

TROLL E: TRACKED ROBOTIC OUTDOOR LOAD-LUGGING ESCORT

By

Ben Wang

Daniel Ly

Hyun Been (Robin) Park

Final Proposal for ECE 445, Senior Design, Fall 2026

TA: Tianda Huang

18 September 2026

Team 25

Contents

1. Introduction.....	3
1.1 Problem.....	3
1.2 Solution.....	3
1.3 Visual Aid.....	4
1.4 High-Level Requirements.....	4
2 Design.....	6
2.1 Block Diagram.....	6
2.2 Sensing Subsystem.....	6
2.2.1 Ultrasonic.....	7
2.2.2 Weight Sensor.....	8
2.2.3 Sensing Requirements.....	8
2.3 Following Subsystem.....	9
2.3.1 Ultra-Wideband(UWB).....	9
2.3.2 Remote UWB Anchor.....	10
2.3.3 Potential Issues to Consider.....	10
2.4 Drivetrain Subsystem.....	10
2.4.1 Mecanum Wheels.....	10
2.4.2 Motors.....	11
2.4.3 Drivetrain Requirements.....	12
2.5 Control Subsystem.....	12
2.5.1 MCU.....	12
2.5.2 Decision Logic.....	13
2.5.3 Control Requirements.....	13
2.6 Power Subsystem.....	14
2.6.1 Lithium Battery.....	14
2.6.2 Remote Battery.....	14
2.6.3 Buck Converter & Power Distribution.....	14
2.6.4 Power Requirements.....	15
2.7 Tolerance Analysis.....	15
2.8 Software Design.....	17
3. Cost Analysis.....	21
4. Schedule.....	22
5. Ethical, Safety, and Societal Impact.....	23
5.1 Ethical Considerations.....	23
5.2 Safety Considerations.....	23
5.3 Impacts.....	24
References.....	26

1. Introduction

1.1 Problem

Carrying groceries, sports equipment, or other gear is a routine part of daily life, but it carries real physical costs. Hauling loads by hand, especially on one side, alters balance and stresses the body, and health organizations identify carrying items as a contributor to falls, the leading cause of injury among adults over 65[1]. Wagons and carts reduce the load on the body, but they still require the user to push or pull them, occupying at least one hand and placing strain on the shoulder and back. This solution would be more suitable for younger individuals who can handle the level of strain associated with pulling a wagon, but older or physically incapable individuals may not have the same strength. Commercial follow-me carts address this continued issue, but they typically cost over \$2,000. There is a need for an affordable carrier that follows the user hands-free while safely navigating pedestrian environments.

1.2 Solution

TROLL E aims to relieve users of the responsibility of carrying items. We plan for TROLL E to be used under various loading conditions, focusing on carrying groceries, with the addition of sporting equipment, picnicking items, and other outdoor gear. While not entirely strenuous, these items could be high in volume, so being able to offload some to a carrier will greatly improve the user's overall experience wherever they are. Our desired load that TROLL E can support is 20 lbs and may be subject to change after initial testing phases.

Along with assisting in carrying load, TROLL E will avoid objects and other obstacles that may be easily collided with. TROLL E will utilize a mecanum wheel drivetrain along with Ultrasonic sensors to recognize optimal pathing and move across the ground/floor with ease. Since we are dedicating a motor to each wheel within the drivetrain, this will allow for ample power when carrying variable loads.

TROLL E will also follow the user via Ultra-Wideband(UWB) to make sure it follows the user at a good trailing distance while traveling at a safe speed. There will be 3 UWB tags mounted on TROLL E, with the user holding an additional anchor beacon for the mounted sensors to triangulate and determine how far the user is from the trolley, moving accordingly to close or extend the distance.

Each sensor and motor will communicate with our central MCU, which acts as TROLL E's microcontroller. With this, TROLL E's objective is met as a Tracked Robotic Outdoor Load-Lugging Escort.

1.3 Visual Aid

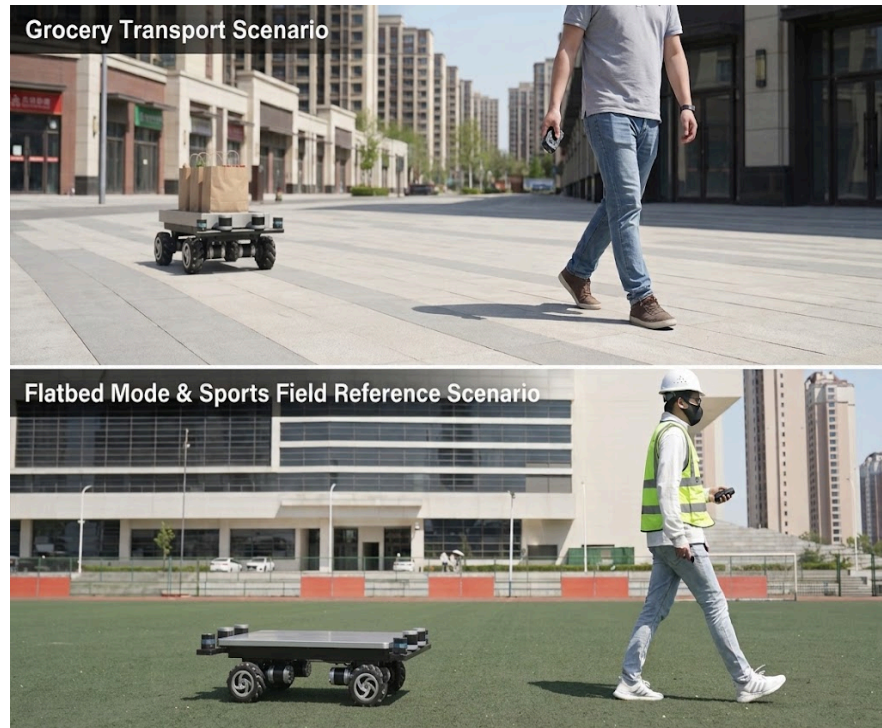


Figure 1. Conceptual TROLL E image showing grocery transport and outdoor load-carrying.

1.4 High-Level Requirements

To consider our project successful, TROLL E must fulfill the following:

1. TROLL E must follow the user while maintaining a distance of approximately 1 meter. The UWB tracking system must determine the user's relative position and allow TROLL E to adjust its movements to remain within the defined following-distance range.
2. TROLL E must detect obstacles in its path and stop before making contact with them. The ultrasonic sensing system must detect obstacles within the vehicle's operating path and command the motors to stop when an obstacle enters the defined safety distance.
3. TROLL E must detect when the cargo load exceeds 20 lb. The weight sensing subsystem must measure the cargo load within a defined tolerance, and if the measured load exceeds

20 lb, TROLL E must remain stationary and pause all operations until the load is reduced below the limit.

