DESIGNING HELP-SEEKING STRATEGIES AND AFFORDANCES FOR NON-HUMANOID ROBOTS IN PUBLIC SPACES

2026

MSc THESIS MICHIEL MOLENAAR

DESIGNING HELP-SEEKING STRATEGIES AND AFFORDANCES FOR NON-HUMANOID ROBOTS IN PUBLIC SPACES

By

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In partial fulfilment of the requirements for the degree of:

Master of Science
in Integrated Product Design

at the Delft University of Technology,
to be defended publicly on Tuesday 15 September, 2026 at 15:45.

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1 ABSTRACT

Advancements in computing power and robot control algorithms are making robots increasingly capable. They have become so proficient that companies are now starting to deploy robots on public roads for tasks traditionally performed by humans, such as delivery and inspection. However, like humans, robots are not infallible and will occasionally need assistance if they get stuck or lost. While a human in this situation might ask someone nearby for help, this does not yet seem to be a common strategy for robots, despite its potential to significantly simplify their incident recovery procedures.

This thesis investigates how autonomous robots can communicate their need for help, and how to facilitate the process of helping a robot. It begins with an exploratory design process to evaluate various communication and assistance strategies. To efficiently iterate on these help-seeking methods, a small-scale robotic system was designed and built using off-the-shelf components and 3D-printed parts. This platform was then used to gather insights into how users experience these communication methods in a laboratory environment. Finally, the findings from these tests informed the final design of a larger-scale robot communicating its need for assistance in a public setting. Using this robot, it was found that 12% of random bystanders were willing to and able to assist the robot when stuck in a public space.

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INTRODUCTION

3 INTRODUCTION

Robots are increasingly being used in public areas for tasks such as delivery or inspection (Serve Robotics Inc., 2026; Starship - Robot Product Detail | RobotATTA!, n.d.). However, these robots are not perfect and will sometimes fail, requiring a technician to come repair or assist them. How often this happens determines how many people need to be hired to operate a robot fleet and impacts the operational availability of that fleet. This, in turn, will determine to a significant extent whether a fleet of robots is actually useful for a specific task.

3.1 LIMITATIONS OF ROBOTS IN UNCONTROLLED ENVIRONMENTS

Robots rely on sensors that feed data into a control algorithm, which then triggers the system's actuators. Because sensors always introduce noise or error, there is always a chance that a system will encounter a failure it cannot recover from on its own. Decreasing environmental complexity, such as placing robots in a controlled setting like a factory, reduces the likelihood of these errors, though it can never eliminate them entirely. Simpler robots which operate in static environments have proven very successful in for example factories and warehouses.

However, advancements in sensor technology and control algorithms are making it more common for robots to operate in unconstrained environments, such as public streets or lobbies of hotels or companies. Increased environmental uncertainty brings more frequent failures, raising the potential for unrecoverable errors. One method of designing robots to operate in these complex surroundings involves adding mechanical features or recovery strategies to keep them from getting stuck, but this comes at the price of added system complexity. For example, a wheeled robot requires only two actuators to drive and steer, whereas a legged robot typically requires twelve. A higher actuator count demands significantly more complex control algorithms, which increases the resources required to design, build, and operate the system. As a result, highly complex robots are less likely to see mass adoption, which is why currently deployed delivery robots tend to be simple wheeled designs.

3.2 INCIDENTALLY CO-PRESENT PERSONS INTERACTION

Traditional HRI (Human-Robot Interaction) research tends to focus on the design of robots that help people with specific tasks such as painting (Asadi et al., 2018). This fits a world where a robot is used as a tool for achieving a goal or helping humans with a specific task. We are now seeing robots driving around in public spaces doing their own tasks without any direct relation between the robot and the bystanders it meets in the environment where it operates (e.g., taxis, delivery, inspection). This creates new opportunities for research into how robots should interact with these so-called "incidentally co-present persons" or InCoPs (Rosenthal-von der Pütten et al., 2020). For example to make them feel more comfortable and avoid creating situations where pedestrians walk into them due to a lack of feedback about what the robot is doing (Hoang et al., 2023; Okal & Arras, 2016).

3.3 BYSTANDERS HELPING ROBOTS

The concept of robots that actually need the help of bystanders to function is also starting to be explored in literature (Huttenrauch & Eklundh, 2003). However, if we want bystanders to help these robots, we need to know how to best communicate this need for help to them. Methods of communicating this need, as well as comparisons between various methods, are now also being explored in literature (Holm et al., 2022; Yu et al., 2024a, 2024b, 2025).

3.4 RESEARCH GAP

While various methods of communicating the need for help in robots are already explored in literature, there appears to be limited research exploring how various methods of asking for assistance combined with methods of assisting the robot compare when used in nonhumanoid robots and tested in a real environment using a robot designed from the ground up with asking for help from bystanders when it gets stuck in mind.

BACKGROUND RESEARCH

4 BACKGROUND RESEARCH

4.1 RESEARCH GOAL

This literature review explores current state-of-the-art solutions for signalling need for assistance in robots.

Then it explores various methods of collecting position and state information about bystanders around the robot. Which are necessary to determine when and to which bystander the robot should ask for assistance.

This knowledge provides a basis to develop a robot that uses expressive movements as help-seeking behaviour and evaluate that robot in user test against other state of the art help-seeking behaviour using different methods.

This literature review tries to generate an overview of methods to communicate this need of assistance to bystanders described in literature and used by real robots in industry. The various methods are divided into visual, auditory and expressive robot movements. And an overview of the main advantages and disadvantages of these methods is given. Additionally, advantages and disadvantages of explicit and less explicit methods of communication need for assistance are described.

Finally, an overview of the dimensions of currently used robots in public spaces in given to get an understanding of the relevant scope. And an overview of problems robots generally run into was also done to get an understanding in what kind of scenarios public robots generally need assistance.

4.2 METHODS OF COMMUNICATING NEED FOR ASSISTANCE IN ROBOTS.

4.2.1 AUDITORY

A commonly explored method to a have robot ask for assistance is by using computer synthesised voices and directly asking bystanders for help. As this is of course the method humans would use when asking for assistance from other robots (Seaborn et al., 2021; Srinivasan & Takayama, 2016).

Weiss et al. (2015) for example used this method combined with an expressive pointer appendage on a humanoid robot to ask bystanders for directions to make to robot navigate around a real urban environment. They also found that the speech modality was the most preferred way bystanders wanted to interact with the robot, and they give some guidance in how such a speech interaction should function. Their robot was however a humanoid looking one, and this result might thus not be relevant for nonhumanoid robots or the humanoid appearance might make people expect people to interact with it like they would with a human and thus speak with the robot.

While exploring non verbal help seeking strategies for robots Yu et al. (2024b) found that participants believed that a robot suddenly talking to them in a public place would be awkward, and possibly so distracting as to be dangerous and some felt this direct way of asking for assistance would make them feel like their labour was being exploited by the large company owing the robot.

The recent widespread availability of Lage language models has made it easier to add human like speech and conversational abilities to social robots. This provides many opportunities for improved conversations with bystanders. But if this humanlike speech is not properly combined with human like non verbal communication and proper design (Kim et al., 2024) .

4.2.2 VISUAL

As our society is deeply reliant on screens for interaction with most systems so it is no surprise that screens are a widely explored way for robots to communicate the need for assistance to bypasses. Commercial delivery robot company Serve Robotics Inc (Serve Robotics Inc, 2026) for example uses LED eye shaped lights, and a LED ring which surrounds the whole robot. These light change animation pattern and colour when the robot is for example in trouble or read to deliver their payload. Interestingly these lights are used in combination with a screen on top of the device which constantly shows the current task of the robot in written text. Some commercial robot companies even change the information providing screens into animated eyes which communicate robot state when they are not providing information (Pudu Robotics, 2023).

Another interesting option is using projections to communicate to bystanders. As projections are displayed on top of other objects, they can directly communicate a position or object while also communicating more nuanced information like text or icons at the same time. This allows the robot to intuitively communicate complex information to bystanders. Yu et al. (2024a) uses this method to project game like animations on the ground in order to communicate the specific assistance a service robot needs. They compared this playful asking for assistance to a verbal asking for help method and a visual animated eyes on a screen method and found

that the playful engagement improved willingness to help by bystanders especially in situations where the assistance required more effort. They also found that the verbally asking for help was perceived as impolite and the eyes on screen method was perceived to be insincere. A significancy limitation of this study is however that it was done in a VR environment. This limits the effort participants must exert to assist the robot and might thus not be comparable to the same study with a real robot.

4.2.3 EXPRESSIVE ROBOT OR ROBOT JOINT MOVEMENT

As discussed earlier Weiss et al. (2015) found that an expressive pointer appendage was found to be a significantly less preferable way of communicating need of assistance compared to verbally asking in a humanoid robot. Other work (Yu et al., 2024b, 2024a) however argues that the advantages of visual and auditory methods of asking for help, namely clarity and widespread familiarity with the modality by users, will be negated by users feeling more disturbed and less internally motivated to assist the robots. Additionally there are practical concerns like audibility, and visibility in busy environment for these methods. (Backhaus et al., 2018; Yu et al., 2024a) so using expressive movement of robot or appendages would be a more successful method to get people intrinsically motivated to assist robots. Participants are able to determine what a robot is trying to communicate by using robot movement gestures (Bucolo et al., 2025; Koay et al., 2013) and they are even able to determine what emotion a robot is trying to communicate (Embgen et al., 2012; Hashimoto et al., 2024; Koay et al., 2013; Sharma et al., 2013) this communication of the emotional sate of the robot helps to improve interaction quality depending on the use context (Hu et al., 2025)

Machine learning techniques are becoming a more common way to control robots. Methods like reinforcement learning are for example used in autonomous navigation (e.g., drone flight control (Geles et al., 2024)) and increasingly utilized within Human-Robot social robotics (Akalin & Loutfi, 2021). The goal is often to enable robots to learn complex social behaviours by observing human interactions, such as navigating crowded spaces (Luo et al., 2025) or adapting strategies in interactive games (Guckelsberger et al., 2018). These methods also provide new opportunities to add expressive movement patterns to a robots normal functional movement (Grandia et al., 2024) this possible improvement in expressive movement quality of robots might improve this method of communicating need for assist in robots.

4.3 METHODS OF DETERMINING WILLINGNESS TO HELP IN BYSTANDERS

In addition to communication methods for help seeking research also states the need to “sense” humans in order to select humans which are willing and able to help the robots (Backhaus et al., 2018). And to finetune the communication method based on feedback from the human. Various methods of how this could be done are discussed below:

By measuring various biological signatures like galvanic skin response, and hart rate variability, or facial expressions a rough estimate of a person’s emotional state can be made. This so called “biofeedback” is emerging as a valuable tool in therapeutic applications (Liang et al., 2018) and to evaluate the effectiveness of robots in HRI applications (Tiberio et al., 2013). Examples include measuring engagement levels during interactions with children with autism (Alban et al., 2023), assessing user comfort and anxiety related to robotic movements (Kulic & Croft, 2007) Additionally, previous work exploring how people interact with robots in public also shows there are various ways people behave around robots in public and these might also be connected to how willing or able these people are to assist the robot (Babel et al., 2022), especially combined with camera based methods of detecting pose, emotion and movement direction in humans.

4.4 SIZE AND SHAPE OF CURRENT PUBLICLY DRIVING ROBOTS

ROBOT NAME	TYPE OF ROBOT	MASS (KG)	LENGTH (CM)	WIDTH (CM)	HEIGHT (CM)
STARSHIP ROBOT	DELIVERY (6 WHEELS)	23	67.8	56.9	55.4
KIWIBOT	DELIVERY (4 WHEELS)	17	55.9	43.2	55.9
SERVE	DELIVERY (4 WHEELS)	73	79	64	105
AMAZON SCOUT	DELIVERY (4 WHEELS)	45	76.2	61	73.7
MEAN		39.5	69.725	56.275	72.5
BOSTON DYNAMICS SPOT	INSPECTION (LEGGED)	33.8	110	50	61
ANYMAL	INSPECTION (LEGGED)	50	93	53	89
MEAN		41.9	101.5	51.5	75

Sources: (Dimensions | Database of Dimensioned Drawings, n.d.; “Our Robots,” n.d.; “Spot,” n.d.; Starship - Robot Product Detail | RobotATTA!, n.d.; Ridden, 2024)

To gain an understanding of the size of delivery and inspection robots used in public, some literature research was conducted. The shape and size of these robots are important because they determine the weight and scale people must interact with, which ultimately changes the quality of the interaction.

These values were hard to find and might not be accurate as delivery robot companies do not generally share exact data on the specifications and details about their robots for competition reasons. Thus, most of these values are from secondary sources which might not be accurate. But a rough concept of publicly used public robot size and shape is still valuable to get an approximate understanding of the specifications of these robots.

From the means in this data a rough scope for a future public robot I would like to focus on was made:

ROUGH SELECTED SCOPE ROBOT	
WHEELS	4
MASS	25 KG
LENGTH	~70 CM
SPEED	~5 KM/H
WIDTH	~70 CM
HEIGHT	< 80 CM

4.5 HELP RECRUITMENTS RESEARCH AND OVERVIEW

From literature (Del Duchetto et al., 2023; Dobrosovestnova et al., 2026; Sathyamoorthy et al., 2020), a list of problems encountered by current public robots was made. Like the specifications of the public robots this data was hard to find and might not be accurate as public robot companies do not generally share data about what they are struggling with as they want to seem successful for marketing reasons. Thus, these problems should not be taken as fact but as a start for getting an understanding of what public robots are struggling with.

FOUND PROBLEMS	
GETTING LOST	*SENSOR CONFUSION (SNOW, RAIN, MUD, ETC), GPS PROBLEMS (URBAN CANYONS)*
GETTING STUCK	*BAD PAVEMENT, HOLES, TREES, GRASS, SLIPPERY SURFACES, (RAIL)ROAD CROSSINGS*
BYSTANDER ATTACKS	*THEFT, VANDALISM, ACTIVISM*
HARDWARE FAILURE	*TIRES FALLING OFF, MECHANICAL WEAR*
BATTERY PROBLEMS	*TOO COLD OR WARM ENVIRONMENT, UNEXPECTEDLY FAST BATTERY DRAIN*
PEDESTRIAN OBSTRUCTION	*NARROW SIDEWALKS, WHEELCHAIRS, STROLLERS*

4.5.1 expert review

These findings were discussed in conversation with people at the robotics team of a large company in the Netherlands to confirm that they are indeed real problems.

The following problems were found to be serious and recognized by them while they were less confident the others where real problems they dealt with.

EXPERT AGREED WITH PROBLEMS	
GETTING LOST	*SENSOR CONFUSION (SNOW, RAIN, MUD, ETC), GPS PROBLEMS (URBAN CANYONS)*
GETTING STUCK	*BAD PAVEMENT, HOLES, TREES, GRASS, SLIPPERY SURFACES, (RAIL)ROAD CROSSINGS*

They also added these problems as things they were worried about:

ADDITIONAL PROBLEMS FROM EXPERTS	
LEGAL PROBLEMS (APV)	*MUNICIPALITIES MIGHT GET SCARED OF ROBOTS AND START TO RESTRICT THEM IN LOCAL LAWS*
AI ACT AND GDPR	*SOME CURRENTLY USED DATA ANALYSIS TECHNIQUES USED IN ROBOTS MIGHT BREAK GDPR AND NEW AI ACT RULES*
HARD TO ACCESS PLACES	*UNDERNEATH BRIDGES, SMALL DOORWAYS, GATES*

4.6 CONCLUSION

This literature review provides some insights into state of the art in communication methods robots can use to signal for need of assistance, from academic work and industry. Additionally, it combines some work outside this specific context to get a feeling how new technologies might improve certain communication methods in the future.

An interesting finding is the opposition between explicit communication methods, like text based visual and conversational auditory communication methods, and implicit methods like expressive robot movement and more subtle auditory and visual methods. Where the explicit methods are clearer, but might be perceived as less sincere and polite, while the implicit methods are less clear but are perceived as more authentic. This could mean that in a future with many robots constantly asking for assistance people will start to ignore robots explicitly asking for help as they feel the robots are being rude or annoying, while they keep helping the robots implicitly

conveying the need for help as these are perceived to be more polite.

4.7 DISCUSSION AND INSIGHTS

The main takeaway from this literature review was the large amount of complexity and nuance which there is to explore in this subject. Authors seem to have many different visions of how to do HRI and how future robots should be designed. And while some papers provide clear and actionable design guidelines, it is not clear how widely applicable these guidelines are if the context or robots are altered compared to the one the authors in the paper used.

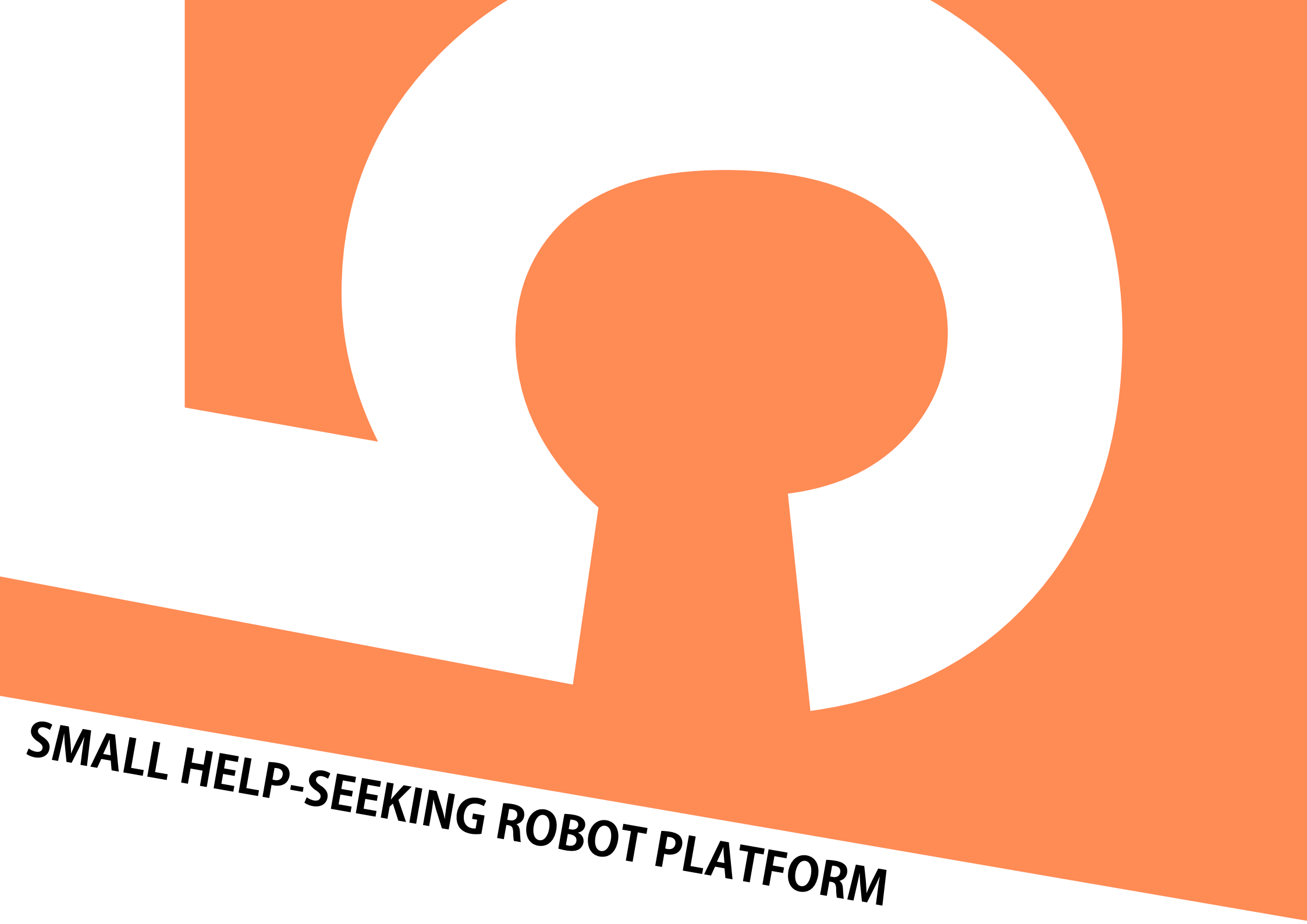
This does however make the field really interesting for designers as this provides opportunities for iteration and user testing, which makes the topic a relevant topic to further explore.

It was decided to focus on more implicit help-seeking communication methods for the rest of this project and to explicitly exclude auditory feedback, due to the discussed problems of bystanders becoming annoyed and being unable to tune out the robot if they do not have the time or resources to help it. Additionally, much research on how humans and robots should talk to each other has already been done. Furthermore, auditory feedback might not always be possible in, for example, busy public streets or quiet places like libraries.

It is important to give bystanders the opportunity to take control and "help" the robot at any moment, rather than only when the robot decides it needs help. This is both because the robot might be harming bystanders in ways it does not detect. For example by obstructing the street and preventing bystanders from passing. And because many of the situations where a robot needs help are ones where the robot does not realize something is going wrong. The robot might, for example, be stuck without noticing it, or doing something dangerous because of sensor or hardware failures. A purely bystander-initiated help action, however, does require participants to have a good understanding of what the robot is doing. The robot thus needs to communicate its internal navigation logic during both normal operation and when it thinks something is going wrong.

