Mechanical Platform for Social Navigation

ROB 450 WN 2025

Short Bot Among Us

Team Members:
Reina Mezher
Adam Hung
Joseph Fedoronko
Anuhea Tao

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Abstract

For our capstone project, we present the design, development, and evaluation of a mechanical robot platform built for social navigation research. After evaluating multiple concepts via a weighted Pugh chart, we selected a project building on top of on the ETH Zurich Ballbot and the University of Michigan ROB311 platform. Motivated by the limitations of existing commercial robots, such as high cost, short height, limited omnidirectional mobility, and insufficient social presence, we sought to build an affordable, adaptable platform that researchers could use to test social navigation algorithms in real-world settings. The final robot is 1.24 meters tall, drives omnidirectionally, visually navigates using a RGB-D camera, and uses LED lights to increase legibility of motion. In addition to making use of off-the-shelf components such as aluminum extrusions and the camera, we manufactured low-cost 3D-printed and laser cut parts with a total spend of \$80.00. Some of our key requirements include human-like (> 0.35 meter) height, small footprint (< 0.4 square meters), sufficiently powerful motors, and the capability to accurately track and travel to a target. Our final testing verified all of our requirements. We were able to analytically verify requirements such as height, footprint, and motor torque, whereas we experimentally verified navigating to a target.

Executive Summary

In the context of robotics, social navigation can be defined as the use of robotics principles to enable a robot to move through an environment while adhering to the social norms of that environment. Current researchers in the field of social navigation implement their advanced navigation algorithms on physical platforms that do not satisfy the mechanical aspects of social robots. The current practice is ignorant of human-robot interaction (HRI) factors that are a key consideration to social robots.

We've explored the intersection of HRI and social navigation in order to address the lack of a suitable mechanical platform for software solutions in this space. Current solutions fall short of particular design considerations such as size, mobility, speed, and accessibility. This project addresses this critical gap in social navigation research by offering an human-perceivable, accessible, and omnidirectional robot platform optimized for human–robot interaction (HRI). Key design requirements included human-like height ($> 0.35\,\mathrm{m}$) to be perceivable, compact footprint($< 0.4\,\mathrm{m}^2$) to navigate social environments safely, and sufficient drive torque to allow for omnidirectional drive. Our team built upon the University of Michigan ROB311 ballbot implementation by extending its chassis to a human-perceivable height, integrating an RGB-D camera for visual navigation, and adding an LED matrix to convey state changes.

Our analytical verification via CAD and dynamic torque modeling confirmed compliance with height, footprint, and motor torque specifications. Experimental trials demonstrated consistently precise target acquisition and safe stopping behavior under a virtual safety fixture. Despite an initial focus on dynamic balancing, mobility constraints led to a successful proof of concept prototype that fulfills all core mechanical and HRI objectives.

The design and development of this mechanical platform addresses current key problems with mechanical platforms for social navigation while also uncovering critical challenges in exploring this design space.

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1 Introduction

The objective of this project is to develop an autonomous robot that is capable of navigating social environments, and it is sponsored by Christoforos Mavrogiannis, a robotics professor at the University of Michigan. This project was created to investigate an improvement in current solutions for social navigation robot platforms. Fundamentally, social navigation is defined as when movement from one object is the result of the activity of another. In our robotics context, social navigation is defined as using robot design, algorithm design, and computer vision to enable a robot to perceive its environment and move through it while adhering to the social norms of that environment [1]. Researchers developing these algorithms for social navigation lack the suitable mechanical platform needed to deploy them and accurately assess their functionality. The algorithms may allow for a robot to traverse a social environment; however, the robot must also seamlessly integrate into that environment from a sociocultural perspective as well, meaning, the robot and its movement should be perceived by those within the environment. If that robot is not perceived, one cannot assess the sociocultural performance of their robot (human-robot interaction (HRI)). We seek to provide social navigation researchers with a platform that possesses the mechanical qualities needed to navigate human environments while adhering to the social cues of those environments.

1.1 Background

To properly develop an approach for this project, it is important to understand the gaps in the current solutions of this space, and contextualize relevant concepts related to the problem we are trying to solve. We do this through both examining existing literature and recording feedback from our sponsor through interviews [2].

1.1.1 Current Solutions

Multiple existing social navigation platforms detail robots that are limited in height, speed and social presence (see Figure 1). These robots are listed at a price point that makes them not feasible for performing research on. Certain systems such as TidyBot [3] show a mobile robot that can perform a select number of tasks with the use of a robotic arm. While TidyBot performs these tasks autonomously with relatively precise movements, the social aspect and price point are considered drawbacks for researchers looking to conduct social navigation experiments. Furthermore, TidyBot++ is designed for mobile manipulation, not necessarily social navigation, so the form factor of the robot is somewhat bulky. Similar to TidyBot, TurtleBot is a robotics learning platform that resembles a home cleaning robot with a slightly larger height. This system lacks social presence with the tallest model's height coming in just over 1 foot [4].

(a) TidyBot++ (b) TIAGo (c) TurtleBot

Figure 1: Social navigation robots: TidyBot++ [3], TIAGo [5], and TurtleBot [4].

Despite consisting of complex hardware components, many of the existing solutions fail to address some of the most important robotic aspects as they relate to HRI research. This research suggests that there is a need to develop a platform that addresses the concerns of cost as well as human-like speed and height.

1.1.2 Human-Robot Interaction (HRI)

Robot aesthetics greatly affect how the robot is perceived. Specifically for robots in the social context, aesthetics influence how their functionality is reflected [6]. Robot aesthetics are generally categorized to be mechanical or anthropomorphic where some are designed for functionality and others are designed to replicate human characteristics, respectively. These categories do not only refer to visual aesthetics but also the fluidity of motion of the robots, defined as robot movement that is unconstrained in mobility in order to smoothly adapt its motion to the given environment [6]. Both the visual and mobility components of social robot aesthetics are important for the legibility of motion.

In the context of robotics and motion, the legibility of motion can be defined as the ability of a human to understand the intention of the robot based on its motion [7]. Social navigation robots are to not disturb the social norms of the environment that they act in; therefore, humans must be able to anticipate the behavior of the robot either through its movement, physical design, or other cues. Hence, robot aesthetics are important to increase the legibility of motion factors, as they address these key factors.

1.1.3 Mobility

Delving deeper into the mobility aspect of social navigation robots, we've already identified the importance of mobility in this context above, as well as the shortfalls in this space in current robotic solutions. Mobility in social navigation robots must not be constrained by the system in order to preserve fluidity. Meaning, the robot should be able to move in any direction it needs to while navigating and adapting to its environment. This type of mobility can be referred to as omnidirectional.

In the robotics design space, a popular solution to omnidirectionality is the exploration of ballbots. At a high level, ballbots are agile systems where a robot balances and drives on a single ball [8]. The advantage of this system is its maneuverability and ability to restabilize, directly reflecting fluid motion. Many universities, including ETH Zurich and Carnegie Mellon University, have developed their own ballbots for mobility and navigation research [8,9]. Although their mobility satisfies the omnidirectional need for social navigation robots, none of these solutions have been explored in social contexts.

1.2 Design Context

Upon consideration of our specific problem, we aimed to identify what groups would be most impacted by our work as a way to further influence our design. As primary stakeholders, our group defined the people who would be directly affected by this work and determined that these would firstly be our team and our project sponsor. As secondary stakeholders, we identified companies/manufacturers to be people who might be indirectly involved but are still impacted by our results in some fashion. Lastly, we had to consider what long-term ramifications our work would have and what groups would be considered secondary stakeholders. These groups are public area owners and pedestrians as they would be involved in future social navigation studies where this platform is utilized.

With this project, we also found it useful to identify which of our stakeholders would be positively or negatively impacted by our work, as seen in Figure 2. Considering a group such as competing companies led us to recognize that they could experience a decline in sales if our product is offered at a significantly lower price than their existing products. Conversely, this concept also sparked discussions about the potential positive impact of our work. For example, with our developed prototype, companies may be encouraged to implement some of the features we have added to our platform, resulting in an improved overall product. Additionally, companies might consider purchasing this platform as a means of integrating these features into their existing solutions, further expanding the positive impact of our design.