2 Design

2.1 Block Diagram

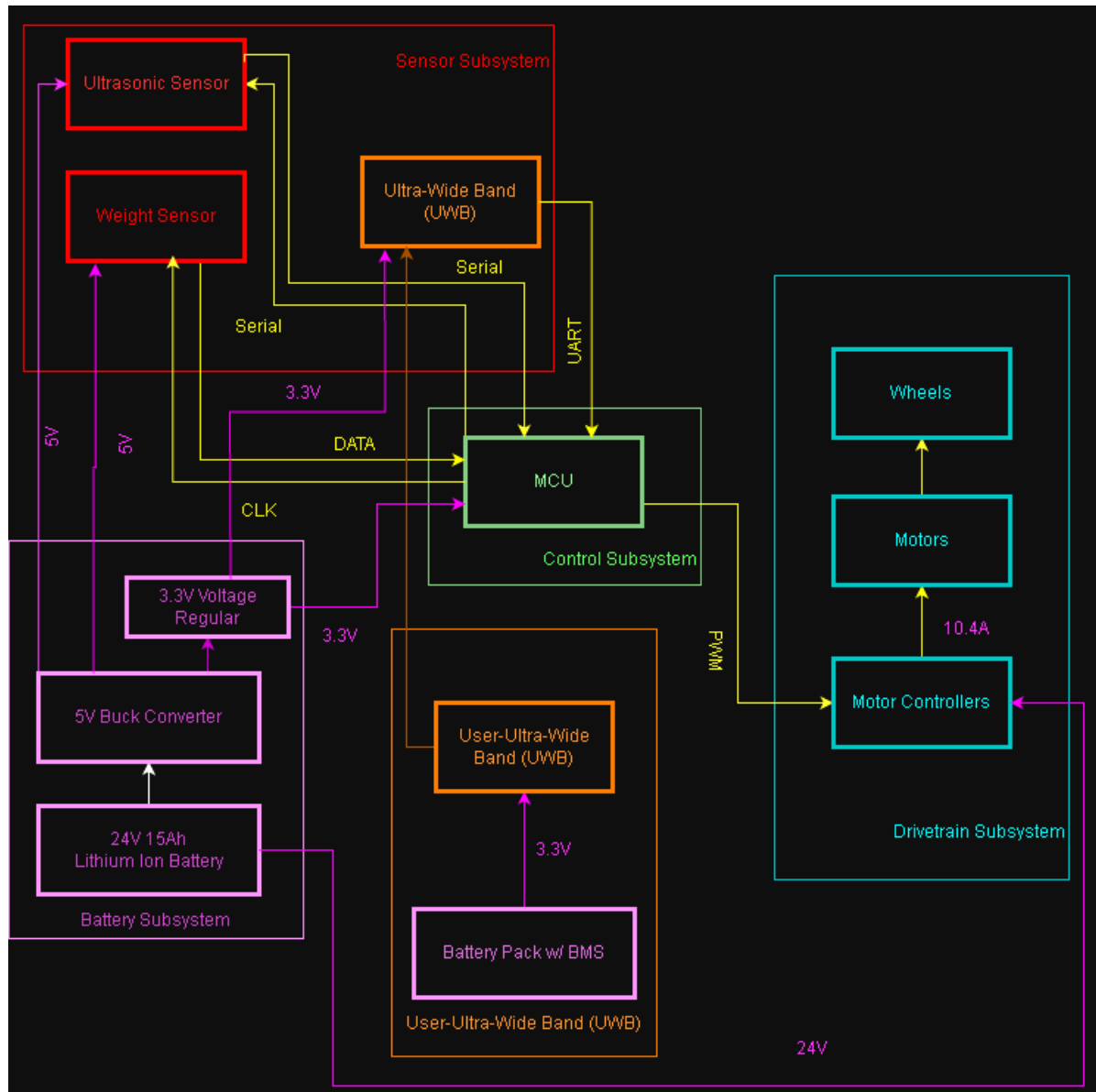


Figure 2. TROLL E system block diagram

2.2 Sensing Subsystem

To develop an autonomous design, TROLL E needs sensors to detect obstacles that impede the following path to the user. We will focus on forward detection as TROLL E will only be following

the user. To achieve this, we will be using Ultrasonic sensors to detect obstacles that appear in front of TROLL E. The sensing subsystem will be supplied by a regulated 5V power supply capable of providing at least 500 mA continuously.

2.2.1 Ultrasonic

We want to use Ultrasonic sensors for forward sensing, adjusting the path to follow the user or stopping the cart when any obstacle is detected within 30 cm, moving to a side until the obstacle is out of view. We are planning to use RCWL-1601 sensors, a smaller upgraded version of the HC-SR04 sensors we used as a reference in the proposal. This ultrasonic sensor operates at 5 V and draws approximately 2.2 mA during operation [2]. We will be using three of these sensors to get a strong forward-facing view, one placed at the center of the front of TROLL E, then one at each corner angled out enough to see over the wheels. This will guarantee TROLL E's ability to detect obstacles that would impede its movement and result in an adjustment in pathfinding to follow the user.

The three individual sensors will connect to the MCU through the trigger and echo pins, occupying 6 pins total. Through programming the trigger signals for each sensor and their corresponding echo signals, we can measure the distance from the nearest object. The sensors need to be fired one at a time, as they only recognize a returning signal without knowing which sensor fired it. Through isolation of trigger signals, we can then determine if a specific side of TROLL E is closer to an object and avoid or move away from that side, with a full stop option as a failsafe. Additionally, knowing the speed sound travels at room temperature, which is around 343 m/s, we can use the simple formula below to calculate the distance between TROLL E and any obstacles in front of it. A small extension to keep in mind is that the time the echo signal is high doesn't tell us where in the range the object is, just that there is something. With respect to this design, TROLL E doesn't care where the obstacle is, so this is not a design flaw.

$$distance\ (cm) = echo\ time\ (\mu s) / 58$$

Ideally, TROLL E is following the user closely, with about 1 meter between. However, these sensors will need a timeout to ensure functionality should there be nothing in the path for the ultrasonic signal to rebound off. A reasonable timeout is 18 ms, as that would be about 3 meters traveled. If the Echo signal is high for this time or longer, we can treat it as "path clear" and continue the existing pathing towards the user.

2.2.2 Weight Sensor

The weight sensor will continuously measure the load placed on TROLL E's cargo platform. Four SparkFun SEN-10245 load sensors will be placed under the platform, one in each corner [3]. The sensor is rated for up to 50 kg (110 lb) and is the same type of strain-gauge sensor commonly used in digital bathroom scales. Using four sensors will allow the weight of the cargo to be measured even when the load is not placed directly in the center of the platform.