Thus for the rest of the project, it was decided to focus on the following list of problems by giving bystanders the opportunity to move a robot around at any time with a goal specified by the robot or as a correction of incorrect robot behaviour.

PROBLEMS IN SCOPE	
GETTING LOST	*SENSOR CONFUSION (SNOW, RAIN, MUD, ETC), GPS PROBLEMS (URBAN CANYONS)*
GETTING STUCK	*BAD PAVEMENT, HOLES, TREES, GRASS, SLIPPERY SURFACES, (RAIL)ROAD CROSSINGS*
PEDESTRIAN OBSTRUCTION	*NARROW SIDEWALKS, WHEELCHAIRS, STROLLERS*


SMALL HELP-SEEKING ROBOT PLATFORM

5 SMALL HELP-SEEKING ROBOT PLATFORM

Getting an understanding and a feeling of non-humanoid robot behaviour and the possible quality of help-seeking methods is quite hard to do with normal prototyping methods, like sketching or low-fidelity modelling, as these methods are static and are thus not suitable to let the designer experience the complex, dynamic behaviour of an autonomous robot. Richer methods, like making low-fidelity storyboards or videos of a robot interaction, will give more insight into how a robot behaves and are more useful, but these still lack real insights into the interaction with the robot. Building real interactive digital prototypes using, for example, a game engine is possible, but these methods miss the real physical interaction barriers (like having to actually lift a physical robot) one experiences when assisting a real robot. Finally, Wizard of Oz methods, where one acts out the behaviour of the robot using a non-functioning model, lack the surprise of when the robot will actually get stuck, which is a very important part of the context I would like to explore.

Thus, it was decided to actually design and build a small, non-humanoid robot. This robot platform would need to be a small-scale robot platform with limited autonomous navigational capabilities to simulate the robot navigating around a space, and to create realistic scenarios where the robot would get stuck and need help. Additionally, it should be easy to change the software and the hardware of the device to allow for quick and unconstrained exploration of various help-seeking methods, and to quickly change the navigation or driving behaviour of the robot.

This small robot device can be seen as a physical artefact in a research-through-design approach (Frayling, 1994; Zimmerman et al., 2007). In this method, the design and development of this small-scale, help-seeking robot artefact should generate knowledge and insights into how one should design help-seeking robots, which could then be used in possible future iterations or in the development of real robots in industry. The value of generating knowledge through various higher- and lower-fidelity prototyping methods is also called exploratory prototyping, and it can be a valuable method for generating knowledge in the human-robot interaction field (Zamfirescu-Pereira et al., 2021).

5.1 SMALL ROBOT PLATFORM GOALS

As discussed earlier, to explore how an autonomous robot might get stuck and communicate help it was decided that the research artefact had to be able to do simple autonomous navigation. Additionally, it needed to be small for easy transportation and demonstration to others. The hardware and software of the robot needed to be easy to modify and allow for extension and for the addition of more actuators and motors. From these basic requirements the following hardware, software and configuration decisions where made.

5.2 ROBOT CONFIGURATION

One of the main advantages of a robot that can be helped by bystanders is the reduced need for complex hardware methods of getting the robot unstuck, or methods of allowing the robot to traverse obstacles, like legs, robot arms, or tracks. Thus, for this small exploratory platform, it was decided to exclude robot configurations that needed many actuators, like legged robots or complex transforming robots. As the explorations with this robot would take place on flat indoor floors, robot configurations that included complex suspension systems, which are needed if the robot needs to traverse rough terrain, like tracks or the rocker-bogie systems that some Mars rovers use, were decided not to be necessary. Finally, only three general robot configurations were left (see figure 25). From these configurations, the Ackermann steering configuration was excluded, as this configuration does not allow rotation in place and needs more complex control algorithms, and the reduction in wheel slippage while steering was not deemed necessary, as this robot will not be driving very fast. Finally, the 4-wheel, 4-motor configuration was excluded, as the increased complexity of adding four motors, which has the advantage of making the robot more stable and more able to drive in difficult terrain where one or more of the wheels might be lifted in the air, did not outweigh the disadvantage of requiring more motors and more wheels.

Thus, finally it was decided that the simple differential drive robot with two motors, two wheels and a slip pad in the front of the robot would be the best option for this small exploratory robot.

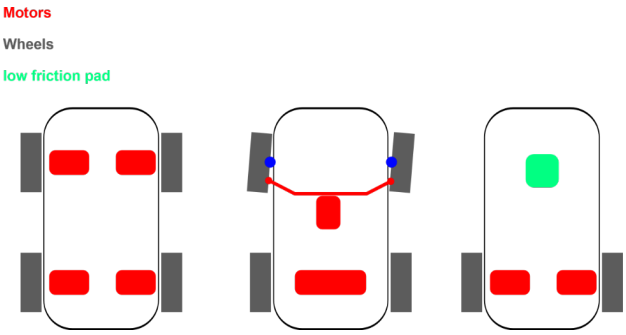


figure 1. Possible robot configurations for small robotic platform.

5.3 ELECTRONICS

5.3.1 Part list

PART FUNCTION	PART NAME	NR
MAIN CONTROL BOARD	ROMEO MINI ESP32-C3 ROBOT CONTROL BOARD (INTEGRATED MOTOR & SERVO DRIVER)	1
MOTOR WHEEL	N20 MOTOR 500 RPM 6V	2 (ONE FOR EACH WHEEL)
BATTERY	14500 BATTERY 2S	1
MULTIZONE DISTANCE SENSOR	VL53L5CX	1
SCREW M2.5		6
SCREW M3.0		3

5.3.2 Schematics (pins in the same row are connected)

VL53L5CX	MAIN CONTROL BOARD	MOTOR RIGHT	MOTOR LEFT	BATTERY
VIN	3V3			
GND	GND			
SCL	SCL (9)			
SDA	SDA (8)			
	M1 +	-		
	M1 -	+		
	M2 +		-	
	M2 -		+	
	VIN +			+
	VIN -			-

5.3.3 Controller

The robot controll board needed to have two motor controllers and wireless control for stopping the robot from a separate device and for easy uploading of code without accessing the robot. The controller also needed to be able to deal with 2s LiPo voltage as this would be necessary for the motors. And the controller needed ample extra connections for possible future servos, LEDs or displays. An integrated controlled with all these elements build in would be preferred as this reduces complexity, size and weight. As this robot prototype did not need to do real navigation it did not need to do computationally complex calculations required in SLAM or optical recognition algorithms, and thus a simple microcontroller would be sufficient and a microcomputer like a raspberry pi was not required. After the consideration of various hardware options an ESP32-C3(ESP32-C3 Wi-Fi & Bluetooth 5 (LE) MCU, 2020) based robot development board(Compact ESP32-C3 Control Board | Robotics WiFi/Bluetooth Solution - DFRobot, n.d.) with 2 motor drivers and various connections for servos and batteries was chosen as the main controller for the robot. This controller was found to have a nice balance of many features and small size.

5.3.4 Motors

For the motors, the main selection criteria were ease of sourcing, small size, low weight, compatibility with the 2S LiPo battery voltage, and a lower speed with a reasonable amount of torque so the wheels would not get stuck. For motor selection, inspiration was taken from other small robots (specifically the ones used in 150-gram antweight combat robots), and finally, 6V 500RPM N20 brushed DC motors were chosen.

500 RPM with a wheel radius of 13mm corresponds to a maximum robot speed of 0.68 m/s, calculated as follows:

$$v = 2\pi \cdot 0.013\ \text{m} \cdot \frac{500\ \text{RPM}}{60\ \text{s}} = 0.68\ \text{m/s}$$

Video measurements of the real robot showed a velocity of 0.63 m/s, which was more than enough to create a robot that would be able to realistically drive around.

5.3.5 Sensor

As the robot needed to be able to avoid obstacles, it needed to detect roughly where these obstacles are in relation to the robot so it can steer around them. A simple way of doing this is by using a distance sensor aimed towards the front of the robot. This, however, does not provide insight into whether the obstacle is towards the right or left of the robot, which does not allow the robot to efficiently steer around the obstacle. So, multiple distance sensors are needed to generate this information. Professional robots in industry often use a rotating lidar sensor to generate data about how far obstacles are around the robot. These sensors are, however, too large and require too much power and computational resources to be relevant for this robot. Multiple smaller distance sensors, like ultrasonic or IR light-based ones, can be positioned around the robot to generate this information, but this configuration increases complexity and price, as multiple sensors now have to be constantly read out and fitted into the robot body. Luckily, distance sensors which can measure multiple distances in a grid also exist, and this allows us to measure where obstacles are in front of the robot without needing to interface with a large amount of distance sensors. Many different types of these sensors exist with various prices, maximum detection distances and amounts of measurement points. Finnaly, the VL53L5CX 8x8 time-of-flight sensor (VL53L5CX | Product - STMicroelectronics, n.d.) was selected for its 64

measurement points and 4-meter range. Despite these capabilities, it remains cost-effective, compact, and energy-efficient, with readily available development boards and ESP32 library support.

5.4 ROBOT BODY

When the electronic hardware was decided upon a robot body could be designed. The following process was done to design the robot body.

5.4.1 Outer robot shell

First, a general shape of the robot could be roughly determined based on the sizes of these parts. To create the outer shell of the robot, CAD models of the internal components (Parts for which the official CAD models could not be found were measure and modelled from scratch.) were arranged into the robot's general shape, leaving some room for wires. It was decided to leave the battery on the top of the robot and to constrain it using a wire attached to the top of the robot frame. This allows the battery to be quickly switched out for a new charged one. This layout of the internal components was then used to get a general idea of the minimum shape required to fit the electronics. The outer body of the robot was modelled around these internal parts, ensuring everything fit securely inside, and leaving an indentation on top of the robot to constrain the battery mounted on top of the robot. The shape of the shell was a smooth curved rectangular form fitted around the components and having a minimal and sleek look. This shape was then hollowed out keeping a 1.8mm thick wall thickness. 1.8mm was chosen as this is a whole multiple of the 0.6mm nozzle which would allow for faster and less complex 3D printing with an FDM printer.

Finally, to ensure the inside of the robot body was easily accessible for installing and swapping out components, the body was split into two parts, and screw holes were added for easy assembly.

After multiple iterations of these steps (arranging the parts, drawing the outer shape and checking if everything fits) a sleek and compact robot design was designed.

Finally, this robot was printed using grey PETG filament using a FDM 3D printer. This version of the robot did not leave enough room for the connectors of the ToF sensor wires and thus a ring was fitted between the two halves of the robot shell to create more room inside the robot and to allow the connectors to easily fit inside.

This version of the robot measured 86 mm by 60 mm, and was used to explore various control algorithms and to remove obvious hardware problems. Many small hardware design problems, which meant some parts of the robot body broke, bended or had to be removed to make parts fit, were discovered. Thus, another iteration of the robot platform was done to resolve these issues.

figure 2. Design process with of the outer body of the robot with the following steps: Layout parts, Draw outer shell shape around parts, Hollow and split shape, Add details and screw holes.

figure 3. Front and sideview shell, and electronics.

5.4.2 Robot platform body redesign

In addition to fixing various interference and tolerance problems with the first 3D printed robot body the general shape and fixtures between the 2 halves of the shell where altered. The shape of the shell was made smaller in the front and wider towards the back of the robot. This made the robot look smoother and more streamlined and less boxy. It also gave the robot a clearer visual distinction between the front side and the backside. The configuration of the wires attaching the battery to the top of the robot was also changed and an opening in the robot body to connect an USB-C cable to the control board was also added.

5.4.3 Materials

PETG FDM filament was used for the lower part of the body because this section needed to be rigid to support the attached motors and mechanical components. For the upper shell of the robot, a stiff but still flexible TPU filament (Shore hardness 68D) was used to provide impact resistance while till being relatively stiff. This impact resistance would allow the robot to for example fall of furniture or stairs without damaging the electronics inside. As this top shell of the robot could deform this allowed the robot to use various differently shaped batteries.

5.5 CONTROL ALGORITHM

The initial control algorithm (figure 5) checked the sensor readings and triggered a full 180-degree turn whenever the robot got too close to an obstacle. If an object was detected at a medium distance on either the left or right side of the sensor, the robot steered slightly in the opposite direction to gradually veer away. When no obstacles were within the threshold range, the robot simply drove forward.

This simple version of the control algorithm allowed the robot to avoid simple obstacles like walls and furniture but as the robot could only steer at a constant rate or turn around this algorithm made the robot move around in a non smooth jittery way, which made the robot feel like it was not deliberately driving around.

5.5.1 Obstacle avoidance algorithm with smooth robot motion

To make the robot driving around behaviour feel more deliberate it was decided that the control algorithm had to be changed to go from a simple constant turning speed to a more complex varied turning speed based on how many and how close obstacles appeared in front of the distance sensor. The concept behind this algorithm was to instead of just looking at the number of obstacles and if

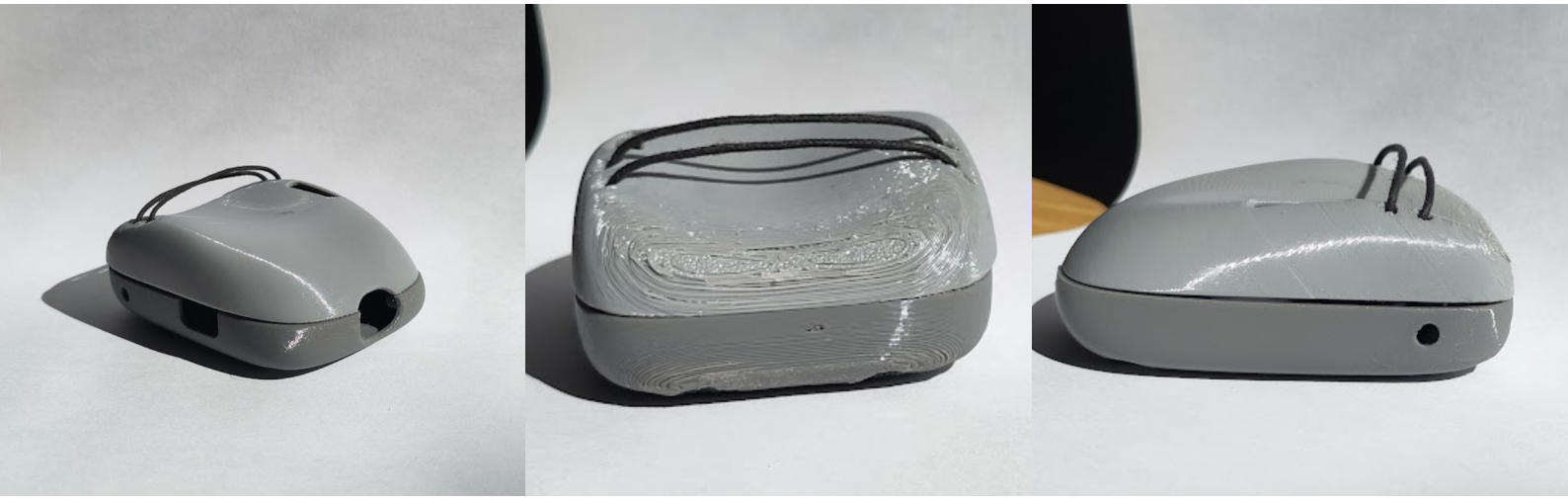


figure 4. New robot body design.

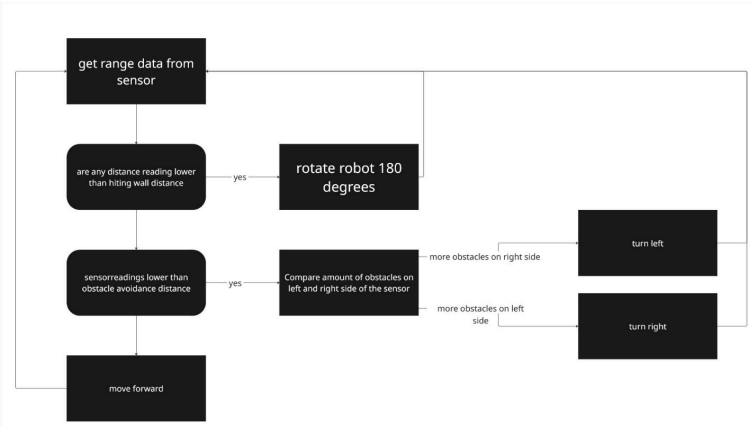


figure 5. Flowchart initial obstacle avoidance algorithm.

they are to the left or to the right of the sensor the robot should look at all the readings of the sensor and calculate a turning value and a breaking value for each of the readings. These values turning and breaking values should be based on the distance reading and the relative position of the reading on the sensor. Adding these values together then generates a general breaking and steering value for the robot. This method allows the robot to smoothly and deliberately drive around obstacles.

5.5.2 Explanation of algorithm

Let the sensor readings be represented as an 8×8 matrix $D \in \mathbb{R}^{8\times8}$, where each element $d_{y,x}$ denotes the measured distance in millimetres at row y and column x, with indices $x, y \in \{0,1,\dots,7\}$. We set the sensor to only report readings with a confidence level of at least 50%.

We define two weights vectors for the horizontal field of view. The steering weight vector $\mathbf{w}^s \in \mathbb{R}^8$ defines the steering behaviour for the robot (If there are obstacles on the left steer right and inversed), while the braking weight vector $\mathbf{w}^b \in \mathbb{R}^8$ prioritizes breaking for central obstacles. These values were selected by choosing the behaviour at the edges (Break hard in the centre and steer hard on the sides) and then linearly interpolating:

$$\mathbf{w}^s = [1.0, 0.7, 0.4, 0.1, -0.1, -0.4, -0.7, -1.0]^T$$

$$\mathbf{w}^b = [0.1, 0.4, 0.7, 1.0, 1.0, 0.7, 0.4, 0.1]^T$$

The algorithm ignores the bottom four rows of the sensor data as these parts of the sensor are aimed at the floor and are used to check if the robot is still on the floor. We define the set of valid, active obstacle coordinates V as those located in the top four rows ($y \leq 3$) that fall within 2 mm and the maximum reaction distance d_{max}:

$$V = \{(x,y) \in \mathbb{N}^2 \mid 0 \leq x \leq 7,\ 0 \leq y \leq 3,\ 2 < d_{y,x} < d_{max}\}$$

For every valid sensor reading in V, the repulsive force scales linearly based on distance. We define the normalized distance factor $\alpha(d)$ as:

$$\alpha(d) = \frac{d_{max} - d}{d_{max}}$$

The resulting steering force F_x and forward force F_y are calculated as the sum of all valid repulsive forces. Let K_{ry} and K_{rx} be the proportional gains for steering and braking

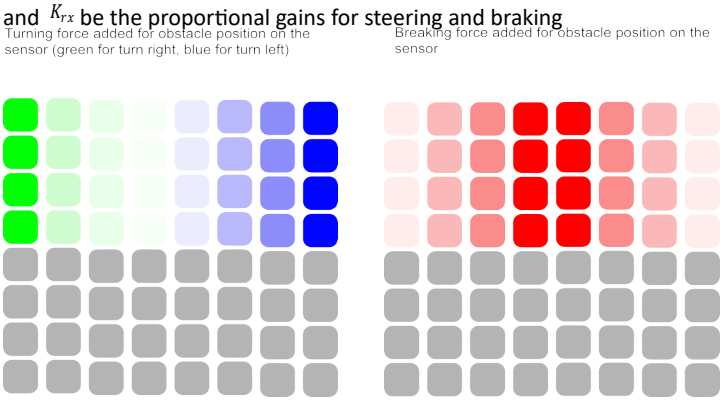


figure 6. Overview of force added per obstacle position on sensor.

respectively (these can be changed to tweak the robot driving behaviour), and v_{base} be the nominal base forward speed of the robot:

$$F_x = K_{r\,x} \sum_{(x,y)\in V} \alpha\,(d_{y,x}) w_x^s$$

$$F_y = v_{base} - K_{r\,y} \sum_{(x,y)\in V} \alpha\,(d_{y,x}) w_x^b$$

The wheel PWM signals were calculated from the steering and the breaking force variables in the following way:

$$\text{PWM value left motor} = F_y + F_x$$

$$\text{PWM value right motor} = F_y - F_x$$

By adjusting various settings, gains and constants in these formulas, the robot was able to smoothly drive around simple obstacles like walls and large furniture. Tweaking these settings could also alter the navigation behaviour in order to change the movement quality of the robot. Of course, the robot still had to get stuck to communicate the need for assistance to bystanders. This was achieved by checking how long obstacles in front of the robot were within the avoidance distance or if the robot had reduced speed so much by breaking that it was under a specific value and triggering a “help mode” after a certain time interval, which would stop the robot. Other behaviours could then be initiated once the robot entered this help state.

