y_{cm},$$

where m is the total mass, g is the acceleration due to gravity, and Δy_{cm} is the change in the height of the center of mass when the robot is tilted from resting to the tipping angle. For a robot with a base length of about 450 mm, the ability to increase the energy of tipping to values greater than about 100 J is limited. Instead, we analyze the modes of the tipping problem.

There are two cases in which we expect the robot to be put into a tipping condition. First is the contact case, wherein an outside force interacts with the robot. Second is the drive case, wherein the tipping occurs as a result of the motor drive kinetics.

The first case may arise when anything comes into contact with the robot, including normal loading and unloading, shutoff operation, and configuration. This also includes inadvertent or emergency contact, in which a person or moving object (e.g. stretcher) may collide with the robot.

During normal operation, we believe the robot is capable of remaining upright. The average force required to tip the robot from rest is

$$F_{avg} = \frac{E_{tip}}{\rho \quad \theta_{tip}},$$

where ρ is the distance from the pivot axis to the point of contact and θ_{tip} is the angle required to bring the robot to the tipping condition. When this is applied to our robot in its typical configuration and the force is applied at the farthest possible point, we obtain an average force of 65 N applied tangent to the rotation about the tipping axis. This is equivalent to about 14.6 lbf, a significant load that most operators should not be applying to the robot.

When it comes to inadvertent contact, the same worst-case average force applies. This would be an issue in the case of a person or a stretcher running into the robot--such contact forces can be tens of times larger. However, the case itself should be examined. Our robot is designed to operate inside the specified 0.6-meter zone outside the 1.8-meter hallway clearance, a space specifically reserved for obstacles. For this case to occur, the person or stretcher would already have to be operating outside its designated zone, a scenario we cannot be expected to control. In the event the robot is struck in this zone, it may remain upright, hit the wall and remain upright, or fall in the direction of impact travel. In any of these cases, the robot presents less of an obstacle than any larger object (e.g. cart, fixed furniture), which may also be in this zone, and the question of its tipping is irrelevant.

For the case in which the drive kinetics cause tipping, we have found that the torque required to bring the robot's rear wheels off the ground exceeds the torque our motors can provide:

$$\tau_{tip} = mgx_{cm} = y_{cm}\frac{\tau_m}{r_w} \rightarrow \tau_m = \frac{x_{cm}}{y_{cm}} r_w mg,$$

where x_{cm} is the horizontal distance from the wheel axis to the center of mass, y_{cm} is the vertical distance, and r_w is the wheel radius. Since acceleration and braking are wholly torque-dependent, we cannot tip the robot with the drive.

Therefore, we conclude that tipping is not a functionality concern for this robot.

6.1.7 - Hospitals' robot requirements

The question of robot interaction became a concern when we were planning the route algorithm for a hospital floor. To assess whether this was a problem that might require robots to encounter each other on the same path, we investigated whether multiple robots would be required per hospital floor. For this analysis, we used linen distribution numbers from the Bispebjerg Hospital, a 500-bed hospital in Copenhagen which provides laundry services for other surrounding facilities as well as for the hospital itself.

Constant		*Equation*		*Units*		*Units*
robots/cart	Bispebjerg		4			
hours/day		Estimated major window	12	hours/day		
mins/day		hours/day*60	720	mins/day		
equivalent floors	Bispebjerg		4			
Input		*Equation*		*Units*		*Units*
carts/day			75			
Lc	cycle length		400	m		
vr	robot speed		2	mph	0.894	m/s
Calculated		*Equation*		*Units*		*Units*
robots/day		carts/day*robots/cart	300			
	per floor	robots/day/floor	75			
robots/min		robots/day / mins/day	0.417	robots/min		
	per floor	robots/min/floor	0.104	robots/min		
Tc	cycle time	Lc/vr	7.46	min/cycle		
T_delay	delay time		2.00	min/cycle		
Tc_real	true cycle time	Tc+T_delay	9.46	min/cycle		
robots/cycle		robots/min*min/cycle	3.940	robots/cycle		
	per floor	**robots/cycle/floor**	**0.985**	**robots/cycle**		
Nrobots	**robots needed**	**ceiliing(robots/cycle)**	**1**	**robots**		
Ncycles	**daily cycles**	**robots/day / robots/cycle**	**75**	**cycles**		
Tcycles	**time of cycles**	**Ncycles*Tc_real**	**11.82**	**hours**		

Figure 47: Material distribution and robot allocation requirements for hospital linen delivery.

With these numbers, we found that a single robot should be able to meet the daily linen needs for a single floor-equivalent of a hospital in 12 hours. This allowed us to avoid complications and time-and-cost increases associated with a more complex algorithm.

6.2 - Electrical and computer engineering analysis

6.2.1a - Controller Evaluation

In our initial research, we extensively looked at plausible controller options to best fit our design capabilities and evaluated performance. We first choose a wide variety of control methods ranging from data based to more traditional in order to compare benefits and downfalls of each. To numerically assess, we took a look at previously conducted research on line following simulations where robots were scored based on following a track from a starting point and ending when one of the following conditions happens: (i) the robot completes the path and reaches the end point, (ii) the robot loses the track, and (iii) the robot turns and follows the track in the opposite direction. The results were clearly summarized by the following.

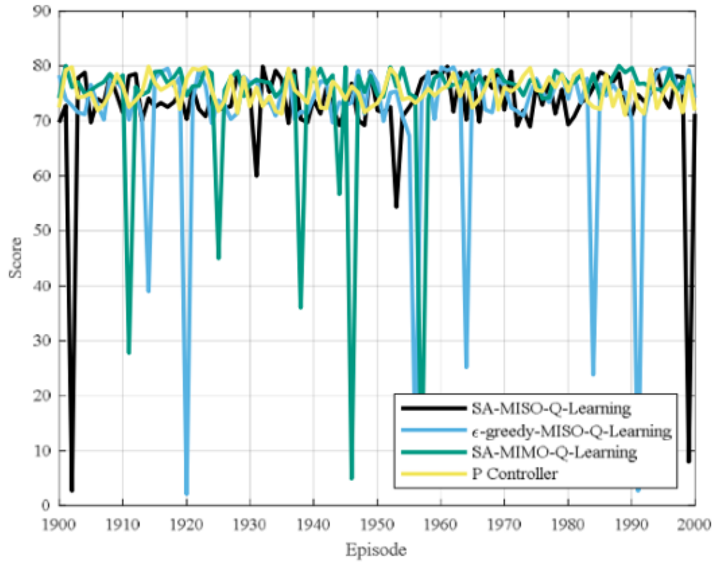


Table II. Simulation results for the robot scores on the complex path

The best score out of five tries	
Algorithm	Score
P controlled	317.72
ε-greedy Q-learning single controlled	314.36
SA-based Q-learning single controlled	314.53
SA-based Q-learning double controlled	318.26

Figure 48: Simulation results for Algorithm performance on a line following robot [12].

We then looked into other controller algorithms and line detection sensor subsystems like quadratic and linear interpolation and using weighted averages. The Figure below shows the experimental verifications of the line detection algorithms via weighted average (left), and quadratic interpolation (right) respectively by using calibrated sensor outputs as done in a study at the Lunghwa University of Science and Technology. The mean-square-errors (MSE) of these methods are also shown in the titles of these plots. It was seen that the line detection algorithm via weighted average has the least mean-square-error, although the mean-square-error for the method of linear interpolation is only a little bit bigger.

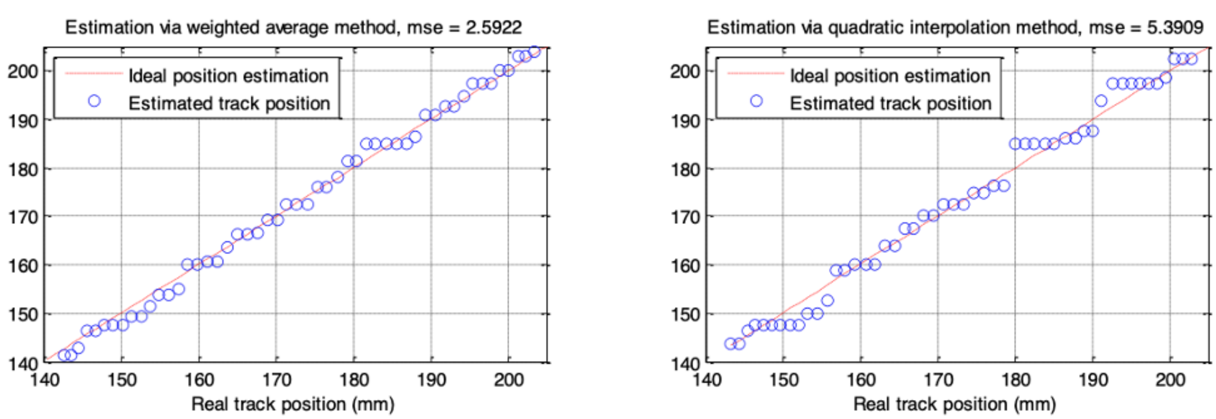


Figure 49: Other controllers algorithm results for accuracy on a line following robot [11].

We then summarized our results within our particular scope.

Algorithm	Capability	Language	Dependencies/drawbacks	Summary
PID	Complete controller	Python and Matlab	python modules, Mathworks module	Easy to run, holistic, works in webots and for analytical simulation
Q-learning	Complete controller	Python or C++	Good training data	More complicated, more dependent on specific method (not an easy tuning process), additional data processing
Quadratic or linear interpolation	Complete controller	Python or C++	Good position continuity but velocity is not, often results in jerky trajectories	Less reliant than weighted average or PID (almost double the error)
Weighted average	Line detection subsystem	Python or C++	Number of sensors	Simple and works well in conjunction with MSE but doesn't offer much customization, still need PID or some feedback control

Table 6: Controller determination.

With this we concluded that given our robot is operating within a very controlled environment on a path that does not vary wildly in any way, PID is a simpler way to implement our controller without losing any of the functionality or consistency.

6.2.1b – Trajectory analysis

We then turned to specific evaluation of our controller using trajectory analysis. Trajectory analysis was a great evaluation technique for our robot's motion performance given the specific constraints of our robot positioning. Trajectory analysis allowed us to measure deviations and ensure our robot safely stayed within our confined space. As a reminder our robot was to adhere to the following dimensions per hospital guidelines involving hallway space.

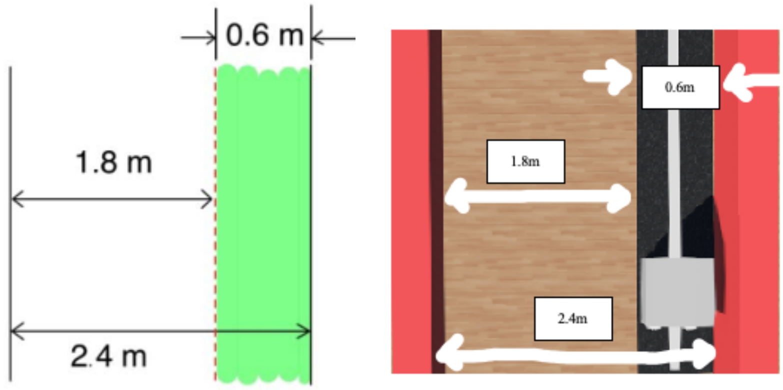


Figure 50: Webots translation of our system.

With these dimensions, we decided to create a line for the robot to follow in our simulation but also a floor distinction to show the 0.6m operating space as well. This way we could demonstrate our ability to stay within these confinements visually as well.

The following table shows the analytical trajectory followed by the robot and on the left shows the webots track line was based on. The robot trajectory is the path of robot movement from one point to another by following a predetermined path as discussed earlier. In other words, the trajectory is the result of the robot's action based on the PID controller.

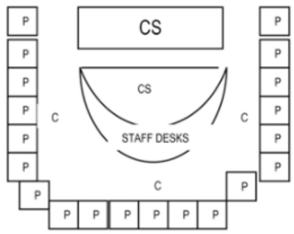
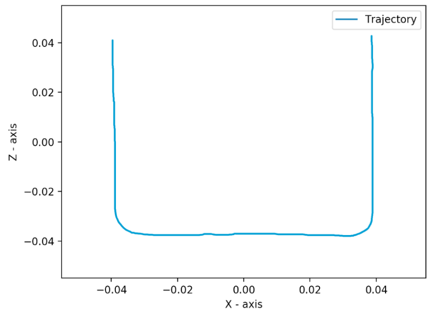
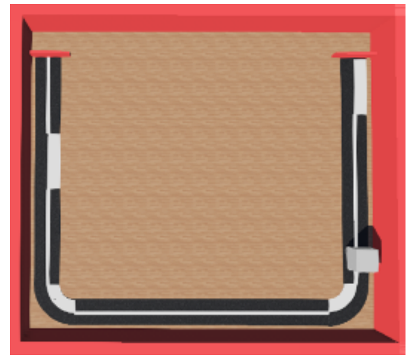
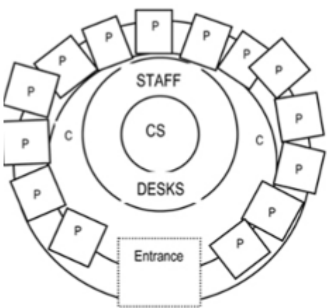
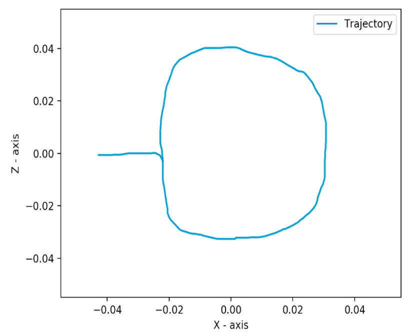
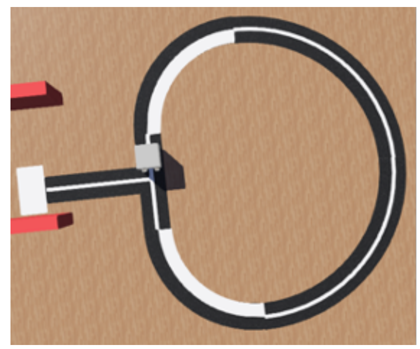
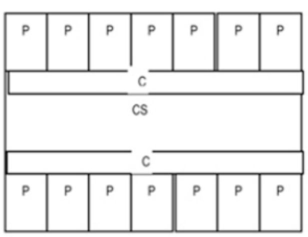
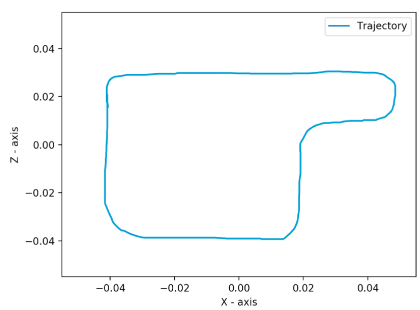
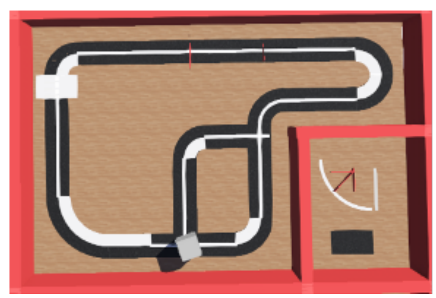
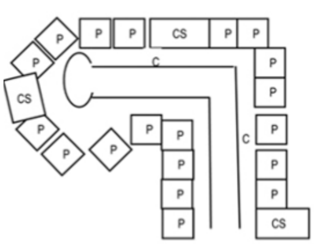
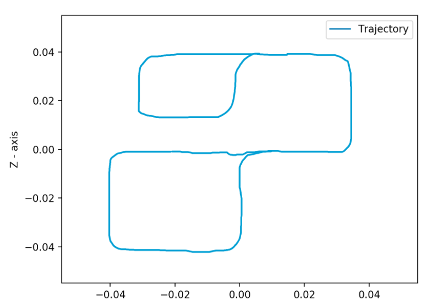
<table>
<tr><th>Unit illustration</th><th>ROBOT TRAJECTORY</th><th>WEBOTS TRACK LINE</th></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td></tr>
</table>

Figure 51: Webots renderings and trajectories.