The outputs of the four load sensors will be connected to a SparkFun BOB-13878 Load Sensor Combinator [4]. The combinator joins the four 3-wire sensors into a single four-wire Wheatstone bridge output, which will then be connected to a SparkFun SEN-13879 HX711 Load Cell Amplifier [5]. The HX711 will amplify and convert the small analog signal from the load sensors into a digital value that can be read by the MCU. It operates from 2.7 to 5V and draws less than 1.5mA during normal operation, allowing it to operate from the 5 V supply used by the control electronics. The HX711 will communicate with the MCU using one data line and one clock line.

The MCU will use the measured value to determine whether the cargo exceeds the 20lb weight limit. If the measured load is greater than 20lb, TROLL E will remain stationary, and the user will be alerted that the cargo must be reduced. Normal movement will be allowed again once the measured weight falls below the allowed limit.

2.2.3 Sensing Requirements

1. The sensing subsystem can detect obstacles in front of the TROLL E early enough for the control system to stop movement or adjust the device's path before a collision occurs.
2. When an obstacle is detected within an unsafe distance (no closer than 30 cm), the sensing subsystem can send the obstacle information to the control system so that TROLL E can stop and change direction.
3. The weight sensor can measure the total weight of the load on TROLL E and will not begin autonomous movement when the measured load exceeds 20 lb.
4. When the load exceeds 20 lb while TROLL E is already moving, the control system will stop the drivetrain and prevent further movement until the load is reduced below the weight limit.

2.3 Following Subsystem

With the sensors navigating past obstacles, we can now choose where we want to go. Using a beacon design, we want TROLL E to identify where the user is and follow at a trailing distance of about 1 m, subject to change after testing.

2.3.1 Ultra-Wideband(UWB)

Following the user is our main method TROLL E will use for pathfinding. We will use three tags, which give the system three distance measurements that should make the estimated user position more reliable and reduce ambiguity when determining the user's location. The UWB tags will be mounted at three fixed locations on TROLL E, with two positioned at the front corners and the third centered at the rear of the device, while the user will carry a UWB anchor. Each tag will measure its distance to the user's anchor, and the three distance measurements will be used to estimate the user's position relative to the vehicle. Since the tag positions are fixed and known, the MCU can use the measured distance to determine whether the user is in front of TROLL E and whether they have moved to the left or right.

TROLL E will aim to follow the user at a distance of about one meter. If the user moves further away, the MCU will command the motors to move TROLL E closer. If the user moves too close, the system will slow down or stop until the desired following distance is restored. We want to cap the top speed at about 2 mph, so this may influence how fast TROLL E will be able to catch up to the user, but this prioritizes safety, which we think is more important.

For the three tags mounted on TROLL E, we plan to use the Makerfabs MaUWB_DW3000 chipset [6]. The module is based on the DW3000 UWB transceiver and is designed for systems with multiple anchors and tags. Makerfabs states that the module can support up to eight anchors and 64 tags, which is well above the requirements of TROLL E. It supports data rates of 850 kbps and 6.8 Mbps, and its ranging refresh rate can be configured up to 100 Hz. The module communicates through a 115200-baud serial connection and supports both UART and I2C communication protocols, which we will be using UART as that is the protocol that reports ranges. The MaUWB_DW3000 module operates from a 3.3V supply and has a working current of approximately 34mA. Since TROLL E's control electronics will already use regulated low-voltage power, the UWB tags can be supplied from the 3.3V electronics rail. With three tags, the UWB sensors mounted on TROLL E will draw about 102 mA during normal operation, excluding the separate user anchor.

2.3.2 Remote UWB Anchor

The user anchor will use the Makerfabs MaUWB ESP3253 UWB module [7]. This module also uses the DW3000-based MaUWB system and can be configured as an anchor while communicating with the three tags mounted on TROLL E. Makerfabs provides support for configuring the modules as either anchors or tags through AT commands, which allows four UWB devices to operate within the same positioning system.

2.3.3 Potential Issues to Consider

One issue with the following system is that the UWB signal may not always give a perfect position estimate. Obstacles between TROLL E and the user or temporary loss of communication could cause inaccurate distance measurements. If the MCU receives inconsistent measurements from the tags or loses the user's anchor completely, TROLL E should stop rather than continue moving based on an unreliable position.

The user will also have control over the beacon. A switch can be added to turn the user tag off when needed. If TROLL E stops receiving a valid signal from the anchor, the vehicle will stop and remain in place until the signal is restored.

2.4 Drivetrain Subsystem

The drivetrain subsystem is responsible for moving TROLL E based on commands from the control system. Since TROLL E must follow the user while avoiding obstacles, the drivetrain must be capable of various motions. The current design uses four mecanum wheels, each equipped with its own motor, so the device can move forward, backward, sideways, and rotate in place. This should give TROLL E the maneuverability to adjust its path without needing a large turning radius.

2.4.1 Mecanum Wheels

We are going to be using the Nexus Robot 152mm Aluminum Mecanum Wheel. Mecanum wheels were chosen because they allow movement in multiple directions without requiring the device to turn first. This will be useful for TROLL E because the cart has to make many position adjustments while following the user to avoid obstacles and people. The ability to rotate in place also reduces the amount of space needed for position adjustments, which could be useful in tighter environments. We decided on these wheels to allow for more mobility within turns and variability for control from the microcontroller.

The only tradeoff is that mecanum wheels depend on all four wheels being controlled properly. If one wheel is moving at the wrong speed or direction, the device will not move in the direction the control system expects. Because of this, the motor speeds need to be controlled together so that the intended motion is consistent with the expectation. Outside of these tradeoffs, these wheels help maneuver within hard-to-move places without the need to do very many point turns. Outside of the wheel's functionality, we decided that the Nexus Robot Aluminum wheels are rated to support significant loads up to 15 kg, which is about 33 pounds per wheel. These wheels, in combination, are able to handle about 132 lbs, which is about 100 lbs of extra load outside of the wooden base/frame. We are also making sure these wheels are mounted properly with a metal bracket that is compatible with the motor and serves as support for the wheel.

2.4.2 Motors

Each mecanum wheel will be driven by its own motor, allowing the control system to change the speed and direction of each wheel independently. The motors will receive commands through motor drivers rather than directly from the microcontroller, since the motors require more current than the microcontroller can provide.