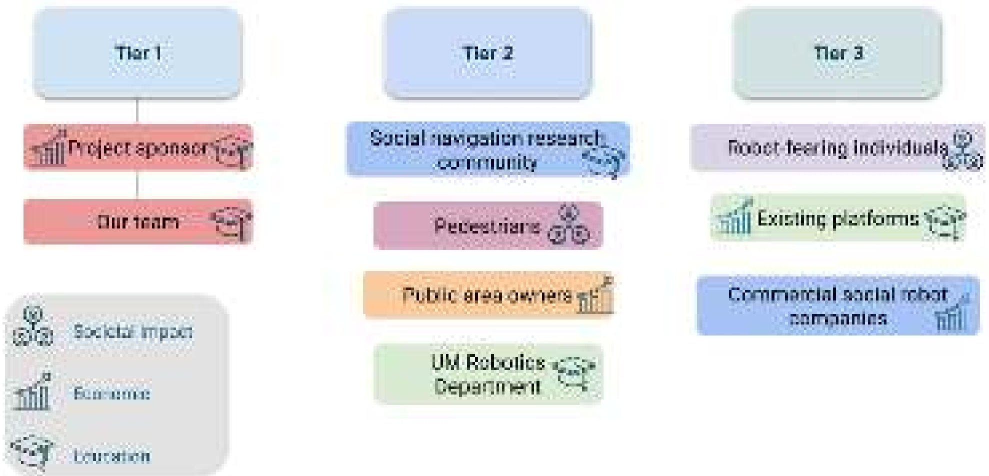


Figure 2: Stakeholder map.

In addition to the broader impact of our design, we must also account for the responses of individuals participating in human-robot interaction (HRI) studies using this platform. As students experienced with robotic systems, we are accustomed to working with these robots; however, we recognize that participants in these studies may have varying levels of comfort. This consideration led us to define stakeholders as anyone worldwide who interacts with this system. Therefore, throughout the development process, our group prioritized inclusivity, ensuring that the system accommodates individuals with diverse perspectives and familiarity with robots.

1.3 Concept Generation

Applying the concepts that were introduced to us in class, our team was able to combine multiple of them to generate the concept map shown in Figure 3. The first idea that was used is called "brain purge" where we began with first defining all parts of our problem and all issues identified with existing market solutions. This served as a good starting place to prevent us from focusing too much on a specific solution. From there we defined each of our first leaves on our map as these problems, branching off with smaller concepts that would need to be considered when addressing these problems.

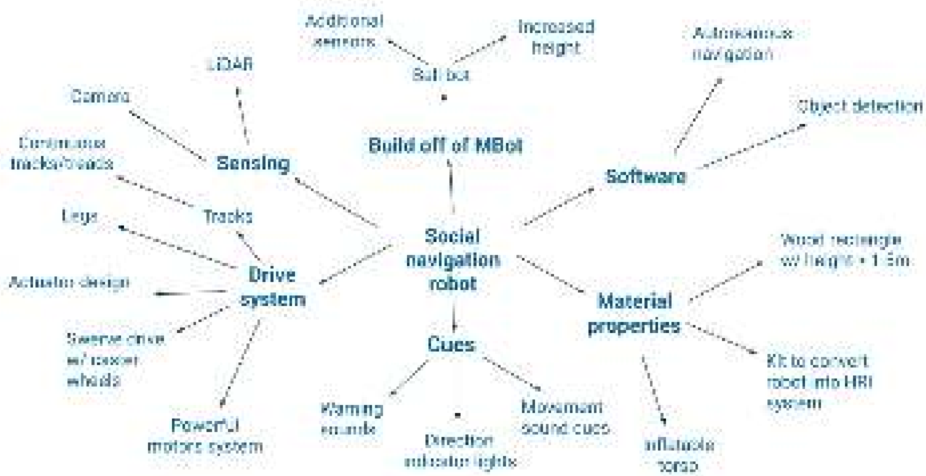


Figure 3: Stakeholder map.

After generating an initial map, we then sought guidance from the instructors and were able to create ideas that were outside of our initial scope. Some of these ideas, for example, included concepts of mobility where we considered systems that both model human behavior and systems that do not. From there we were able to achieve ideas such as tank treads, and human legs. These ideas showcase our team widening our concept generation as to not constrain ourselves to pre-defined notions of what is possible. Other ideas include implementing cues to an existing robot. This concept was intriguing to us due to its human-like nature. From this idea, we generated ideas that focus on direction lights to indicate the robot's future path as well as ideas related to human footsteps and warning indicators. When considering these ideas, however, we found ourselves diving into the HRI concepts where we would be straying away from the mechanical aspect initially decided for our project.

1.4 Concept Selection

From our concept generation process, we began the down-selection process with a few metrics in mind. In order to strategically rate each design idea, our team made use of the Pugh chart method. This chart contains requirements that our team defined as important considerations. These requirements address many of the previously discussed metrics such as speed, height, and cost. Additionally, we defined some other metrics that we determined as important factors in our future project such as novelty and also desire to work on the project. By rating each of our major designs on these criteria (defined in Appendix A.2) we were able to numerically assign a score to each design, ultimately helping us decide which final design to choose. Each of these criteria were weighted based on their importance to our stakeholders, with cost, usefulness, and speed ranked the highest in this sense; and then based on our team's motives with feasibility, size, novelty, and fun following. We assigned these weighted scores to three designs from our concept generation: an actuator module for omnidirectional wheel control, building off of an existing ROB 311 ballot Mbot, or developing a visual and auditory cue system for social navigation robots.

Our initial concept selection led us to design an actuator system to allow for omnidirectional wheel control (see Appendix A.3); however, through an in-person meeting, we were able to get a better understanding of what deliverables we should be working towards by the end of the semester. The most notable piece of feedback we received was that a working prototype would be more useful than a proof of concept design such as an actuator and drive system. While still preserving the mobility factor our team was initially led to, our sponsor recognized the potential of the University of Michigan ROB 311 ballbot for our design problem.

This feedback allowed us to redefine the specs that we had originally defined relating to height, speed, and usefulness. In order to reflect the feedback we received, our specifications for height became ¿0.35m and our speed requirement became a 'nice to have' element rather than required. The 0.35m specification is derived due to the dimensions of the existing solution. The ballbot developed for ROB311 courses totals 0.35m including the height of the basketball. After redefining the requirements of our solution we made use of the Pugh chart and reevaluated the design possibilities with our new considerations in mind, as shown in Table 1.

Table 1: Second iteration Pugh chart with team-defined metrics.

Requirement	Weight	Actuator Score	Actuator Total	MBot Score	MBot Total	Cues Score	Cues Total
Useful	4	0	0	1	4	1	4
Cheap	5	1	5	1	5	1	5
Feasible	4	0	0	1	4	1	4
Novelty	2	1	2	0	0	0	0
Size	3	0	0	1	3	–1	–3
Speed	4	1	4	0	0	–1	–4
Fun	3	0	0	1	3	0	0
Totals			**11**		**19**		**6**

Though our team had to complete this process twice, we were able to gain valuable information about what metrics should be most important to us as we work toward our final design.

1.5 Requirements and Specifications

To define our requirements and specifications, we use a combination of interviews with our sponsor [2] and supporting research as shown in Table 2.

Table 2: Requirements and specifications with citations.

Requirement	Specification	Citation
Human-like height	$> 0.35\,\mathrm{m}$	[2]
Small footprint	$< 0.4\,\mathrm{m}^2$	[2]
Load bearing motor	$\geq$ 70:1 gear ratio	[10]
Drive to target	Precision to target: $\pm 100\,\mathrm{mm}$	[11]
HRI-centered design	Aesthetic covering around torso: 78 mm (enclosed radius + 2 mm)	[6, 10]
Weight	$< 16\,\mathrm{kg}$	[12]
Virtual safety feature	$> 0.3\,\mathrm{m}$ (enclosed radius of basketball + 1 ft)	[13]
Speed	$> 1.5\,\mathrm{m/s}$	[2]

Human-like height, small footprint, and speed in the project's initial stage are all must-have requirements defined by our sponsor [2]. The size requirements are important for the robot to have a social presence and be easily perceived by humans. The form factor must be minimized to reduce the risk and impact of harming humans. The small form factor coupled with the size requires that the robot be tall enough to be perceived, but compact and light enough to be generally harmless. Our sponsor emphasizes the notion of not predefining constraints for our system without reason, so he defines the need for an omnidirectional drive and high speed and acceleration so that the robot is adaptable to the changing environment.