The unit illustrations are composed from the consolidation of independently reviewed U.S. hospital designs done by the Agency for Health Research and Quality (AHRQ) not including ICU's [8]. The ones shown here are the U-shaped, surrounded, parallel corridor and embedded. The classification served as basis for the webots world creation, and we tried to emulate as best could while also combining some of the shapes into one track. We felt this was a holistic and deterministic way to try and generalize our system's testing. Based on the figures in Table I, the robot is able to move according to the line paths. The trajectories are perfectly centered through straight portions and although our adjustments are not perfectly smooth around curves, all stay within the black bounds. Here is the error deviation data for each of the tracks seen above running across 500 trials. Our deviation percentages were all below 5%.

Number of trials	Track	Percentage deviation outside of outside barrier for 1 loop	Percent deviation per run
500	U-shaped	0.68%	0.00136%
500	Surrounded	1.89%	0.00378%
500	Parallel corridor	3.59%	0.00718%
500	Embedded	4.98%	0.00996%

Table 7: Track Deviation results.

6.2.1c – Safety

In addition to the safety insurance given from the trajectory analysis above, we also used this design criteria to formulate our choice of path following. We wanted to create a way to designate certain areas of track as regions where increased sensitivity was necessary. This was the origin of our choice to use the edge following as a signal for our robot to slow and this can be seen live in the simulation as with the obstacle detection discussed earlier. We included speed outputs in the console that reflect the process as seen below.

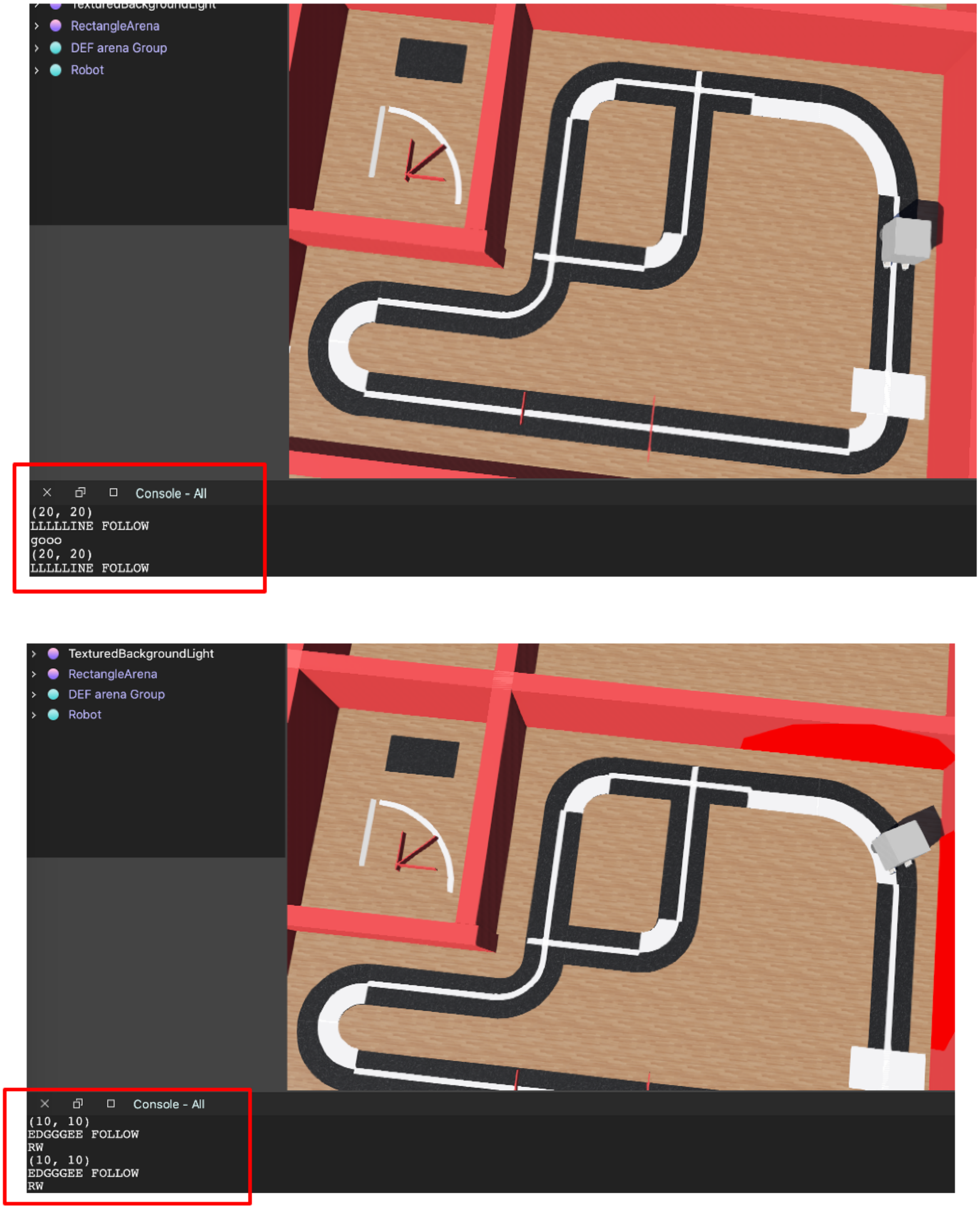


Figure 52: Live time path type output in console.

7 – Design outcome versus requirements

To validate our design outcome to our original requirements, we took advantage of a couple of different resources and analyses.

7.1.1 – Nurse Review

Throughout the quarter, we conducted three rounds of nurse reviews. One week 3, one week 8 and one week 10. In week 3, we discussed the feasibility of certain design aspects and got the opportunity to ask questions on the hospital setting and how to benefit nurses as much as possible. This was discussed heavily in our CDR, but there were a few major takeaways for our design that can be re-summarized here. First, we confirmed our narrowing of scope to strictly carrying linens. Nurses supported this and gave us a rundown of the complication behind certain items like food and medication that we were initially unaware of. For example, when nurses grab medications, they have to go through a checklist, (i.e. checking the correct patient, the correct medication, etc.) all of which our robot would need to do if we considered carrying this, which was a bit out of scope for our team this quarter. Next, we confirmed that the wall following worked and that it was a viable strategy for our robot and its path. Our nurses told us that the portable workstations hospitals use are usually along the outer wall of a hallway. Thus, we could put our line along the opposing wall and expect to have a clear path. Lastly, we cleared an important issue surrounding conflict with our robot during emergencies. The Nurses assured us that we did not need to be concerned with our robot blocking a large obstacle in the walkway as long as the robot can be manually pushed away in such a case and adheres to the standard guidelines for hospital walkway clearance width (which our robot satisfies). To ensure we properly met this requirement, we designed the following.

Nurse request	Completed corresponding design choice
Robot needs to be manually push-able in case of emergency	● Designed a kill switch ● Significantly lowered our base weight compared to competitors (<75 pounds base, max load of 250 lbs) ● The free wheel system

Table 8: Week 3 Nurse Feedback.

In week 8, we meet again with the same nurses in order to validate and ask more questions following our main design phase of the quarter and CDR feedback phase (our nearly completed design). Past our updated design, the general run down of new information included floor cleaning and the effect on our line, general installation of the line itself, and the battery model. The information is again summarized in the chart below.

Nurse request/information given	Completed corresponding design choice
Floor cleaning is a category II surface according to the CDC (meaning cleaned about once a day)	● 5350 chemical resistant urethane clear topcoat to cover the line in order to avoid cleaning and walking damage
Cleaning the robot	● Advice cleaning once per day with approved COVID-19 disinfecting surface wipes during charging
Hospital floors are typical welded sheet rubber, Nurses also use and place surgical tape in rooms for certain occasions	● 3M surgical grade Dri-fit double sided adhesive tap for strength and durability (also hospital approved)
Battery: less time nurses need to spend tending to the robot the better	● Formulation of the automatic navigation to a charging station based on the loop counter explained in section 5

Table 9: Week 8 Nurse Feedback.

In week 10, we went over our final design and just looked for advice on pitching the product and how the business side of the hospital might look for other aspects we had yet to include. This meant reaching out to some other resources past our nurses and fortunately, we were lucky to make contact with the Chief Executive Officer of Dignity Health, the fifth largest hospital system in the nation and the largest not-for-profit hospital provider in California, Dr. Robert Quinn. Our time with him was spent formulating our sales pitch and looking at the product in terms of marketability as opposed to design given that our time for the quarter at this point was basically done. We also had him take a look at our design criteria and give us his take on the importance of each and how we demonstrate these. His feedback and advice is summarized in the chart below.

Feedback/Advice	Corresponding pitch emphasis/ design choice
Take advantage of Covid in terms of marketing	● Our Johnese Spisso clip and incorporation
Make sure it generalizable across hospitals with different sizes and needs	● One of design criteria, “adaptability” (discussed in detail in section 4 and later in section 7)
Most important design aspects you must cover... ● Speed ● Investment return ● Aesthetics ● Self sufficiency	● faster max speed than competitor within CDC guideline ● decrease in price, investment return after only about # hours ● Original, friendly approved design look by nurses and healthcare business workers ● Increased deliverable reliability and predictability

Table 10: Week 10 Dignity Health Feedback.

We felt that these feedback sessions throughout the quarter were a good way to not only validate our system for more realistic purposes, but also serve as a comparison for assessing our achievement of design outcomes.

7.1.2 – Quantifiable Competitor Review and Design requirements analysis

Another way we compared our outcomes was through the use of competitors. This was especially useful because we could quantitatively assess ourselves with a comparison to our main market competitor. The results are summarized here.

<table>
<tr><th>Design Specification</th><th>TUG</th><th>OUR</th></tr>
<tr><td>Adaptability</td><td>Required mapping with emptied out hospital</td><td>Simple line installation</td></tr>
<tr><td>Reliability</td><td>17 years in the market in over 200 hospitals
routes and delivery points are programmed on map</td><td>(detailed results seen previously in section 5/6)
loading FoS
suspension
cooling
tolerance check
tipping analysis
Simulation analysis of track deviation
Increased navigation predictability (because of reliability, we know accurately predict where the robot will be at any time)
Increased navigation reliability (0.248% error in track deviation)</td></tr>
<tr><td>Safety</td><td>secure carts
audible feature for awareness
17 years in the market with no accidents</td><td>Structural safety factor > 10
Simulation analysis of track deviation across 500 trials (max error of only 0.248%)
Max speed confirmed by CDC regulations (42% increase) along with path following techniques for regional safety
Designed switch for manual control in times of need
Emergency subsystem</td></tr>
<tr><td>Cost</td><td>$105, 000</td><td>~$24, 000 including line installation and robot (17% of the cost)</td></tr>
<tr><td>Aesthetic</td><td></td><td>
Simple colors for non-threatening look
Minimal external lighting</td></tr>
</table>

Table 11: Competitor Design Specification comparison

In review, we perform at similar or higher levels of performance across all of our design requirements. We feel that this is a great metric for our product and our achievement of goals throughout the quarter especially given the experience and established nature of TUG. It is also important to note that with more time, we feel we could have even better optimized our robot and achieved some of the additional features TUG does include.

8 - Conclusion

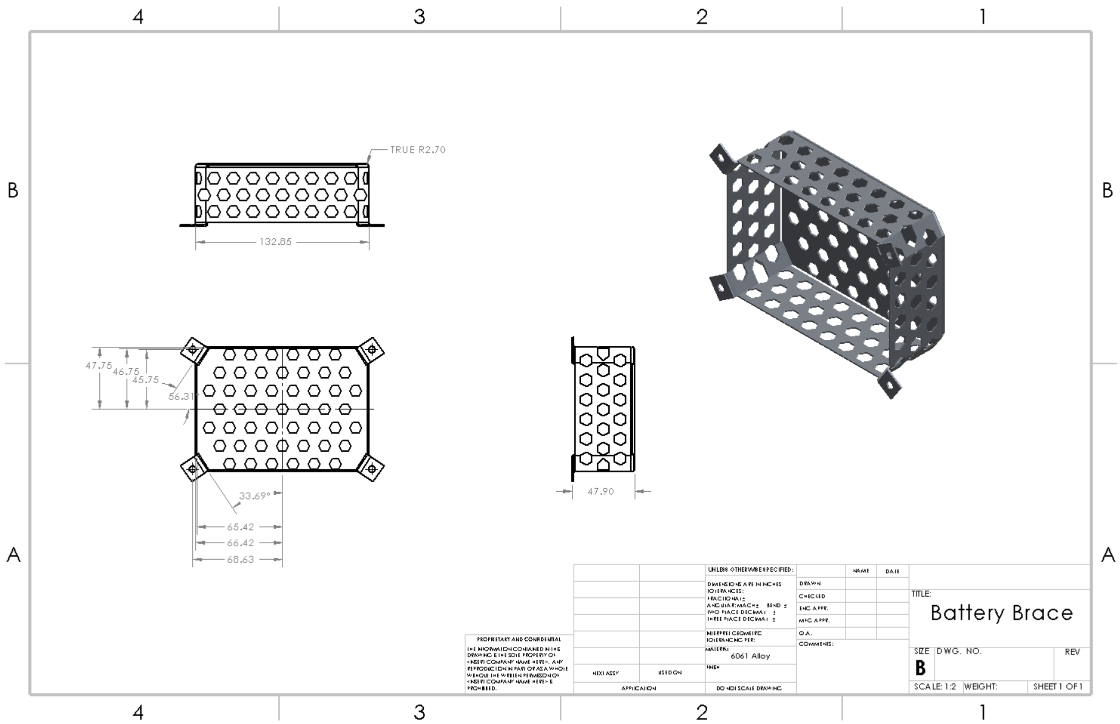
Our robot has demonstrated the ability to adapt in a variety of hospital settings thanks to its nimble size and non-invasive nature of operation. Our robot has proven to be reliable. It has a high navigation accuracy with a robust algorithm. In terms of mechanical reliability, our robot passes all the testings including structural, vibrational, and thermal analyses. It operates within the proper spaces in the hospital and does not obstruct hallway traffic.