For the current design, the E-S 36 mm Brushless DC Planetary Gear Motor, 24 V, 160 RPM is being considered [8]. This motor uses a 51:1 planetary gearbox and operates from a 24 V supply. According to the datasheet, the motor draws less than 0.4 A under no-load conditions and less than 2.6 A at its rated operating point. For the 51:1 configuration, the no-load speed is approximately 160 RPM, while the rated speed is approximately 80 RPM with a rated torque of 30 kg·cm. The motor has a specified protection current of 3 A [8]. With four motors operating near their rated load, the drivetrain could therefore draw up to approximately 10.4 A at 24 V, with the power system designed to tolerate approximately 12 A total based on the 3 A protection-current rating of each motor. The drivetrain power interface will therefore provide 24 V to all four motors and should support at least 10.4 A continuously, with additional current margin for startup and short-duration load changes.

The motors will need to provide enough torque to move TROLL E while carrying its intended load. They also need a quick response time to changes in direction so the cart can follow the user and stop when an obstacle is detected. The final motor choice will depend on the weight of the cart, the maximum load limit, and the amount of torque needed to move the device.

2.4.3 Drivetrain Requirements

The Drivetrain Subsystem should meet the following requirements:

1. TROLL E can move forward, backward, sideways, and rotate in place using the four mecanum wheels.
2. The drivetrain can move TROLL E while carrying the maximum intended load of 20 lb.
3. TROLL E can operate at a maximum speed of 2 mph.
4. When a stop command is given, the drivetrain can bring TROLL E to a complete stop before 30 cm while traveling at its maximum operating speed.
5. The four motors are being controlled independently so that the drivetrain can perform the wheel-speed combinations needed for omnidirectional movement.
6. The drivetrain can travel on intended terrains without the motors stalling under the maximum load.

2.5 Control Subsystem

The control subsystem will bring all the other subsystems together. It will take in information from the Ultrasonic, UWB, and weight sensors and use that data to decide what TROLL E should do next. Depending on what the sensors detect, the device will continue to operate, adjust its path, slow down, or stop completely.

This subsystem will also handle safety-related situations. If the user's beacon signal is lost, the weight limit is exceeded, an obstacle is detected, or the emergency stop is activated, the control system will respond and react accordingly before resuming normal operations. Once a decision is made, the MCU will send the necessary commands to the motor drivers so the mecanum wheels move in the correct direction at the proper speed.

2.5.1 MCU

The central microcontroller is how TROLL E communicates with each of its peripheral devices. It reads data from every sensor to decide its next action, including the path it takes to follow the user and stop commands for dangerous conditions.

We have chosen the STM32G474RET6, a 170 MHz Arm Cortex-M4 microcontroller with a hardware floating-point unit, 512 KB of flash, and 128 KB of SRAM, in a 64-pin LQFP package [9]. It operates from a 3.3 V supply, which matches the UWB modules directly and removes the need for level shifting between the MCU and the UWB subsystem.

The MCU will communicate with each sensor using the specified methods in the block diagram. In total, this will include 3 UART connections for the UWB sensors, 8 PWM outputs for 4 bidirectional motors, 6 GPIO pins for the ultrasonic sensors, and 2 for the HX711. The motor controller that we will be using is the 30A RC Brushless Motor Electric Speed Controller ESC 3A UBEC with XT60 & 3.5mm Bullet Plugs. This is just a cheaper ESC that needs an external potentiometer to control the PWM duty cycle. We decided that this potentiometer (X9C104 Digital Potentiometer Module 5V 40R~100K) will be controlled by the MCU to allow for full control inside the software.

Additional pins that will need to be used include the crystal oscillator, which we can get from the lab and requires 2 HSE inputs. Then there is the SWD programming and debugging, which will need an SWDIO and SWCLK pin. For safety, we also want to add a battery voltage monitor pin, which will be an ADC, along with an emergency stop sense, a GPIO with interrupt. Finally, we can include our status LEDs, all GPIO.

2.5.2 Decision Logic

TROLL E will need to start by reading distance data from the Ultrasonic sensors. This will help compute a pathfinding algorithm to reach the beacon the user holds on to, which is obtained through the Ultra-Wideband sensors. Through the combination of triangulating the user's position along with data on the surroundings, TROLL E will decide to follow the user with any adjustments in pathing or to come to a stop. Finally, with these decisions made, the MCU will need to tell motor controllers how to act in order to follow the path laid out post-computation. The motor controllers will then spin the motors in their predetermined directions to execute the pathing that the MCU decided on. We qualify each step in section 2.8, with Figure 4 showing each state and the actions TROLL E will take when given specific inputs.

2.5.3 Control Requirements

The Control Subsystem should meet the following requirements:

1. Testing each communication protocol to validate data transmission using test LEDs.

2. The MCU is able to send trigger signals to each Ultrasonic sensor independently.
3. The control subsystem can send independent commands to all four motor drivers so that TROLL E can move forward, backward, sideways, and rotate in place.
4. If an obstacle is detected, the control system can stop or redirect TROLL E before allowing normal operation.
5. If the UWB beacon signal is lost or turned off, the control system will stop TROLL E and keep it stopped until the signal is restored.
6. If the weight sensor detects a load greater than 20 lb, the control system will prevent the drivetrain from operating.

2.6 Power Subsystem

The power subsystem will provide the energy to the motors, sensors, microcontroller, and other electronics on TROLL E. A rechargeable lithium battery will be used as the main source of power, with its output distributed to the drivetrain and control electronics, and voltage regulation used where lower voltages are needed by the sensors and microcontroller.

2.6.1 Lithium Battery

The lithium battery will supply the main power for TROLL E. We will be using the Aegis 24V 15Ah Lithium Ion Battery Pack NMC 24V Lithium Battery. The total motor requirements are 24 volts and 10.2 Ah, which this battery supplies sufficiently[10]. The battery pack has a rated 360 Wh, which allows for TROLL E to have a runtime of 1.44 hours minimum. This accounts for the worst-case scenario of maximum current load output calling for 250 W nominal. Outside of this, this battery is quite light and petite in volume, which helps with the overall load and undercarriage economy. Then, to power our sensors, we will need to step the voltage down to 5V and 3.3V through a buck converter and voltage regulator.

2.6.2 Remote Battery

The user's remote will house the UWB anchor for TROLL E's tags to measure their distance. We have the option to utilize the MaUWB_ESP32S3 UWB module from Makerfabs, which comes prebuilt with the UWB chip ready to be programmed[7]. However, this comes installed with USB-C

connections, which will power the PCB. This requires us to use some form of USB-C power, with the easiest solution being a handheld power bank.

The alternative we are considering is to use the UWB chip but build this user anchor PCB ourselves, which will give us the flexibility to power the board ourselves. The UWB chipset will still need to be purchased, but having the option to develop our own board will reduce the amount of redundant features as well as focus on just the UWB signal and how the tags on TROLL E read off this anchor.