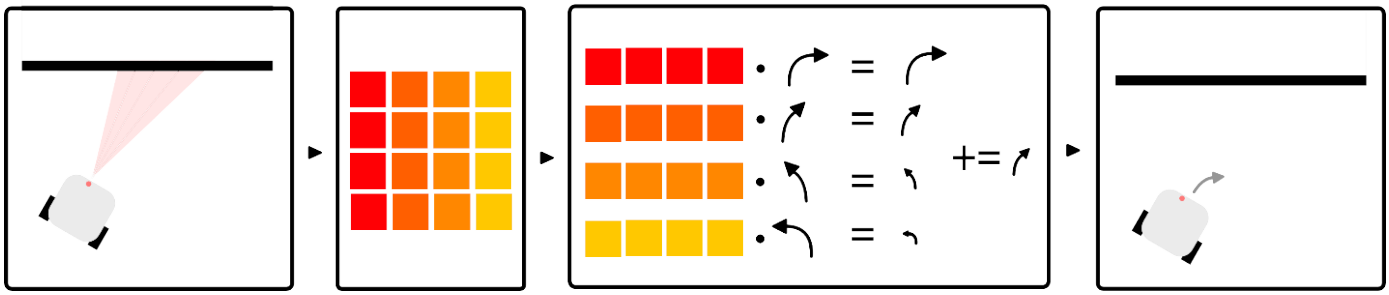


figure 7. Schematic overview of one iteration of the obstacle avoidance algorithm using a 4x4 sensor instead of 8x8. From left to right: The robot detects an obstacle (a wall in this case), the ToF sensor sees the obstacle, robot calculates turning force based on the steering weights, robot turns to the right based on the sum of the steering forces.

5.6 BROWSER BASED TELEMETRY AND SETTINGS MENU

During the development of the small robot platform it was found that getting constant feedback and data about what the current state of the robot was and what sensor readings the robot was getting, was almost required to be able to make changes to the code and the control algorithms. As one needs a lot of data to debug and improve the robot. An interface to teleoperate the robot and to put the robot in different modes also significantly increases the ease of use of the robot. Thus it was decided to design and build a web interface to operate, change settings and show the sensor readings of the robot.

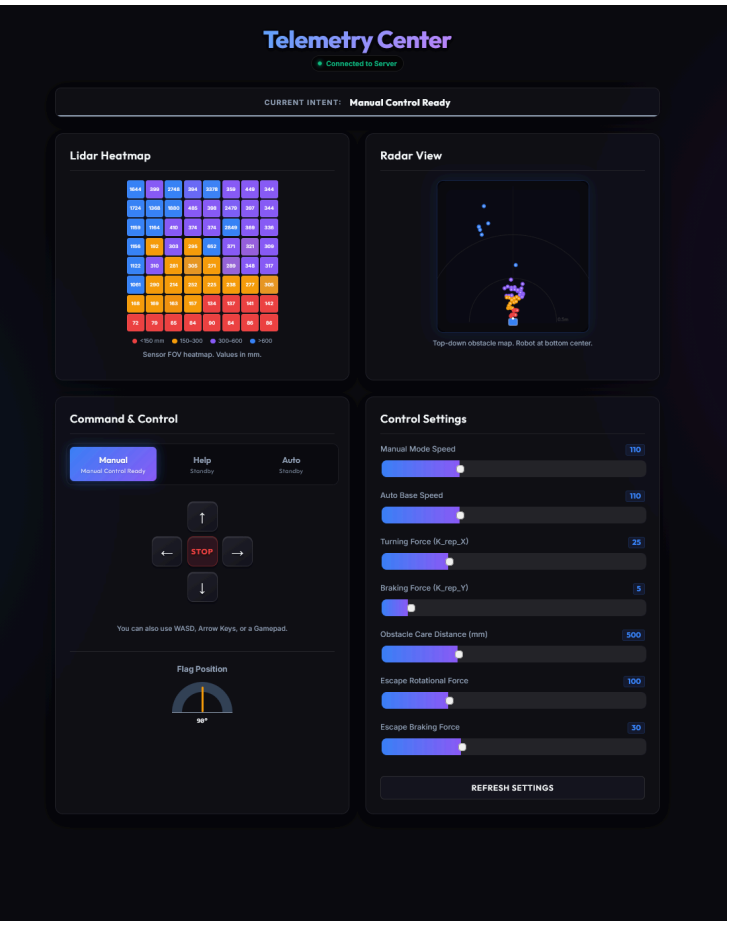


figure 8. Browser based telemetry and settings interface.

5.6.1 Web interface

The web interface consists of a main page divided into various boxes housing the interaction or information panels. This modular design allows individual panels to be swapped out or new pannels to be added without needing to redesign the entire page.

To make it easier to understand the sensor readings sensor data pannel was build. This pannel gave an overview of the sensor data from the ToF sensor. Both as a heatmap of the raw sensor output, and as a “radar view” showing dots for detected obstacles in a top-down perspective. These panels used a colour gradient to quickly show the distance of the readings.

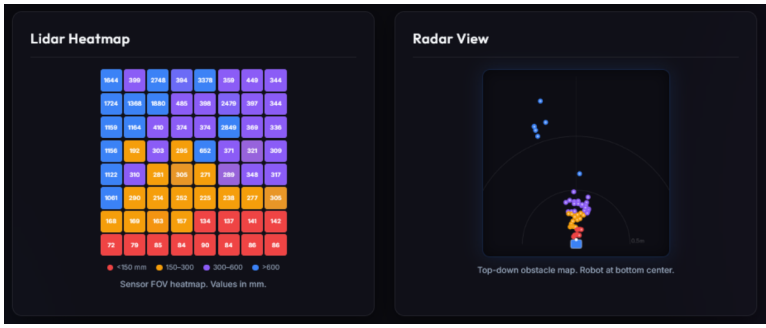


figure 9. ToF sensor reading panel

Additionally, the web interface made it possible to easily change various settings of the robot which allowed for easier exploration of navigation behaviour (see figure 10).

Finally, the web interface allowed for manually driving the robot around and switching between automatic navigation or help mode. This panel also showed some additional details about the state of the actuators on the robot (see figure 11).

The web interface consisted of three main parts (also see figure 12):

a webpage *(using HTML + CSS + Javascript)*

WebSocket server *(using Python)*

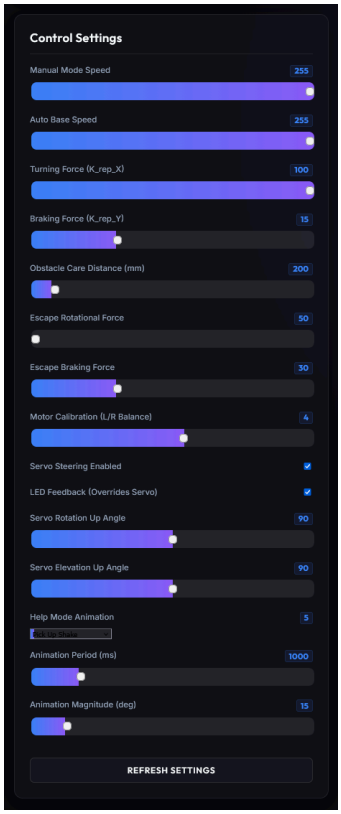


figure 10. Settings panel

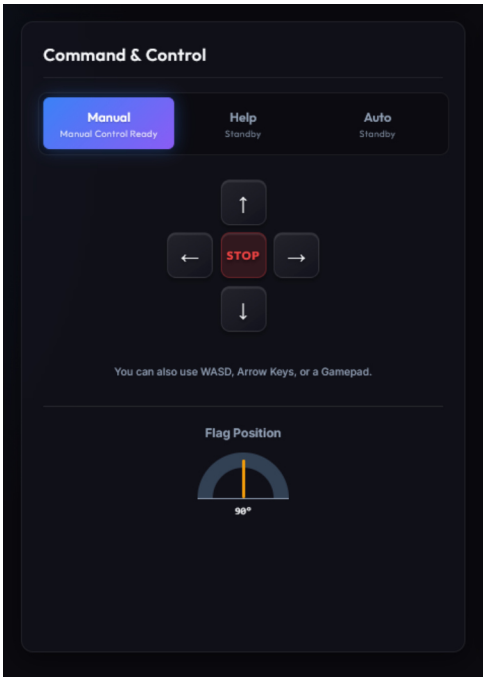


figure 11. Manual control panel.

Robot *(using C++ & the Arduino library)*

The website talks to the WebSocket server which sends any changes in robot settings or navigation commands to the robot using WebSocket. The robot sends sensor and state data to the WebSocket server which then forwards it to all connected webpages. This distributed system allows for local operation by running the WebSocket server locally on the same pc as the webpage is on. The connection between the WebSocket server and the robot is then achieved using the local network. To make sure the WebSocket server, the webpage and the robot can find eachother on the local network MDNS was used.

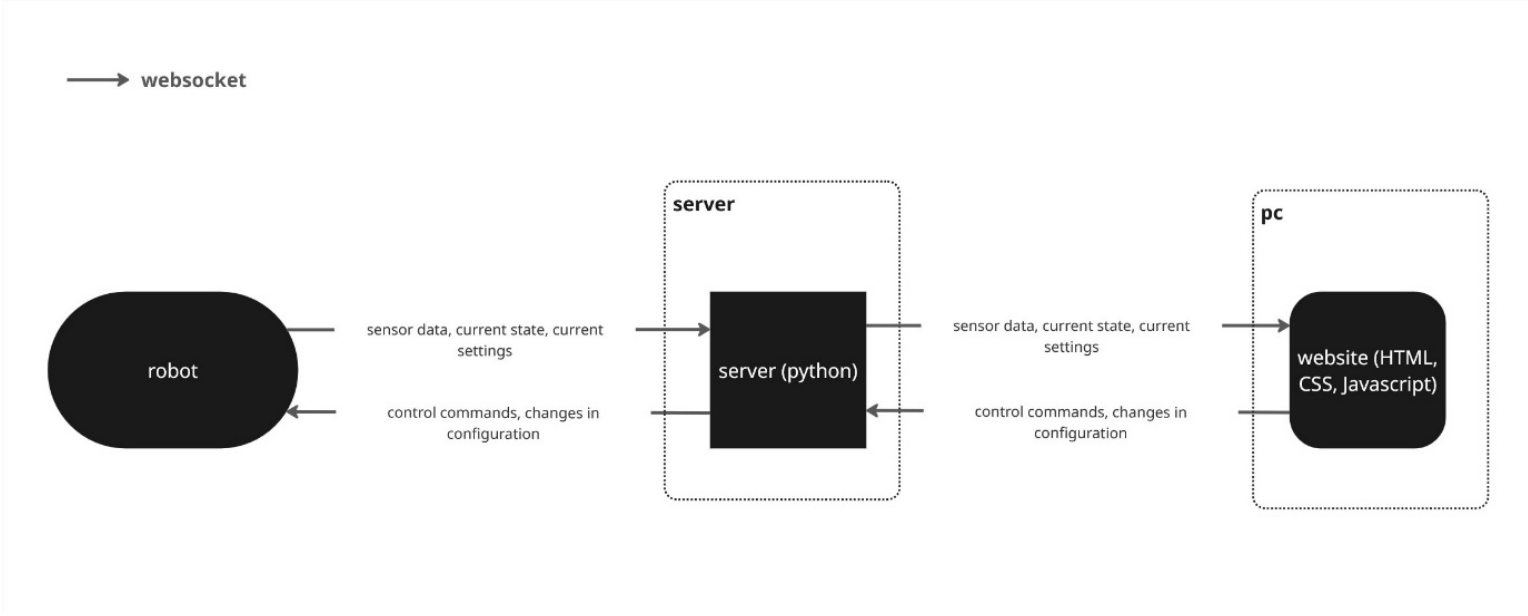


figure 12. System overview of web interface.

EXPLORATIONS WITH SMALL HELP SEEKING ROBOT

6 EXPLORATIONS WITH SMALL HELP SEEKING ROBOT

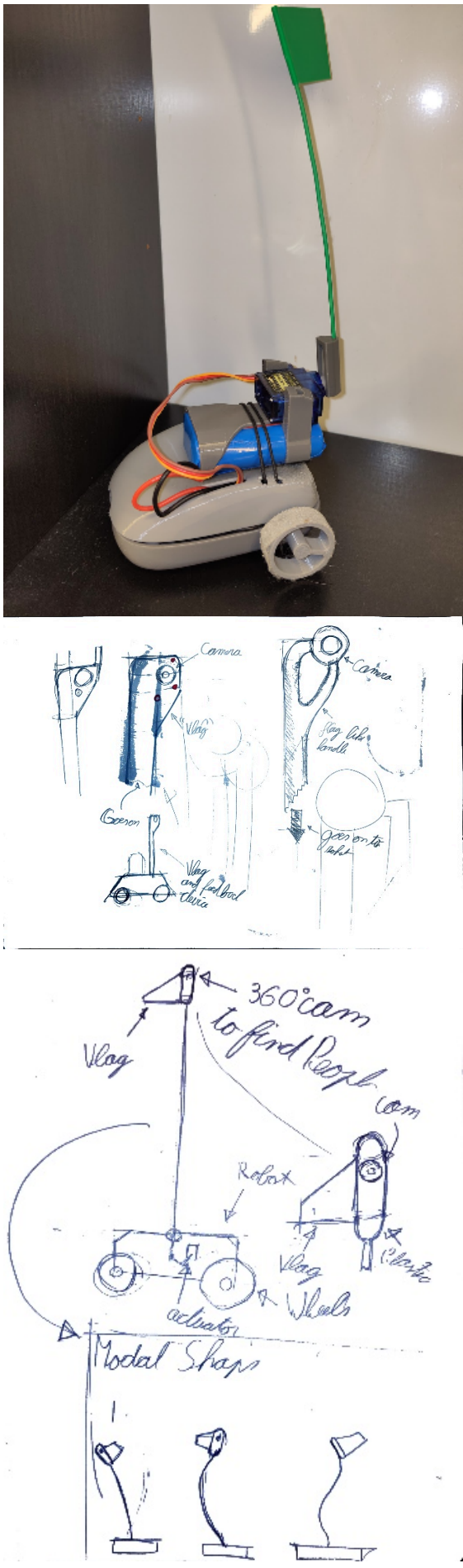


figure 13. Prototype and sketches flag version robot.

After building the robot platform various explorations of different methods for getting help from bystanders were explored using this prototype.

6.1 EXPRESSIVE WAVE MOVEMENT

Small flags are commonly attached to delivery robots to make them easier to view from a distance, especially from the viewpoint of a car. Some delivery robots just use these flags as a static attention grabbing device or just for safety, but others like startship robotics (Home, n.d.) add alternative feedback devices like LED lights into the flags. The attention-grabbing qualities of the flag on a robot are also explored in the Tweenbots project by Kacie Kinzer(Tweenbots - Kacie Kinzer, n.d.) where a robot with a navigational goal written on the flag was let loose around New York to see if people would move the robot and point it towards its goal. Additionally, these flags are an explicitly designed added feedback device, which means they could also possibly be used to communicate other information about the robot. Inspired by these qualities of robot flags a small exploration on using the robot flag to communicate when the robot gets stuck was done.

After some exploratory sketching a prototype was build using a servo and a FDM 3D printed attachment. The servo would move the flag around between 45 and 135 degrees in a sinewave pattern. The flag would also rotate proportional to how hard the robot was turning to give some extra feedback about the current state of the robot while it was driving.

Based on personal observations, this robot provided significantly more feedback about its internal state while navigating. The device's small size, combined with the tiny flag trailing behind it, gave it a distinctly cute appearance. However, while its status was clear during navigation, and the moving flag explicitly signalled that an action was occurring, it failed to communicate what exactly was wrong or how an observer could help. Because the goal of this artifact was for a bystander to pick up and reposition the stuck device, simply waving the flag from side to side did not clearly signify the affordance (Norman, 2008, 2013) of “pick me up and reposition me”.

figure 14. Small help seeking robot platform with flexible shell and flag as feedback mechanism.

figure 15. Small help seeking robot platform with flexible shell and ring as feedback mechanism.

To gain better insight into the flag feedback device, a new version was designed to improve the robot's physical durability and ease of use. To achieve this, a small, 3D-printed flexible part with space for a switch was designed and secured to the mount holding the battery and the flag servo. The flag itself and its attachment mechanism to the servo were also enhanced so that the flag would detach less frequently. This resulted in easier operation and a safer robot that can now be confidently demonstrated and tested with participants.

To provide a stronger signifier for the “pick me up” affordance, the flag robot's shape was redesigned with the intention of clearly communicating “lift the robot here.” This was achieved by adding a simple ring shape to the top of the moving appendage on the back of the robot. The size of the ring was chosen to easily fit a single finger. This shape will hopefully communicate to bystanders that they should grab the ring and reposition the robot if it gets stuck and is signalling for help. These two robot versions, which both used expressive movement to signal that they were stuck, could then be compared.

These versions of the robot were informally shown to various people. From these informal user tests and personal observations, repositioning the robot using the ring was a nice and logical interaction. Because it was quite clear that the robot was getting stuck as it waved its flag in a position where its front faced an obstacle, bystanders found it clear that it was signalling that it was stuck. People were, however, deeply reluctant to help the robot without clear verbal confirmation that it was okay to pick it up and reposition it. When people were repositioning the robot, they mostly grabbed it by the sides of its body and not by the ring. Many people found the ring too flimsily attached to the robot and thus did not want to touch it for fear of breaking it off. Additionally, the movement of the ring and flag was found to be too intense by many people. This was not helped by the fact that the servos used to move the flag created a rather jittery motion, which caused the flag and ring to vibrate a bit when moving around. After telling people that it was

okay to pick the robot up by the ring, they seemed to be able to easily do so, although some comments about the weak-feeling construction of the robot were still made.

6.2 EXPLORATION OF EXPRESSIVE MOVEMENT ANIMATIONS

In addition of the sinewave movement of the flag / ring robot other movement patterns where also explored.

As the simplest pattern, basic sine wave felt somewhat mundane. Furthermore, a notable trend observed across all tested movement patterns was that participants in the informal user study were highly hesitant to touch the ring while it was in motion.

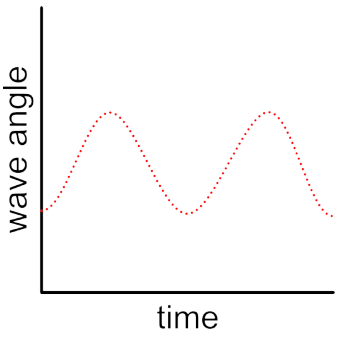


figure 16. sine wave

In this pattern, the flag rapidly transitions back and forth between servo positions at maximum speed. While this high predictability makes the movement easy for users to comprehend, it ultimately feels too abrupt and harsh.

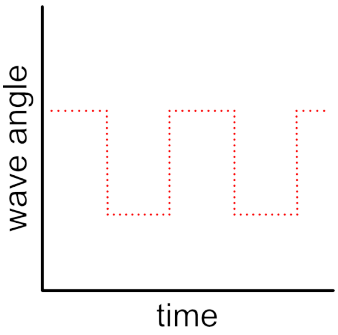


figure 17. square wave

To give the motion a more "dance-like" and expressive quality, a second-order Fourier approximation of a square wave was implemented. This added a brief shaking effect at the outer limits of the flag's swing. While intended to boost expressiveness, the result did not feel significantly more engaging than the basic sine wave. Instead, it simply appeared shakier and more jittery.

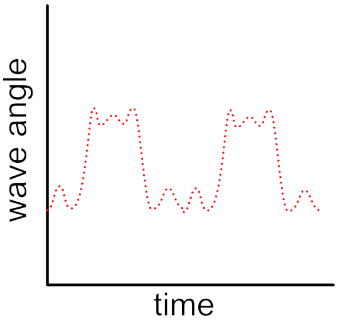


figure 18. fourier wave

Because users were hesitant to grab a moving handle, this pattern features a rapid shake followed by a distinct pause. This intermittent pause allows bystanders to safely grab the handle and reposition the robot without requiring complex sensors to detect human touch. However, this design relies heavily on the assumption that a bystander is actively monitoring the robot when it gets stuck. Additionally, when the robot stops moving entirely during the pause, it risks looking broken rather than temporarily stuck.

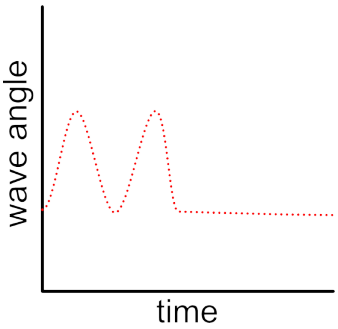


figure 19. small shake and stop

figure 20. Expressive simulated failure with small ball attached by wire.

6.3 EXPRESSIVE SIMULATED FAILURE

In this version, a ball attached to the robot by a wire rested on its moving appendage. When the robot detected it was stuck, the appendage would shake, dropping the ball to the ground. A bystander could then use the wire to pull the robot away from obstacles and reposition it.

The concept is inspired by the inherent affordances of broken or stuck objects, which often lose pieces, and the intuitive interaction of dragging a robot by a wire, similar to a child pulling a toy car. However, while a part falling off effectively signals that something is wrong, physically repositioning such a small robot via a wire is awkward and introduces several practical concerns.