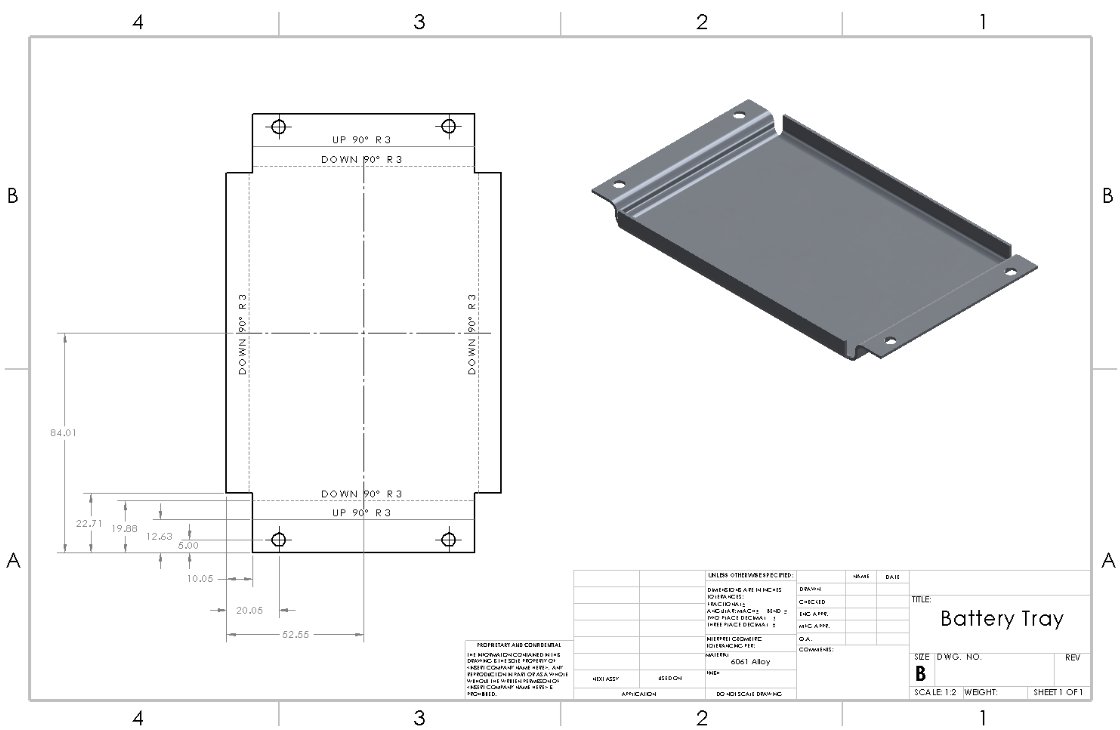
With the ever-increasing demand for autonomous assistance in the healthcare industry, especially during the pandemic, our robot is a viable, cost-effective alternative at a fraction of the cost than other manufacturers in the industry. The professional and modern look of our robot is aesthetically appealing. Our robot is a combination of quality and value in a beautifully crafted package.

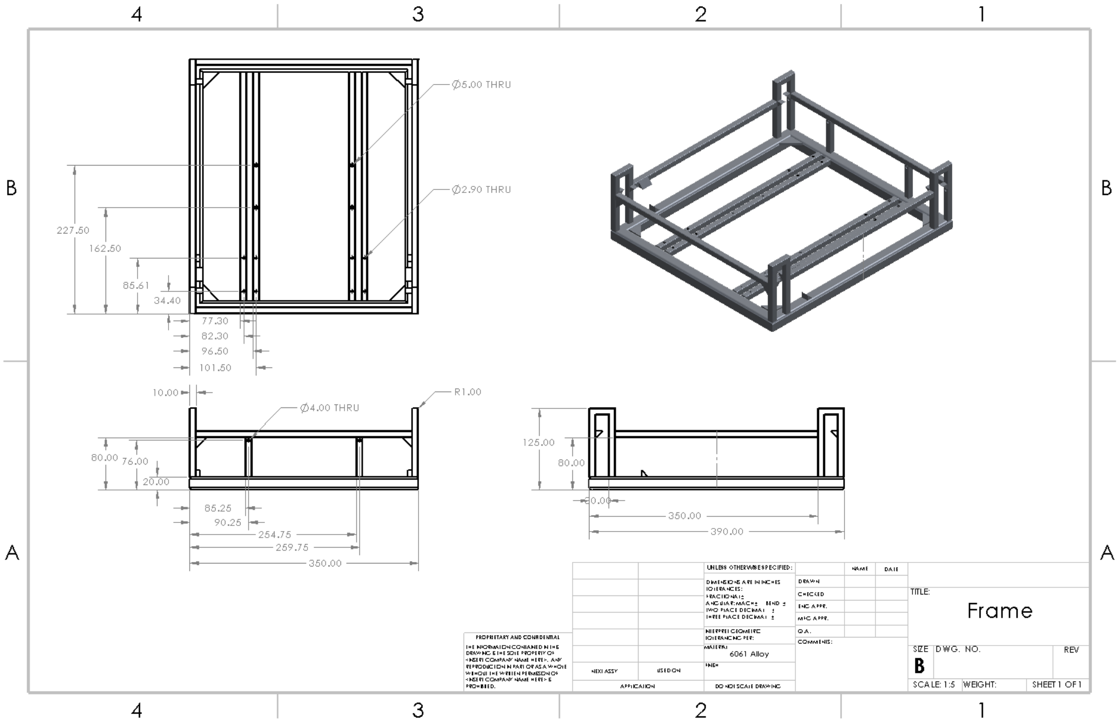
With little to no modification of the current design, our robot can also help distribute medicine, food, and equipment thanks to its modular design of the storage unit. If we were given more time in the development our robot will have the ability to adapt to terrains with slopes, resistance, and debris. Future work can include, but not limited to, collaboration with Team People to expand the robot's capability of receiving and delivering goods, which in turn will further alleviate the nurses' workload so they can focus more on bringing quality care to the patients.

We hope that our solution will inspire an improved sense of trust and safety in hospitals, especially during health crises like this pandemic. Our work may become a starting point for more sophisticated or more complete reworking of hospital supply chains (e.g. permanent installations). Most importantly, even a fractional solution to our problem will have measurable health benefits.

Appendix 1 - Technical drawings



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Ø2.90 THRU
Ø4.00 THRU
R1.00
227.50
162.50
85.61
34.40
77.30
82.30
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101.50
10.00
80.00
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90.25
254.75
259.75
350.00
125.00
80.00
10.00
350.00
390.00
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6061 Alloy
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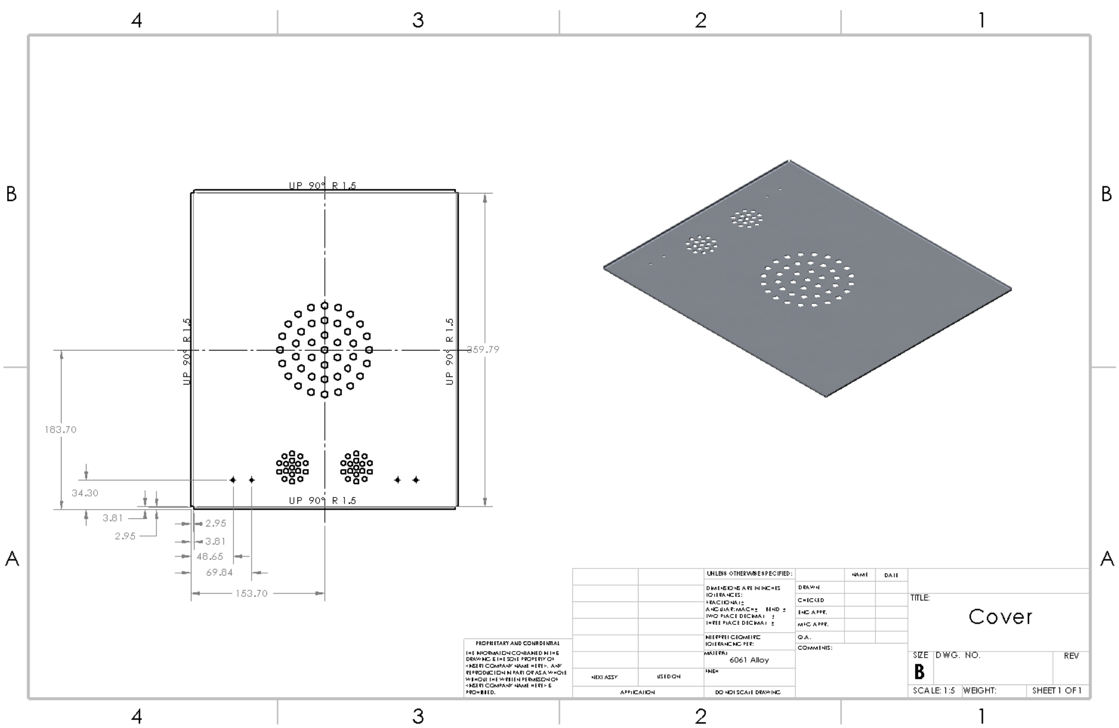
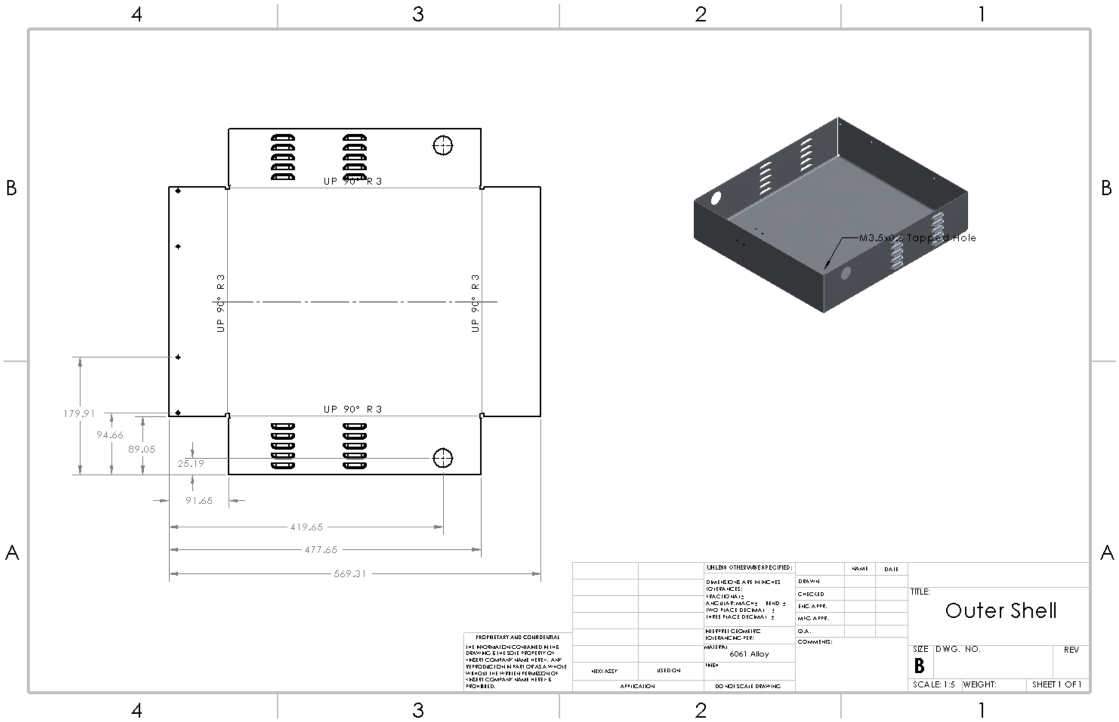
B
REV
SCALE: 1:5 WEIGHT:
SHEET 1 OF 1


UP 90° R 1.5
359.79
183.70
34.30
3.81
2.95
2.95
3.81
48.65
69.84
153.70
TITLE:
Cover
6061 Alloy
SIZE DWG. NO.
B
REV
SCALE: 1:5 WEIGHT:
SHEET 1 OF 1


