ECE 191 - Engineering Group Design Project

Final Report
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Executive Summary

The Mobile Robotic Base for Human Rescue is a step forward in a new field of human-robot interaction. We created a robust, stable, and maneuverable base that is designed specifically for search and rescue operations. We are under the sponsorship of Professor Yip, Jason Lim, and Elizabeth Peiros, from the Advanced Robotics and Controls Laboratory (ARCLab). The project's objective is to develop a base that is integrable with Franka Pandas robotic arms to perform low-risk search and rescue; this would create safer rescues by removing the risk of sending a human into a dangerous situation.

The motivation behind this project comes from the new ability of robotic arms to perform safe and accurate movements which can help injured people. Traditional rescue operations involve risks, especially to the human rescuers which is undesirable especially when robotics has reached the ability to be able to switch out in place of the human. However current systems are focusing primarily on finding people (search) in these situations but cannot assist in their extraction or positioning them more safely (leaning them off their wounds). We address this by developing a robotic platform that can travel in dangerous environments and assist in the safe extraction of individuals situated in these environments.

Our approach involved several phases: research and design, design engineering, prototype development, testing and iteration, and final product development. Our process involved motor research and controller system research, robust CAD design, and safety/robustness calculations. We selected BLDC motors paired with ODrive Pro motor controllers to ensure precise control of the base. The frame is constructed with 80/20 T-slot aluminum, which provides robustness to hold high loads as needed by our physics calculations. Wired communication is facilitated through an Arduino Uno R4 WiFi module and Bluetooth connectivity, enabling remote control in future implementations.

Throughout the project, we faced and overcame several challenges. One significant challenge was finding motors with torque output that met the constraints set by our mentors. Another challenge was motor and motor controller documentation. With limited information, we had to research various methods to get the motor to operate properly. Our testing and validation process was extensive. We conducted load-bearing calculations, and stability calculations to ensure the system's ability to perform under various conditions.

The development of this mobile robotic base also holds societal, and economic considerations. Socially, our design offers a new form of robot-human interaction that can seriously help search and rescue operations in dangerous situations but can also be applied to many contexts even outside of wartime and natural disasters. These arms can be switched out for different applications and give us tons of uses such as helping the elderly. Economically the base is much cheaper than other forms of robot-human interaction for search and rescue purposes, one example the BEAR robot was made in the 2010's but cost millions of dollars in development and construction fees and was discontinued due to these significant financial costs. Our design is extremely cheap compared to the BEAR robot and total costs were around 2000 dollars for the entire base excluding the arms, including the arms cost is around 35000 dollars which is still orders of magnitude cheaper than the BEAR robot which opens avenues for the mass production of these devices to assist people.

In conclusion, the Mobile Robotic Base for Human Rescue project represents a step in the right direction for the field of human-robot interaction for emergency scenarios. We have constructed a prototype that meets the design goals and specifications with great potential for further work and application. We believe future work could focus on enhancing the system's capabilities such as creating a fully enclosed base for all-weather applications and exploring additional uses beyond search and rescue. This project demonstrates the feasibility of integrating robotic systems into rescue operations.

Introduction

Motivation

Currently, rescue operations involve risks to human rescuers. The current robotic systems that exist locate victims, however, they are unable to extract or manipulate them. This project addresses the gap where robotics would be able to manipulate and extract victims in these environments. The development of this base is to reduce the reliance on human rescuers and provide a safe search and rescue system that can be deployed in wartime and natural disaster scenarios.

Problem Statement

The project is working to solve the problem of maneuvering and stabilizing a base that can safely operate in dangerous environments. This base must be robust and designed well enough to be able to go through rough terrains. The base needs to be stable to be able to support the weight and movements of the robotic arms, which are imperative for performing rescue operations.

Societal and Economic Context

The development of this robotic base is a prototype and an improvement to the need for improved low-risk rescue operations. Current methods of search and rescue are risky to human rescuers and as such are quite costly. This project provides a prototype low-cost solution. The robotic base's design incorporates considerations for the safety of the individuals in need of rescue. Finally, the design was made to be usable in various scenarios, such as natural disasters to military operations.

Expanded Project Background

For example, the Battlefield Extraction-Assist Robot (BEAR), is a remotely controlled robot developed by Vecna Robotics for use in the extraction of wounded soldiers from the battlefield. Even with its capabilities, BEAR is not capable of human repositioning or extraction. Other robots do not consider the ability to rescue the person and focus solely on the search portion of the rescue operations. This project seeks to address this gap in features of the search and rescue robots. The robotic base is designed to be stable, maneuverable, and compact while being able to be remotely controlled.