6.4 STATIONARY HANDLE

To also explore non-moving communication methods, a simple non-moving handle was designed and tested. The handle had a rounded rectangular profile and was angled to roughly match a hand when grabbing the robot from ground level. This handle might clearly signal to bystanders that the robot is meant to be picked up and gives a method of doing so. It was found that the robot braking and then stopping for an obstacle might sometimes give enough feedback to understand that it is stuck, but this might not be the case if someone just notices the robot and is not actively monitoring it. While informally demonstrating this iteration, the very minimal rectangular handle shape was found to appear like an antenna, which made people reluctant to grab it.

figure 21. Render of stationary handle exploration.

6.5 EXPLORATION RESULT

Using insights from previous iterations, two new versions of the robot were designed. The goal of these new iteration was to combine successful elements from the initial exploration into two designs with vastly different help-signaling strategies, which could then be compared in a formal user test.

Previously, the different feedback mechanisms were attached directly to the top of the original robot platform frame. While this allowed for rapid iteration, since the top shell did not need to be redesigned, it left the battery and other electrical components visible from the outside. Consequently, the robot looked like a patchwork of mismatched parts. Furthermore, these exposed, unsecured components made the robot unsuitable for formal user testing, as participants might touch them, potentially damaging the robot during the test. To resolve this, the feedback mechanisms for the new robots were integrated directly into the frame of the robots, resulting in a much more cohesive and unified robot design. This shape of the shell of both robots was designed using the same iterative process discussed in chapter 5, while also trying to design a clear front and backside of the robot. Similar to the previous iteration of the robot platform the top part of the frame of the robots were 3D printed using TPU and the bottom part using PETG.

6.5.1 Integrated handle with LED feedback

This version of the robot was designed to prioritize the clarity of how the robot should be manipulated and low-complexity signalling. The chassis features an integrated handle to provide a clear grasping affordance for repositioning, alongside a small red LED indicator used for status communication. This LED lights up to notify the user when the robot has encountered an obstacle and blinks when the robot is in help mode.

figure 22. Robot with handle integrated in frame and small red feedback LED.

6.5.2 Expressive moving handle

This iteration of the robot was designed to improve upon the waving flag feedback device but incorporating feedback from the previous version and allowing for more complex movement patterns for the handle. Following feedback and insights regarding apparent flimsiness of the flag and the ring of the feedback device, the animated handle was designed to feature a significantly thicker, more robustly structure. The darker grey colour of the handle was chosen as this was hypothesized to also give a sturdier appearance. The shape of the handle was inspired by shapes that clearly afforded grabbing like the handle of a coffee cup.

The robot conveys information regarding its navigation state, such as braking or turning to avoid an obstacle, by moving its handle while driving. The handle is rotated using a servo inside the robot's body, which is linked to the handle via a 2:1 gear ratio. This ratio was chosen because the SG90 micro servos being used can only rotate 180 degrees, and a full 360-degree rotation was desired to allow the handle to point in any direction.

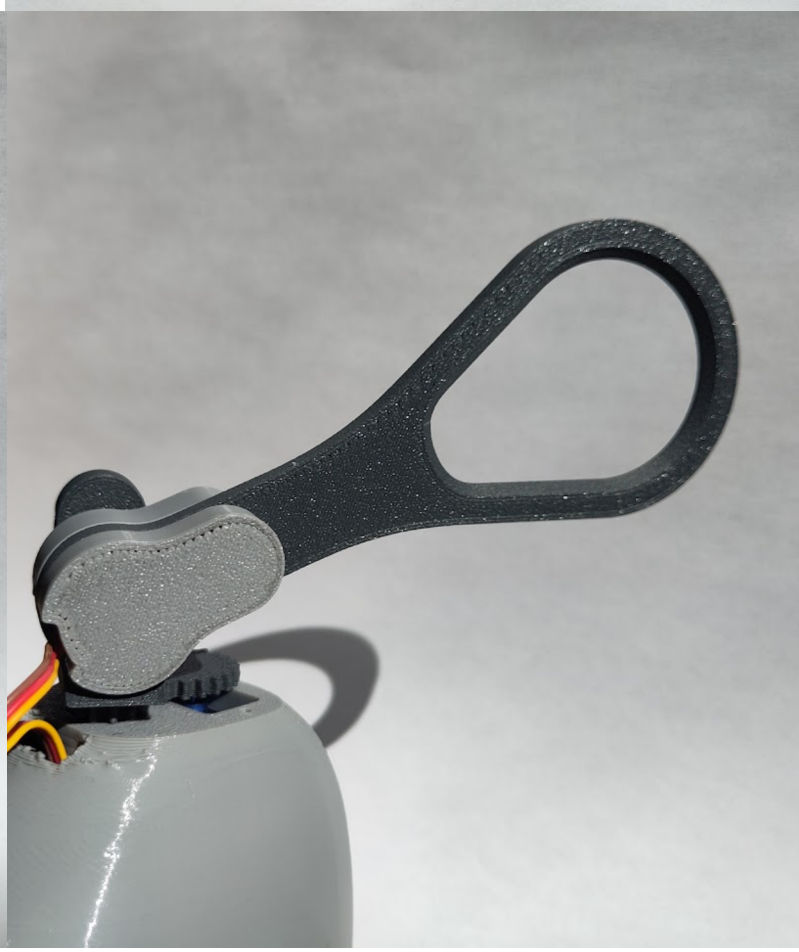


figure 23. Robot with expressive moving handle.

The rotation of the handle during autonomous navigation is described by the following function:

$$\theta_{\text{rotation}} = \left(\frac{PWM_{\text{right}} - PWM_{\text{left}}}{PWM_{\text{base}}} \times 45^\circ\right) + 90^\circ$$

Where θ_{rotation} is the rotation angle, and PWM represents the 8 bit pulse-width modulation values for the motor speed controller.

This function causes the handle to lean into the robot's turns proportionally to the radius of the turn.

The handle's elevation is controlled by a second SG90 micro servo, which is attached to the output gear of the rotation servo using a 3D-printed part (figure 25). The elevation of the handle is described by the following function:

$$\theta_{\text{elevation}} = 90^\circ - \left(\frac{F_y}{PWM_{\text{base}}} \times k_{\text{response}}\right)$$

Where $\theta_{\text{elevation}}$ is the elevation angle, F_y is the 8 bit forward/backward velocity value, and k_{response} is the elevation response strength.

This function causes the handle to tilt backward while the robot drives forward, and forward while the robot is braking, proportionally to how fast the robot is moving or how hard it is breaking. This emulates the movement of a flexible beam attached to the top of the robot, but with greater intensity.

If the robot gets stuck, it repeats a dance-like, figure-eight movement pattern by moving the handle's elevation and rotation sinusoidally to communicate that it needs to be repositioned.

6.6 PRELIMINARY USER TEST

A qualitative study was conducted with the new, small robots to evaluate how participants perceived different help-feedback strategies. The study compared the more complex feedback system of the "expressive moving handle" robot against the less complex "integrated frame handle with LED feedback" robot. To avoid biasing the participants' responses, they were simply instructed to reposition the robot and told they could touch or hold it anywhere, with the sole caution to watch out for the wheels. The primary goal of this study was to gain a general understanding of how users naturally interact with the robots, and to identify any major usability issues before conducting a larger-scale test.

6.6.1 Results

During the user test, distinct differences were observed in how participants interacted with the two robot prototypes. With the moving-handle robot, although participants were able to grab both the body and the handle, (see figure 24) the movement of the handle itself created a barrier to interaction. One participant was notably hesitant to touch it because of its motion, stating, "I did not want to touch the handle because it was moving." However, this participant still used the figure eight, dance-like movement of the handle to verify that the robot needed help.

In contrast, the light-based communication failed to resonate with participants. One participant could not decipher what the LED blinking signified because it occurred both while driving and while the robot was stuck, while the other participant did not notice the LED at all. Despite this, both participants were still able to recognize when the robot needed help by noticing changes in its driving path or by observing that the LED robot simply stopped driving near an obstacle. While the repositioning process itself was successful across both conditions, these observations suggest that the current feedback methods are not as intuitive as hoped and should be further iterated upon.

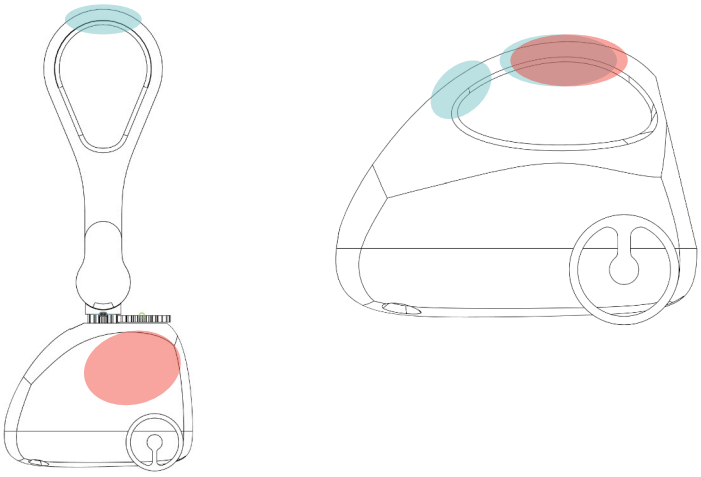
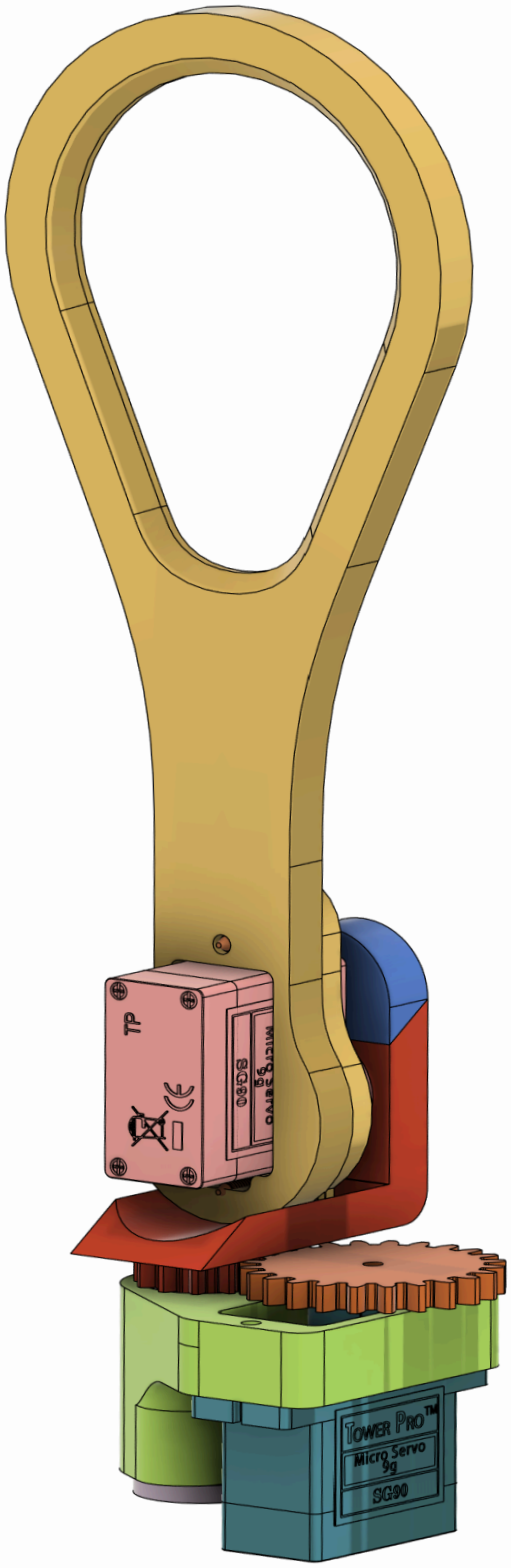
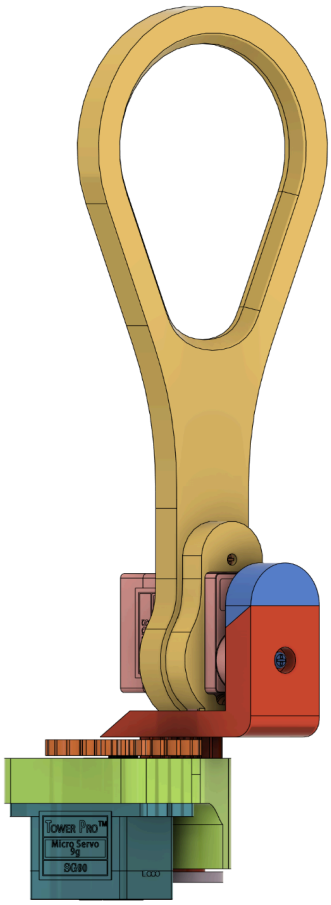


figure 24. Touchpoints robots (P1 red, P2 blue)

6.6.2 Conclusion and design implications

While these preliminary findings require validation through a larger participant pool, they provide some design implications for future iterations of the system. To ensure effective communication of current navigation status, the feedback device must be explicitly tied to the robot's physical behaviour, and clearly visible. Furthermore, the results suggest that the handle should remain stationary for a while to prevent user hesitation and encourage tactile engagement. Future exploration may involve testing non-moving handles with a separate moving flag. In this test the transition from driving to stopping served as the main feedback device participants used to determine if the robot needed help, and they used the added feedback devices of the LED and the moving handle to a lesser degree. This suggests that the current versions of these added feedback devices are not intuitive enough to be easily understood by people in a first use context.





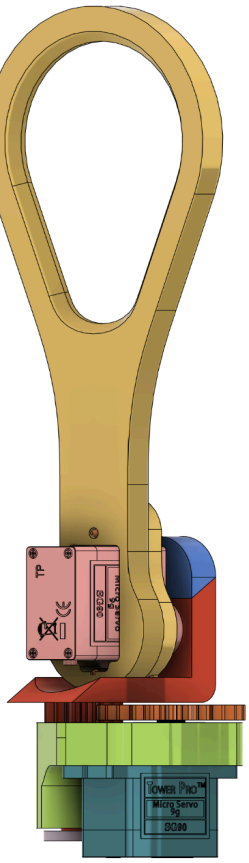


figure 25. Animated handle mechanism without servo covers and the robot.

USER TEST WITH SMALL HELP SEEKING ROBOTS

7 USER TEST WITH SMALL HELP SEEKING ROBOTS

7.1 UPDATES STUDY SETUP FROM FEEDBACK PRELIMINARY USER TEST

Following the preliminary user test, the robots were redesigned based on participant feedback. Several variations and system upgrades were developed for the next phase of testing.

figure 26. Baseline robot without handle or help-seeking feedback.

7.1.1 no feedback baseline version

A baseline version was created to determine if standard robot behaviours alone is sufficient for users. As participants in the preliminary test noted that they often relied on the basic robot behaviour to determine if the robot was stuck instead of looking at the added feedback mechanisms. This baseline version which keeps the robots aesthetics and behaviour the same but removes the added feedback mechanisms allows for a comparison between a baseline robot and the robots with the the additive feedback mechanisms. This model shares the same general shape as the LED version but has a slightly lower profile.

7.1.2 LED strip version

The original single red LED was replaced with four addressable RGBW LEDs covered by a 3D-printed diffuser. This array is mounted directly beneath the handle in the body of the robot. This placement ensures the lights are visible from a distance while logically connecting the "stuck" feedback to the physical point of user interaction.

The LEDs communicate obstacle proximity using a simple colour gradient. The system displays green for a clear path, orange for approaching objects, and solid red when an object is very close. If the robot gets stuck and goes into help mode, the strip blinks red to signal for help. These colours where picked as they commonly signify stop and go or good and bad in western culture. The blinking when stuck pattern was selected to have a distinct switch between normal operation of the robot when just the colours are changing and the pattern of the LED stays the same and stuck mode where the colour stays the same and the animation pattern of the LED changes.

7.1.3 Handle version animation redesign

Additionally, the handle movement while in help mode was redesigned. preliminary user test participants were hesitant to touch the handle when using the original figure-eight like movement pattern. To resolve this, the animation was simplified to a brief backward shake separated by a long pause. This handle movement animation was achieved by elevating the handle to the full backwards position and then quickly rotating it back and forth 45 degrees to emulate a shake like movement, afterwards the handle was moved back up to the 90-degree position. This pattern was repeated every 10 seconds to give participants a clear an easy to anticipate pattern which could allow them to pick the robot up in between the pauses of the handle animation pattern.

7.1.4 Robot state Log and settings system

A few features were added to the teleoperation software to make the testing process more efficient and to allow for more and easier data collection. First, a new data logging system which logs the state of the robot and allows for easy exporting of the data to a csv file, was implemented to better document the robot state during the test. Finally, as it was found that the switching between the different robot configurations was a bit cumbersome, the software now includes configuration templates for each of the

robot configurations. These settings could be easily edited and saved for each of the robot configurations allowing the researcher to quickly switch between different robots during the test.

7.1.5 Sound reduction

Initial pilot testing informed the study design, specifically highlighting the necessity of the participants not being able to hear the sound generated by the wheel motors in the robots, as this could be used as a feedback mechanism to detect when the robot was stuck and we are explicitly not evaluating sound-based feedback mechanisms. Thus, it was decided to try to reduce this motor sound as much as possible. This was first done by replacing the 500RPM version of the wheel motors with a 1500RPM version of the same motor. These motors, with a smaller gear reduction, were deemed to produce less sound from empirical observation, which is logical as a lower gear reduction should produce less sound. In addition to the quieter motors the participants were also asked to wear noise cancelling headphones during the experiment.

7.2 STUDY SETUP

With the robot redesigned using the feedback from the preliminary user test a new study was designed. The primary objective of this study was to generate insights regarding bystander experiences when assisting the three different robot types. The study was conducted in a single room environment and aimed to collect both qualitative and quantitative insights into the effectiveness of the robot's physical interface and the overall quality of the help giving interaction.

7.2.1 Log system

To ensure accurate data collection, a logging system build into the teleoperation software was utilized. The system logged the robot's state and timestamps. The robot could be in one of the following four states: Auto, where the robot was operating normally and not stuck; Stuck, where the robot was very near an object and tried to turn and break aggressively as a last-ditch effort to avoid the obstacle; Help, where the robot had been stuck for a long time and was actively trying to get help from a bystander; and finally, Manual, for when the robot was being teleoperated. Saving these states generated quantitative metrics that could be cross-referenced with the subjective feedback gathered from user questionnaires.

7.2.2 Same environment for all tests

All test sessions were conducted in one consistently configured room. Maintaining a uniform spatial setup minimized external confounding variables, ensuring that any differences in participant behaviours and interaction quality were directly attributable to the robot's specific

figure 27. LED robot version showing LED feedback colour. From top to bottom; no obstacles, some obstacles and stuck state

figure 29. The room the study was conducted in.

interface configurations rather than environmental changes.

7.2.3 Questions and setup

Prior to the arrival of each participant, the researcher completed a standardized preparation checklist. This included verifying camera positioning and storage, testing baseline functionality for all robots, confirming stable network connectivity, ensuring full charge on both the robots and the noise-cancelling headphones, and loading the correct initial robot software configuration.

The experimental procedure began with onboarding, where participants were welcomed and signed an informed consent form. Participants were then seated at a chair in the corner of the room, provided with the noise-cancelling headphones, and instructed to behave as they naturally would if encountering a robot in a public environment.

The order of the 3 robot conditions was randomized using a balanced Latin square for each participant

During the first task, the first robot configuration was deployed to navigate the space until it encountered an obstacle and prompted for help. Researcher observed and documented whether the participant organically attempted to assist. If the participant did not intervene, the researcher verbally informed them that they were permitted to interact with and touch the robot, and this prompt was noted in the observational logs. The task was finished when the robot needed help from the participant around 5 times.

Following this initial task, participants completed a laptop based mixed-methods questionnaire regarding their experience with the first robot configuration. This section measured how easy the robot was to help and how clearly it communicated need for help through two 5-point Likert scale statements: " It was easy for me to provide the help the robot needed" and " it was clear to me when the robot required assistance" It also included open-ended questions asking participants to explain any difficulties they experienced while attempting to help or in understanding when the robot required assistance.

After completing the first questionnaire, the researcher demonstrated the second and third robot configurations to the participant. The participants were asked to fill out the mixed-methods questionnaire for each robot configuration in-between tests.

The session concluded with the second part of the questionnaire. Participants ranked all three robot configurations from easiest to least easy to help and ranked them again based on the clarity of their communication regarding the need for help. For both rankings, participants were asked to provide written explanations justifying their choices.

Observation notes and video recordings were used to record how the participants helped the robots, and where the participants touched the robots.

7.3 RESULTS

9 participants participated in the experiment. Participants were recruited from the TU Delft Industrial Design Engineering faculty. Four of the participants were in the age range of 18-24 and 5 participants were within the age range of 25 to 34. The first participant participated in the pilot test, after the pilot test various element of the experiment were changed and thus the data of this participant is excluded from most of the results.