UP 90° R 3
M3.5x0.6 Tapped Hole
179.91
94.66
89.05
25.19
91.65
419.65
477.65
569.31
UNLESS OTHERWISE SPECIFIED:
6061 Alloy
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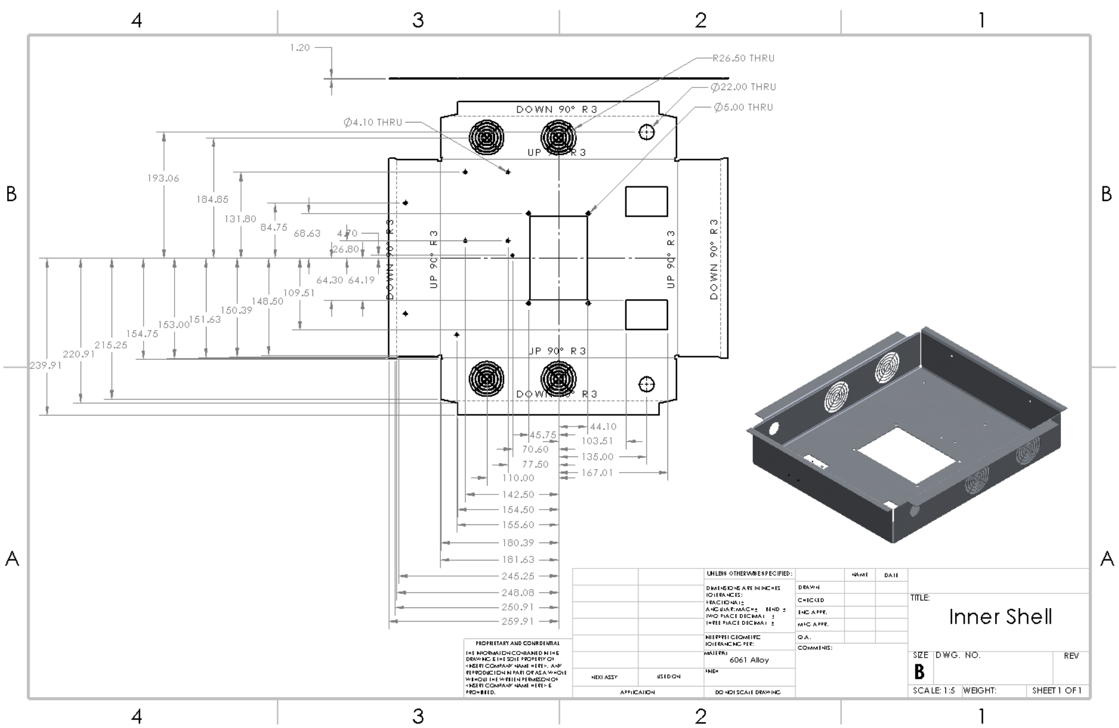
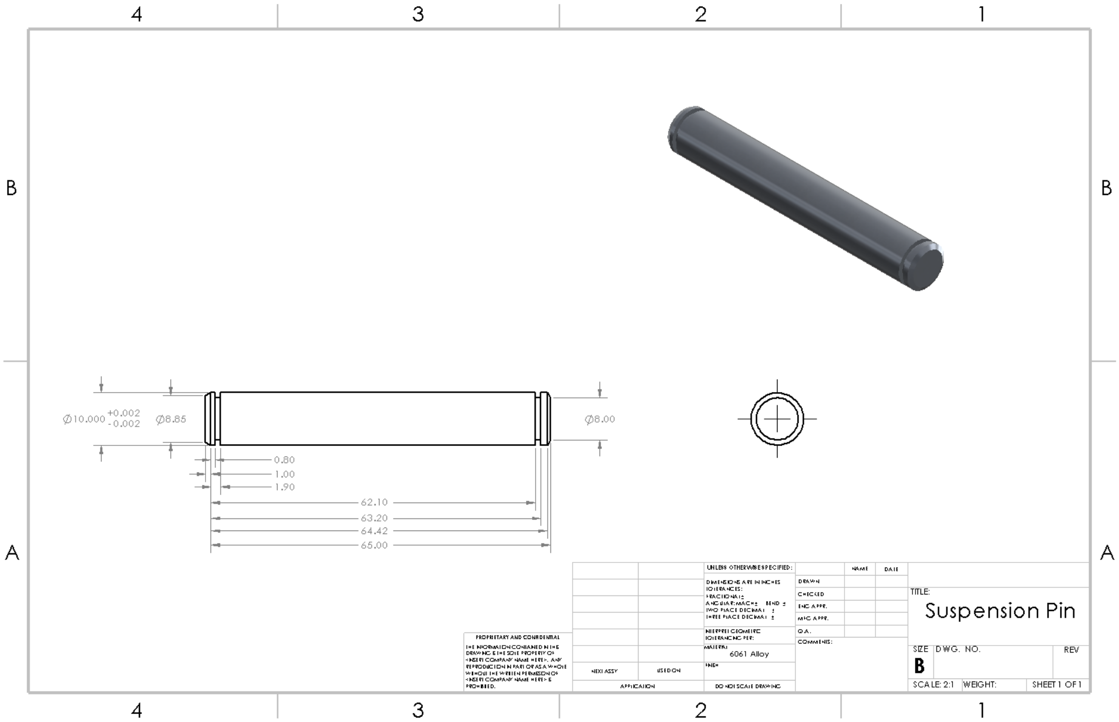
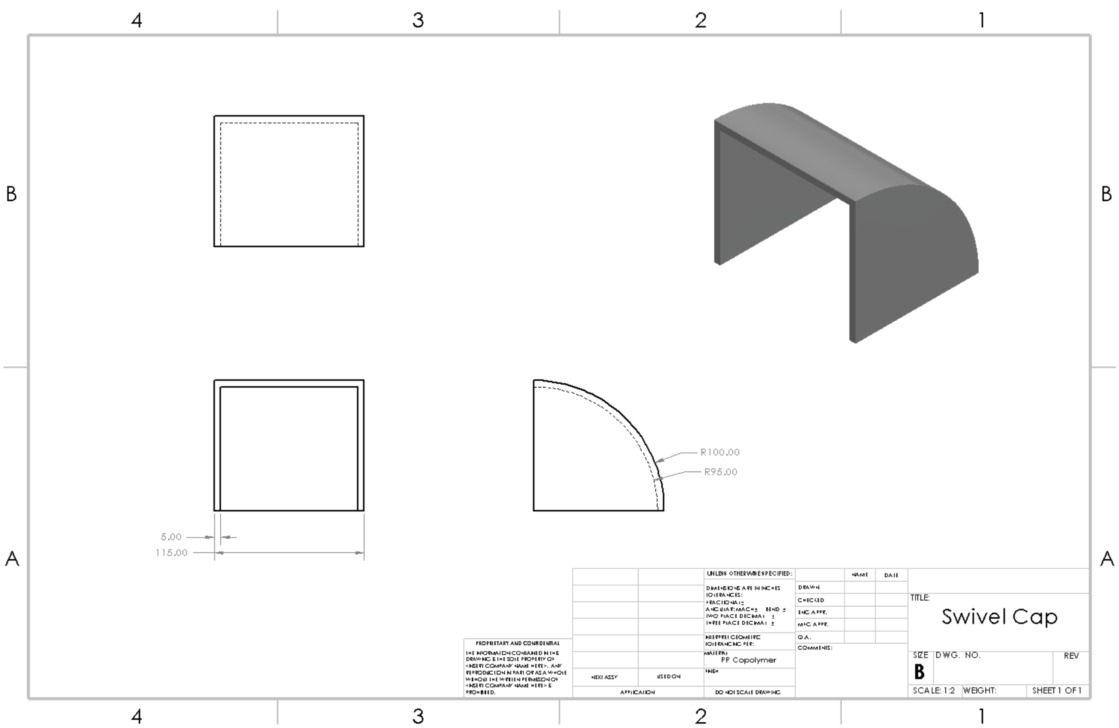
Outer Shell
SIZE DWG. NO.
REV
B
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1
DO NOT SCALE DRAWING

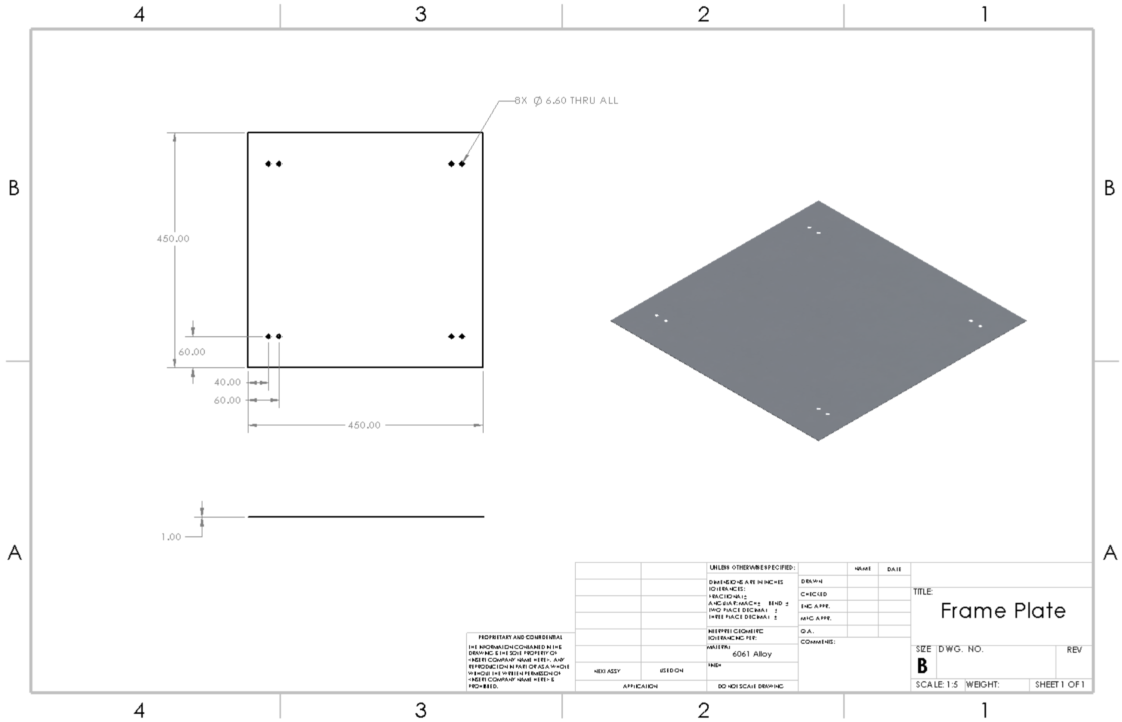

1.20
R26.50 THRU
∅22.00 THRU
∅5.00 THRU
∅4.10 THRU
DOWN 90° R 3
UP 90° R 3
193.06
184.85
131.80
84.75
68.63
4.70
26.80
64.30
64.19
109.51
148.50
150.39
151.63
153.00
154.75
215.25
220.91
239.91
45.75
70.60
77.50
110.00
142.50
154.50
155.60
180.39
181.63
245.25
248.08
250.91
259.91
44.10
103.51
135.00
167.01
UNLESS OTHERWISE SPECIFIED:
6061 Alloy
TITLE:
Inner Shell
SIZE DWG. NO.
REV
B
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1
DO NOT SCALE DRAWING

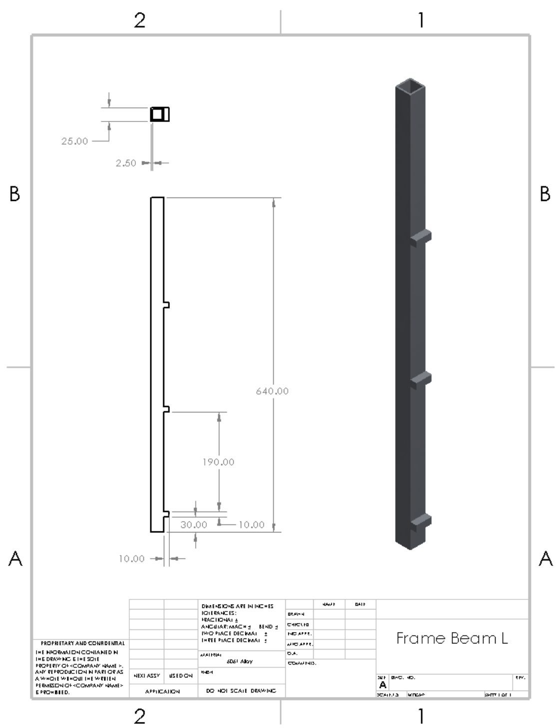


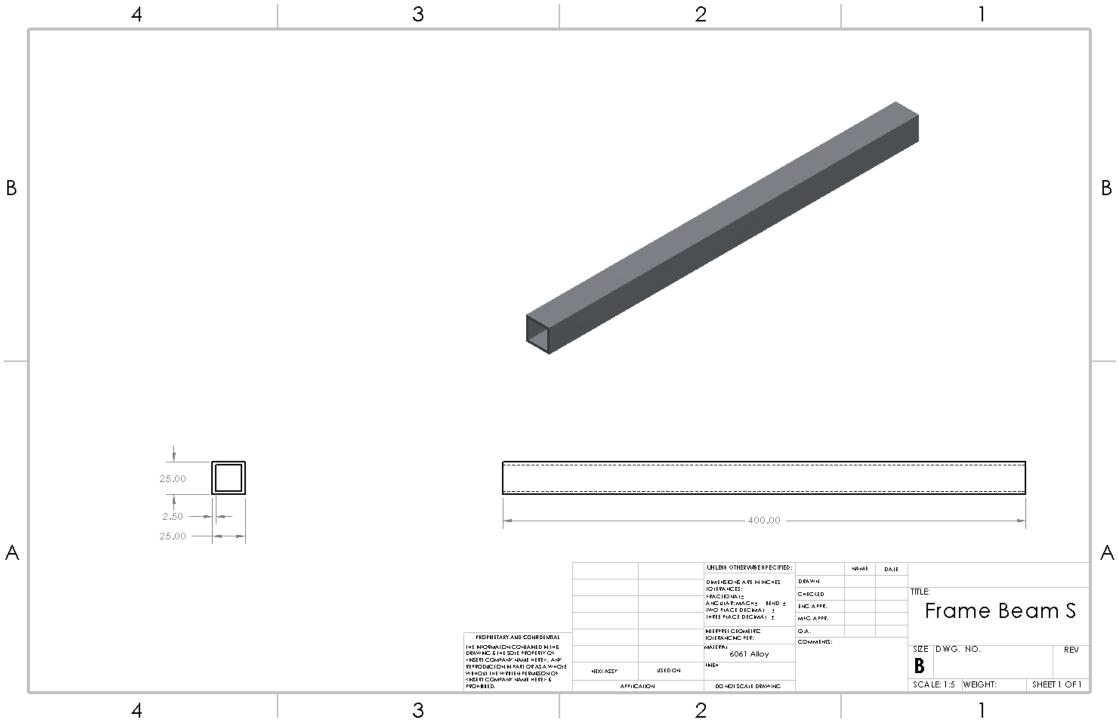
Ø10.000 +0.002 -0.002
Ø8.85
Ø8.00
0.80
1.00
1.90
62.10
63.20
64.42
65.00
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
6061 Alloy
TITLE:
Suspension Pin
SIZE
DWG. NO.
REV
B
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1



R100.00
R95.00
5.00
115.00
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
PP Copolymer
TITLE:
Swivel Cap
SIZE
DWG. NO.
REV
B
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1


8X ∅ 6.60 THRU ALL
450.00
60.00
40.00
60.00
450.00
1.00
6061 Alloy
TITLE:
Frame Plate
SIZE
DWG. NO.
REV
B
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1