After redefining these requirements during the concept selection process, speed transformed into a “nice to have requirement” since we decided to prioritize mobility in omnidirectionality over speed given our selected design of the ballbot. The ballbot originally could not move with increased speed, so it was important to not define this as a needed requirement and lose sight of the original objective of the project by working towards satisfying it.

Given the increased load on the ROB 311 ballbot system, we must have a motor that can handle the load. This specification is derived from the current motors used in the ROB 311 design. After analysis, we can determine if the current motors suffice, or if we will need to increase the gear ratio.

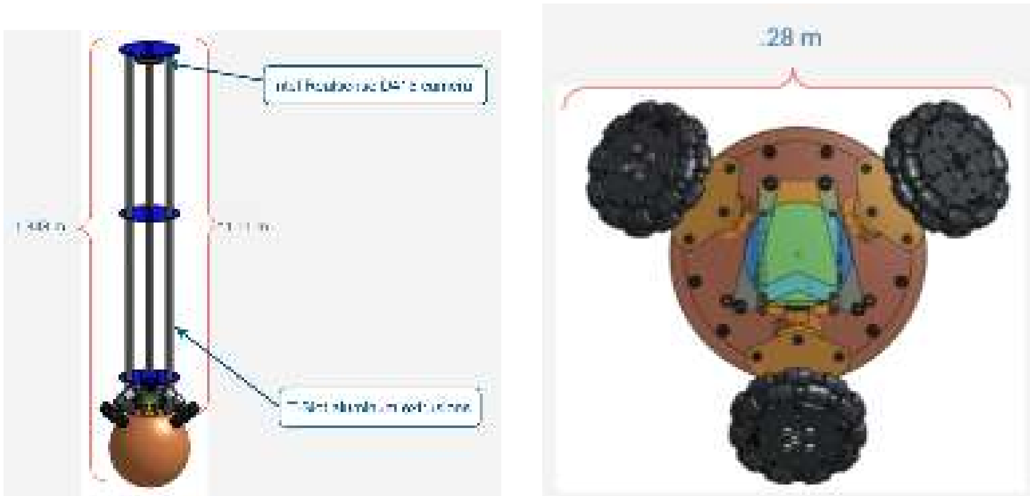
Since the project scope has moved to a proof of concept design, the robot must be able to demonstrate driving to a target. This specification is derived from common precision to target using RGB-D cameras since we decided to use this sensor in our system.

Given HRI is the basis of social robot platforms, our design should implement some sort of physical aesthetics. This is translated into a covering to hide the hollowness and electronics of the robot, giving it a more appealing appearance.

Finally, a virtual safety feature will be implemented around the system to ensure safe tolerances when navigating an environment populated with humans and to avoid collisions. Given the use of RGB-D cameras, we plan to use the depth information to set a minimum distance to any object in front of the camera. This specification is derived from the widest part of the current system, which will be the center of the ball.

1.6 Alpha Design

Our alpha design consists of several improvements and modifications we plan to make to the existing ballbot in order to meet our requirements. However, we also plan to reuse many of the components, particularly the electronics, in order to save time and budget. We present a summary of our modifications in Figure 4.



(a) Front View

(b) Bottom View

Figure 4: CAD of alpha design building up Mbot.

Firstly, we plan to greatly extend the height of the ballbot to 1.3 meters using T-Slot aluminum extrusions. We selected these extrusions because they are light, cheap, and convenient to fasten parts to. To enable our robot to navigate an environment and follow targets or waypoints, we also add an RGB-D camera (Realsense D415, Intel) to the top of the robot.

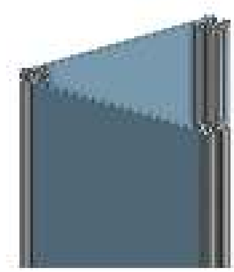


Figure 5: 3D-printed sheets which slot into the aluminum extrusions to cover the surface of our robot.

Next, as shown in Figure 5, we have designed 3D-printable sheets which can easily slot into the aluminum extrusions in the frame. With our HRI-related goals in mind, our motivation behind these sheets is to make the robot more perceivable by humans, and give it a fuller, more appealing appearance.

1.7 Problem Domain Analysis

One of our initial concerns with this alpha designs was the effect of the increased weight of the system on the kinematics of the ballbot behavior. At the time of our first design review, we were concerned about the weight of the aesthetic covering given we designed it with PLA. We aimed to switch this to a lighter material for our final design. However, we did not have a concern for the effect of the weight of the extrudes we added for height until implementation. These extrudes were added to satisfy our height requirements, but their effect on our mobility requirement became a concern. Weight had become such a concern because of the mobility of the ballbot. In its initial state, when functional, the ballbot should balance on a ball and be able to drive at its small height; however, the combination of added height and weight posed a concern for the ability of the ballbot to do either of these tasks. This would limit the omnidirectional aspect of our system, which is a key part to the mobility requirements needed for the social navigation platform.

Furthermore, one assumption our team made was that the ROB 311 ballbot that we would be building off of could already drive omnidirectional, however, once we began working on the initial prototype, the codebase was not actually functional. This caused our design iterations to shift towards creating a balancing ballbot at a small height and then move on to building up to actually satisfying our requirements. Due to this, it was easy to veer away from our initial problem, but our team recentered to address this concern and make key requirement and design changes to the final design in order to mitigate these concerns.

While keeping each of these concerns in mind, our ultimate deliverable at the end of the semester is to create a working prototype that is able to traverse from an arbitrary point A to point B, some distance away. This prototype will serve to show that a platform of this stature is feasible and has the possibility to enable researchers to conduct more realistic experiments and studies.

2 Final Design Description

Our final design stands at 1.24 meters (4.08 ft) tall and features a Realsense camera for navigation, lights for visual and directional cues, omnidirectional wheels, and reinforced mechanical supports to meet inertial stability requirements. While the ETH Zurich Ballbot served as our foundational platform, we continuously refined the mechanical design throughout the semester, resulting in several visual and structural changes. The final system can be broken down in three parts: the original ETH Zurich ballbot-inspired base, the mechanical upgrades we introduced, and the additional hardware components we integrated to create a more intelligent and legible robot.

2.1 ETH Zurich Ballbot

Our final design was adapted from the ETH Zurich Ballbot [8], which was created in 2010 as a bachelor thesis project at ETH Zurich. The ETH Ballbot is a dynamically balancing, omnidirectional mobile robot that balances and steers on a spherical ball. The robot balances using real-time feedback from an inertial measurement unit (IMU) and achieves motion and stability through controlling the ball's rotation beneath its center of mass. The ballbot has 3 axes of rotation, allowing it to translate in the x and y directions as well as rotate about the z-axis.

To implement our system, we utilized the existing ROB 311 Ballbot as a mechanical and electrical starting point, as it closely follows the ETH Zurich design. To ensure consistency with the system, we retained the original mechanical dimensions, including the wheelbase and wheel radius, to preserve the angle of contact between the wheels and the ball. Our implementation used the same hardware stack as the ROB 311 platform, which includes a Raspberry Pi Pico microcontroller, an MBot control board, and a Raspberry Pi 4 running as the primary operating system. The Raspberry Pi Pico handles low-level communication with the sensors and motor drivers on the MBot control board. The Raspberry Pi 4 provides a flexible development environment that allows us to write and execute Python scripts, teleoperate the robot, and run multiple processes simultaneously without the need to reflash the microcontroller.

2.2 Mechanical Frame

We used two layers of aluminum extrusions to increase the height of the robot. To support these extrusions, we 3D-printed two custom PLA plate parts to hold everything together rigidly. We also designed several laser cut acrylic pieces: a top plate, a plate to house the battery, and a plate to join the two layers of aluminum extrusions.

Figure 6: Final 3D printed supports to prevent robot from tipping

Additionally, we designed three support ”legs” that extend outward from the base plate, positioned between each of the omni-wheels. Each leg is 3D printed using PLA filament with a high infill density to maximize structural integrity. They are secured to the base using four M4 screws to ensure they remain firmly attached and do not shear off during operation. As shown in Figure 6, the legs incorporate a triangular reinforcement feature at the junction with the base. This geometry was added after early prototypes of the legs failed under stress due to the sharp 90-degree angle. The added triangle distributes mechanical loads more evenly and significantly reduces the risk of fracture. These legs play a critical role in preventing the robot from tipping over during rapid acceleration or external disturbances.