2.6.3 Buck Converter & Voltage Regulator

The power subsystem will have a 5V buck converter to provide the required voltage to the different parts of the system. Parts such as the motor controllers will operate directly from the main battery voltage, while the MCU, UWB system, and Ultrasonic sensors will operate using the lower converted voltage. We will be using the MP1584EN 5-30 to 5V Buck Converter on Amazon for converting our 24V down to 5V [11]. This power distribution design will separate sudden motor current changes from the MCU and sensors so they don't lose power or reset during high-load moments for the motors.

Additionally, the UWB sensors require 3.3V to operate, so we can use the TLV73333PDBV chip that was used in the Soldering Assignment for voltage regulation from 5V to 3.3V. The ECE 445 CAD assignment uses this device as a 3.3V low-dropout regulator connected to a 5V rail. The three UWB modules mounted on TROLL E draw approximately 102 mA total during normal operation, so this regulator will provide enough current for the UWB subsystem.

With this setup, the 24V battery will supply the drivetrain directly, the buck converter will create the 5V rail for the control electronics and sensors, and the TLV73333PDBV will create the 3.3V rail needed by the UWB modules.

2.6.4 Power Requirements

1. The power subsystem can provide enough current to operate all four motors and the control electronics at the same time under the maximum intended load.
2. The battery can provide at least 30 minutes of continuous operation under normal use.
3. The power subsystem can provide the required regulated voltage for the MCU and sensors.

4. The battery management system can protect the lithium battery from overcharging, over-discharging, overcurrent, and overheating.
5. The power subsystem can continue supplying stable power to the MCU and sensors during motor operation and changes in motor current.
6. Battery wiring and connections remain secure during vehicle movement and vibration.

2.7 Tolerance Analysis

One of the more prominent risk components is the motors and the drive shaft. A lot of the weight will be distributed amongst the joints of TROLL E, and with this comes reliability related to the structural integrity of the frame and wheels. The rigidity of the wheels and the strength of the frame are both things that we have already considered, and we have manufactured a frame with competent wood supplies as well as understanding the amount of support wheels needed in order to evenly spread the force placed upon different loads of the cart. We drew up simple force diagrams and concluded that the easiest way to mount wheels was to place them on all corners of the frame, as well as under the frame. This allows for more down force on the wheels instead of applied torque on the sides if mounted otherwise. Along with this, we saw that this helped with the possibility that the center of gravity of TROLL E may not be even at times since all wheels were on all corners, as well as the center of gravity always being between the wheels of the frame.

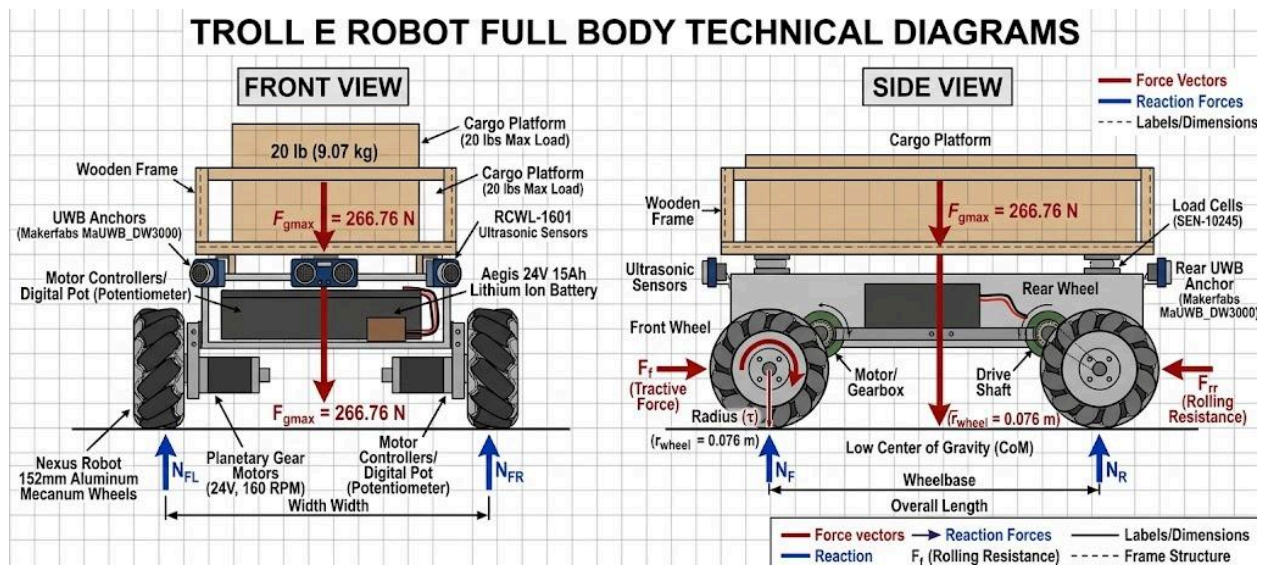


Figure 3. TROLL E full body diagram.

Being fully reliant on the wooden frame as structural support isn't something we decided on; however, we will be mounting the wheels on a metal drivetrain that will mostly house all of the motors, battery, and controller components. To ensure that each component is safe, we decided on implementing further structural support like cross bars and drive shafts, outside of the wooden frame.

Another thing that required some mathematical analysis was the amount of torque needed to move a total max load of 20 pounds distributed across 4 wheels to move at 2 mph. With this, we learned that a good motor that can generate about 150 rpm and a minimum of 2 N*m allowed for easy clearance of this hurdle. We found that overestimating what we need allows for more comfort when implementing.

Here are the more prominent numbers when thinking about how TROLL E will function:

Total weight and payload budget:

$$m_{total,max}=m_{robot}+m_{payload}=18.15\text{ kg}+9.07\text{ kg}=27.22\text{ kg}$$

$$F_{g,max}=m_{total,max} \cdot g=27.22\text{ kg} \times 9.80\text{ m/s}^2=266.76\text{ N}$$

Normal Force Distribution:

$$N_i=F_{g,max}/4=266.76\text{ N}/4=66.69\text{ N per wheel}$$

Under worst-case asymmetric loading conditions (60:40 offset)

$$N_{max,wheel}=0.60 \times F_{g,max}/2=160.06\text{ N}/2=80.03\text{ N}$$

$$N_{min,wheel}=0.40 \times F_{g,max}/2=106.70\text{ N}/2=53.35\text{ N}$$

Friction limit vs Rolling Resistance Torque:

$$F_{f,total} = \mu \cdot F_{g,max}=0.60 \times 266.76\text{ N}=160.06\text{ N (at } \mu=0.60)$$

$$F_{f,wheel}=160.06\text{ N}/4=40.014\text{ N per wheel}$$

$$T_{traction}=F_{f,wheel} \times r_{wheel}=40.014\text{ N} \times 0.076\text{ m}=3.041\text{ N} \cdot \text{m}$$