Project Goals and Design Requirements

Designing a stable mobile-wheeled platform that can carry out rescue operations is required. The design requirements include stability, maneuverability, mobility, safety, compactness, and remote control. This platform needs to be robust to be able to handle the weight and movements of the robotic arms while navigating through rough terrain and also when the arms are extending or contracting. The system needs to be compact to be able to go into confined spaces, which are common in disaster-stricken areas. Additionally, the platform needs to be remotely controlled to allow for safe operations from a distance, minimizing the risk to human operators.

Technical Background

Technologies Used

The project utilizes several technical components, including the Brushless DC Motor (BLDC), the ODrive pro motor Controller, and an Arduino microcontroller capable of Bluetooth and wifi connectivity.. Central to the system are the Brushless DC (BLDC) motors and ODrive motor controllers. The BLDC motors are selected for their high efficiency and reliability, while the ODrive controllers are crucial for precise motor control and stability. These controllers provide high-precision controls and are equipped with many forms of feedback and feedforward control systems for a diverse array of control techniques for many motors. This type of diverse and high-precision control is very important in rescue operations, where both stability and precision are required to safely maneuver the robotic base and perform the required tasks.

BLDC motors utilize a three-phase system to receive instant torque to a system without friction, current is supplied through the stators (windings along the outer edge that create magnetic fields when current is pushed through them) These Motors can deliver instant high torque, with low maintenance cost and highly efficient power consumption.

The ODrive Pro also allows for precise control of BLDC motors that require huge power input into the three-phase system, the Odrive Pro can withstand up to 80 continuous Amps with cooling at a voltage ranging from 12V-60V making it ideal for application in electrical drive systems which have potential to be upgraded. The ODrive Pro uses Field Oriented Control (FOC) without Flux Weakening Control (FWC) enabled, this can be seen by the d-axis current never going above a minimal amount.

FOC and FWC are two recent advances in control technology that involve the use of a change of axes for the BLDC motor which then allows for simpler and higher precision control of the motor at the cost of computational cost, because of this computational cost FOC and FWC have only begun to emerge as favorites in the control of BLDC motors in the early to mid-2000s when computational components became cheap enough to employ these high-quality control methods onto smaller systems such as a BLDC motor controller. These Methods of Control are fairly complex and we leave a few papers in case the reader is interested in learning about FOC/FWC.

Another component for the base is the Arduino Uno R4 WiFi microcontroller, which we use for wireless communication and Controller Area Network (CAN) control signals. We chose the Arduino because it can send Transmission and Receiving signals which we then can input into a CAN transceiver which sends CAN data to our ODrives through our wire network. The WiFi capability of the Arduino Uno R4 enables serial control and possibly in the future remote control, a feature that is particularly important in hazardous environments where the base would be minimizing human presence ensuring a safer form of rescue.

CAN is a form of communication between large groups of robotic components and controllers which is a form of serial communication. CAN allows many motors to be controlled at once because it allows each motor to have its ID where you can send individual signals all at once to each ID.

The structure of the base is designed using Computer-Aided Design (CAD) software called SolidWorks. SolidWorks was used to model the frame, ensuring all components would fit and the structural integrity of the base was able to withstand operational stresses. The use of SolidWorks allows for detailed planning, which reduces the likelihood of design flaws in the robotic base.

System Design

The system design of the base is designed to be modular. The hardware components were chosen to ensure the stability, safety, and functionality of the base. Of the modules, we have power management, the microcontroller, motor and controller integration, frame design, and communication design. We configured these components to make sure they are carefully integrated and achieve the project's goals.

The microcontroller setup uses the Arduino Uno R4 WiFi, which is the center for the control signals and communication. This microcontroller receives input from serial communication and sends commands to the motor controllers through the CAN transceiver. The WiFi capability of the Arduino Uno R4 allows for real-time monitoring and adjustments, which are extremely important in rescue scenarios where quick response times are essential. The integration of the motor controller with the Arduino microcontroller is shown in **Figure 1**, the Arduino is connected to the CAN transceiver which then connects to the ODrive.