25.00
2.50
640.00
190.00
30.00
10.00
10.00
6061 Alloy
Frame Beam L
A


25.00
2.50
25.00
400.00
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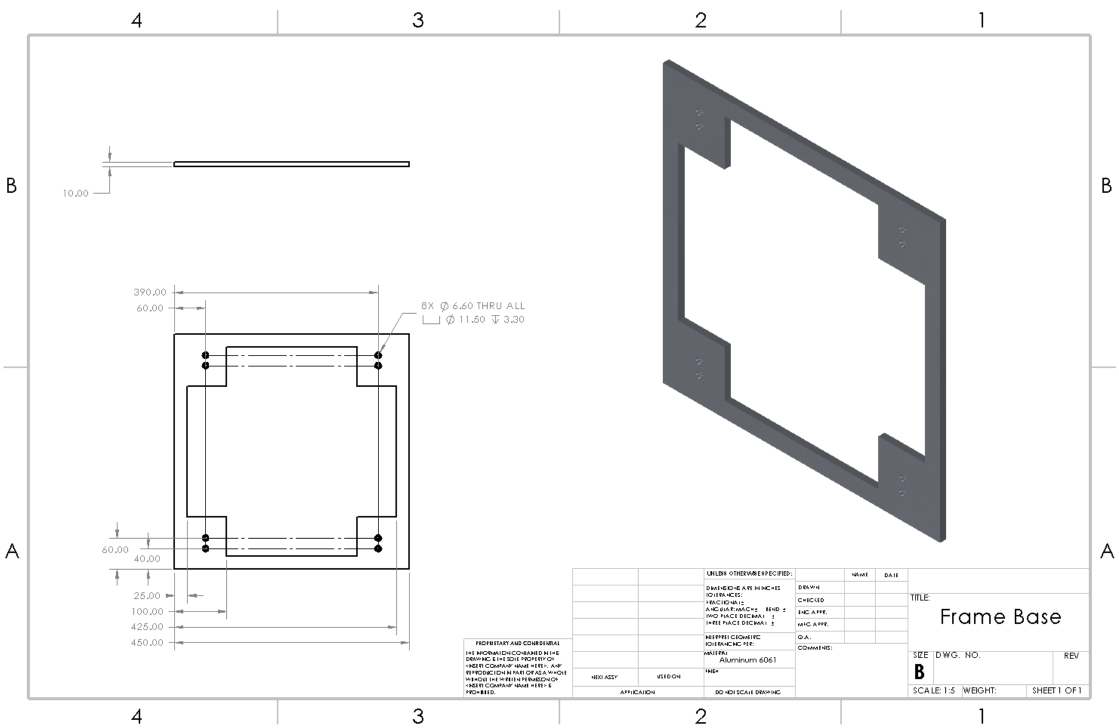
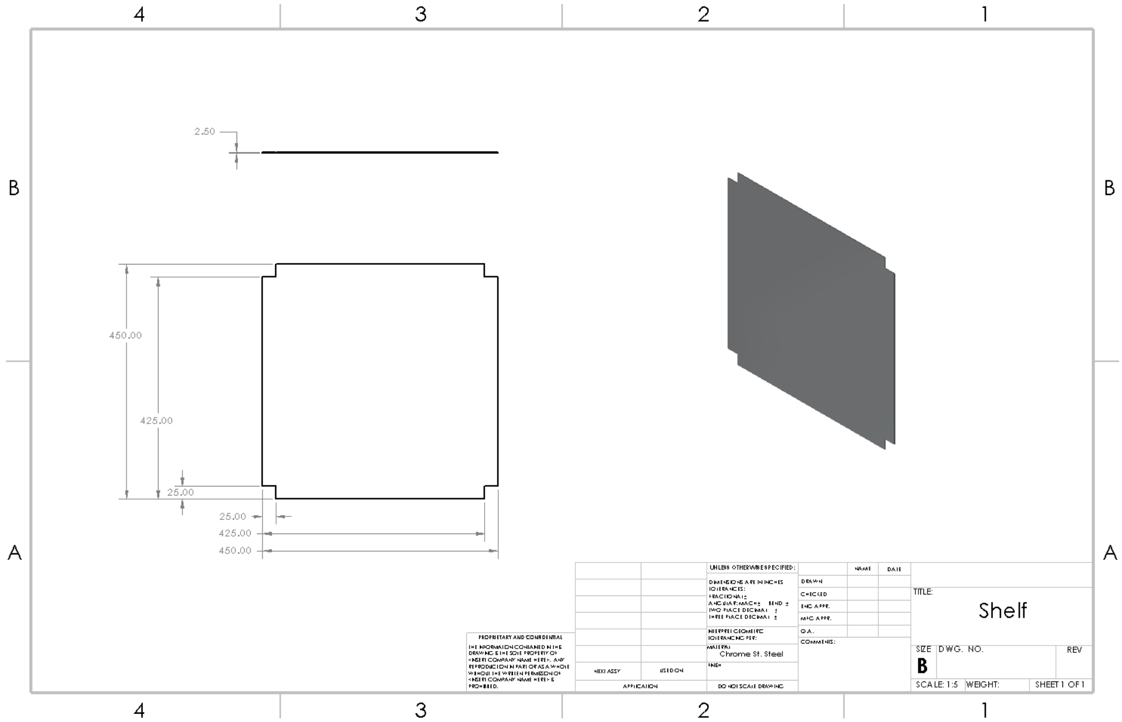
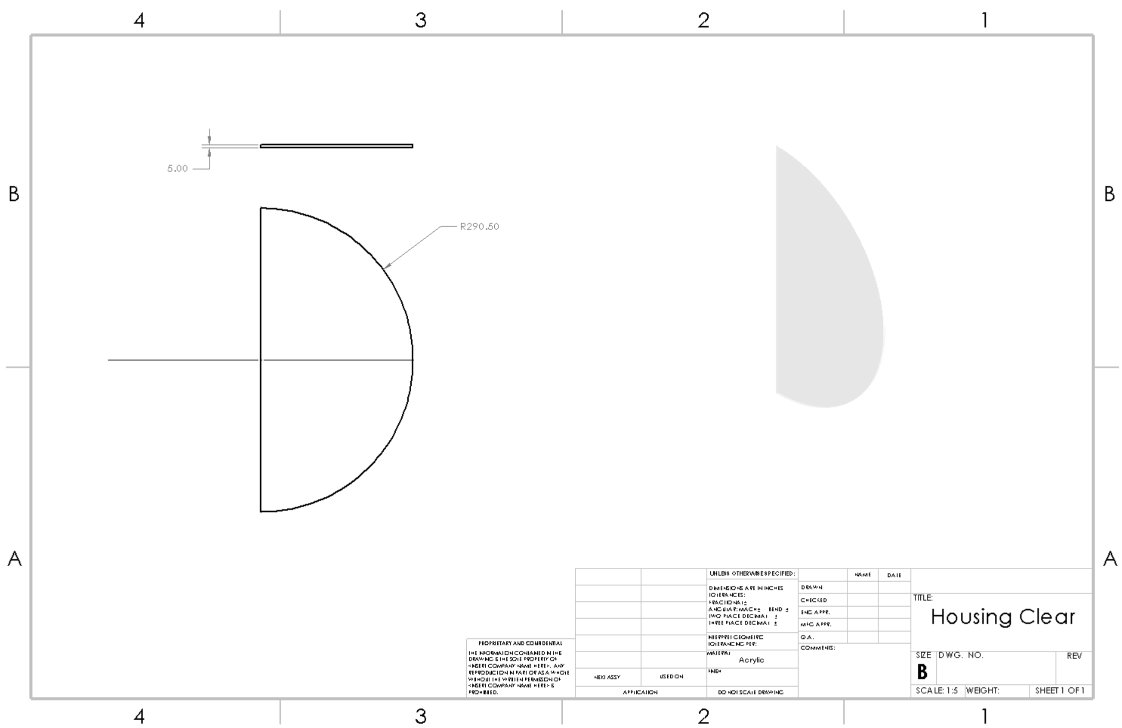
6061 Alloy
TITLE:
Frame Beam S
SIZE DWG. NO. REV
B
SCALE: 1:5 WEIGHT: SHEET 1 OF 1

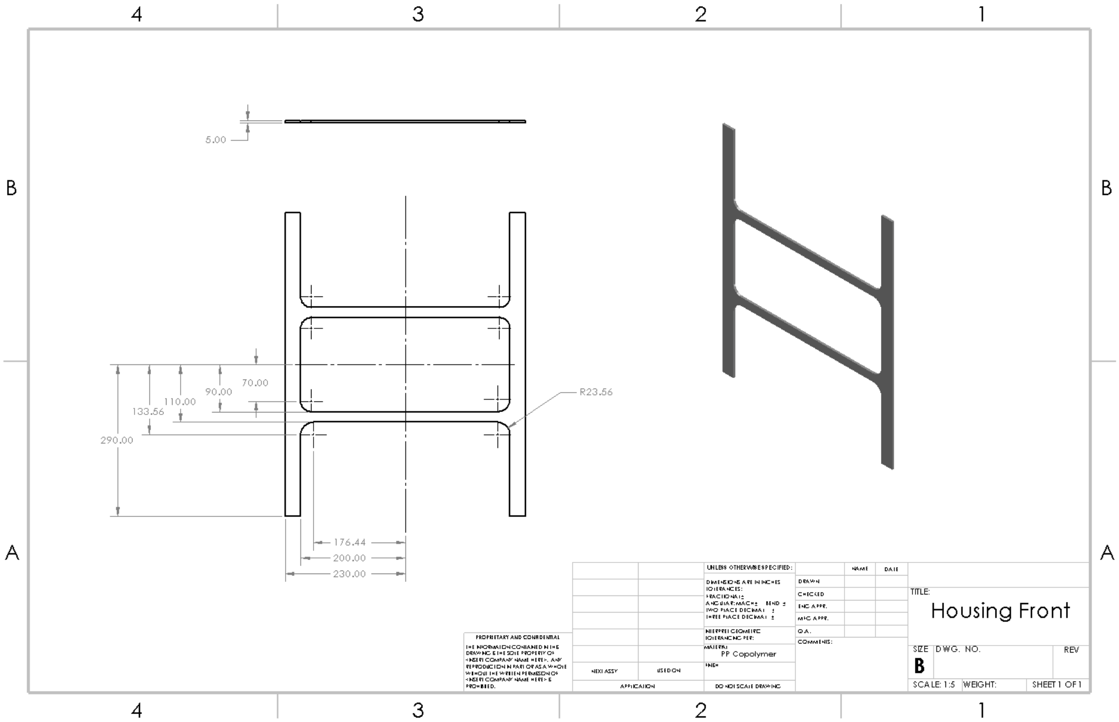

10.00
390.00
60.00
8X ⌀ 6.60 THRU ALL
⌴ ⌀ 11.50 ↧ 3.30
60.00
40.00
25.00
100.00
425.00
450.00
UNLESS OTHERWISE SPECIFIED:
Aluminum 6061
TITLE:
Frame Base
SIZE DWG. NO. REV
B
SCALE: 1:5 WEIGHT: SHEET 1 OF 1

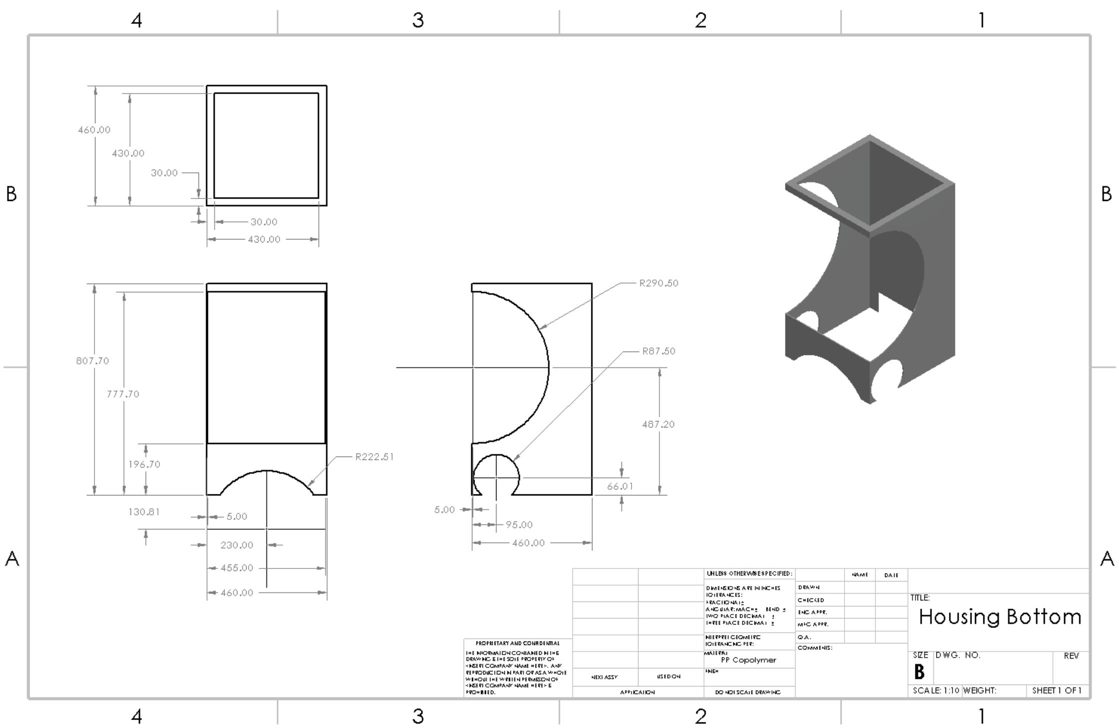


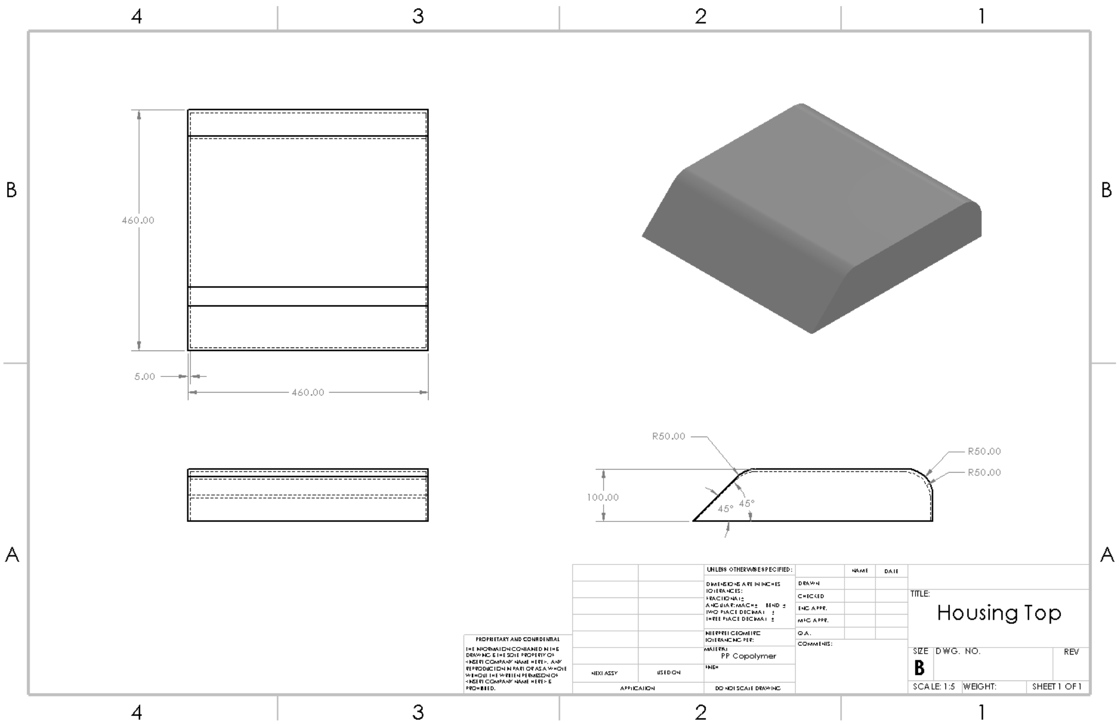
2.50
450.00
425.00
25.00
25.00
425.00
450.00
Chrome St. Steel
TITLE:
Shelf
SIZE
DWG. NO.
REV
B
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1