When $\mu=0.85$

$$T_{traction,max}=(0.85 \times 266.76\text{ N})/4 \times 0.076\text{ m}=56.687\text{ N} \times 0.076\text{ m}=4.308\text{ N} \cdot \text{m}$$

Rolling Resistance Drive Requirement:

$$F_{rr,total}=C_{rr} \cdot F_{g,max}=0.08 \times 266.76\text{ N}=21.34\text{ N}$$

$$F_{rr,wheel}=21.34\text{ N}/4=5.335\text{ N per wheel}$$

$$T_{rr,wheel} = F_{rr,wheel} \cdot r_{wheel} = 5.335 \text{ N} \times 0.076 \text{ m} = 0.405 \text{ N} \cdot \text{m}$$

Incline Tolerance Calculation (5 degrees)

$$F_{incline} = F_{g,max} \cdot \sin(5 \text{ degrees}) = 266.76 \text{ N} \cdot 0.08716 = 23.25 \text{ N}$$

$$F_{incline,wheel} = 23.25 \text{ N} / 4 = 5.81 \text{ N per wheel}$$

$$T_{incline,wheel} = F_{incline,wheel} \cdot r_{wheel} = 5.81 \text{ N} \times 0.076 \text{ m} = 0.442 \text{ N} \cdot \text{m}$$

Total Operating Torque vs Motor Capability

$$T_{operating} = T_{rr,wheel} + T_{incline,wheel} = 0.405 \text{ N} \cdot \text{m} + 0.442 \text{ N} \cdot \text{m} = 0.847 \text{ N} \cdot \text{m per wheel}$$

$$T_{rated,motor} = 30 \text{ kg} \cdot \text{cm} \times 0.0980665 \text{ (N} \cdot \text{m)} / (\text{kg} \cdot \text{cm}) = 2.942 \text{ N} \cdot \text{m}$$

$$\text{Safety Factor (SF)} = T_{rated,motor} / T_{operating} = 2.942 \text{ N} \cdot \text{m} / 0.847 \text{ N} \cdot \text{m} \approx 3.47$$

2.8 Software Design

The software integration of all our sensors is key to proper implementation for TROLL E's functionality. Each sensor will be used to tell the MCU what its next step should be to ensure the safety of the load it is carrying as well as the safety of the people that could be around it. Thus, TROLL E's MCU will take the three Ultrasonic echo signals, the UWB distance signal to the user, and the load cell signal as inputs to properly determine what the motors should respond with. On every control loop, the MCU will check each of these inputs using the priority shown in the flowchart below to pick a single state for operation.

The possible states of operation for TROLL E are as follows:

- IDLE: TROLL E powers up in this state, with its stop latch already set, and commands all four motor controllers off. It stays here until the UWB signal from the user's remote has been steady for 2 seconds. In other words, until the user switches the remote on, which keeps TROLL E from driving off the moment it powers on.
- STOP: Command all four motor controllers to bring TROLL E to a full stop. TROLL E records why it stopped, as the reason decides how it leaves this state, where latched stops require physical intervention before restart, and unlatched is autonomous.
 - *Overload (more than 20 lb):* Latched.

- *User signal lost for more than 1 second*: Latched. This includes the user switching the remote off.
- *Still blocked after 3 seconds of turning*: Latched.
- *Any sensor reading under 30 cm*: Not latched. TROLL E waits 1 second so passing people or objects can clear. Then it moves to FOLLOW if the path is clear, or to TURNING if not.
- **HOLD**: The UWB shows the user within 1 m, so we tell the motor controllers to stop. This is a pause while the user is close by, so that TROLL E doesn't keep catching up to the user. TROLL E returns to FOLLOW once the user is more than 1.2 m away. The gap between 1.0 and 1.2 m prevents rapid stopping and starting at the boundary.
- **FOLLOW**: Command the motor controllers to drive toward the user's direction as reported by the UWB. Speed increases with how far the user is beyond the 1 m following distance, up to the set maximum of 2 mph. This is the normal operating state of TROLL E.
- **PATH CHANGE**: An obstacle is detected between 30 cm and 150 cm ahead. TROLL E continues toward the user but slows down as the obstacle gets closer, using its omni wheels to slide sideways, away from the obstacle:
 - If only one corner sensor sees the obstacle, TROLL E slides to the opposite side.
 - If only the center sensor sees it, TROLL E slides toward whichever corner reads farther.
- **TURNING**: Entered after an obstacle stop when the path is still blocked. TROLL E rotates in place. The direction is chosen once, when the state begins, and held until it ends, so TROLL E doesn't wiggle back and forth as readings change during the rotation:
 - Turn toward the corner sensor with the farther reading.
 - If the two corner readings are within 15 cm of each other, turn toward the side the user is on.
 - If the user is also straight ahead, turn right by default.

Many of these values here are subject to change once they have been tested, especially the 150 cm avoid distance, as it will require TROLL E to first check UWB before identifying if the Ultrasonic sensors are seeing objects or the user.