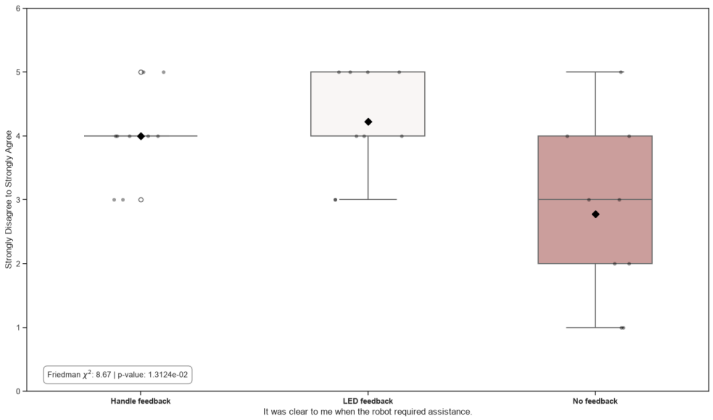


figure 28. Answers to “it was clear to me when the robot required assistance” questions per robot type

7.3.1 Quantitative

7.3.1.1 Likert scale statements

As can be seen in figure 28 participants generally preferred getting feedback if the robot needed helped over not getting feedback. Additionally, it can be seen that the LED feedback method is preferred over the Handle

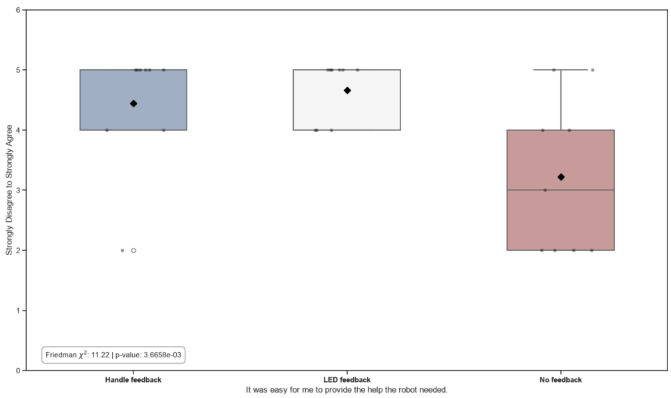


figure 30. Answers to "it was easy for me to provide the help the robot needed" question per robot type

feedback method but not significantly so, while the no feedback condition was significantly more disliked.

Participants thought the robots which had a handle like the moving handle and the LED feedback robots were easier to help compared to the robot which did not have a handle.

7.3.1.2 Log data

The robot state data for each participant can be see in figure 31. All test followed the same pattern of 3 tasks and a break in-between the task for setting up the next robot and filling out the questionnaire. Test 2 has a second break in task 3 as the battery of the robot had to be replaced during the test. During test 8 the robot had an electrical failure and thus a robot component had to be replaced in the breaks between the 2nd and 3th test. From this data it can be clearly seen that because the robots drive around in a semi random pattern and thus get stuck in a semi random pattern, the help mode state is also distributed throughout the test in a semi random pattern.

From the log data it can also be seen that all the stuck states events were short. This can be explained by the fact that the robot will quickly steer away form the obstacle which makes it stuck or go into help mode. The state data (figure 31) also show the many extremely short (under a few seconds in duration) help mode states. As participants can not help the robot is such a short time, this is most likely explained by the robot getting stuck and going into help mode, and then recovering from help mode by itself. This inability to separate these self recoveries from participants helping the robot can be filtered out by excluding auto mode states which take shorter than 4 seconds. As a participant would not have been able to

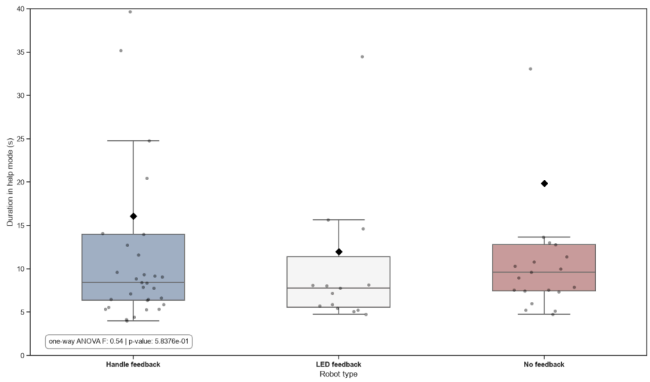


figure 33. How long the robot spends in help mode for each robot type for all tests.

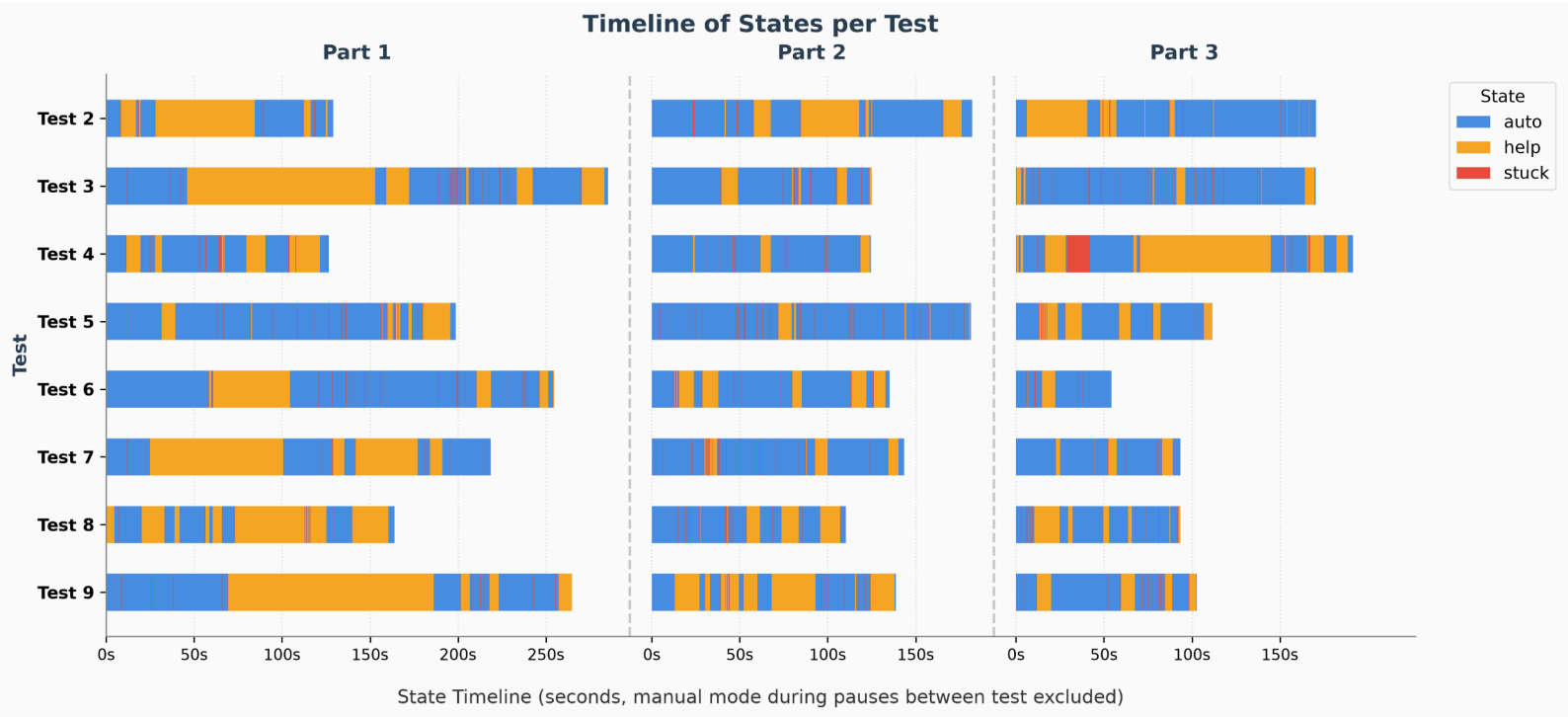


figure 31. Overview of robot states per for each test.

help the robot in such a sort time. The following graphs thus only include help mode states which lasted longer than 4 seconds. Additionally, the amount and distribution of these short duration help mode states should roughly be the same for all robots and thus should not change comparative results.

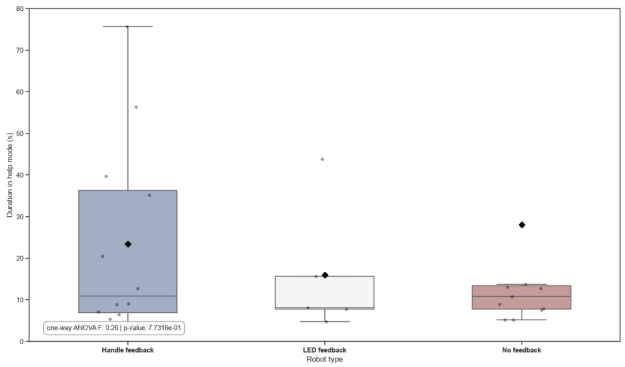


figure 34. How long the robot spend in help mode for each robot type for only the first test.

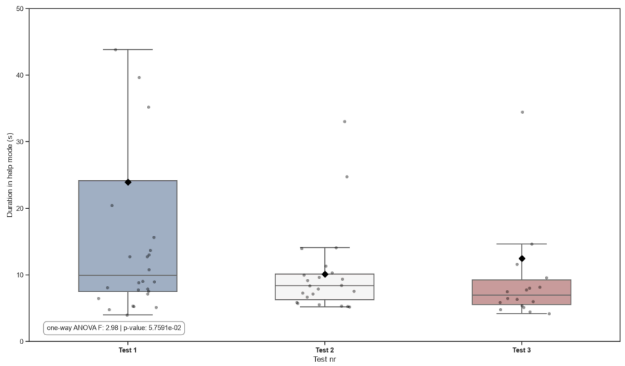


figure 35. How long the robot spend in help mode for the first second and third test.

figure 33 shows that the mean duration the robot spend in help mode during the experiment was the longest for the no feedback baseline version the shortest for the LED feedback version, this difference is however not significant.

figure 34 shows the same order in how long the robot spent in help mode for the first robot the participant interacted with.

figure 35 shows how participants got better at helping the robots when they got more familiar with helping the robots, as the mean time the robots spend in help mode decreased for the second and third test. This deference was however not statistically significant.

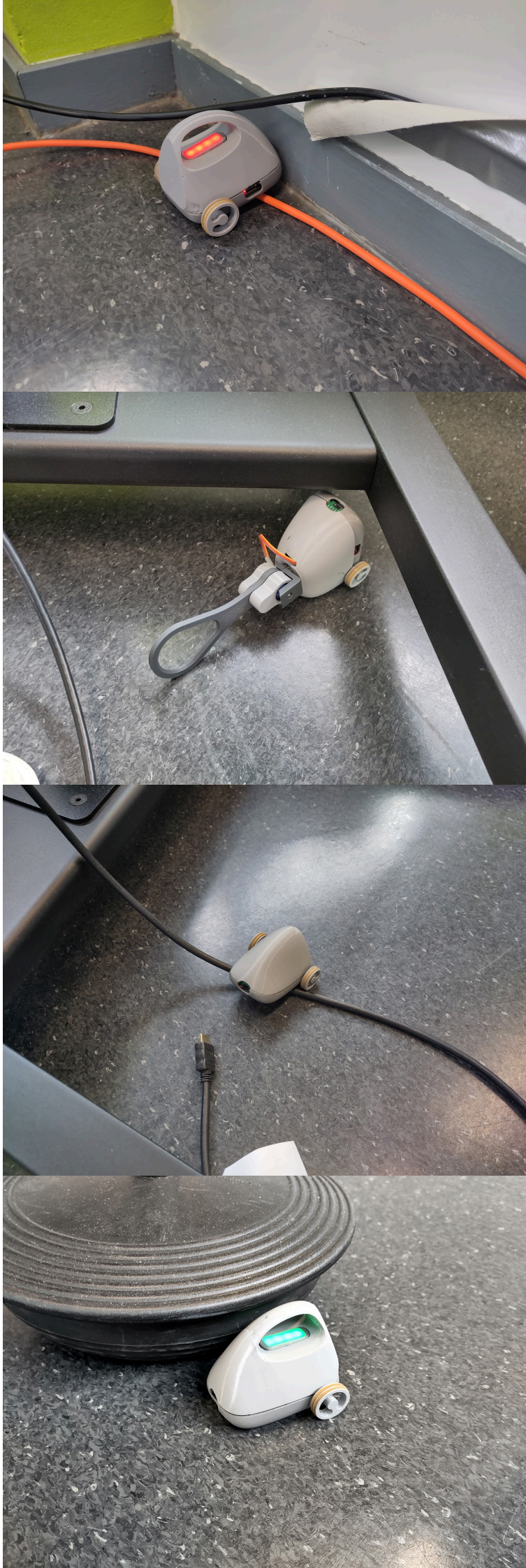


figure 36. Examples of the robots being immobilized by various obstacles.

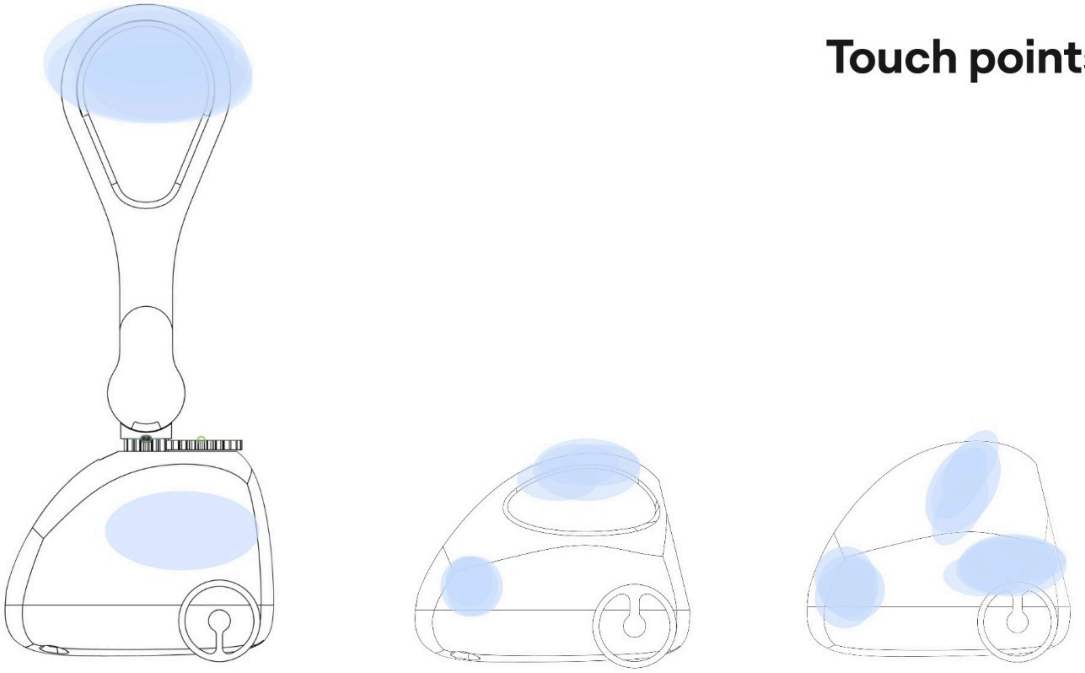


figure 37. Overview of where the different robot versions were touched during the tests.

7.3.1.3 Touch points

From the observations most participants started helping the robots by grabbing the explicit handles in the moving handle and LED robot and gabbing the body of the robot in the baseline version. When the participants started to roughly understand how the robots worked and that they needed to remove the obstacles in front of the robots to help them. They started to use different strategies like giving the robots a small push to rotate them away from an obstacle and moving the obstacles out of the way of the robot. Some participants tried more interesting strategies like kicking the robot and placing the robot on top of tables or chairs to stop them from driving around and thus getting stuck.

7.3.1.4 How many people helped

4 participants did not want to assist the robot unprompted and had to be verbally told they could help the robot. 2 participants asked the researcher if they were allowed to touch the robot and 2 participants assisted the robot unprompted.

7.3.1.5 Which condition did participants prefer

6 Participants found the LED version robot with the static handle integrated into the frame the easiest to help and 2 participants preferred the animated moving handle. No participants preferred the baseline robot.

4 participants said they found that the expressive handle robot communicated that it needed help the clearest. The other 4 participant preferred the LED version.

7.3.2 Qualitative

7.3.2.1 Thematic analysis

A Reflexive thematic analysis (Braun & Clarke, 2006) approach was used to generate themes from the open answers participants gave in the questionnaire. From this analysis the following 4 themes were discovered in the data:

physical affordance and perceived safety

While sturdy handles provide excellent physical affordance, offering intuitive grip points and optimal height for easy lifting, combining them with a robot that could start to move unexpectedly also trigger concerns regarding perceived safety. Users expressed hesitation when grabbing the robot due to a fear that the robot or the handle would start to move unexpectedly during handling. This made the users hesitant to use the animated moving handle robot while they did like the height of this handle compared with the lower handle of the LED robot. Thus, users should be confident that the device they use to reposition a robot is sturdy and at a ergonomical height, and the robot should not behave in and unexpected way while users are operating it.

The following quotes from participants in the study are relevant to this theme:

> *"The handle is pretty and clear hints for holding."*
>
> *"Grabbing a moving part felt a bit difficult, because even though it did stop moving, maybe it would move again? Grabbing it by its body... Felt safer and more secure."*
>
> *"The 3rd robot was a bit difficult because of the moving part, I was a bit more hesitant to grab it because of the big moving object."*
>
> *"The second one have a clear indicator for me for holding the handle... But also felt a bit flimsy."*

signal ambiguity LED feedback

The use of LED light colors and blinking patterns suffers from signal ambiguity, as participants interpreted these visual cues inconsistently. For instance, color changes were often mistaken for power or emotion indicators rather than clear status updates regarding obstacle distance or being stuck. Additionally, participants are not easily able to separate the normal LED color gradient mode used during normal driving and the bilking pattern which signalled the robot is stuck.

The following quotes from participants in the study are relevant to this theme:

> *"It would sometimes be green but slowly move. It also turned red when it bumbed into something... Meaning red isn't a 100% indicator that it needs help."*

> *"I did notice the light bar but I would think it's more like a power indicator or emotion indicator to me."*

> *"The other times it just got stuck on something... I was wondering is it trully get stuck? Because I guess it would figure it out by itself like before, but finally it cannot."*

> *"I also had one moment where it got stuck but the LED was green, here I still intervened."*

psychological barrier to help intervention

The robot's behaviour and aesthetics can create a psychological barrier to intervention. Depending on the participant's affective response, which ranged from empathy to viewing the robot as "needy", users either felt motivated to help or lacked the motivation to intervene when the robot simply stopped moving or appeared stuck as they felt the robot would be able to help itself.

The following quotes from participants in the study are relevant to this theme:

> *At one point it looked like a fish flopping, that was funny and also motivated me to help."*

> *"One time it hit to something strongly makes me feel sad for it."*

> *"I am more empathy for the first robot, I feel sorry for it the most, it's kind of like a lost lonely little creature to me..."*

> *The third also had a shape that suggested that it was sturdy enough to survive on its own. Reminds me a bit of that rock that is shaped like a turtle shell when flipped being able to get back up.*

learning communication through environmental interaction

Participants learn to decode the robot's communication by observing its interaction with the environment and experimenting with the robot and seeing how it responds. By connecting cues in how the robot interacted with the physical world, such as the cessation of movement or obstacles in front of the robot, with the robot's signalling methods, participants eventually develop an understanding of how to interpret the feedback mechanisms the robot uses.

The following quotes from participants in the study are relevant to this theme:

> *"It stopped moving... And one time it started waving."*

> *"It would stand still and not try to move. It would also be red..."*

> *"Red blinking light means stuck I know from watching the*

7.4 DESIGN INSIGHTS

Participants were initially reluctant to assist the robot unprompted, even within the controlled laboratory setting of this study. Only two participants intervened without prior prompting, while half required explicit verbal permission. This suggests that very few participants would be willing to assist the robot unprompted in a non-laboratory setting unless they explicitly received permission to do so.

While participants universally preferred robots with explicit handles over the baseline version without a handle, there was a distinct tension between physical affordance and perceived safety. The animated handle successfully communicated the need for help, however, qualitative feedback revealed that the unexpected movement of the handle induced hesitation and safety concerns. This explains why most participants rated the static-handle LED robot as the easiest to assist.

Although providing feedback was preferred over the no-feedback baseline robot, the modalities themselves presented some interpretative challenges. For example, participants were sometimes confused about what exactly the LED feedback meant. Consequently, participants needed to observe the robot physically getting stuck, experiment with its responses, and mentally map the

environmental context to the feedback signals. As evidenced by the log data, this experiential learning was effective as the time the robot spent in help mode decreased as participants became more familiar with the system.

While the feedback mechanisms altered how participants perceived the quality of the robot interaction as the baseline condition was significantly more disliked, this did not translate into large quantitative gains. The mean duration the robot spent in help mode was longest for the baseline and shortest for the LED version, but this difference lacked statistical significance. This suggests that while feedback is crucial for an improved user experience, it does not necessarily reduce the time it takes for a user to help the robot in a lab setting. The small sample size in this experiment might also explain this lack of statistical significance.