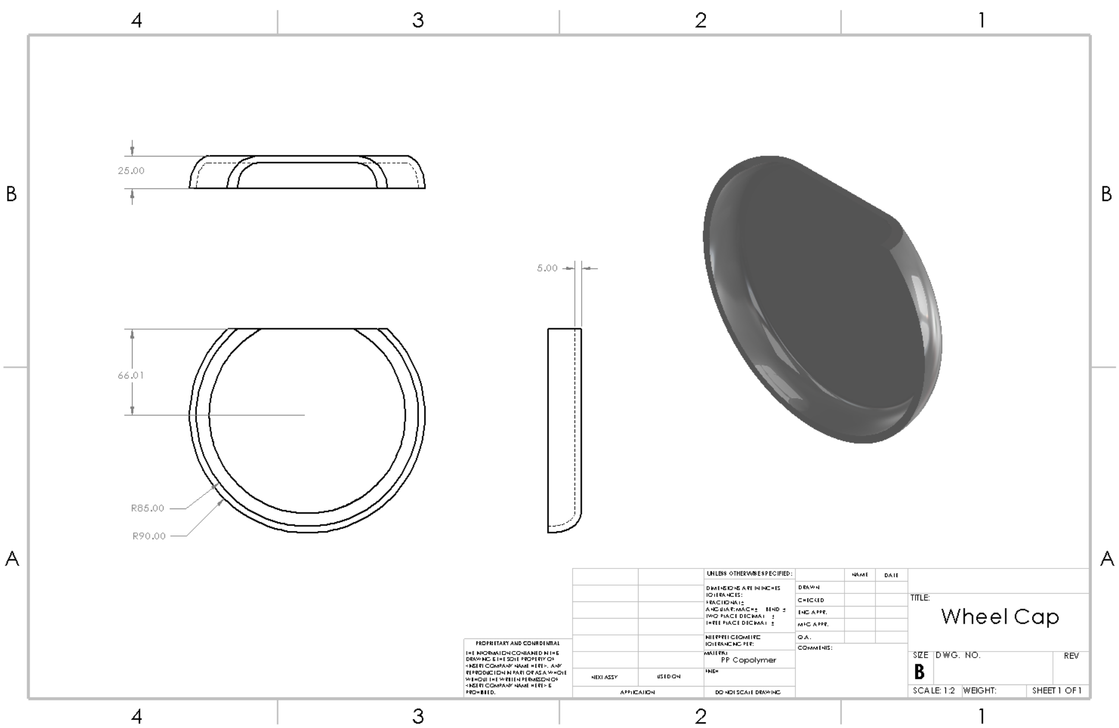


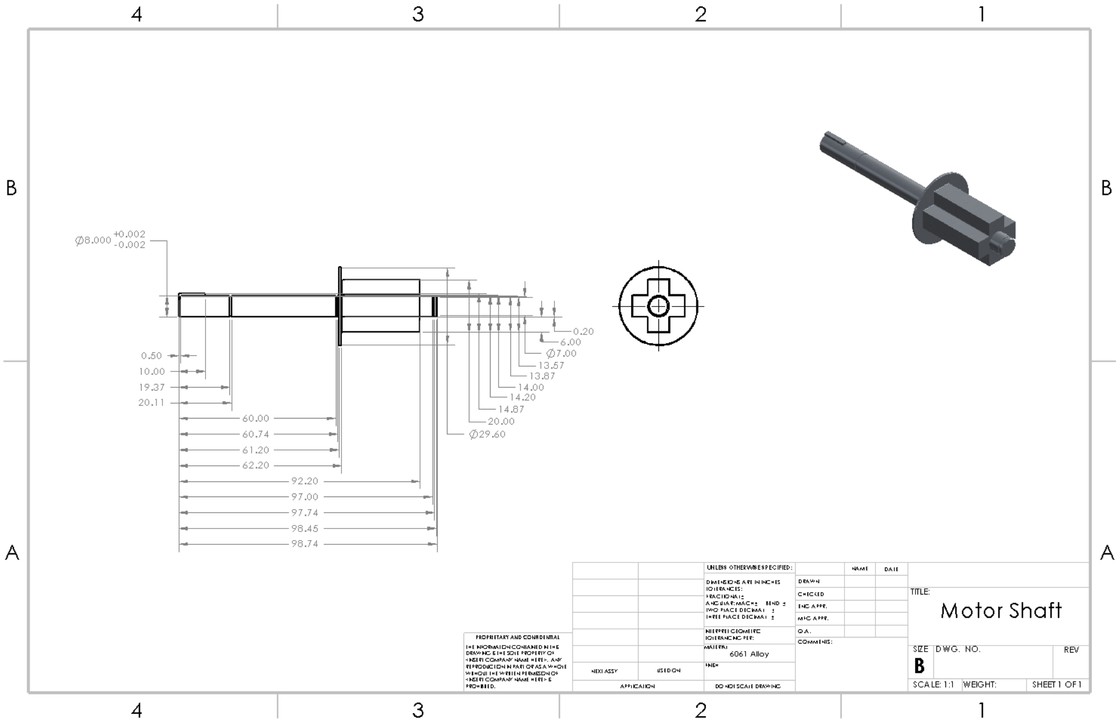
5.00
R290.50
Acrylic
TITLE:
Housing Clear
SIZE
DWG. NO.
REV
B
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1

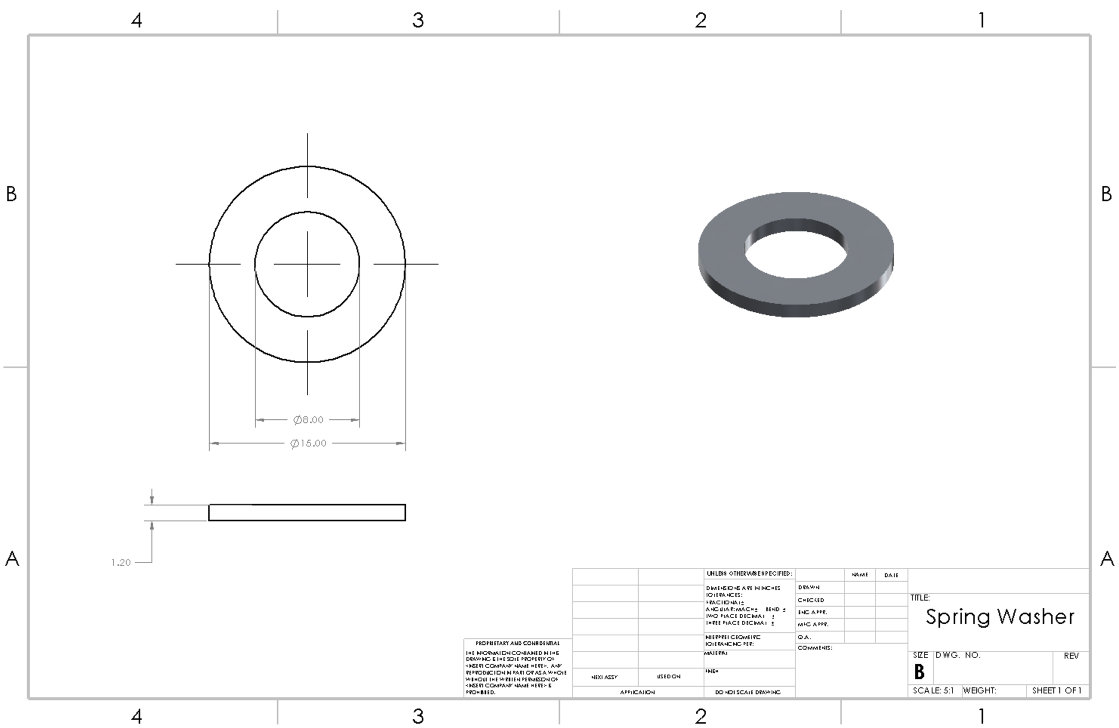

5.00
70.00
90.00
110.00
133.56
290.00
R23.56
176.44
200.00
230.00
UNLESS OTHERWISE SPECIFIED:
PP Copolymer
TITLE:
Housing Front
SIZE
DWG. NO.
REV
B
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
DO NOT SCALE DRAWING

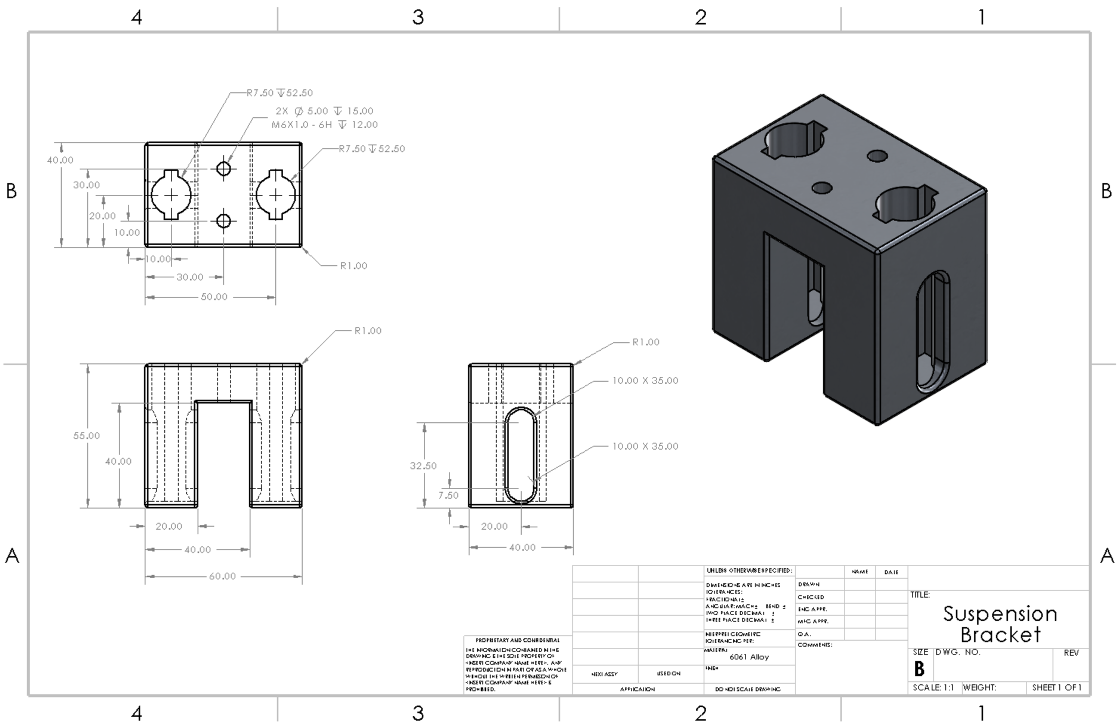

460.00
430.00
30.00
30.00
430.00
807.70
777.70
196.70
130.81
R222.51
5.00
230.00
455.00
460.00
R290.50
R87.50
487.20
66.01
5.00
95.00
460.00
UNLESS OTHERWISE SPECIFIED:
PP Copolymer
TITLE:
Housing Bottom
SIZE
DWG. NO.
REV
B
SCALE: 1:10
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
DO NOT SCALE DRAWING

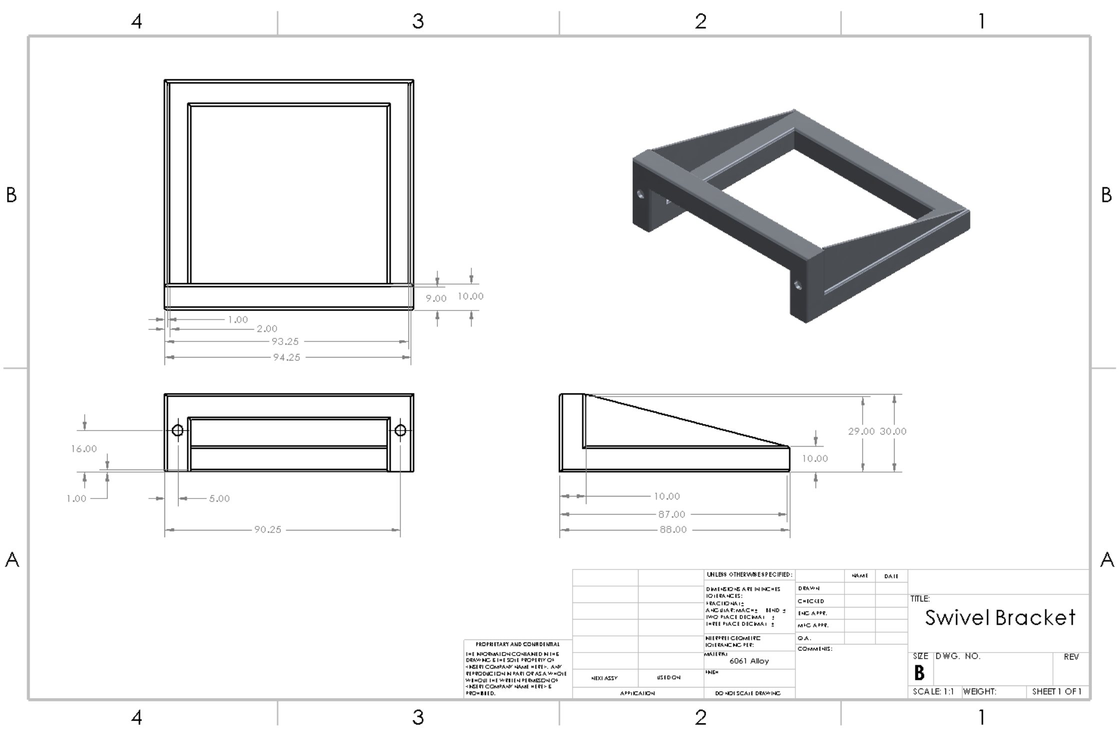

460.00
5.00
460.00
R50.00
R50.00
R50.00
100.00
45°
45°
TITLE:
Housing Top
PP Copolymer
SIZE
DWG. NO.
REV
B
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1