Figure 7: Final design with LED matrix mounted to middle plate and aesthetic covering added around metal extrusions

2.3 Camera

We used an Intel Realsense D415 camera and designed a 3D-printed mount to fix it to the top of the robot. This camera is able to take both RGB and depth images, which it can use to locate April tags and determine their relative position from the robot.

2.4 LED Lights

A matrix of LEDs (Light Emitting Diodes) was introduced near the middle of the robot to provide visual cues to users. The LED matrix is mounted on the robot using a 3D printed cylindrical mounting platform made from PLA, as seen in Figure 7. The intention behind the addition of this visual cue was to provide users with some sense of what the robot is "thinking". Due to the omnidirectional feature of the robot, it is difficult to determine the direction it intends to drive. In addition, there were previously no visual cues indicating whether or not the robot had found its target pose or reached its destination. The LEDs provide a simple interface to improve the robot's legibility of motion.

The LED matrix is connected to our robot using the GPIO pin 18 on the Raspberry Pi 4. The code reads torque values from each of the motors to determine if the robot is moving towards its goal or if it is searching for the pose. When the robot is searching for its goal, it will rotate about the z-axis searching for its target, and the lights will illuminate red. Once the target has been located, the lights will immediately turn green and the robot will begin to traverse in the direction of its target. If at any point during its trajectory the robot its target, or the target leaves its field of view, the lights will turn red to indicate that it is again in a "searching" state. Once the robot has reached its goal pose, the lights will change from green to red, to indicate that it has stopped all motion and is waiting for its next command [14].

2.5 Aesthetic Cover

To make the robot appear more 3-dimensional and human-friendly in social navigation settings, our team decided to add a lightweight system that would hide the wiring and internal electronics of the robot. Figure 7 depicts an additional cover made from white poster paper that wraps around the metal extrusions. The poster paper effectively achieves the goal of hiding our electronics, so the main focus of users' attention is the LED matrix.

2.6 Motion Planning

For the motion planning of the robot, we employ two different strategies. First, we implemented laptop keyboard tele-operation. By detecting keystrokes while running our program, we can omnidirectionally control the robot.

Secondly, we implemented a April tag detection and following program. April tags are patterns of black and white squares which can be used to find the six-degree-of-freedom pose of a camera relative to the tag. Once we detect an April tag, we utilize a proportional controller on the virtual torque about the vertical axis, where the error is the number of pixels between the center of the camera frame and the centroid of the April tag. Once the April tag is within a threshold (50 pixels) of the center of the frame, we consider it centered, and drive forward towards the tag at a fixed speed. Since we can also extract the depth of the April tag centroid from the camera depth image, we stop the robot once it is 0.5 meters away from the tag. If the tag isn't in the frame at all, we rotate in an arbitrary direction until we find it.

3 Design Testing

To evaluate whether our final design met both mechanical and software performance requirements, we conducted validation tests using mathematical analysis, CAD modeling, and experimental testing. Mechanical verification included checks for height and footprint constraints, both of which were satisfied through careful design and measurement. We also performed a dynamic motor characterization using an inverted pendulum model to analytically estimate torque demands. Additionally we performed experimental tests to ensure software verification ensured the robot could reliably perform core navigation tasks, such as approaching visual targets while respecting safety constraints.

3.1 Mechanical Verification

Mechanical verification focused on validating the robot's structural design constraints. The robot was designed to exceed 1.2 meters in height and have a small footprint under 0.4 square meters to ensure it could navigate tight spaces. Using CAD and physical measurements, the final build achieved a height of 1.24 meters and a footprint of only 0.1156 square meters, even after accounting for added support legs. These results confirm that the mechanical design adheres to both spatial and dimensional requirements specified at the outset of the project.

3.1.1 Height

The height requirement for our robot was that it exceeded 1.2 meters. The robot needs to be sufficiently tall so that it can have a human-like presence in a social setting. This allows it to be perceived naturally and for humans to navigate around it and alongside it naturally. A typical elementary school student is able to navigate social settings, and 1.2 meters is the height of an average elementary school student. We used CAD modeling to design our robot at 1.24 meters tall, meeting this requirement.

3.1.2 Footprint

Our robot required a footprint of no greater than 0.4 square meters. The small footprint requirement set forth by our sponsor ensures that the robot does not take up more space than an average human in social settings [2]. In this way, the small footprint allows for smooth navigation within crowded environments.

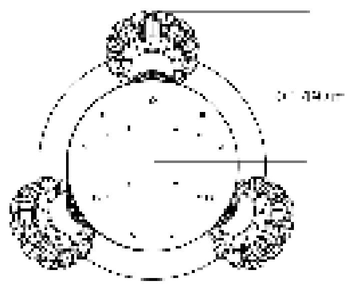


Figure 8: Footprint verification diagram using CAD

We used CAD modeling to ensure the robot would meet our constraints around the footprint. As seen in Figure 8, the distance from each wheel to the center of the robot never exceeds .15 meters. We can then mathematically determine the area in square meters that the robot will cover [1].

$$(0.1497 + 0.1497)^2 = 0.0896 \text{ m}^2 \tag{1}$$

The robot will not exceed more than 0.0896 square meters, therefore it meets our minimal footprint requirements of less than 0.4 square meters.

After testing and manufacturing our parts, we also added a support feature to brace the robot from tipping over. Prior to adding the support feature, we performed standard calculations for how much each support would add to the diameter of our robot. In total, the supports increased the diameter of the robot by 0.06 meters.

$$(0.1497 + 0.1497 + 0.06)^2 = 0.1292 \text{ m}^2 \tag{2}$$

Therefore we recalculate our total area and determine that the addition of the supports do not interfere with our footprint requirement [2].

After manufacturing and assembling all the parts, we validated that our footprint met the requirements using a tape measure. The diameter of the entire robot, including the newly added supports was less than 0.34 meters, meaning that our entire robot's footprint was no greater than 0.1156 square meters3.

$$(0.34)^2 = 0.1156 \text{ m}^2 \tag{3}$$

3.1.3 Load Bearing Motor

To verify that our motors could support the increased height and footprint of the updated chassis, we analyzed the torque requirements under dynamic balancing conditions. This motor characterization followed the equations presented in the ETH Zurich Ballbot paper, adapted with our parameters. We used the Pololu 37D Metal Gearmotor with encoder, which has a 70:1 gear ratio, a no-load maximum speed of 150 RPM, and a stall torque of 27 kg $\cdot$ cm (approximately 2.47 Nm). To compute the expected torques, we used the ballbot's kinematic equations and updated the mass properties of our system using Onshape's built-in tools. While the original ROB311 CAD model had a mass of 1.72 kg, our modifications (six 80-20 extrusions, PLA shrouding, and a camera) raised the total mass to approximately 3.43 kg, nearly doubling the original. The total height also increased to 1.24 m, which raised the overall moment of inertia and center of mass.

To model the system, we treated it as an inverted pendulum and set constraints for translation in the x-direction [4] and wheel rotation [5].

$$x_k = r_k \rho \tag{4}$$

$$\psi = \frac{r_k}{r_w}(\rho - \theta) - \theta \tag{5}$$

After our constraints have been set we can derive the velocity of the ball by taking the derivative of the ball's rotation and relating it to the linear velocity [6].

$$\dot{\phi} = \frac{\dot{x}_k}{r_k} \tag{6}$$

Next, we can solve for the tangential contact force [8]. We will use an intermediate variable to simplify this equation and make it easier to understand [7].

$$\gamma = L \cdot m_a + (r_k + r_w) \cdot m_w \tag{7}$$

$$F_{W2} = (m_a + m_w) \cdot \Big(g \cdot \sin(\vartheta) - r_k \ddot{\phi} \cos(\vartheta)\Big) - \gamma \ddot{\vartheta} \tag{8}$$

The contact force gives us the force between the wheel and the ball. We will use it to solve for the virtual torque about the x-axis [9].

$$T_x = r_w F_w + I_w \frac{d^2\psi}{dt^2} \tag{9}$$

Finally, we converted the virtual torque T_x to the individual motor torque. The equations are derived from those given in the ETH Zurich Ballbot Thesis [10].

$$\begin{aligned} T_1 &= \frac{1}{3}\left(T_z - \frac{2T_y}{\cos(\alpha)}\right) \\ T_2 &= \frac{1}{3}\left(T_z + \frac{1}{\cos(\alpha)}\left(-\sqrt{3}T_x + T_y\right)\right) \\ T_3 &= \frac{1}{3}\left(T_z + \frac{1}{\cos(\alpha)}\left(\sqrt{3}T_x + T_y\right)\right) \end{aligned} \tag{10}$$

Since we're analyzing motion primarily in one axis, we focus only on Motor 1 [11].

$$T_1 = \frac{1}{3}\left(T_z - 2T_x \cos(\alpha)\right) \tag{11}$$

Figure 9 plots the torque on Motor 1 as a function of lean angle θ. The maximum torque occurs at the largest lean angle of 0.5 radians (28.65 degrees), reaching approximately 0.1 Nm. The code for plotting these torques is included in Appendix A.4.