FINAL DESIGN

8 FINAL DESIGN

Using the insight from the user test a new version of a robot driving around in public space designed to be helped was designed. The goal for this iteration was to design a general non function specific mobile robot platform using the rough dimensions of a real public robot which were found in chapter 4. The goal for this iteration was to summarize the findings from the small scale user study into a final design, and to then validate if these insights also applied to a larger scale robot by doing a small-scale qualitative user study, in a more realistic setting.

8.1 IDEATION

After a brainstorming and ideation session, it was decided that, based on insights from the user tests, a public help-seeking robot should have the following features.

From the user tests, it was found that participants generally liked the movement of the animated handle but disliked touching it, as they were afraid of the robot moving during the interaction. Thus, it was decided to add a separate, flag-like device that is free to move with the robot's motion and uses a servo motor to move when the robot is stuck. A separate, static handle will also be added at a higher level for easier operation. Additionally, a switch or other detection method should be implemented to stop the robot from operating when a bystander is helping it, as this will reduce safety concerns.

During the small robot test, participants were often unsure if they were allowed to touch the robot, as it is generally not permitted to handle publicly operating robots or autonomous vehicles. To resolve this, clear text or an icon should be added stating that it is okay to touch the handle.

Finally, an LED bar should be placed around the robot to communicate its internal navigation logic, using one color of light while driving and another while communicating its stuck state. This allows bystanders to gain insight into what the robot perceives as an obstacle, so they can step in and assist if it is about to run into something. Additionally, communicating this internal obstacle-avoidance logic will help people gain a better understanding of what the robot is about to do.

By combining these feedback modalities, a robot can effectively communicate its state and need for assistance across various distances. Transmitting a help-seeking request over a greater distance allows the robot to reach a larger number of bystanders. As a bystanders approaches, they will observe the robot's more detailed communication cues, ultimately leading them to provide assistance. This conceptual model of the robot's help-seeking communication funnel is summarized in figure 38.

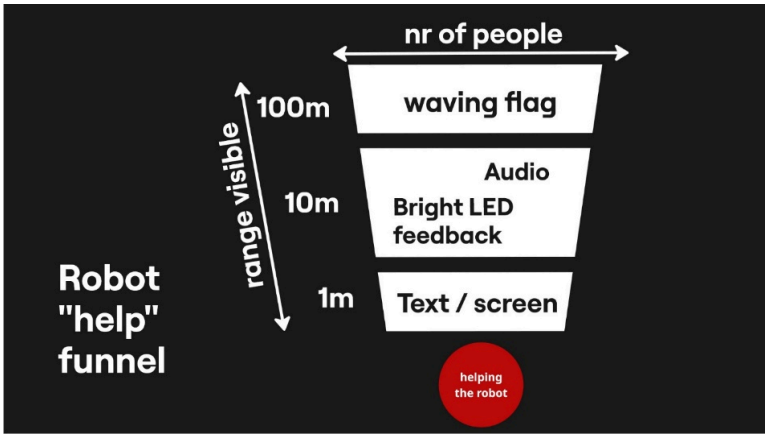


figure 38. Conceptual model of the robots help-seeking communication funnel.

8.2 ROBOT CONFIGURATION

The main goal of the larger-scale robot was to evaluate whether the findings from the small robot platform experiments translated to a scale commonly used in public places. Because the robot needed to remain simple and allow bystanders to help it get unstuck, it was decided to retain the two-wheel differential drive used on the small robot. However, as this robot would be larger and heavier, the low-friction PTFE pad was replaced with swivel wheels. These allow the robot to turn without generating too much noise or friction. Two swivel wheels were chosen to keep the robot stable and prevent it from tipping to one side when bystanders operated it.

The handle of the robot needed to be at an ergonomically appropriate height so people could easily grab it and reposition the robot without physical strain. This was one of the main advantages participants described regarding the animated handle on the small robot in the initial study. The handle was positioned at the back of the robot to allow participants to operate it like a shopping cart. This positioning enabled them to see the robot's pointing direction while pushing it toward a specific destination.

It was decided to place the driven differential wheels at the front of the robot and the swivel wheels at the back. This arrangement allows a bystander to easily maneuver the robot using the handle. The rear swivel wheels permit rotation around the front wheels, providing a large turning moment and thus enabling easy rotation without having to push the robot forward first. This design was believed to make it easier for bystanders to push or pull the robot out of situations where it became stuck.

For the general shape and appearance of the robot, inspiration was taken from standard mobile platforms with a flat top on which other devices or equipment could be mounted. This was done to partially

exclude effects that might be caused by people interacting with a highly specific type of robot, and to demonstrate that the explored feedback mechanisms would also work on more generalized robots.

For the size of the robot, benchmarking research results were utilized. It was found that currently deployed public robots tend to have a length of 55 cm to 80 cm and a width of 40 cm to 65 cm. The lower end of this range was chosen to keep the robot easy to manufacture and transport.

figure 39. Functional model

8.3 FUNCTIONAL MODEL

Using the rough outline of the robot's shape, size, and features, a functional model was built from a scrap wooden plate and small 3D-printed parts. This allowed me to explore the hardware and software necessary to create a convincing prototype.

The functional model used the same software and ToF sensor as the small robot platform. The wheel size was increased to 14 cm to allow the robot to drive over small

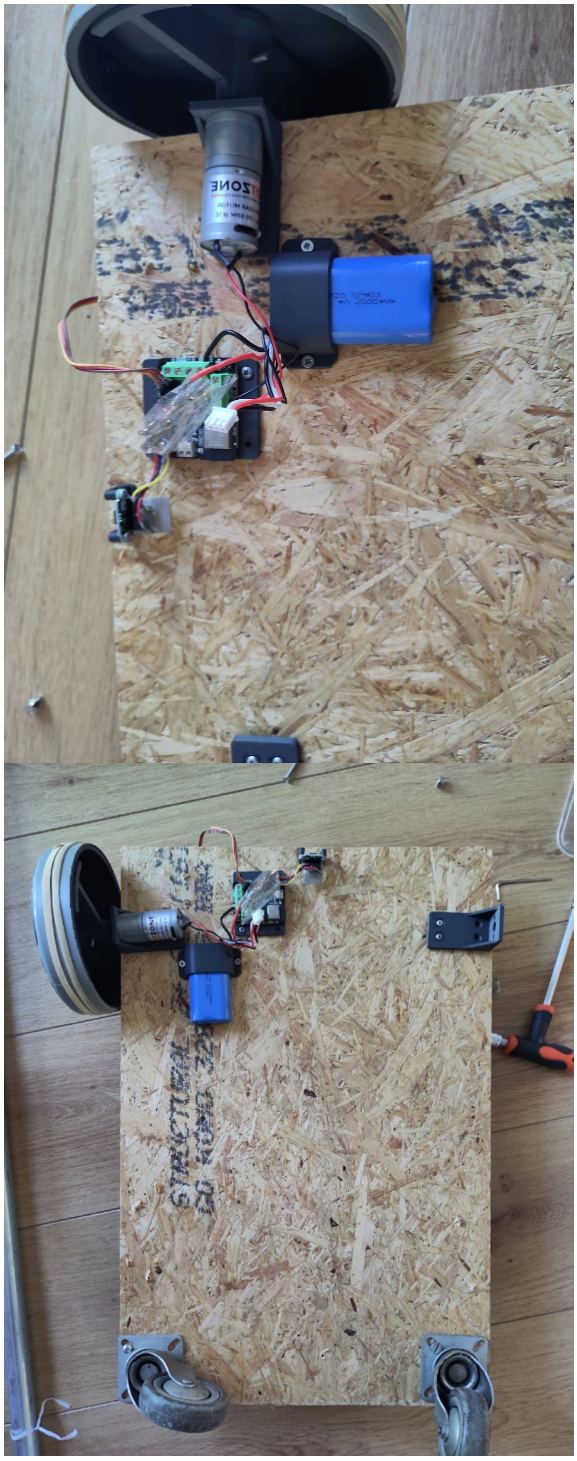


figure 40. Electronics and wheels underside functional model.

bumps typically found on, for example, streets and door frames. The larger wheels required higher-torque motors, so the motors were replaced with larger 124 RPM 12V motors. A larger-capacity LiPo battery was used, as the increased size of this robot allowed for a bigger battery and thus more useful operating time. A 36:9 geared flag rotation mechanism with a small SG90 digital micro-servo was designed to allow the robot to move the small beam attached to the front if it were to get stuck.

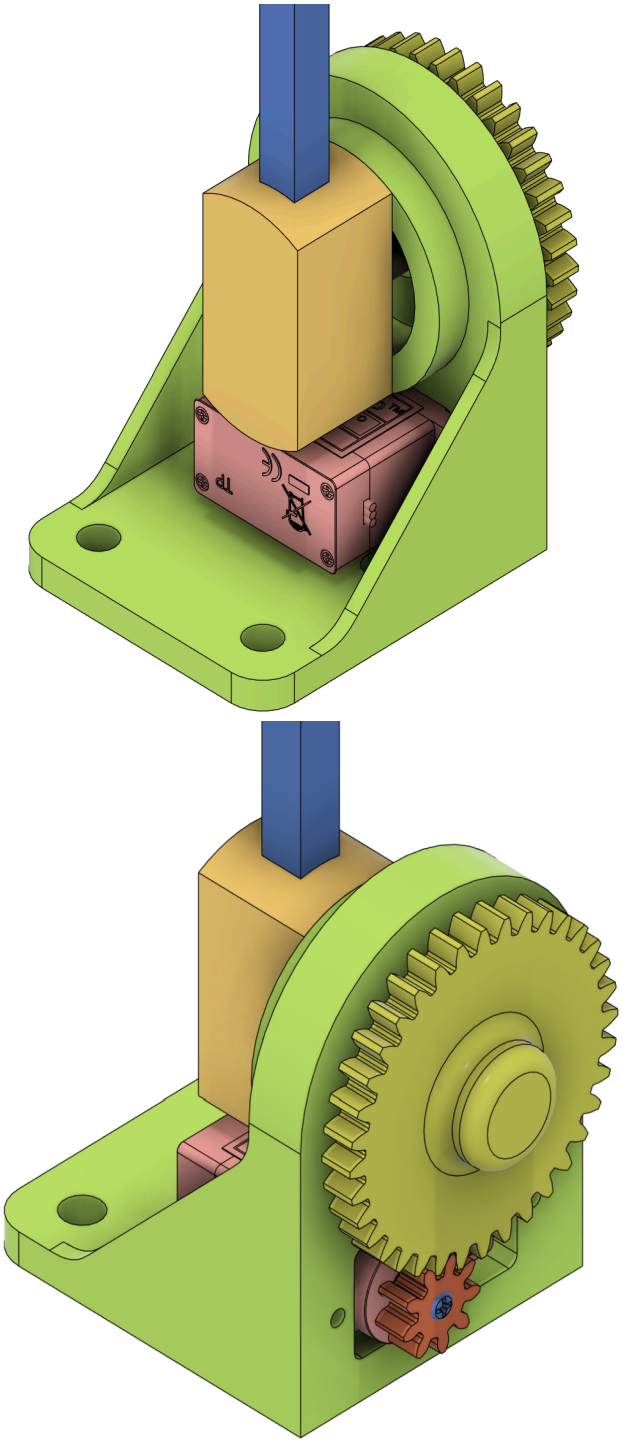


figure 41. CAD drawing of flag rotation mechanism for functional model.

A wooden beam attached to two 50 mm metal tubes was used as a handle. A small 3D-printed plastic plate connected to a microswitch was mounted on top of the beam to function as a switch to stop the robot's operation when it is being operated by a bystander.

The model's ability to easily physically navigate stone pathways in Dutch cities was then tested. This ensured the hardware and software configuration was suitable for a more embodied Wizard of Oz model, which would be used in the final user evaluation, and it allowed us to evaluate if the interaction with the robot and the software worked before designing the final robot for the user evaluation.

8.4 FINAL MODEL

From the evaluation of the functional model, it was found that the general mechanical setup in combination with the motors worked well generally, but the wheels still struggle with some small obstacles. Therefore, it was decided to increase the size of the wheels to 160 mm and add a flexible TPU tire, which would increase grip by deforming a small amount. It was also decided that a size of around 60 cm by 40 cm would be a nice midpoint between feeling like a real robot one could possibly encounter in a public place, while still being easy to manufacture and transport. Additionally, it was found that the handle used was too high to be ergonomic. After some test with different handle heights, a height of 90 cm from the top of the handle to the ground was chosen.

8.4.1 Final model shape

The prototype needed to look and feel realistic, coherent, and physically safe, as an unfinished or prototype-like appearance would create a less realistic scenario during the user evaluation. To define the look of the robot, a brief exploration of its visual aesthetics was conducted. First, based on the general feature requirements, the robot's target shape and size, and the goal of creating a minimal yet professional-looking design, various low-fidelity sketches were created. These sketches were used to explore possible directions for the robot's shape and overall look. An interesting element from these iterations was the idea of echoing the angled line of the handle in the robot's body panels.

After several sketch iterations, 3D renders were created to specify the appearance and colours of the various body parts. Finally, this led to the final design of the robot's body and shape. The final dimensions of the robot were 635 mm in length and 425 mm in width. This final design was used to further refine all components of the robot so they could be manufactured.

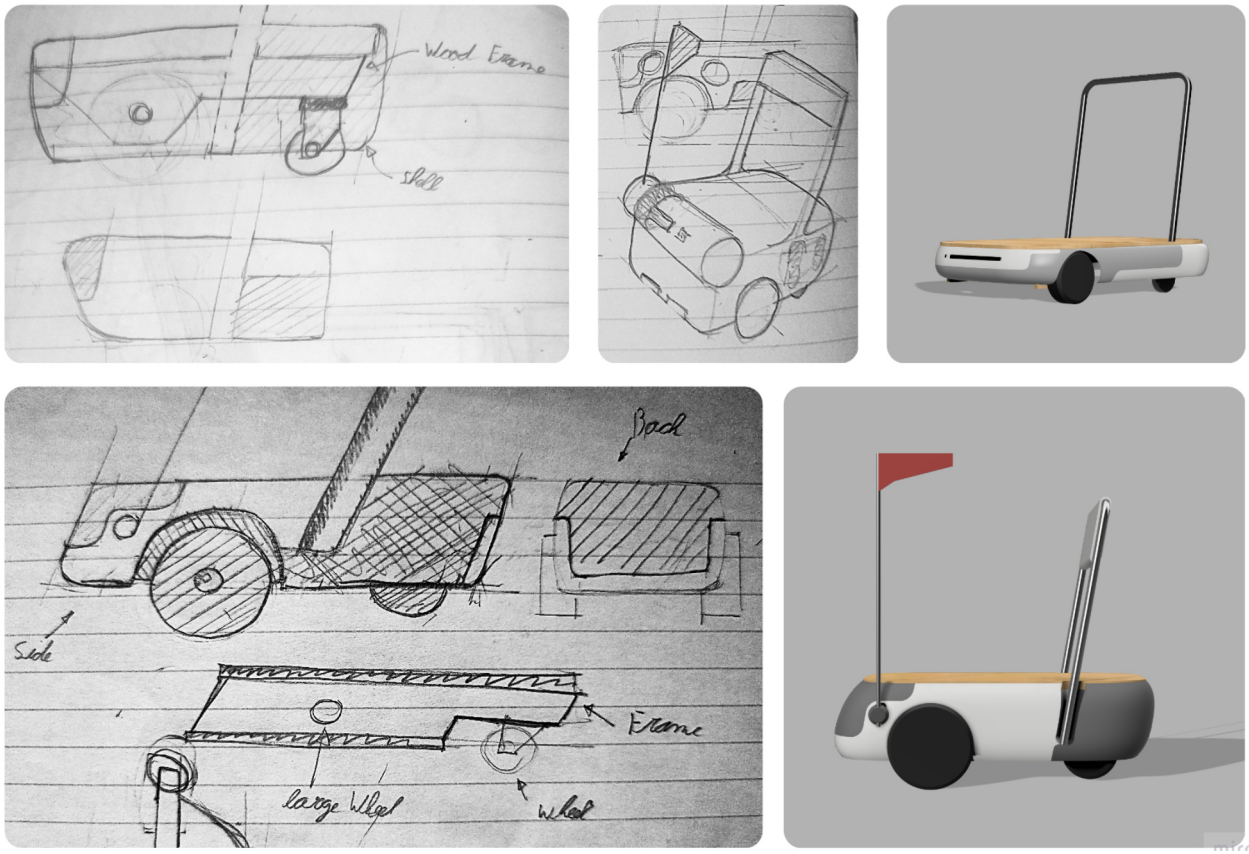


figure 45. Sketches and renders exploring shape and aesthetics of the robot.

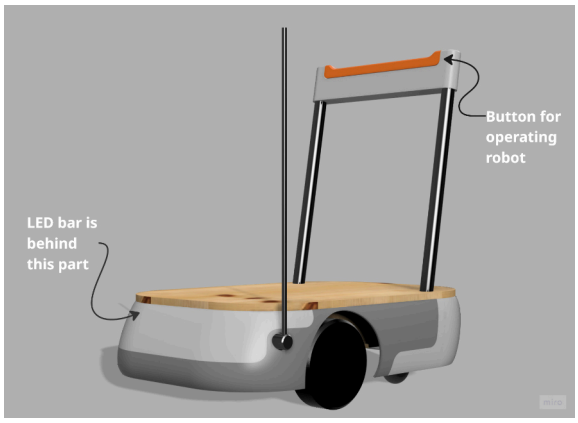


figure 44. Final design of the robot's body and shape.

8.4.2 Mechanical design

The main structural element of the robot consisted of a 12mm-thick, laser-cut, and glued plywood frame. This frame carried all loads from the handle, the mass of the device, and any objects placed on top of the robot down to the wheels. Laser-cut plywood was chosen because this material and manufacturing method allowed for the quick and easy production of large, relatively stiff 2D parts that could then be assembled to form the frame.

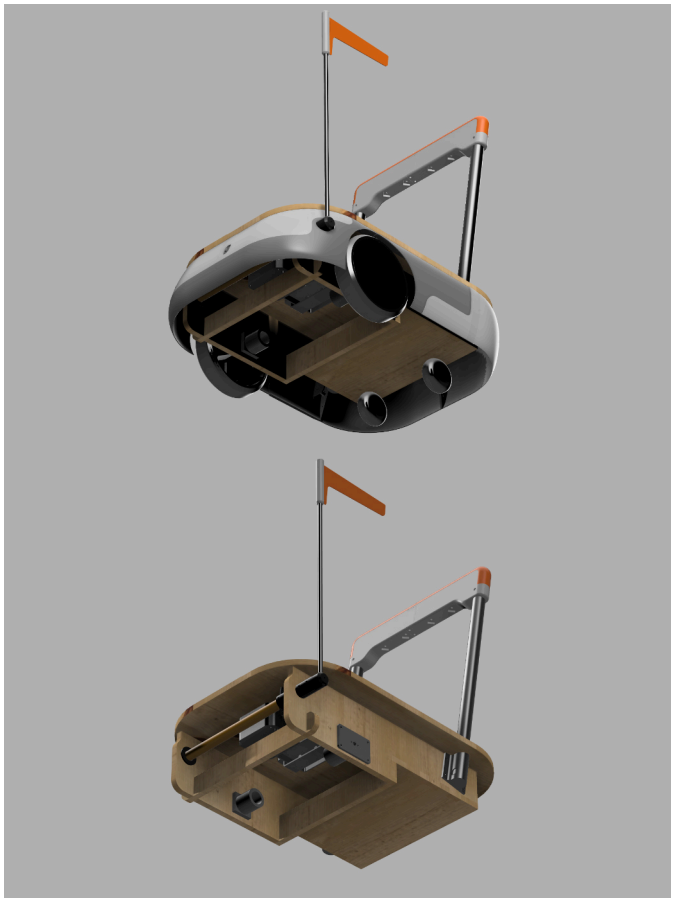


figure 42. CAD model showing Wood frame and 3D printed shell prototype.