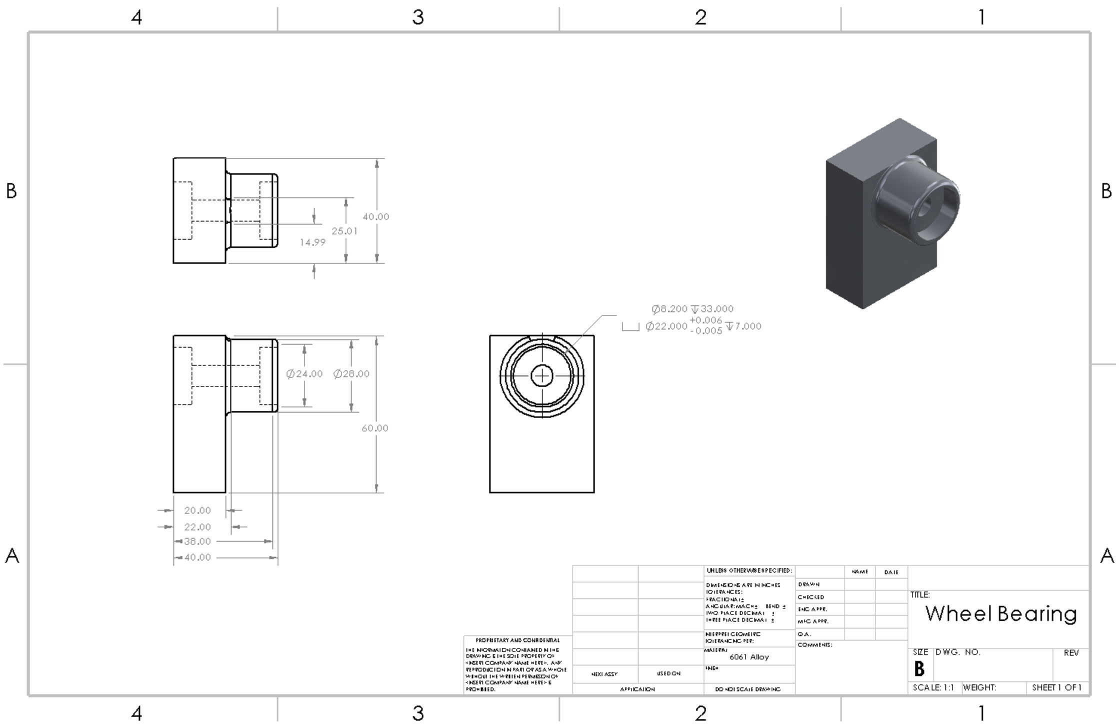

25.00
5.00
66.01
R85.00
R90.00
TITLE:
Wheel Cap
PP Copolymer
SIZE
DWG. NO.
REV
B
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1


Motor Shaft
6061 Alloy
SCALE: 1:1
SHEET 1 OF 1
Ø8.000 +0.002 -0.002
0.50
10.00
19.37
20.11
60.00
60.74
61.20
62.20
92.20
97.00
97.74
98.45
98.74
0.20
6.00
Ø7.00
13.57
13.87
14.00
14.20
14.87
20.00
Ø29.60


Spring Washer
SCALE: 5:1
SHEET 1 OF 1
Ø8.00
Ø15.00
1.20

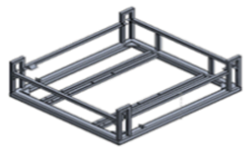
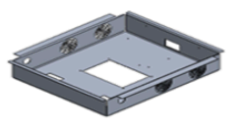
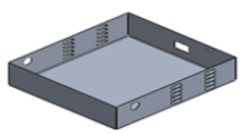
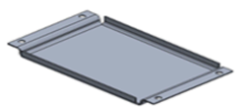
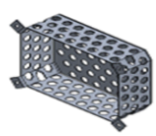
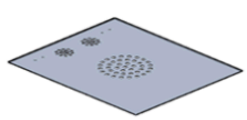
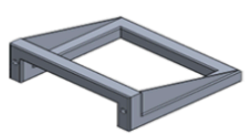
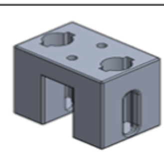

R7.50 ⌵52.50
2X ⌀ 5.00 ⌵ 15.00
M6X1.0 - 6H ⌵ 12.00
R7.50 ⌵ 52.50
40.00
30.00
20.00
10.00
10.00
30.00
50.00
R1.00
R1.00
55.00
40.00
20.00
40.00
60.00
R1.00
10.00 X 35.00
10.00 X 35.00
32.50
7.50
20.00
40.00
UNLESS OTHERWISE SPECIFIED:
TITLE:
Suspension Bracket
MATERIAL
6061 Alloy
SIZE DWG. NO. REV
B
SCALE: 1:1 WEIGHT: SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
DO NOT SCALE DRAWING

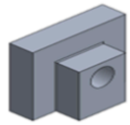
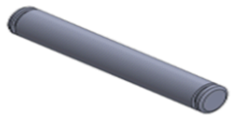
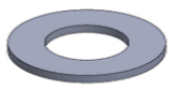
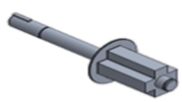
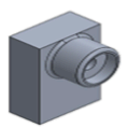
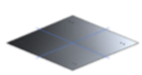
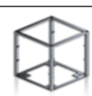

9.00
10.00
1.00
2.00
93.25
94.25
16.00
1.00
5.00
90.25
29.00
30.00
10.00
10.00
87.00
88.00
UNLESS OTHERWISE SPECIFIED:
TITLE:
Swivel Bracket
MATERIAL
6061 Alloy
SIZE DWG. NO. REV
B
SCALE: 1:1 WEIGHT: SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
DO NOT SCALE DRAWING

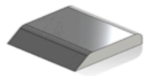
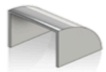
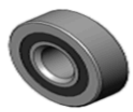
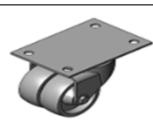


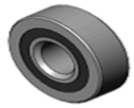
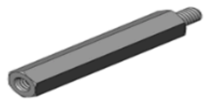
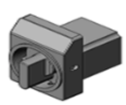
40.00
25.01
14.99
Ø24.00
Ø28.00
60.00
20.00
22.00
38.00
40.00
Ø8.200 ↧33.000
⌴ Ø22.000 +0.006 -0.005 ↧7.000
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
6061 Alloy
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL
TITLE:
Wheel Bearing
SIZE
B
DWG. NO.
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1

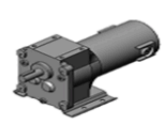
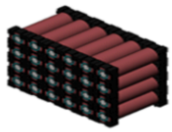
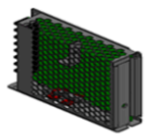
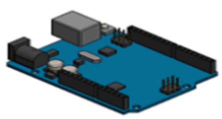
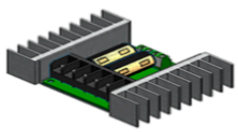
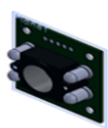
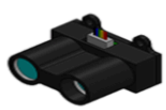
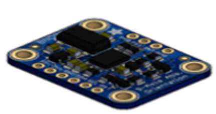
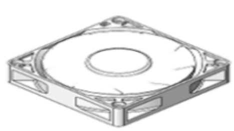
Appendix 2 - Bill of Materials

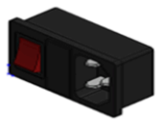
Hospital Robot BOM						
Made-In-House Bottom Half Items						
Item #	Item Name		Item Description	Price per item($)	Quantities	Total Cost($)
1	Frame		6061 Alloy Square tube_10 x 10 x 1.5 x 2660mm(H x W x T x L)	19.65/6ft	2	39.3
			6061 Alloy Square tube_20 x 20 x 2 x 1480mm(H x W x T x L)	27.93/6ft	1	27.93
2	Bottom Inner Shell		6061 Alloy Sheet Gauge 18_485mm x525mm	42.65/24"x24"	1	42.65
3	Bottom Outer Shell		6061 Alloy Sheet Gauge 18_575mm x 535mm	42.65/24"x24"	1	42.65
4	Battery Tray		6061 Alloy Sheet Gauge 18_175mm x 110mm	7.23/8"x8"	1	7.23
5	Battery Brace		6061 Alloy Sheet Gauge 18	25	1	25
6	Bottom Cover		6061 Alloy Sheet Gauge 18_370mm x 310mm	28.91/18"x18"	1	28.91
7	Swivel Bracket		6061 Alloy Square tube_10 x 10 x 1.5 x 525mm(H x W x T x L)	19.65/6ft	2	39.3
8	Suspension Bracket		6061 Alloy Billet_40 x 60 x 55mm	15	4	60

9	Suspension Block		6061 Alloy Billet_40 x 35 x 20mm	12	4	48
10	Suspension Pin		6061 Alloy Rod_Ø8 x 66mm	2.64/1ft	4	2.64
11	Suspension Spring		PC058-281-10500-MW-1280-CG-N-IN	3.6	8	28.8
12	Suspension Spring Washer		6061 Alloy Billet	2	8	16
13	Shaft		6061 Alloy Billet_ Ø1 ¼" x 6ft	51.94	2	103.88
14	Wheel Bearing Block		6061 Alloy Billet	25	2	50
					Total	**562.29**
Made-In-House Top Half Items						
15	Frame Base		6061 Alloy Sheet Gauge 18_450mm x 450mm	42.65/24"x24"	1	42.65
16	Frame		6061 Alloy Square Tube_25 x 25 x 2.5 x 650mm 6061 Alloy Square Tube_25 x 25 x 2.5 x 450mm	21.47/3ft 15.55/2ft	4	148.08
17	Frame Plate		6061 Alloy Sheet Gauge 18_450mm x 450mm	42.65/24"x24"	1	42.65
18	Housing Bottom		PP Copolymer	40	1	40

19	Housing Top		PP Copolymer	30	1	30
20	Wheel Cap		PP Copolymer	15	2	30
21	Swivel Cap		PP Copolymer	15	2	30
22	Housing Clear		Acrylic	15	2	30
					Total	**393.38**
			McMaster Catalog Items			
23	Suspension Bearing		5972K211	7.86	8	62.88
24	C-clip		97633A150	9.6(pack of 100)	6	9.6
25	Set Screw Shaft Coupling		5395T212	6.86	2	13.72
26	E-clip		98543A116	9.4(pack of 100)	8	94
27	Swivel Wheel		2390T600	8.9	2	17.8
28	Wheel		4941T21	33.7	2	67.4

29	Wheel Bearing		2349K744	25.27	4	101.08
30	M2.5 Standoff		93655A359	5.1	4	20.4
31	M2.5 Standoff End Screw		92125A084	6.7(pack of 25)	4	6.7
32	M3 Bolt		91290A111	9.32(pack of 100)	4	9.32
33	M3.5 Bolt		91290A382	13.33(pack of 10)	10	13.33
34	M3.5 Washer		98688A113	4.29(pack of 100)	8	4.29
35	M4 Bolt		91290A180	8.33(pack of 50)	6	8.33
36	M5 Bolt		91239A228	9.58(pack of 100)	16	9.58
37	M6 Bolt		91290A321	13.59(pack of 100)	8	13.59
38	Panel-Mount Compact Disconnect Switch		65915K12	67.14	1	67.14
					Total	**519.16**

			Electronics			
39	Motor		Crouzet Gearmotor 808050Y15.31Z	101.4	2	202.8
40	Battery Pack		Panasonic B(NCR18650B)(6S8P 26.8Ah,39A,21.6V)	196.8	1	196.8
41	Power Supply		LRS-100W24V	14.99	1	14.99
42	Motor Controller		Arduino Uno	17.6	1	17.6
43	Motor Driver		Sabertooth 2x25	124.99	1	124.99
44	IR Sensor		TCS3200 Module	7.9	16	126.4
45	LIDAR Sensor		SparkFun Electronics LIDAR Lite v3	129.99	2	259.98
46	IMU		Adafruit BNO055	34.95	1	34.95
47	Fan		60mm x 60mm x 11.25mm	11.95	4	47.8

48	Power Receptacle		Jameco IEC-GS-1-100	3.49	1	3.49
					Total	**1029.8**
					Grand Total of robot	**2504.63**

LINE INSTALLATION

49	3M double Sided surgical tape		25.4mm x 32.91m	36.00	60	2160.0
50	5350 chemical resistant urethane clear flooring topcoat		15 gallons	1521.46	1	1521.46
					Total	**3411.46**
					Grand Total of Line	**3411.46**

***line installation figures based on urban, non-student hospital size**

FINAL ALL-INCLUDED GRAND TOTAL

$ 5916.09

With a 4x production markup, our final product price comes out to

$ 23,665

Appendix 3 – Pitch Slides

A3.1 - Elevator Pitch

Elevator Pitch

Team Search

Nursing and its importance

- Registered Nurses encompass one of the biggest segments of the US workforce at nearly 3.8 million
- These Nurses dedicate years of their life to specializing in areas that make them valuable to multidisciplinary teams that care for patients with a variety of different complexities
- Nurses are the heart of any hospital
  - They know products that work best
  - They are the patient advocates
  - They identify inefficiencies

"The hospital will never be healthy for patients if it's not a healthy environment for nurses, where their voices are heard and where they can care for their patients and use the full extent of their knowledge, abilities, and skills. After all, hospitals today have become one big intensive care unit: all patients need intensive caring."

-Tilda Shalof
Bestselling Author and experienced ICU nurse

So where's the problem?

Problem

- Hospitals have thinly spread medical staff, frequent personal contact, and high disease transmission rates.