As previously mentioned, the Pololu motor can accommodate a maximum stall torque of 2.65 Nm. Therefore, we proved that despite the increased

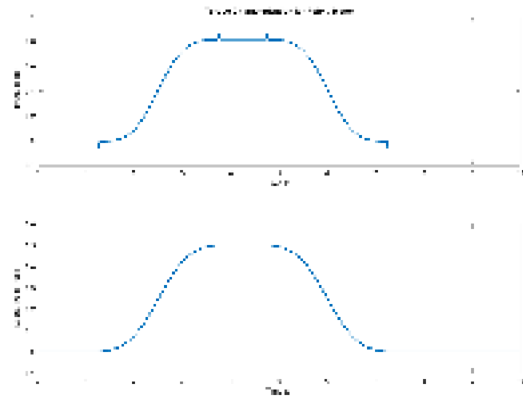


Figure 9: Torque characterization for Pololu motor with 70:1 gear ratio.

moment of inertia, our motors are well within their operating limits, and they are more than capable of handling the added load of our chassis.

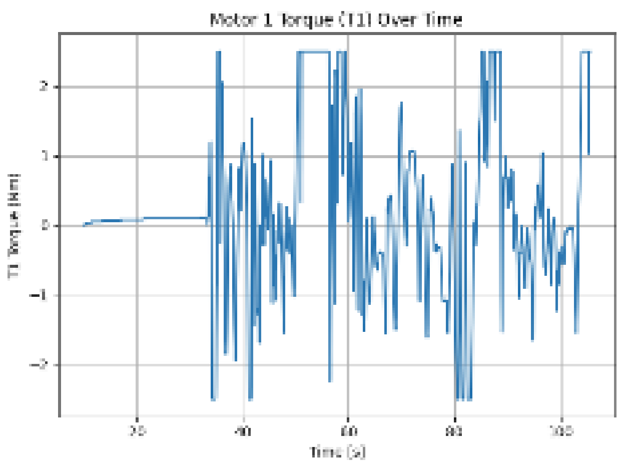


Figure 10: Torque characterization for Motor 1 while balancing on ball.

After all parts were assembled on the robot, our team wrote a balance controller script to validate our analytical analysis of the motors [14]. Despite the ballbot's ability to react to the torque commands, after repetitive trials, it was unable to independently balance itself. Figure 10 illustrates the motor output torque from Motor 1 during the robot's most accurate attempt to balance on the ball.

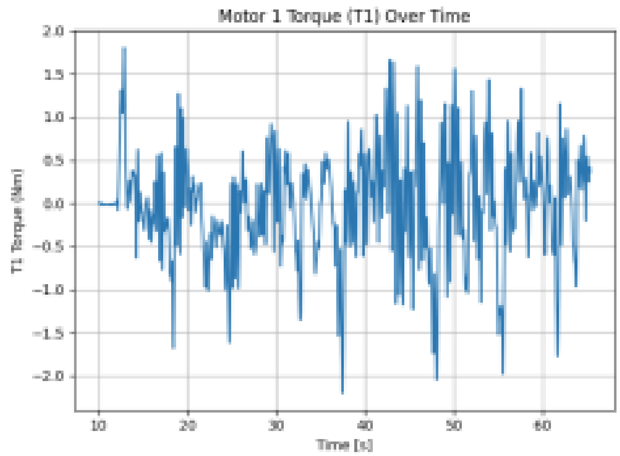


Figure 11: Torque characterization for Motor 1 driving on floor.

As seen by the clipping effect in Figure 10, the torque on the motor is spiking and then being clipped when it goes out of range. Each motor should not be exceeding 2.65 Nm according to the Pololu data sheet. The clipping of the motor torques indicates that the motors are being pushed beyond their torque limits.

The issue, most likely caused by the wheel slippage between the wheels and the ball, created a unique problem for our team. While our sponsor had initially requested a functional ballbot system [2], we faced substantial limitations in both budget and time following high manufacturing costs. Given these constraints, we made the strategic decision to pivot away from the ball-based design and instead focus our efforts on satisfying the original project constraints through an alternative, more feasible solution.

We ran the robot on the floor without the ball and once again recorded the motor torque outputs for Motor 1. As seen in Figure 11, the torque on the motor stayed within 2 Nm, even as our team aggressively drove the robot in all directions. As the output torque of Motor 1 remained well below the motor limits of 2.65 Nm, we concluded that the motor is capable of handling the worst-case loading scenarios expected during operation.

3.2 Software Verification

Software verification focused on testing whether the robot could reliably reach a visual target, such as an April tag. We designed experiments to evaluate the robots ability to achieve positional accuracy as move safely in response AprilTag targets.

3.2.1 Drive to Target with Virtual Safety Fixture

We required our robot to drive to an April tag without falling over or exceeding a virtual safety fixture. This means that it should not move closer than a certain distance to the target. This requirement is motivated by social navigation applications, where it can be very important not to fall over, or get too close to other agents or obstacles.

We also required the robot to achieve accurate target-reaching within 0.1 meters. In our experiments, this meant that it must stop at most 0.6 meters away from the target, but no less than 0.4 meters. Being able to move to precise locations is very important for robots, and having high precision allows for less noise when testing algorithms or more complex motion planning behaviors.

We conducted 8 experimental trials, where we randomly placed the robot 1 to 10 meters away from the April tag, at a random starting angle. In all trials, the robot approached the tag and then stopped at approximately 0.5 meters away. We measured the error with a tape measure for all trials to be 0.0 meters, which was due to the very high precision of the Realsense camera. These results showed that our robot could very reliably and precisely reach a target.

4 Discussion

4.1 Problem Definition

Our project sought to address a growing need in the research community: a social navigation robot that is affordable, appropriately sized, and functional for experimental algorithm testing in human environments. Currently, the market offers robots that are either too large and unwieldy, too small to be useful for real-world interaction, or priced far above what academic and independent research teams can afford. If we had more time and resources, our first step would have been to refine and expand our problem definition. Specifically, we would have explored the needs of secondary and tertiary stakeholders—such as educators, startup developers, or institutions with limited budgets—to understand whether a scalable, market-level solution could serve broader user groups.

To do so, we would have conducted structured interviews, online surveys, and observational studies to map out diverse use cases and constraints. An extended benchmarking of existing products, including analyses of size, cost, and interaction models, would have informed our design constraints more effectively. We could have also looked into ways to make the robot's design more flexible or partnered with others to create a base that can be adapted for different social navigation uses.

4.2 Design Critique

4.2.1 Strengths

Our design demonstrates some critical features of social navigation in a compact and user-friendly way. The robot's ability to locate and navigate toward an AprilTag and visibly signal its status (red while searching, green when tracking) effectively conveys intent—an essential aspect of human-robot interaction (HRI). This visual feedback was intuitive for users and positively received during testing, validating one of our core HRI assumptions. The robot also functions well within constrained indoor spaces, making it practical for lab testing.

4.2.2 Weaknesses

Despite these successes, the robot suffers from significant limitations. Most notably, its slow movement speed undermines the realism of its social presence; it does not replicate human-like navigation behavior. In future iterations, we would redesign the drive system, perhaps switching to more powerful motors or optimizing the wheelbase-to-weight ratio to enable smoother and faster locomotion.

Another limitation is the robot's limited capacity for rich user interaction. Aside from the visual color cues, there's minimal real-time engagement between the user and robot. Adding multi-modal feedback, such as sound, expressive movement, or even simple speech capabilities, would improve the interaction quality significantly. These additions would require both hardware accommodations and real-time software integration for context-aware responses.