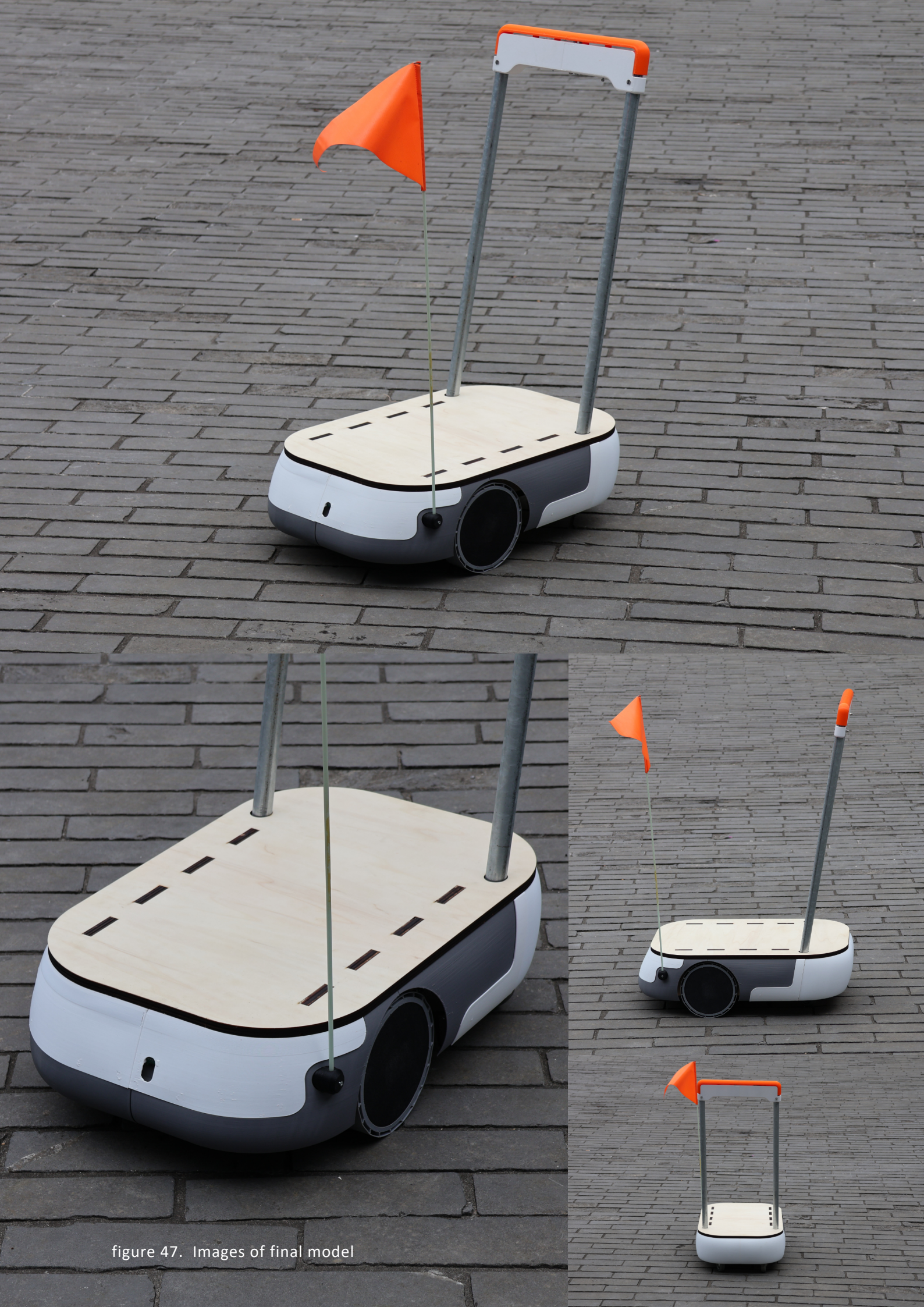


figure 47. Images of final model

Because the outer shell of the robot featured complex curved surfaces, it was decided to 3D-print these parts. The complete outer shell consisted of ten 1.2mm-thick PETG panels, which were bolted together using M3 bolts and screwed onto the plywood frame.

The handle consisted of a 50mm steel tube with a 3D-printed white PETG handlebar featuring an integrated orange button on top. A microswitch, integrated into the

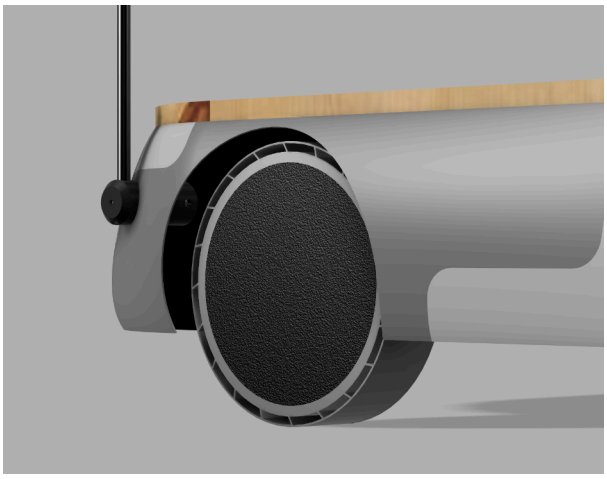


figure 48. Wheel and TPU tire

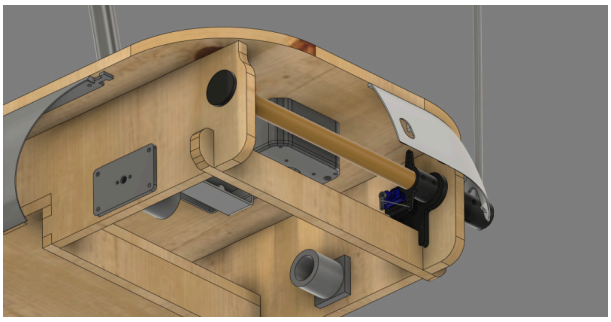


figure 50. Mechanism to actuate the flag

top of the handle, was actuated whenever a bystander pressed the button. This triggered the robot to stop all its motors until the button was released, allowing the bystander to reposition the device without fear of it moving unexpectedly.

The two front wheels were 160mm in diameter and featured TPU tires that deformed to allow the robot to drive over small obstacles. Two swivel caster wheels were attached to the back of the plywood frame.

To actuate the robot's flag, a simple mechanism was designed and built. This mechanism consisted of a tube connected to the flag via a 3D-printed connecting piece. The tube ran through two 3D-printed PETG bushings within the robot's frame. A 3D-printed plug glued to one end of the tube, along with the flag's connecting piece on the other end, prevented the tube from sliding out of the frame. A small linkage connected the tube to an SG90 servo, allowing the flag to rotate back and forth by 45 degrees. The flag moved in a slow sinusoidal pattern with a period of 1.6 seconds whenever the robot was actively seeking assistance.

An addressable WS2813 RGBW LED strip was glued to the front of the 3D-printed shell, with a 1.2mm-thick white PETG cover plate placed in front of the LEDs. A 0.6mm cutout was made in the white front cover to function as a diffuser for the LED strip. This LED strip blinked red if the robot was stuck and needed help, or it displayed a white light indicating where the VL53L5CX time-of-flight sensor detected obstacles. The LED strip was divided into eight segments corresponding to the eight columns of the time-of-flight sensor; each detection was then displayed on its respective segment. The intensity of the white light was linearly mapped to the detection distance (with a minimum range of 2mm and a maximum range of 3000mm corresponding to the highest and lowest brightness levels, respectively). Thus, a close detection corresponded to a bright white light, while a distant detection resulted in a dimmer light.

8.4.3 Electronics

Almost the same electronics as in the small robot prototype were used, except for the addition of the actuator for the flag, the LED bar, and the switch in the handle. This allowed for minimal alteration of the control software and minimal time spent designing the electronics of the new prototype.

8.4.3.1 Part list

PART FUNCTION	PART NAME	NR
MAIN CONTROL BOARD	ROMEO MINI ESP32-C3 ROBOT CONTROL BOARD (INTEGRATED MOTOR & SERVO DRIVER)	1
MOTOR WHEELS	2-WHEEL DIFFERENTIAL DRIVE WITH 124 RPM 12V MOTORS	2 (ONE FOR EACH WHEEL)
BATTERY	18650 BATTERY 2S	1
MULTIZONE DISTANCE SENSOR	VL53L5CX	1
RGBW LED INDICATOR	WS2813 RGBW LED STRIP - 144 LEDS 1M	1 (73 LEDS LONG)
ACTUATOR FLAG	SG90 DIGITAL MINI SERVO	1
SWITCH HANDLE	microswitch	1

figure 51. LED bar in stuck mode (top) and showing a detected obstacle (bottom).

8.4.3.2 *Schematics (pins in the same row are connected)*

VL53L5CX	MAIN CONTROL BOARD	MOTOR RIGHT	MOTOR LEFT	BATTERY	WS2813 RGBW	TS90D MINI SERVO
	5V				+	+
VIN	3V3					
GND	GND				-	-
SCL	SCL (9)					
SDA	SDA (8)					
	M1 +	-				
	M1 -	+				
	M2 +		-			
	M2 -		+			
	VIN +			+		
	VIN -			-		
	21				DATA IN	
	19					PWM

To make sure a foreign object could not accidentally touch the control board, a PETG enclosure was designed in which all electrical connections were made. To ensure sufficient airflow in the enclosure for the cooling of the components, a small fan was added. For safety and ease of use, a switch was placed on top of the enclosure that physically disconnects the battery from the robot. Finally, to securely hold the battery in the robot, a PETG battery holder was also included and screwed to the plywood frame.

8.4.4 Software

As the hardware of the small robot platform and the final prototype were very similar, almost no changes had to be made to the code running on the platform itself or to the web platform used to control the robot. However, some small changes were made. The web interface was changed to a new white, grey, and orange colour scheme to make it visually distinct from the previous version. The method of quickly switching between robot settings configurations was removed, as this is not necessary if there is only one robot configuration. Additionally, a visualization of the LED

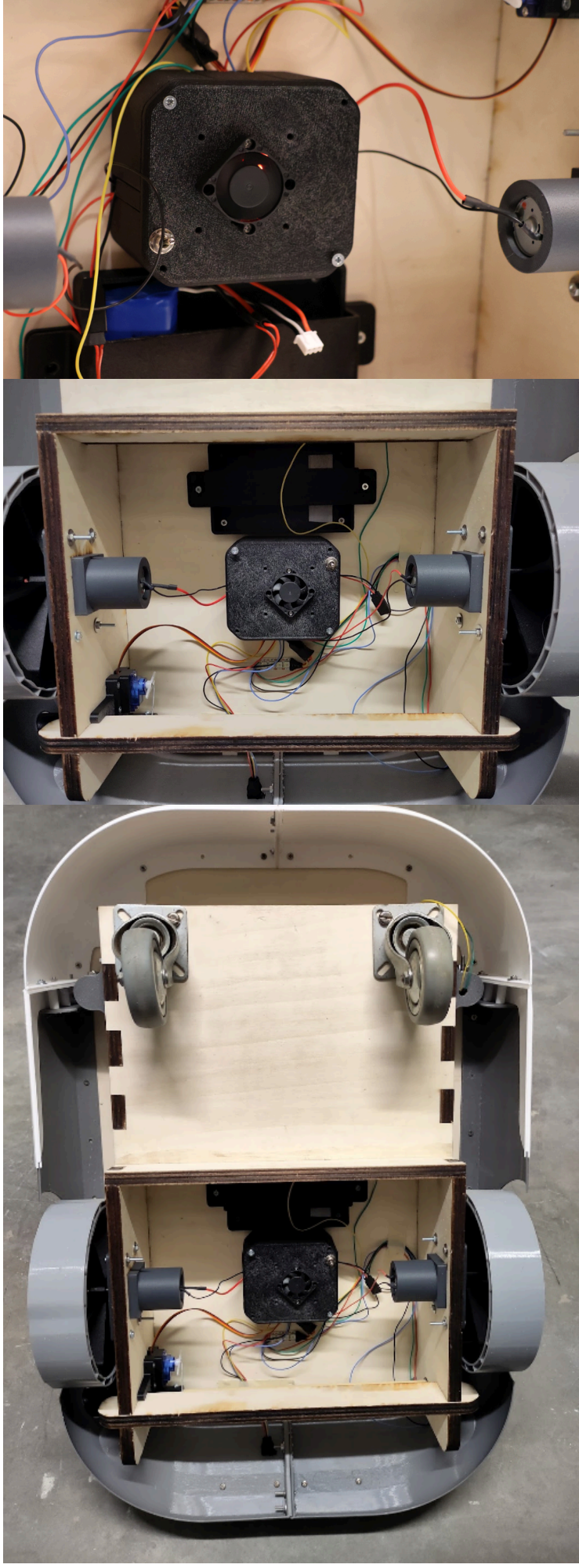


figure 52. Electronics housing positioned on the underside of the prototype.

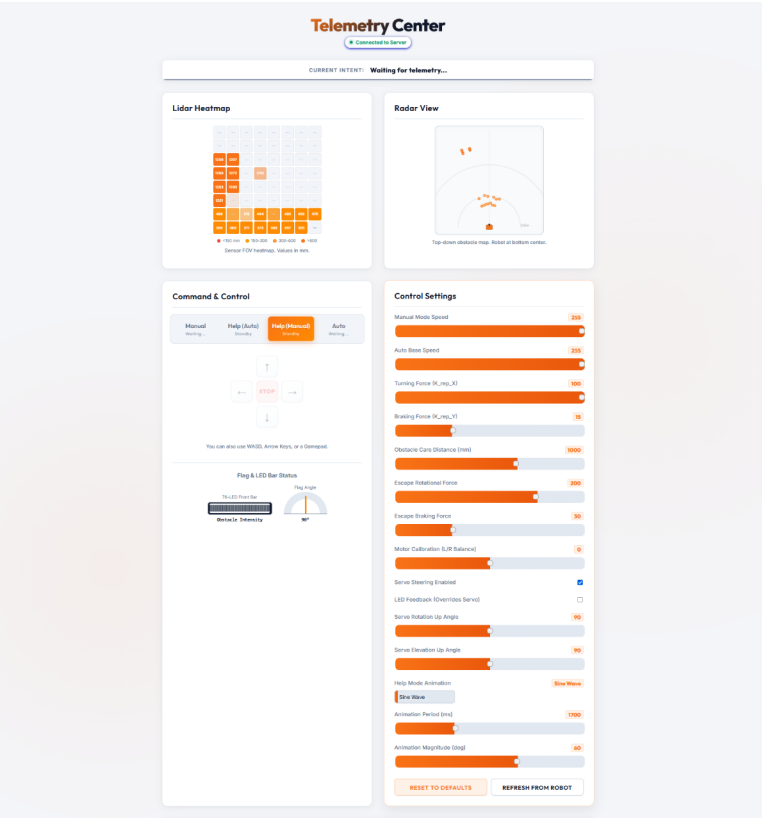


figure 53. White, grey and orange colour scheme for the web interface.

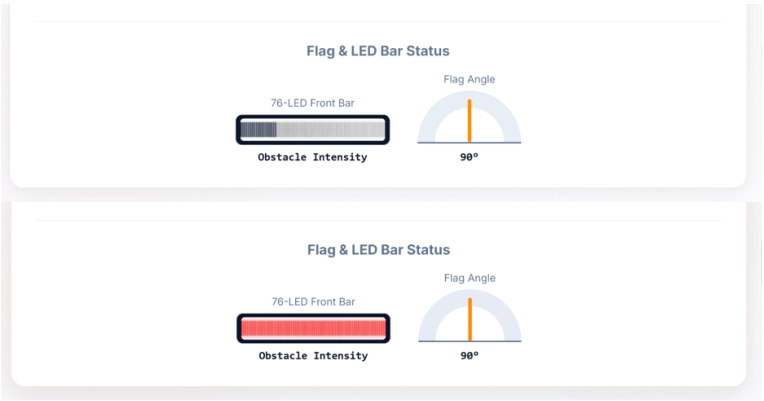


figure 54. Visualisation of the LED bar in the web interface showing a detected obstacle (top) and the help mode (bottom).

strip was created to quickly debug potential problems with the LED visualisation.

8.5 USER VALIDATION

To evaluate how the robot, which was designed using insights from the previous study lab study, would perform in a semi-realistic scenario with unaware bystanders, a user study was conducted. The primary goals were to explore the effectiveness of the handle and help-seeking feedback mechanisms in prompting assistance, as well as to gain insight into how many people are willing to help robots in public spaces.

The study took place in the main hall of the Industrial Design Engineering building at Delft University of Technology. This high-traffic area serves as a primary walkway, ensuring a steady flow of passersby. Because the study was conducted during a holiday, overall foot traffic was lower than usual, and most passersby were university staff rather than students.

The robot was set up to simulate getting stuck near a pipe integrated into a beam (see figure 55). First, the robot was teleoperated around the pipe area where the incident would occur. It then staged a "getting stuck" scenario by driving onto the pipe obstacle. Once immobilized, the robot activated its help-seeking mode, waving its flag and flashing the red LED bar on its front.

While the robot was in help-seeking mode, the researcher counted nearby passersby who did not offer help. Researchers also recorded group passings, including group size, as well as the number of individuals and groups

figure 55. Robot stuck on pipe in the setting of the study.

assisting the robot. Beyond quantitative data, qualitative observations regarding bystander behaviour were also noted down.

When a bystander assisted the robot, releasing the help button on the handle switched the robot from help mode back to standard teleoperation mode. This allowed the researcher to drive the robot away from the pipe and resume its simulated delivery task. The helper was then invited to participate in a brief (maximum 5 minutes) semi-structured interview, signing a consent form beforehand.

During the semi-structured interview, participants were asked why they specifically helped the robot, which feedback mechanisms influenced their decision, and the sequence of what they observed and how it drove their actions. They were also asked how they assisted the robot, what signals guided their specific actions, and their location relative to the robot when they first noticed it. The researcher transcribed responses manually, as this was faster and posed fewer ethical hurdles when surveying public bystanders.

The study was conducted across four 30-minute sessions separated by three 30-minute breaks. These intervals allowed time to recharge the robot's battery, troubleshoot technical issues, and rest. Spreading sessions across different times of the workday (e.g., before, during, and after lunch) helped mitigate possible time-of-day bias. Because assisting the robot, resuming the driving task, and conducting interviews temporarily paused the experiment, higher assistance rates proportionally reduced the active observation time within a given session.

8.6 RESULTS

The four half hour time slots in the study were the following:

TIME	12:00~12:30	13:00~13:30	14:00~14:30	15:03~15:33
SLOT	1	2	3	4

They will be called slot 1 to 4 in the rest of the text.

8.6.1 Quantitative

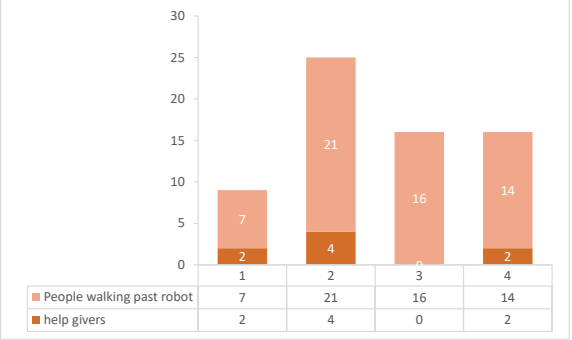


figure 56. Number of people walking past the robot and number of people helping the robot.

A total of 66 people (with groups counted by individual headcount) walked past the stuck robot. Depending on whether the nummer of people assisting the robot is measured by adding all group members together if a group helped the robot or by individual helping acts (which counts one group helping the robot as one), the resulting helping rate is between 12% to 21%. As shown in figure 56, no one helped the robot during timeslot 3, whereas 8 people assisted in timeslot 2. Foot traffic past the robot also fluctuated across timeslots due to routine office activities. For instance, timeslot 2 coincided with typical lunch break hours in the Netherlands, when employees left their offices to purchase food, accounting for the higher traffic.

8.6.2 Qualitative

8.6.2.1 Observations

Observations revealed various behaviours among pedestrians walking past the robot, which were broadly categorized into helping and non-helping responses.

Non-helping individuals were frequently observed looking directly at the robot. When in groups, they sometimes discussed the robot and questioned its purpose before continuing along their original path without altering their course. These individuals appeared to make an active decision not to assist based on their available time. Other non-helpers were visibly absorbed in primary tasks, such as conversing with colleagues or speaking on the phone, and appeared completely unaware of the robot's presence.

Generally, people who helped the robot initially behaved similarly to non-helpers, by looking at it or discussing the robot in groups. However, once they decided to help, they adjusted their walking path, observed the robot to understand what it expected, and assisted it.

interestingly, two individuals actively searched for the operator to determine whether the robot was autonomous or teleoperated, with one participant asking the researcher for permission to assist the robot upon locating them. Additionally, one bystander documented the interaction on their phone while assisting the robot.

8.6.2.2 Interviews

Six out of eight people wanted to participate in a semi-structured interview about the robot. If the robot was helped by a group of people, the specific individual in the group who moved the robot was interviewed.

When asked why they helped the robot, all participants stated they noticed that the robot was stuck. When asked how they noticed this, 4 out of 6 participants stated they first noticed the flag, 1 person said they noticed the handle and wanted to see what the robot was doing, and 1 person first noticed the text. The distances from which the robot was first observed varied quite widely, with 4 out of 6 participants stating they saw the robot at a

distance between 1 and 5 meters, and 2 participants noticing the robot's flag from about 20 meters.

The red blinking LED was less noticed, with only two participants mentioning that they used this feedback mechanism to decide if the robot was stuck when they got close to it. All participants said that they then read the text attached to the sides of the robot before they repositioned it using the handle. All participants correctly used the handle by first clicking the button and then repositioning the robot. However, only 2 participants explicitly mentioned that they noticed they were pressing a button which would then stop the flag waving of the robot, even though this was explicitly written on the handle. This text on the handle was clearly less noticed, as only 2 participants stated they noticed it.

Other interesting insights included two participants who were really interested in trying to find out what the function of the robot was. And one participant mentioning that they wanted to help the robot as it seemed nobody was around to help it.