Motivation

- Medical staff are distracted by nonmedical tasks
- The "population density" of hospitals is high.
- Hospitals are sites of high disease transmission.
- Enhance not replace.

Questions

- Can we limit either contact or the number of people involved?
- Can this be done with an engineered system?

Our solution

Breadth

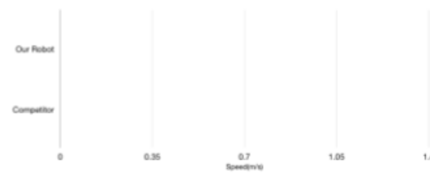
- Previous attempts have been made to address this problem; however, the rarity of robotic systems suggests the problem has not been solved satisfactorily.
- We attempt to modify previous solutions by simplifying navigation and individual robot roles.
- Our solution will be restricted to the physical operation of the supply chain (i.e. direct replacement of manual transportation with robotic transportation).

Table 1, Summary of transportation tasks

Task	*Personnel involved*	*Hours/Week*
Medicine Transport	Porter (2)	50,4
Mail Delivery	Hospital Employee (4)	107,1
Transports to Unit Storages	Porter (1)	27
Transports to Sterile Cabinets	Hospital Employee (2)	69
Food Transport	Porter (5)	98
Transports from central supply	Porter (2)	51,8
Empty beds	Porter (3-4)	113,4
Transport of clothes	Porter (4)	130
Waste Collection	Porter (4)	195,84

Our Value

- Why Us?
  - Integration
    - non-invasive setup with minimal investment that can be tailored to hospitals at any size
  - Navigation reliability
    - Proven high accuracy with emergency subsystems to keep nurses focused on their tasks and not our robots
    - Increased deliverable reliability and predictability
  - Cost
    - Including initial line installation and robot, we are still well u our main competitor (~90% decrease)
  - Speed
    - Getting there faster, saving time for nurses
  - Safety
    - Made with Nurses, doctors, and patients safety a priority
    - Structural safety factor greater than 10



Trusted

- Designed with the Nurse in mind
  - Modeled with Nurse feedback from current Nursing professionals at UCLA and Johns Hopkins University
- Approved by representatives in the health care business industry
  - Pitch and incorporated feedback from Chief Executive Officer of Dignity Health Foundation

JOHNS HOPKINS UNIVERSITY UCLA Dignity Health.

"We had creators to really create tools and technologies to help us through the pandemic... Each year, we look forward to these ideas and really trying to bring them forward for our community."

-Johnese Spisso,
The president of UCLA Health and CEO of the UCLA Hospital System

Thank you!

From all of us at Team Search

A3.2 - Engineering Pitch

Engineering Pitch

Team Search

Nursing and its importance

- Registered Nurses encompass one of the biggest segments of the US workforce with nearly 3.8 million
- These Nurses dedicate years of their life to specializing in areas to make themselves valuable to multidisciplinary teams that care for patients with a variety of different complexities
- Nurses are the heart of any hospital
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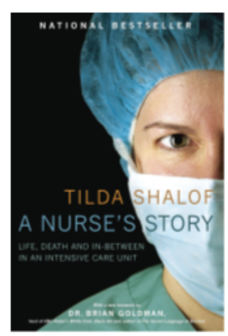

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- Previous attempts have been made to address this problem; however, the rarity of robotic systems suggests the problem has not been solved satisfactorily.
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	Solutions ->			
Sub Functions	1	2	3	4
Holding Object	Safe	Drawers	Cart	Trays
Transportation Method	Autonomous Line-Following	Wall-Mounted Rails	Roof-Mounted Rails	
Accessibility	Patient Interaction	Nurse Interaction	Interaction of Both	No Human Interaction
Ground Interface	Wheels	Treads	Mounted Rails	
Path Sensors	IR	Ultrasonic	Lidar	Camera
Obstacle Sensors	IR	Ultrasonic	Lidar	Camera

Our Value

- What does the consumer want?
    - Adaptability, speed, money, aesthetics, minimal impedance, battery

- Why Us?
    - Integration
        - non-invasive setup with minimal investment that can be tailored to hospitals at any size
    - Navigation reliability
        - Proven high accuracy with emergency subsystems to keep nurses focused on their tasks and not our robots
        - Increased deliverable reliability (~25%) and predictability (~50%)
    - Cost
        - Including initial line installation and robot, we are still well under our main competitor (~90% decrease)
    - Speed
        - Getting there faster, saving time for nurses (~43% faster max speed)
    - Safety
        - Structural safety factor greater than 10
        - Algorithmic safety through our path following system

Competitor comparison (quantifiable specifications)

specification	TUG	OUR
Sensors	sonar/infrared/laser	Lidar/IR
Battery	10 hours with intermittent charging	6.5 hours on one charge
Dimensions	58.9x113.5cm	50x100cm
Drive system	4WD	Front 2WD
Navigation method	internal map and real time lidar	Line following
charging	Navigates to charging station	Navigates to charging station

Where we take the next step...

specification	TUG	OUR
Initial setup	Required mapping with emptied out hospital	Simple line installation
Operating weight	220 ilbs	75 ilbs
Navigation drawback	Requires algorithmic monitor	Entirely self-sufficient
Max speed	1.7 mph	3 mph
Cost	$150000	$5000
Max torque	0.18 NM	5 NM

Trusted

- Made with the Nurse in mind
  - Designed with Nurse feedback from current Nursing professionals at UCLA and Johns Hopkins University
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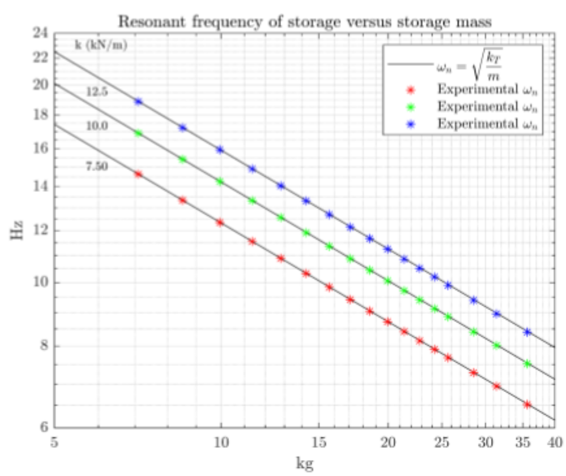
JOHNS HOPKINS UNIVERSITY UCLA Dignity Health.

Design/engineering work results

Number of trials	Track	Percentage deviation outside of outside barrier for 1 loop
500	U-shaped	0.002%
500	Surrounded	0.248%
500	Parallel corridor	0.081%
500	Embedded	0.405%

Table. Deviation across trial runs



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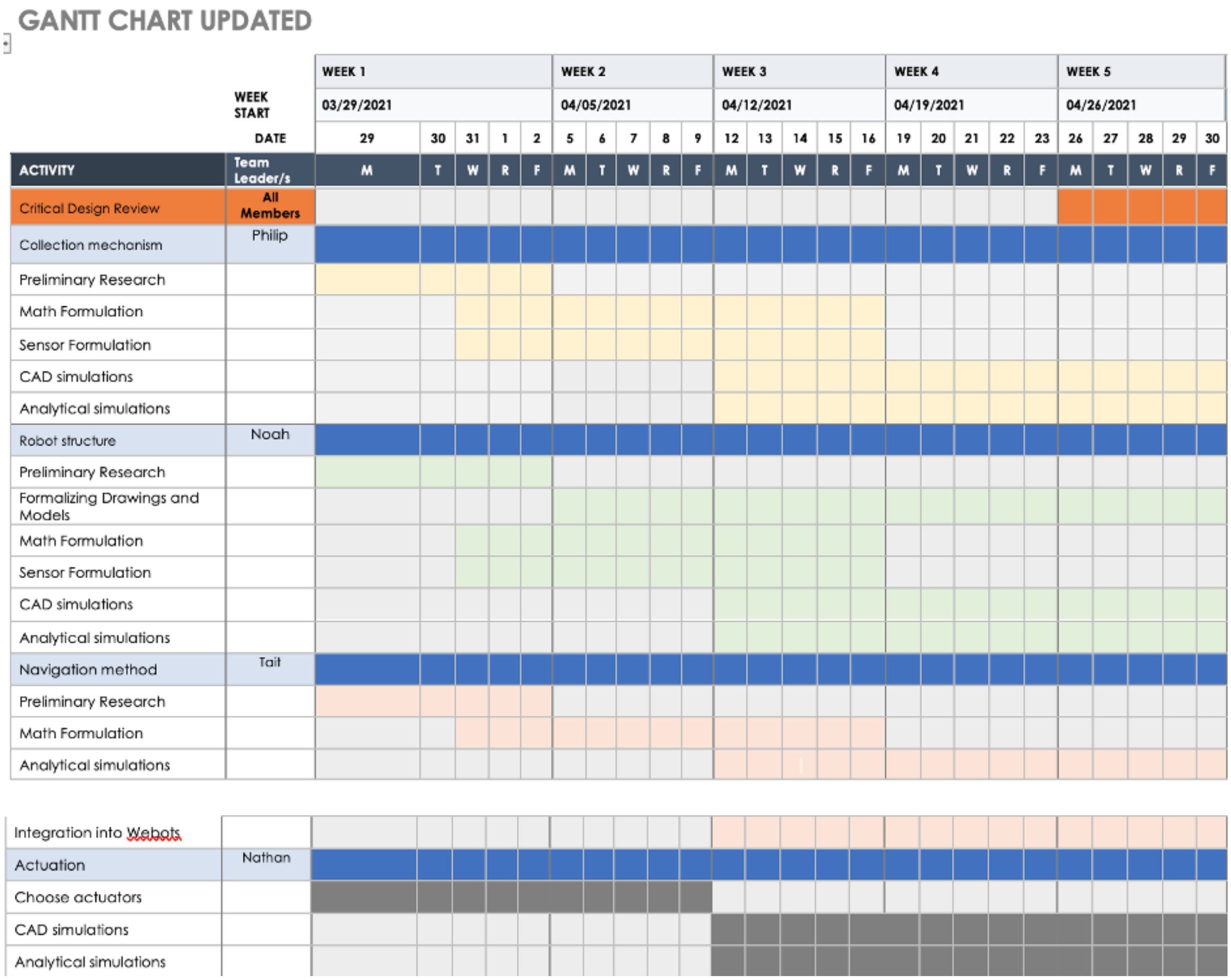
-Johnese Spisso,
The president of UCLA Health and CEO of the UCLA Hospital System

Appendix 4 – Gantt Chart



		WEEK 6					WEEK 7					WEEK 8					WEEK 9					WEEK 10				
	WEEK START	05/03/2021					05/10/2021					05/17/2021					05/24/2021					05/31/2021				
	Date	3	4	5	6	7	10	11	12	13	14	17	18	19	20	21	24	25	26	27	28	31	1	2	3	4
ACTIVITY	Team Leader/s	M	T	W	R	F	M	T	W	R	F	M	T	W	R	F	M	T	W	R	F	M	T	W	R	F
Collection mechanism	Philip																									
Preliminary Research																										
Math Formulation																										
Sensor Formulation																										
CAD simulations																										
Analytical simulations																										
Optimizing control																										
Robot structure	Noah																									
Preliminary Research																										
Formalizing Drawings and Models																										
Math Formulation																										
Sensor Formulation																										
CAD simulations																										
Analytical simulations																										
Integration into Webots																										
Optimizing control																										
Incorporating feedback																										
End-to-end testing																										
Navigation method	Tait																									
Preliminary Research																										
Math Formulation																										
CAD simulations																										
Analytical simulations																										
Integration into Webots																										
Optimizing control																										
End-to-end testing																										
Actuation	Nathan																									
Choose actuators																										
CAD simulations																										
Analytical simulations																										
Integration into Webots																										
Final Deliverables	Lu																									
Presentation																										
Written Report																										

Appendix 5 – Task Collaboration Matrix

	Task	NathanChen	TaitKaminski	PhillipKrings	NoahBallard	ZhiyangLu			Sum	NormalizedSum
Preliminary Analysis	Objective Tree Analysis	0	0	0	1	0.5			1.5	0.3
	Transparent Box Model	0	0	1	0	0			1	0.2
	Performance Specification Analysis	0	0	0	1	0.5			1.5	0.3
	Quality Function Deployment	0	0	0	2	2			4	0.8
	Morphological Chart	1	1	0	1	0			3	0.6
	Weighted Objective Method	0	1	0	0	0			1	0.2
Design	Storage	0	0	30	0	0			30	6
	Chassis	0	0	0	12	15			27	5.4
	Drivetrain	2	0	4	2	19			27	5.4
	Suspension	0	0	4	1	0			5	1
	Cooling	0	0	0	0	10			10	2
	Electronics	5	5	0	0	0			10	2
	Controller	25	15	0	0	0			40	8
	Mathematical Formulation	5	5	0	0	1			11	2.2
	Aesthetics	0	0	4	0	0			4	0.8
Analysis	Design Specifications	19	5	0	0	2			26	5.2
	Motion Analysis	5	30	0	42	2			79	15.8
	Finite Element Analysis	0	0	8	0	5			13	2.6
	Dynamics	2	2	8	0	0			12	2.4
	Control	2	5	0	7	0			14	2.8
	Functional	2	2	5	4	2			15	3
Report	Technical Drawings	10	0	8	0	1			19	3.8
	BOM	0	1	1	0	12			14	2.8
	Video – FDR Comprehensive	1	1.5	2	2	4			10.5	2.1
	Video – Sales Pitch	1	0.5	1	1	4			7.5	1.5
	Video - CDR	2	2	2	2	4			12	2.4
	Engineering Pitch (Demo Day)	1	1	1	1	1			5	1
	Demonstration (Demo Day)	1	1	1	1	1			5	1
	GANTT Chart	0	2	1	0	0			3	0.6
	CDR Report	6	6	8	6	5			31	6.2
	FDR Report	7	10	8	9	5			39	7.8
Management	Group	2	3	1	3	2			11	2.2
	Sub system	1	1	2	2	2			8	1.6
Sum		100	100	100	100	100			500	100

Appendix 6 – Code

Check out our Github Repo here with relevant code

https://github.com/taitk6057/ECE183DB

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Product Data Sheets

https://aethon.com/PDF/TUG_T2_Datasheet.pdf

https://aethon.com/PDF/TUG_2.5_Datasheet.pdf

https://www.oppent-evo.com/wp-content/uploads/2019/01/EVOcart-Family.pdf

https://www.dimensionengineering.com/datasheets/Sabertooth2x25v2.pdf

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