In terms of the development process, a major flaw was the absence of a thorough mechanical and energy analysis before building and 3D printing components. This oversight led to the production of multiple prototype iterations, which consumed both time and materials. With better upfront calculations, such as torque requirements, center of mass estimations, stress analysis on joints, we could have streamlined the design process. We also lost valuable development time focusing on creating a humanoid aesthetic that was ultimately unfeasible within our resource constraints. A more grounded design phase, guided by feasibility, simplicity, and modularity, would have led to more functional outcomes.

4.2.3 Future Improvements

Looking back, one of the key changes we would implement is completing the mechanical subsystem earlier in the project timeline. This would have allowed us to devote more focused effort to refining the HRI components—the real distinguishing factor in social navigation research. Integrating features like gaze tracking, adaptive path planning based on user proximity, or even group-awareness would push the robot's capabilities closer to a socially intelligent system.

From a design perspective, the transition to a modular mechanical platform would support faster iteration and easier part swapping, reducing prototyping overhead. A redesign with simulations (using tools like SolidWorks motion analysis or MATLAB Simulink) could help us virtually test mechanical ideas before committing to print or build.

5 Reflection

Our project, a social navigation robot, was developed with the goal of improving how people interact with robots in everyday environments, improving accessibility, efficiency, and safety in shared spaces. Throughout the project, we remained mindful of the Robotics Department's mission to make the world work better, and we continually revisited the global and societal impacts of our design. Initially, we viewed the main sociality impacts of our project as they relate to our sponsor and researchers that may implement our system. However, as our work progressed, our focus shifted more to examining the societal impacts as they relate to regular citizens and people participating in HRI research studies. This shift of focus coincided with our increased focus on social cues and human-like attributes to our robot.

5.1 Health, safety, and welfare

Public health was a large consideration for this project as our team considered designing for pedestrians and normal citizens rather than just for researchers. With this shift, we found ourselves considering the experience of interacting with our robot and continentally strove to create a non-threatening experience for the user. Additionally, this considerations lead us to implement a stop feature to our robot where there was maximum distance that the robot was allowed to be from its target. We viewed this as an important aspect to contribute to the user feeling safe and preventing any potential collisions from occurring.

5.2 Global Context

Global market considerations influenced our design choices by encouraging us to focus on creating a flexible, adaptable platform rather than a specialized, market-specific solution. In scaling down the robot's size and speed, we produced a proof of concept that could be adapted for research use in different regions with varying regulations, infrastructure, and user expectations. While the prototype was not optimized for immediate commercial release, it lays the groundwork for future iterations that could support global research efforts in human-robot interaction, an area with worldwide relevance.

In addition to primary stakeholders—researchers directly using the robot—we also considered secondary stakeholders, such as facility managers and maintenance staff responsible for integrating robotic systems into their environments. Tertiary stakeholders, including the broader public who might interact with future versions of the robot in public or commercial spaces, were also important to our design decisions, particularly in terms of safety, accessibility, and social acceptance.

5.3 Social Impacts

The social impacts of our design primarily stem from its use and eventual disposal. During use, a social navigation robot has the potential to positively impact communities by improving accessibility in public spaces, assisting researchers in developing safer, more human-centered autonomous systems, and promoting inclusive technology design. However, there are also potential negative impacts: widespread deployment could contribute to concerns about surveillance, job displacement in certain service industries, or inequitable access to advanced robotic systems. Additionally, we used life cycle costing to evaluate how the total costs of our social navigation robot, from development and manufacturing to maintenance and eventual disposal, could impact its societal reach and sustainability. This analysis helped us recognize that high maintenance or disposal costs could limit access for researchers with fewer resources and increase environmental and social burdens, encouraging us to prioritize durability, modularity, and ease of repair in our design choices.

5.4 Economic impact

The economic impacts of our design mainly arise during the manufacturing and use phases of our system. As a research-oriented proof of concept, our robot does not yet create large-scale manufacturing costs; however, scaling the design for broader production could lead to significant investments in specialized components such as sensors, processors, and mobility systems. These costs could influence the general affordability and accessibility of social navigation robots. During use, the robot could contribute positively to economic efficiency by supporting researchers in developing more effective autonomous systems, which could eventually reduce labor costs in sectors such as transportation, healthcare, and service industries. However, if widely deployed, there could also be economic challenges, such as the potential displacement of certain jobs or an increased reliance on costly maintenance and technology upgrades. Disposal adds another layer of economic impact: without proper recycling and materials recovery programs, the loss of valuable materials like rare metals from discarded robots could lead to increased material costs over time.

5.5 Impact of Culture, Identity, and Power Dynamics

Our team brought together members with different cultural backgrounds, technical strengths, and working styles, which influenced how we approached problem solving throughout the project. These differences shaped everything from how we delegated tasks to how we interpreted user needs and ethical concerns. For example, variations in communication preferences and personal work habits led us to adopt more flexible collaboration tools and timelines. At the same time, shared experiences as engineering students at the University of Michigan helped us quickly align on academic and professional expectations, giving us a solid foundation to navigate technical challenges effectively.

We also recognize differences in privilege and access to prior robotics experience among team members. Rather than letting that create imbalance, we made it a point to support one another by taking time to explain unfamiliar concepts or redistribute technical work when needed. This approach fostered a collaborative, respectful team environment that ultimately strengthened both our technical outcomes and our team cohesion.

Our sponsor, a faculty member with deep expertise in robotics, significantly influenced the direction of our project through multiple design meetings. Initially, we had planned to pursue a more traditional actuator-based mobility system. However, after several discussions, our sponsor strongly encouraged us to explore a ballbot design instead, which ultimately led us to change our mechanical approach. Although the suggestion offered an interesting technical challenge, the change also reflected the influence of the sponsor's authority and expertise, introducing a power dynamic that shaped our decision-making.

As students, we were aware that our academic success and project approval were partially related to the guidance of our sponsor, making it more difficult to push back or advocate for alternative directions early on. Over time, we became more confident in communicating our design priorities and constraints, and we learned to balance respectful collaboration with critical evaluation of suggestions. This experience deepened our understanding of how mentor-student dynamics, cultural and communication styles, and differences in technical authority can impact real-world design decisions.

5.6 Inclusion and Equity

Because our project was a proof of concept rather than a deployable product, we had limited engagement with external stakeholders or end users. Our primary stakeholder was our sponsor, a university professor, and while power dynamics played a role in shaping some early decisions, we have already discussed this in the previous section. Our main focus, therefore, was on fostering an inclusive and collaborative dynamic within our team.

Team members had diverse backgrounds, levels of technical experience levels, and working styles, which influenced how we approached both problem solving and communication. Some members had more hands-on robotics experience, while others contributed strengths in organization, design planning, or documentation. To ensure balanced participation, we made an effort to rotate responsibilities, share technical knowledge, and encourage open discussion of ideas. This helped us include multiple perspectives and reduce any imbalance in influence due to prior experience or confidence levels.

Even though we were not working with a wide range of users directly, we still considered how future researchers might adapt our robot for different applications. This motivated us to design for modularity and flexibility, ensuring that the platform could be easily reconfigured for diverse research needs.

Cultural and stylistic differences within the team also shaped how we worked together. We adapted our workflows to accommodate varying communication styles and decision-making approaches, which ultimately strengthened our teamwork. These experiences helped us better understand how inclusion, identity, and collaboration intersect in engineering work, even within a small, academic development setting.

5.7 Ethics

While there were few direct ethical dilemmas influencing our mechanical design, our team did consider potential ethical concerns during the brainstorming and market analysis phases. One concern was that, if our social navigation robot were eventually commercialized, it could contribute to the displacement of existing jobs, such as cleaning staff or greeters in malls and stores. To address this concern, we intentionally focused on developing the mechanical aspects of autonomous navigation rather than designing features—such as robotic arms or task-specific tools—that could directly replace human workers. By limiting the scope of our prototype, we prioritized creating a supportive research tool rather than a direct substitute for human labor. Our personal ethics align closely with the professional standards expected by the University of Michigan and by future employers, particularly in the areas of prioritizing human well-being, promoting responsible innovation, and considering the broader societal impacts of technology. Looking ahead, we recognize that different employers may prioritize these values to varying degrees depending on industry goals, but we intend to uphold a commitment to ethical decision-making, even in the face of commercial or competitive pressures.

6 Recommendations

Based on our experience developing a proof-of-concept social navigation robot, we have identified several recommendations to improve future iterations of the system. These suggestions reflect both the technical challenges we encountered and the design trade-offs we made throughout the project.