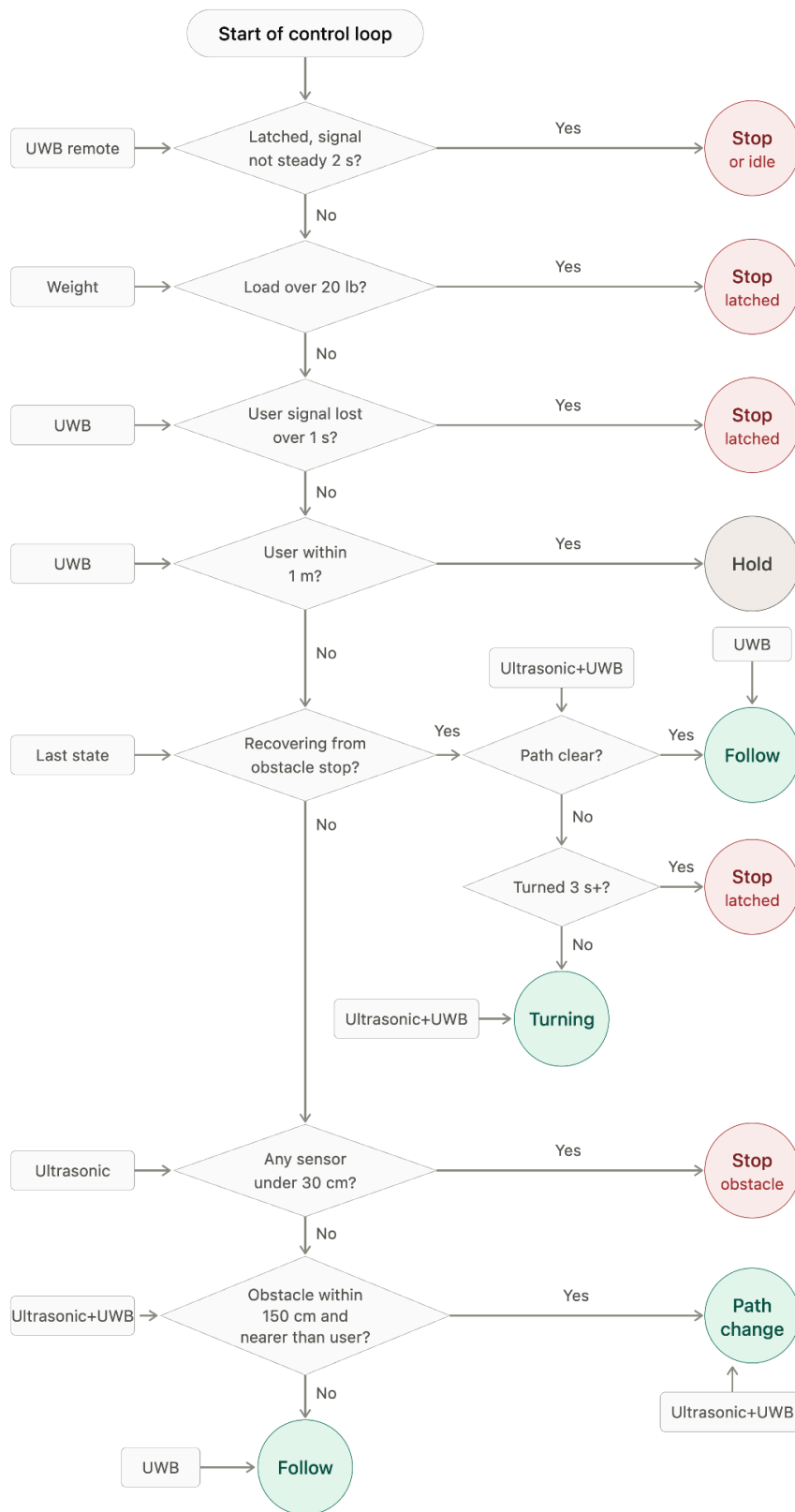


Figure 4: Motor Operation Flowchart

3. Cost Analysis

Description	Manufacturer	Quantity	Extended Price	Link
RCWL-1601 Ultrasonic Sensor	Adafruit	3	\$18.21	Link
50 kg Load Sensor, SEN-10245	SparkFun Electronics	4	\$25.00	Link
Load Sensor Combinator, BOB-13878	SparkFun Electronics	1	\$2.75	Link
Load Cell Amplifier - HX711, SEN-13879	SparkFun Electronics	1	\$4.95	Link
MaUWB_DW3000 Chipset	Makerfabs	3	\$116.70	Link
MaUWB ESP3253 UWB Module	Makerfabs	1	\$54.80	Link
152mm Right Mecanum Wheel	NEXUS ROBOT	2	\$74.18	Link
152mm Left Mecanum Wheel	NEXUS ROBOT	2	\$74.18	
36mm Brushless DC Planetary Gear Motor, 24V, 160 RPM	E-S Motor	4	\$170	Link
STM32G474RET6	STMicroelectronics	1	\$10	Link
Aegis 24V 15Ah Lithium Ion Battery Pack NMC 24V Lithium Battery	Aegis	1	\$239.99	Link
HiLetgo 2pcs X9C104 Digital Potentiometer Module 5V 40R~100K	HiLetgo	2	\$13.99	Link
Metal Bracket for 36D Planetary Gear Motor	E-S Motor	4	\$11.2	Link
MP1584EN 5V Buck Converter Board - 5-30V to 5V, 1.8A Output	Generic / Amazon	1 pack (5 boards)	\$8.99	Link

Figure 5. Itemized List of Components and Costs

4. Schedule

Week	Task	Person
October 1 - October 8	Order parts for prototype	Everyone
	Develop Connector/User PCB	Everyone
	Test Components for the drive train	Ben and Daniel
October 8 - October 15	Assemble Components	Everyone
	Breadboard Demo /w TA	Everyone
October 15 - October 22	Integrate sensors with MCU	Everyone
	Begin UWB and obstacle detection testing	Robin and Ben
October 22 - October 29	Integrate drivetrain and sensing system	Everyone
	Begin user-following tests	Robin and Ben
October 29 - November 5	Progress Demo	Everyone
November 5 - November 12	Improve tracking and obstacle avoidance	Everyone
	Calibrate weight sensing system	Robin and Ben
November 12 - November 19	Mock Demo	Everyone
	Fix issues found during mock demo	Everyone
November 19 - November 25	Mock Presentation	Everyone
	Complete final hardware and software integration	Everyone
November 25 - December 2	Finalize project	Everyone
December 2 - December 9	Final Demo	Everyone
	Final Papers	Everyone

Figure 6. Schedule for Project Progression

5. Ethical, Safety, and Societal Impact

5.1 Ethical Considerations

TROLL E is designed to reduce the physical effort required to transport loads by autonomously following the user. Because the device operates independently around people and carries heavy objects, the team has an ethical responsibility to prioritize the safety of users and bystanders throughout the design process. A malfunction in the tracking, control, sensing, or drivetrain systems could cause the vehicle to move unexpectedly and collide with a person or an obstacle. For this reason, we will consider safety throughout both the design and testing of the project.

The IEEE Code of Ethics emphasizes protecting the safety, health, and welfare of the public and identifying conditions that could put people or the environment at risk [12]. Following the IEEE Code of Ethics, the team will not continue testing a feature that is known to behave unsafely just to prove that the prototype works. If testing shows that a feature is unreliable or creates a safety concern, the team will correct the issue before continuing development.

The IEEE Code of Ethics also states that engineers should be honest and realistic when presenting technical claims and should acknowledge and correct errors when they are found [12]. Because of this, the team will not claim that TROLL E can operate safely in conditions that have not been tested. The team will clearly state and communicate limitations such as terrain, maximum payload, operating speed, following distance, and obstacle detection to the user.

The ACM Code of Ethics emphasizes avoiding harm and considering a system's possible effects before use, as well as its accidental and intentional misuse[13]. Accidental and intentional misuse must be considered as well. Accidental misuse includes overloading the cargo, blocking a sensor, or using TROLL E outside of the conditions it was designed for. Intentional misuse could include riding on the device, disabling the obstacle sensor, or changing the software so that the vehicle operates outside its tested limits. These cases will be considered outside the intended operation of TROLL E, and the team will add safety limitations in order to prevent such misuse from happening.