DISCUSSION

9 DISCUSSION

9.1 HELP RATE ROBOT

The study involving the large-scale robot engaged a significantly high number of willing helpers over a relatively short period. In comparison, other studies investigating robot assistance in public areas, such as Yu et al. (2025), recruited only 8 participants during a 3.5-hour study on a street averaging 7.5 bystanders per minute. This corresponds to approximately 1575 total bystanders ($3.5 \times 60 \times 7.5 = 1575$), yielding a response rate of roughly 0.50%. Because Yu et al. conducted their study in front of a university faculty building, the bystander demographics should be comparable. This disparity could be explained by their robot providing significantly less obvious feedback when requiring assistance, as well as other differences in robot design and help-seeking methods. However, as one participant noted, the difference might also stem from a weaker bystander effect in less crowded areas such as the location used in this study, making people more inclined to assist the stranded robot.

9.2 SUCCESS OF FLAG FEEDBACK

Four out of six participants in the study said they first noticed the moving flag before they decided to further interact with the robot. It could thus be concluded that this moving flag, in combination with the text on the robot, was the most successful mechanism in getting people to help the robot. This finding interestingly goes in opposition to earlier findings (Weiss et al., 2015; Yu et al., 2025) with help-seeking robots, where it was found that expressive appendages did not significantly help in convincing participants to help a robot. This could be explained by our robot having a large-scale and more prominently visible moving flag, or an animated appendage might only work well as the initial attention-grabbing mechanism; afterward, bystanders start to look for other cues that a robot needs help, like for example text, lights, or a clear mechanism to help a robot, and only engage with a robot if the combination of feedback and help mechanisms seems logical.

9.3 INTERFACE FOR HARD TO MOVE ROBOTS

From the small robot study, it was found that participants liked to have sturdy and clear mechanisms to move the robot, and they felt less safe if the robot moved when they were trying to help it. In the final robot study, these insights were used to design a clearly labelled, ergonomically positioned and visibly sturdy handle which would stop all movement of the robot when used and allowed bystanders to easily reposition and move the robot. A problem with such a handle interface is that it relies on the ability of the bystander to physically reposition the robot when it is stuck. This might be okay for small-scale and low-mass robots, but if the robot becomes hard to physically move because it is severely stuck or very heavy, other mechanisms of repositioning the robot need to be considered. Possible options are using the inputs of participants to actuate the robot's motor if they push the input handle in a specific manner to make it easy to reposition heavy robots. This method would directly clash with the finding that participants do not like it if the robot moves unexpectedly, so it needs to be clear to bystanders that the motors of the robot will move when they are trying to help it. Different types of handles, which would for example use the feet of bystanders to reposition the robot, might also be useful by allowing participants to apply more force on a stuck robot.

9.4 CONTEXT

Both the study with the small-scale robot and the study with the larger-scale robot were done in the Industrial Design Engineering building. It might be assumed that people walking around a technical university have a deeper understanding of robots and technology in general, which might make them more willing to interact with and assist robots when they encounter them. This might mean the number of people willing to help robots is larger in these settings compared to other places or communities. Thus, it is important to also validate these types of robots in many different settings, places, and contexts to make sure results translate to other contexts without creating any undue problems.

9.5 AMBIGUOUS ROBOT FUNCTION

The robot used in the final study was designed to be a multifunctional mobile robotic platform that could be used to build robots with a variety of functions. In the test, a cardboard box was placed on top of the robot to simulate a delivery task. Many robots currently used in public spaces are designed for a specific purpose and feature visual characteristics that imply their function—such as an enclosure on top for a delivery robot. While a large built-in container might not intimidate participants, other functional attachments (such as an inspection camera, a robotic arm, or a large-scale measurement device) might make bystanders less willing to help because they are unsure if it is safe to do so. It may therefore be necessary to evaluate whether bystanders are less willing to help a robot based on its type and attached hardware.

9.6 FUTURE WORK

Due to time constraints, most of the experiments in this thesis were done with a relatively small number of people. The validation with the three different small robots, for example, did not get significant results for many of the quantitative measurements, which might be caused by the fact that only 9 people participated and thus a relatively low amount of quantitative measurements was available to do statistical analysis with. Redoing this study with a larger number of people might create stronger quantitative results to provide better argumentation on which robot was best at getting people to help it.

The study involving the large-scale robot was conducted using a teleoperated Wizard of Oz approach. To evaluate the concept of a robot that relies on bystanders when encountering problems, it would be viable to integrate the help-seeking methods explored in this project into an autonomous robot assigned to a genuine task. Observing the robot perform this task with bystander assistance would help identify issues that only emerge once people become accustomed to its presence over a longer duration. Additionally, conducting a pilot study with multiple robots carrying out real tasks in a designated area could clarify whether these methods scale effectively across a fleet of robots or if bystanders eventually experience help fatigue. Because most of the proposed interventions are relatively straightforward to implement at scale, future work could deploy them on real-world systems, such as a delivery fleet, to evaluate their efficacy in everyday environments.

CONCLUSION

10 CONCLUSION

This thesis explores various help-seeking methods in collaboration with interfaces to actually help a non-humanoid public robot. This was first done by exploring literature for various methods of communicating the need for help by robots, followed by a benchmark of the shape and size of currently used public robots and a review of the ways publicly navigating robots get stuck. From this review, it was decided to focus the exploration on robots getting stuck or lost and needing bystanders to help them, and to avoid auditory methods as they were already commonly explored and might have drawbacks in a real-world public scenario.

Next, a small robot platform was designed and built to allow the researcher to easily explore various methods of communicating the need for help and affordances for how people could actually help robots that get stuck. Using this small robotics platform, various methods for help seeking were explored and finally refined into two new robots, which were then tested in a user study. This study informed the design of two new versions of the robot which, together with a baseline robot that did not communicate its need for help, were used in a larger-scale user study. This study provided clear evidence that giving feedback to the user if a robot needs help makes them more sure of when and how to help a robot if it gets stuck, while also providing insights into which specific feedback and interaction methods work well for help-seeking robots.

Using the results and mechanisms discovered during the exploration with the small help-seeking robot platform, a new robotic platform more similar to real public robots was designed and built. This large-scale robot platform used a clearly visible and easy-to-use handle with a switch that allowed bystanders to easily take control of the robot. It also used a signal flag that would wave if the robot got stuck, an LED bar on the front displaying obstacles it detected using white light and a red blinking pattern if the robot was stuck, and text to assure people that it was okay to touch and operate the robot. It was hypothesized that this combination of feedback mechanisms and interaction affordances would draw users in and ultimately help the robot if it were to get stuck.

This robot platform was then evaluated with users in a two-hour test in a realistic environment with a teleoperated robot, where it was found that around 18 percent of bystanders were willing to help the robot. Most participants were drawn in by the waving flag from a variety of distances and used the text to understand that they were allowed to help the robot. All participants were able to do so using the handle.

These results show that the explored methods of help seeking and help-giving devices could be valuable additions to future public robots with various tasks. These methods and insights could thus be used by public robot designers and organizations which want to make their robots more independent without increasing the mechanical or configuration complexity of the robot.

11

ACKNOWLEDGEMENTS

Artificial Intelligence (AI), specifically Large Language Models (LLMs), was used to improve text clarity by correcting spelling and grammar. The content and meaning of the text were not altered and remain purely the responsibility of the author. Additionally, various AI coding agents were used to assist with the development of the programs created for this thesis.

I would like to thank my supervisor, Jordan, and mentor, Dave, for all their feedback, guidance, and ideas during this project. I am also grateful to the robotics team at Alliander for welcoming my visit and answering my many questions. Finally, I would like to thank my parents and friends for their emotional and practical support, which was invaluable in helping me complete this project.

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13 APPENDIX A PRELIMINARY STUDY PROTOCOL

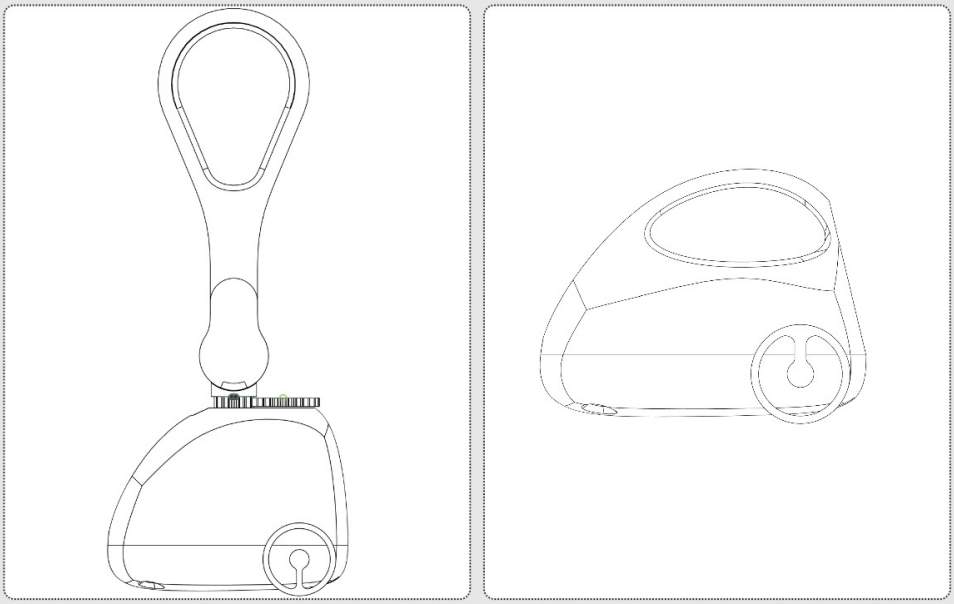
protocol

participant Instruction:
This is a robot it will drive around and sometimes the robot will need your help. You can touch the robot anywhere and pick it up and reposition it. The motors on the robot should not be able to hurt you but do not try to touch the wheels while they are rotating.

study protocol

- Interact with robot for around 5 minutes
- Researcher will write down notes about where user is grabbing robot, what is user looking at, how quickly does user respond to robot.

Repeat experiment with second robot



Put dot on where participant touches the robot to reposition it.

What is participant looking at? how quickly does participant respond to robot? any other observations?

semi structured interview

General impressions:

Did you find it clear when the robot needed help:

Where you able to easily help the robot:

14 APPENDIX B STUDY WITH SMALL ROBOTIC PLATFORM PROTOCOL

User Testing Protocol: Robot Assistance Interface

Study Overview

This study evaluates a physical interface designed to enable bystanders to assist a large-scale robot. Sessions will involve 5–15 participants. During the test, the robot will navigate a simulated public space, encounter an obstacle (get stuck or lost), and prompt the participant for help. Data is collected via video recording for retrospective analysis, followed by a mixed-methods questionnaire to gather quantitative metrics and qualitative feedback on the interface's efficacy.

Pre-Test Setup

Prior to the arrival of each participant, ensure the following checklist is completed:

- **Recording:** Verify camera positioning, storage, and operation.
- **Hardware:** Test all robots for baseline functionality.
- **Connectivity:** Check and confirm a stable network connection.
- **Power:** Verify that both the robots and the noise-canceling headphones are fully charged.
- **Software:** Load the correct initial robot configuration.

Test Procedure

1. Onboarding and Consent

- Welcome the participant and have them review and sign the informed consent form.

2. Participant Briefing

- Seat the participant at the testing table and provide them with the noise-canceling headphones.
- Explain the scenario: Instruct the participant to imagine they are in a public environment and ask them to behave as naturally as they would if they encountered a robot in the real world.

3. Task Execution (Configuration 1)

- Initiate the robot's movement and let it drive until it simulates getting stuck or lost.
- **Observation:** Silently observe and document whether the participant attempts to help the robot organically.

- **Intervention:** If the participant does not assist, verbally inform them that they are allowed to interact with, touch, and help the robot. **Note this down**

4. Post-Task Feedback

- Have the participant complete the mixed-methods questionnaire regarding their experience with the first robot configuration.

5. Demonstrate robot 2 and 3 to the participant

- Let the participant take part two of the mixed-methods questionnaire.

Questions part 1

5 liker scale questions:

I found it easy to help the robot.

I understood when the robot needed help.

Open questions:

Explain what difficulties you had helping the robot.

Explain what difficulties you experienced in understanding when the robot needed help.

Part 2

Open question with ranking:

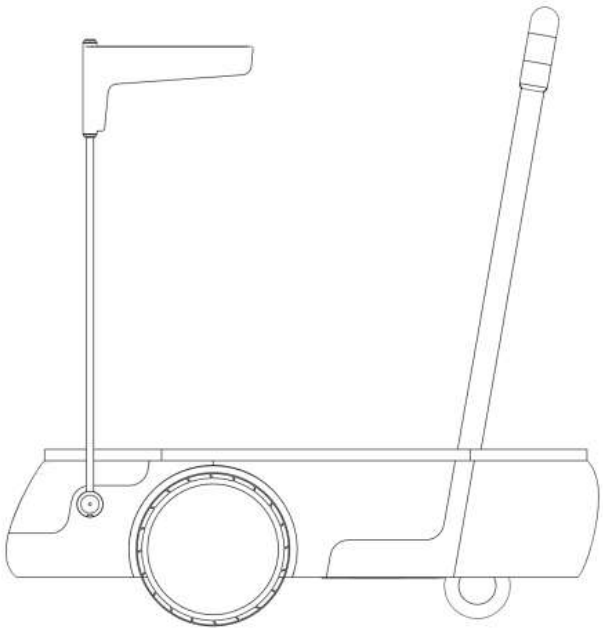
Rank all three robots from easiest to help and least easy to help and explain your ranking.

Rank all three robots on clarity of communication that they needed help and explain your ranking.

15 APPENDIX C SEMI STRUCTURED INTERVIEW LARGE ROBOT STUDY

OBSERVATIONS:

Touch point



Time of interaction

QUESTIONS

Why did you help or not help the robot?

How did you help the robot and why did you do this?

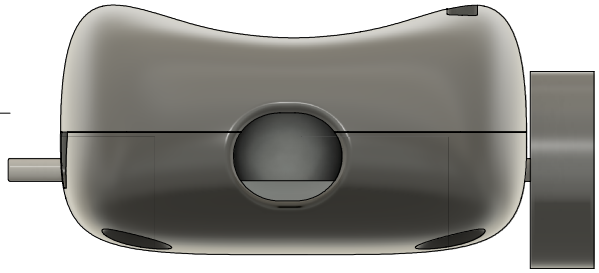
What did you notice about the robot?

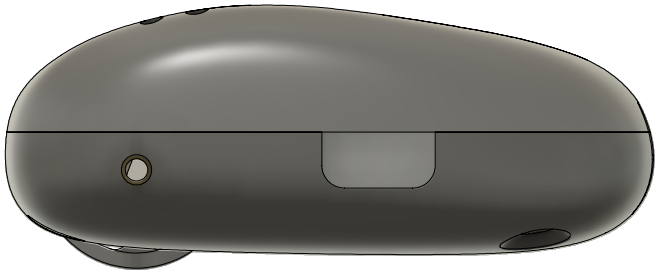
Were did you first notice the robot?

16 APPENDIX D DRAWINGS ROBOTS

small help seeking robot
with annimated handle

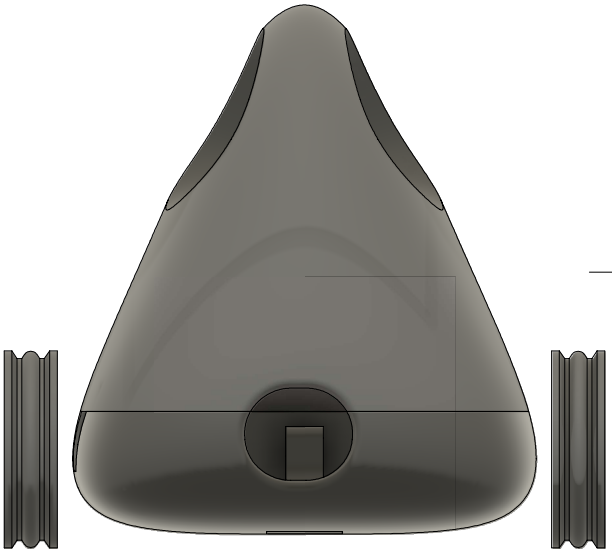
1:1

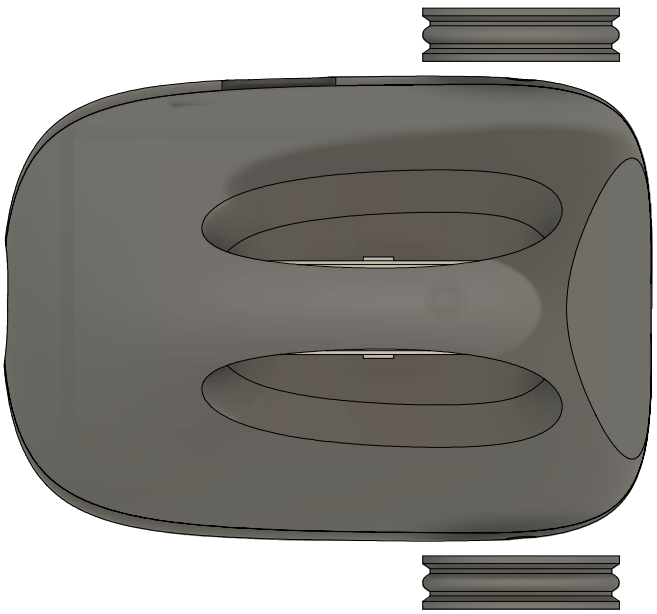




small robot

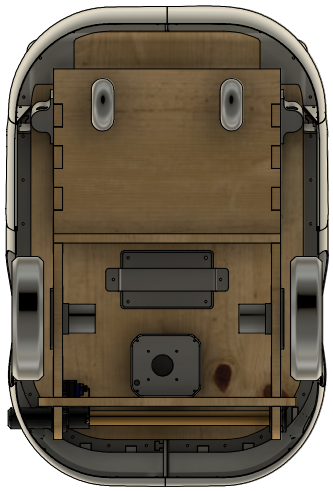
1:1

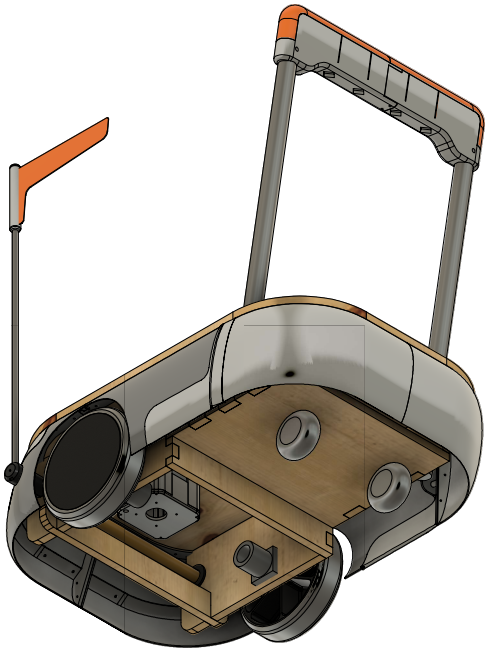


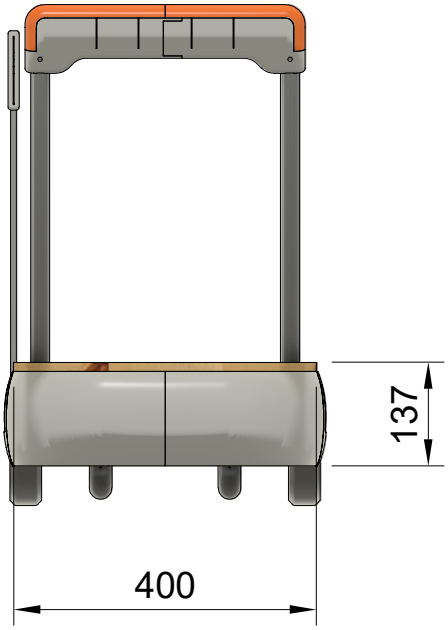


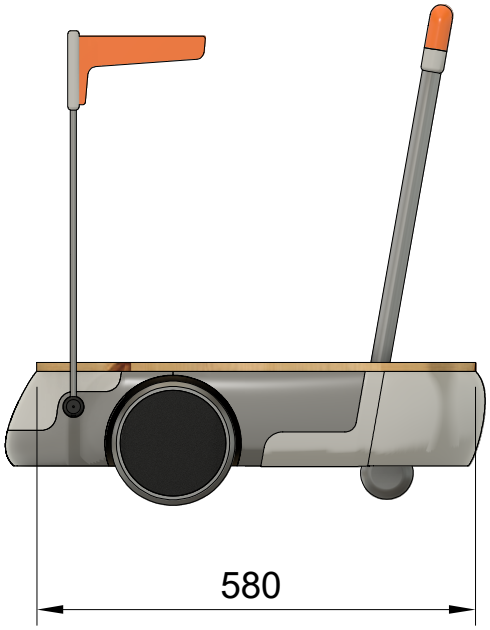
small help seeking
robot with LED strip

1:1









Help seeking robot

1:10