One major recommendation is to reconsider the use of the ballbot platform, particularly with respect to stability and prototyping feasibility. Toward the end of the project, our team made the decision to remove the ball from the design, moving away from the original ballbot concept. Had we made this change earlier in the process, we could have directed more time and resources toward other critical aspects of the robot, rather than spending so much effort on the mechanical system.

Another key lesson was the importance of establishing clear design priorities from the outset. Having a better understanding of the most important features would have guided our decision-making and helped us recognize sooner that balancing on a ball was not essential to meeting our overall project goals.

In addition, our team would have benefited from a deeper understanding of the intended use cases. Gaining exposure to real-world applications of social navigation robots, such as observing them in action or conducting interviews with researchers, could have helped us define the problem more precisely and design a more focused solution.

At the detail-design level, several hardware changes are worth noting. Modifying the wheel base would significantly improve the robot's performance. Since we removed the ball late in the project, we were left using wheels that were not originally intended for ground travel, which limited mobility. Redesigning the wheel configuration would allow for better movement and stability.

Finally, we recommend revisiting the internal layout of the robot. Our initial structure was based on adapting the ballbot as a starting point, but moving forward, this layout could be better optimized for weight distribution and ease of access to electronics. Improvements in internal organization would make future development, maintenance, and expansion of the platform more efficient and user-friendly.

7 Conclusion

We aimed to design a platform that could satisfy the mechanical qualities needed for social navigation researchers to deploy their algorithms. Current platforms lack the size, mobility, and accessibility requirements needed for such a system. Through our design process we found that building of off the ROB 311 ballot platform would be a feasible way to address these needs of the research community that our sponsor defined. The ballbot offered an omnidirectional, low-cost solution that we initially designed to build up from vertically to reach our human-perceivable height, and then tune the controller to compensate for the added height and weight.

Through the implementation, we encountered challenges that we did not anticipate when designing the platform. In making the original platform taller and heavier, we found that it was not a one to one scaling on the original system in terms of control. It was difficult to preserve omni-directionality while advancing the height in an effort to satisfy all requirements at once. With this challenge, it became evident why so few mechanical systems exist with these abilities for our stakeholders. With this in mind, we shifted our focus back to creating a working proof of concept prototype rather than trying to perfect one aspect of the system.

Our final design not only satisfied our height, mobility, and HRI requirements, but the process of achieving this design showcased what kind of challenges can be anticipated when taking on an HRI centered project such as this. It was important for the robot to be functional in a way that was legible to humans.

8 Acknowledgments

We would like to express our sincere gratitude to our sponsor, Christoforos Mavrogiannis, for his generous support and contribution, which made this work possible. We would also like to thank the Rob 450 instructional team for their feedback and guidance, particularly in helping us navigate several large changes to our project.

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A Technical Documentation

A.1 Code Repository

The source code for this project is available at: Team 5 Github Repo [14].

A.2 Pugh Chart Metrics

Useful: can be used as an open source resource for social navigation researchers

Cheap: low-cost, easy to acquire, 'off the shelf' components

Feasible: can be implemented within the team's relative timeline and budget

Novel: the solution does not build off of existing solutions

Size: can be scaled to adhere to initial sponsor height requirement (¿ 1.5 m)

Speed: can be scaled to adhere to initial sponsor speed requirement (¿ 1.5 m/s)

Fun: the desire of team to work on solution

A.3 Actuator Module

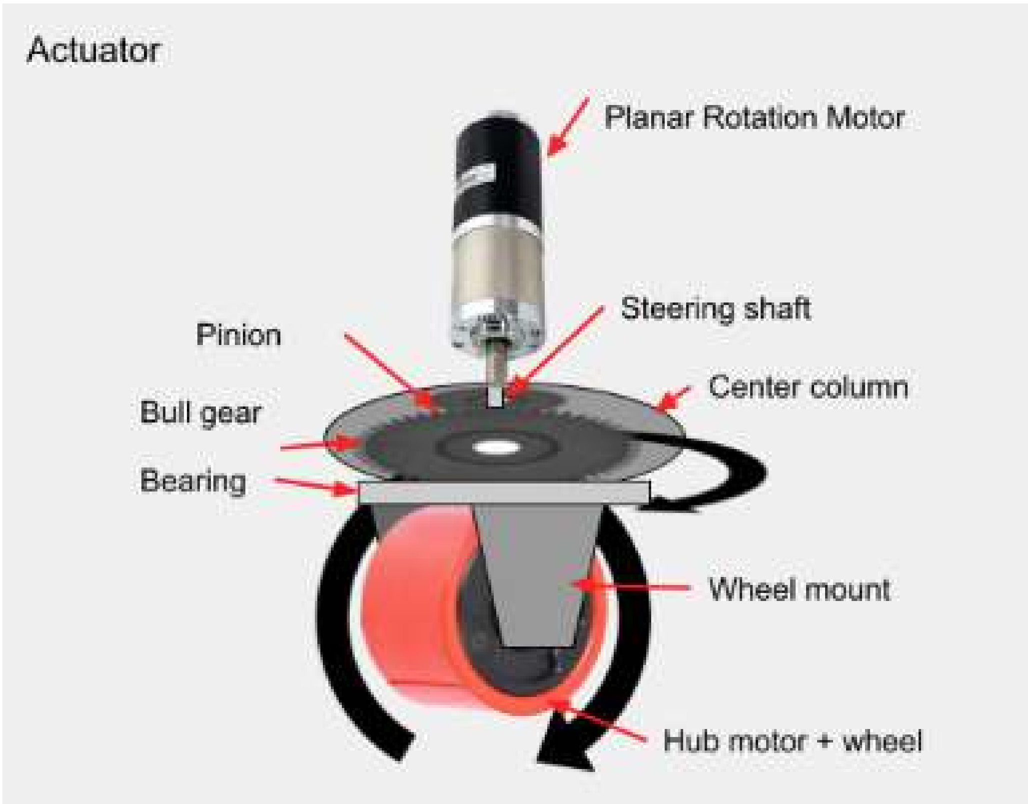

Figure 12: Initial concept selection actuator module design .