5.2 Safety Considerations

The main safety concerns for TROLL E come from its autonomous movement, mechanical drivetrain, electrical power system, and ability to transport significant loads. The most significant

hazard is unintended vehicle motion. A failure in the user-tracking system, motor controller, or software could cause TROLL E to move in the wrong direction or continue moving after the user has stopped. This could result in a collision with a person or an obstacle.

To reduce this risk, Ultrasonic sensors will monitor the surrounding area for obstacles, and the control system will stop the motors when an obstacle is detected. An emergency-stop mechanism will also be implemented so the user can manually disable TROLL E's movement for emergencies. Since TROLL E is intended to operate near its user, its operating speed and following distance must allow enough time for the system to detect an obstacle and stop. Because of this, the obstacle-detection system should be tested and verified under practical operating conditions before the device operates autonomously around other people.

Device stability is another safety concern because TROLL E will be carrying a significant load while moving. The mecanum wheels will allow the device to turn in place and move sideways without needing a wide turning space. However, the device could still become unstable if the load is unevenly distributed or exceeds the intended weight limit. To reduce the risk of tipping or falling, the frame will be designed with a low center of gravity and enough width to support and balance the expected load.

The battery and electrical system also create safety risks. Since TROLL E will use a lithium battery, the ECE 445 battery safety guidelines will be followed. The guideline lists overcharging, over-discharging, excessive current, heat, short circuits, and mechanical damage as major lithium battery hazards [14]. Wiring and electrical connections on TROLL E will also be insulated and secured so that movement and vibration do not cause wires or connections to become loose during operation. The team will also follow the ECE 445 procedures for reviewing and testing battery-related circuitry before connecting it to the system[14].

5.3 Impacts

TROLL-E could have a positive societal impact by giving users an additional way to transport loads during everyday activities. For general use, the device could help carry groceries, gardening supplies, tools, outdoor equipment, or other items that require repeated lifting or manual transport. It may also be useful for elderly individuals or people with physical disabilities who may have difficulty carrying heavier objects regularly. In commercial environments such as supermarkets, retail stores, malls, or storage areas, employees could use TROLL E to move clothing, inventory, merchandise, or other goods.

Economically, TROLL E would likely cost more than a traditional cart or wagon because it incorporates motors, mecanum wheels, sensors, a battery, control electronics, and a wireless user-tracking system. However, these additional components provide autonomous movement and reduce the need for the user to continuously push or pull the load. If the system were developed beyond the team's project design, the team would need to reconsider component cost and manufacturability to make the product economically practical.

TROLL E is electrically powered and therefore produces no direct exhaust emissions during normal operation. However, producing its battery, motors, electronic components, and structural materials still has an environmental impact. Battery disposal and electronic waste would also need to be considered at the end of the product's life. Designing the system so that individual components can be repaired or replaced, rather than replacing the entire device, could help extend its usable lifetime and reduce unnecessary waste.

The potential applications of TROLL E are not limited to one region because the need to transport groceries, tools, supplies, and commercial goods exists in many environments worldwide. However, operating conditions can vary significantly by location because of differences in terrain, infrastructure, climate, and available space. For this reason, the capabilities demonstrated by the TROLL E should only be assumed for environments and operating conditions that the system has been tested on. Future versions could be adapted to better accommodate the needs and conditions of different regions.

References

- [1] Centers for Disease Control and Prevention, "Older Adult Fall Prevention At-a-Glance," CDC Injury Center. [Online]. Available: https://cdc.gov/falls/pdf/CDC-DIP_At-a-Glance_Falls_508.pdf [Accessed: Sep, 2026].
- [2] Adafruit, "Ultrasonic Distance Sensor - 3V or 5V - HC-SR04 compatible - RCWL-1601" Adafruit. [Online]. Available: <https://www.adafruit.com/product/4007> [Accessed: Oct. 2026].
- [3] SparkFun Electronics, "Load Sensor - 50kg (Generic)," SparkFun Electronics. [Online]. Available: <https://www.sparkfun.com/load-sensor-50kg-generic.html>. [Accessed: Oct. 2026].
- [4] SparkFun Electronics, "SparkFun Load Sensor Combinator," SparkFun Electronics. [Online]. Available: <https://www.sparkfun.com/sparkfun-load-sensor-combinator.html>. [Accessed: Oct. 2026].
- [5] SparkFun Electronics, "SparkFun Load Cell Amplifier - HX711," SparkFun Electronics. [Online]. Available: <https://www.sparkfun.com/sparkfun-load-cell-amplifier-hx711.html>. [Accessed: Oct. 2026].
- [6] Makerfabs, "MaUWB_DW3000 Chipset," Makerfabs. [Online]. Available: <https://www.makerfabs.com/mauwb-dw3000-chipset.html>. [Accessed: Sep. 2026].
- [7] Makerfabs "MaUWB_ESP32S3 UWB module," Makerfabs. [Online]. Available: <https://www.makerfabs.com/mauwb-esp32s3-uwb-module.html>. [Accessed: Oct. 2026].
- [8] RobotShop, "36PG-3650BL planetary gear motor datasheet," [Online]. Available: https://cdn.robotshop.com/rbm/a00a7635-653b-4220-aac9-b0c23c5c5e2c/c/c3aad52c-4b01-4ba3-93a6-74b8261d005f/4421dcf7_36pg-3650bl-motor.pdf. [Accessed: Oct. 2026].
- [9] DigiKey, "STM32G474RET6 — STMicroelectronics," DigiKey Electronics. [Online]. Available: <https://www.digikey.com/en/products/detail/stmicroelectronics/STM32G474RET6/10326780>. [Accessed: Oct. 2026].
- [10] Aegis Battery, "Aegis 24V 15Ah Lithium Ion Battery Pack | NMC 24V Lithium Battery," Aegis Battery. [Online]. Available: <https://www.aegisbattery.com/products/aegis-24v-15ah-lithium-ion-battery-pack-nmc-24v-lithium-battery>. [Accessed: Oct. 2026].
- [11] Amazon, "MP1584EN 5pcs Mini 5V Buck Converter Board - 5–30V to 5V, 1.8A Output," Amazon.com. [Online]. Available: <https://www.amazon.com/dp/B0B779ZYN1>

- [12] IEEE, “IEEE Code of Ethics,” IEEE, Jun. 2020. [Online]. Available: <https://www.ieee.org/about/corporate/governance/p7-8.html>. [Accessed: September, 2026].
- [13] Association for Computing Machinery, “ACM Code of Ethics and Professional Conduct,” 2018. [Online]. Available: <https://www.acm.org/code-of-ethics>. [Accessed: September, 2026].
- [14] ECE 445 Course Staff, “Safe Practice for Lead Acid and Lithium Batteries,” ECE 445: Senior Design Project Laboratory, University of Illinois at Urbana-Champaign, Apr. 13, 2016.