A.4 Motor Torque Characterization Code for Plotting

Listing 1: Single Axis Ball-Bot Simulation

```
clear
clc
close all
% BALL-BOT PARAMETERS
m_a = 3.43; % Mass of the body (kg)
m_k = 0.62; % Mass of the ball (kg)
m_w = 0.29; % Mass of the wheel (kg)
r_k = 0.121;  % Radius of the ball (m)
r_w = 0.096/2;  % Radius of the wheel (m)
L = 1.11; % Distance to the center of mass of the body
```

```
I_k = 0.0036; % Moment of inertia of the ball (kgm^2)
I_w = 0.0015; % Moment of inertia of the wheel (kgm^2)
I_x = 0.0115; % Moment of inertia of the body in X-Z plane
I_y = I_x;  % Moment of inertia of the body in the Y-Z plane
I_z = 0.0170; % Moment of inertia of the body in the X-Y
    plane
g = 9.81; % Gravity (m/s/s)
% MOTOR PARAMETERS - found from: https://www.pololu.com/
    product/4754/specs
N = 70; % Transmission ratio
eta = 0.8;  % Transmission efficiency
stall_torque = 2.65/N;  % Motor properties obtained from
    Pololu website
stall_current = 5.5;
stall_voltage = 12;
noload_speed = 15.71*N;
noload_current = 0.2;
Kt = stall_torque/stall_current;  % Torque / back-EMF
    constant (Nm/A)
R = stall_voltage/stall_current;  % Terminal resistance (Ohms
    )
b = (noload_current*Kt)/noload_speed; % Viscous damping (Nms/
    rad)
L_w = 0.023;  % Motor inductance (H)
J = 0.000025; % Motor's rotor inertia (kgm^2) - estimated
    from 35mm Maxon motor
% VELOCITY PROFILE GENERATION
x_k_dot_final = 1;  % Final ball-bot velocity (m/s)
t_final = 10; % Duration of the simulation (s)
t_constant = 6; % Ramp lasts from 2.5 s to t_constant
                                                          %
    Time to reach constant final velocity (s)
dt = 1/200; % Simulation timestep
t_length = t_final/dt;  % Length of time vector
t = linspace(0,t_final, t_length);    % Time vector (s)
x_k_dot_orig = [zeros(1,500) linspace(0,x_k_dot_final, (round
    (t_length*(t_constant/t_final))-500))];  % Velocity vector
     (m/s)
x_k_dot_orig(length(x_k_dot_orig):t_length) = x_k_dot_final;
     % Velocity vector (m/s)
x_k_dot = smoothdata(x_k_dot_orig, 'gaussian', 500);  % Low
    pass filter
% POSITION AND ACCELERATION GENERATION
x_k_ddot = ddt(x_k_dot, dt);  % Ball-bot acceleration vector
    (m/s/s)
```

```
x_k = cumsum(x_k_dot)*dt; % Integrating, ball-bot position
    vector (m)
% LEAN ANGLE - Some constraints on this variable to make the
    simulation realistic.
theta_scale = .25;  % Scaling factor for calculation of lean
    angle
theta = theta_scale * x_k_ddot; % Body lean angle (rad)
                                                             %
    Lean angle starts at zero rads
theta_dot = ddt(theta, dt); % Angular velocity of the lean
    angle (rad/s)
theta_ddot = ddt(theta_dot, dt);  % Angular acceleration of
    the lean angle (rad/s/s)
% BALL ACCELERATION
phi_ddot = x_k_ddot / r_k;  % Angular acceleration of the
    ball
phi_dot = x_k_dot / r_k;  % Angular velocity of the ball
% TEMP VARIABLE
gamma = L * m_a + (r_k + r_w) * m_w;  % Temporary variable
    gamma
% CONTACT FORCE
F_w_2 = (m_a + m_w) * (g * sin(theta) - r_k * phi_ddot .* cos
    (theta)) - gamma .* theta_ddot;    % Contact force between
     wheel and ball
% WHEEL ACCELERATION
psi_ddot = (r_k / r_w) * (phi_ddot - theta_ddot) - theta_ddot
    ;   % Angular acceleration of the wheels (rad/s/s)
psi_dot = (r_k / r_w) * (phi_dot - theta_dot) - theta_dot;  %
     Angular velocity of the wheels (rad/s)
% REQUIRED WHEEL TORQUE
T_x = I_w * psi_ddot + F_w_2 * r_w; % Total wheel torque (Nm)
% GETTING MOTOR TORQUE
alpha = pi/4;
beta = pi/2;
Ty = 0;
T1 = (1/3)* (2*(T_x*cos(beta) - Ty*sin(beta))) * (1/(cos(
    alpha)));
T2 = (1/3)* ((-(sqrt(3))*T_x + Ty)*sin(beta) - cos(beta)*((
    sqrt(3))*Ty + T_x)) * (1/(cos(alpha)));
T3 = (1/3)* (((sqrt(3))*T_x + Ty)*sin(beta) + cos(beta)*((
    sqrt(3))*Ty - T_x)) * (1/(cos(alpha)));
% MORE PLOTTING
figure(104)
subplot(211)
plot(t, T1, 'linewidth', 2)
```

```
title('Torque Characterization for Pololu Motor')
xlabel('Time (s)')
ylabel('Torque (Nm)')
subplot(212)
plot(t, theta, 'linewidth',2)
xlabel('Time (s)')
ylabel('Lean Angle (rad)')
```

A.5 Bill of Materials

Item	**Qty**	**Source**	**Catalog #**	**Cost**	**Notes**
.5m Aluminum Extrude	8	Amazon	–	$30.99/4	–
Intel RealSense D415	1	Team Member	–	–	Provided by team member (already owned).
PLA Filament	2	Amazon	–	$18.99	–
Acrylic	–	ROB 311 Stock	–	–	Supplied by ROB 311 stock for laser-cutting plates.
LED Matrix and Mount	–	Robot Garage	–	–	–

Table 3: Bill of Materials

B Team Member Bios

B.1 Reina Mezher

Reina is a senior (third year) undergraduate majoring in robotics engineering. She originally gained interest in the field of robotics through FIRST Robotics Competition (FRC) in high school. She is still greatly involved in this robotics community as president of the FIRST Robotics and Mentors Network at Michigan (FAMNM). Her main interests include embedded systems and perception and their applications in medical robotics.
Currently, she is researching with Stryker through the Multidisciplinary Design Program to design an autonomous hospital stretcher. Through her robotics coursework and practical experience, Reina gained an interest in human-robot interaction (HRI) and 'people-first engineering'. This project allows her to gain experience in perception and navigating dynamic environments while also satisfying the needs of the stakeholders involved. Concurrently, she is also took ROB 599: Medical Robotics this semester and has enjoyed learning about the current state of robotics in this space. Outside of academics, Reina enjoys reading, cooking, going to concerts, and running.
Moving forward, she will be entering the Robotics SUGS program this fall, and hopes to deepen her understanding in core robotics principles while taking cool courses she enjoys.

B.2 Adam Hung

Adam Hung is a senior (fourth year) undergraduate majoring in robotics. His main interests lie in developing algorithms for generalizable and robust robot manipulation. He also has research experience in bio-inspired design for robotics, robot exploration, and reinforcement learning.
He got his start in robotics research in the Evolution and Motion of Biology and Robotics (EMBiR) Laboratory, where he worked on a brittlestar-inspired tripedal robot for locomotion research, and motor metrics for Quasi-Direct Drive Actuators. He has also interned at Carnegie Mellon University Robotics Institute, where he worked primarily on a project applying imitation learning methods to deformable object manipulation
Currently, he works as a research assistant in the Autonomous Robotic Manipulation (ARM) Laboratory, where he is working on using learning-based methods to enhance trajectory optimization for dexterous manipulation. Outside of academics, he enjoys rock climbing, surfing, and racket sports.

B.3 Joseph Fedoronko

Born in Ann Arbor and from Saline, MI. Joseph Fedoronko is an undergraduate senior studying robotics and computer science at the University of Michigan. He originally started out studying computer engineering and computer science before switching courses to robotics. As a robotics major, he has gained experience in a variety of areas including robot perception, deep learning, and manufacturing.

Joseph is deeply involved in the field of human-robot interaction (HRI) study and teaching. Through being an instructional assistant for ROB204 (intro to human-robot interactions), he is able to educate and guide students as they begin their robotics careers. Additionally, he is currently working on this ROB450 project where he is developing an HRI study robot, furthering his study into the sphere of robotics. However, his main passions lie in the area of robotic perceptions and deep learning. He has always been fascinated by the concept of driver-less cars even from a young age, passionate about how humans are able to teach computers to have recognition similar to a human.

Outside of academics, Joseph is interested in many hobbies such as running, building computers, and solving Rubik's cubes, to name a few. He spent the first 3 years of his undergrad as a member of the Michigan Run and eventually served as the distance training chair where he was able to train and guide fellow athletes to achieve 1st and 2nd place at NIRCA nationals in cross country.

Going forward, Joseph will be working in the area of robotics system integration as a product engineer. This career step will provide valuable insight into what areas of robotics are truly exciting to him and will influence the future career steps he takes.

B.4 Anuhea Tao

Anuhea is an undergraduate junior studying robotics at the University of Michigan. She is originally from San Francisco, but most of her family is in Hawaii. Her research interests include embedded systems and medical robotics, specifically active prosthetics.

Anuhea has spent her time at the University in a variety of student organizations and research labs. Notably, she worked under Elliott Rouse in the Neurobionics Lab on the Open Source Leg project, a lower limb active prosthetic device that is being developed across multiple universities around the world. She worked on a project to quantify and minimize the audible noise created by the load on the motors. She will be continuing her work in this lab as a research intern this summer.

Anuhea has also been employed at the Robotics Makerspace on the 1st floor of the FMCRB for the past 2 years. During her time at the makerspace she has become adept at using 3D printers and now trains other students in how to safely operate and troubleshoot the machinery.

In addition, Anuhea worked as an Instructional Assistant for ROB 311: How to Build Robots and Make Them Move over the Winter 2025 semester. She held office hours where she helped students with their homework problems, worked with students to write and debug code during lab sessions, and even ran a mini lecture about micro controllers to teach students about the hardware stack on their Mbots. Her close proximity to the class helped her to gain mastery of the course material, which became crucial in applying the content to building a taller ballbot.

Outside of academics, Anuhea enjoys rock climbing and crafting. She also often explores new hikes in and around San Francisco with her dog, Duke.

C Additional Content

C.1 Expo Presentation Slides

The presentation slides and videos are available at: Final Expo Slideshow