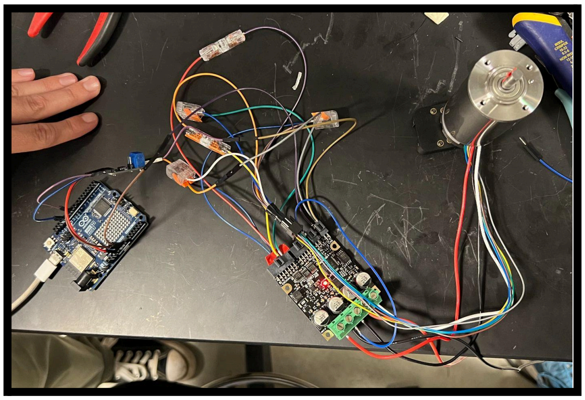

Figure 1: ODrive Motor Controller Setup

For motor and controller integration, BLDC motors are paired with ODrive Pro controllers. These controllers can handle high power and provide precise control of either the motor speed or the position of the rotor. The integration involves setting up feedback loops with the Hall Sensors (to measure the position of the permanent magnet rotor to ensure stable operation, this is critical for maintaining stability and performance during rescue operations. The overall system architecture is illustrated in **Figure 2**, the Block Diagram of System Design. This figure highlights the interconnections between the Arduino, ODrive controllers, and motors, enabling precise control over the robotic base's movements.

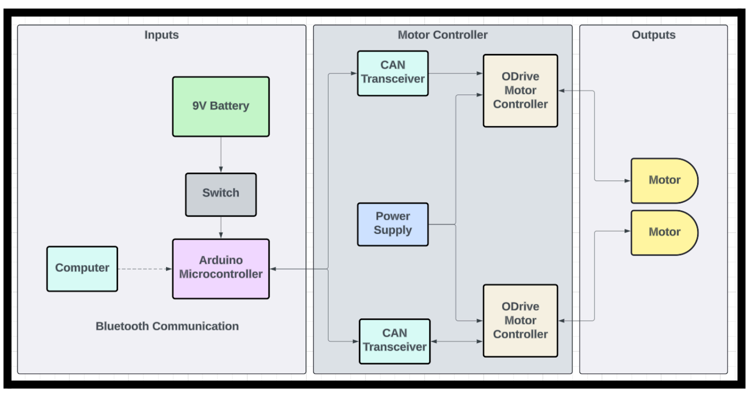

Figure 2: Software and Electronics Architecture Block Diagram

The frame design is another important aspect of the system. The mechanical frame is designed using CAD software and constructed from 80/20 T-slot aluminum. This material is selected for its strength and flexibility, allowing for easy adjustments and modifications. The frame is designed to maintain a low center of gravity, enhancing stability during operation. **Figure 3**, the CAD Model of Robotic Base, provides a detailed view of the frame design, showing the overall structure and placement of key components. Additionally, **Figure 4**, the CAD Model of the Bottom Plate of the Robotic Base, shows the detailed layout of the base plate where key components such as the motors, controllers, and battery are mounted. These CAD models are essential for ensuring that all components fit together correctly and that the structure can withstand the operational stresses it will encounter.

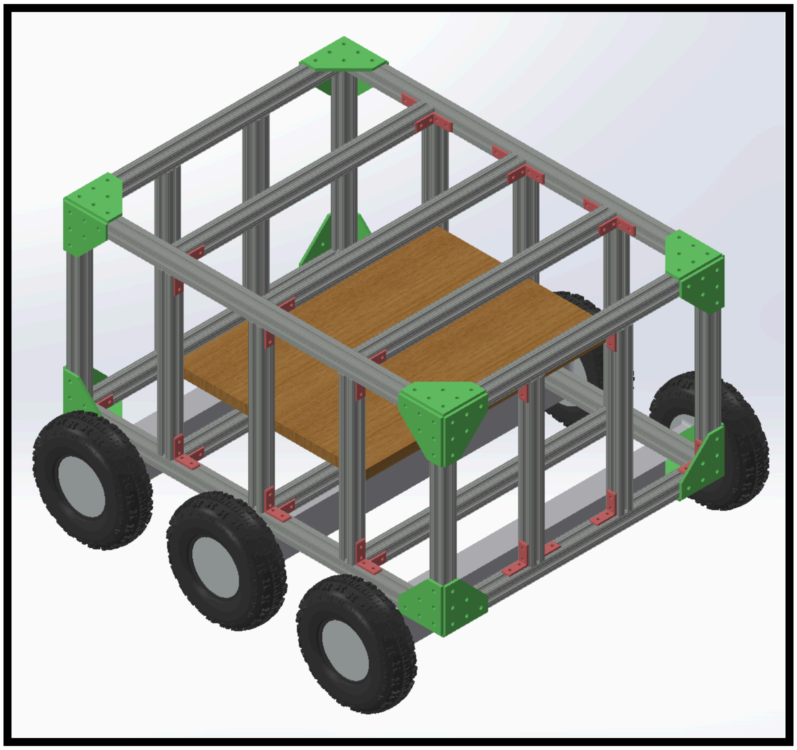

Figure 3: CAD Model of Robotic Base

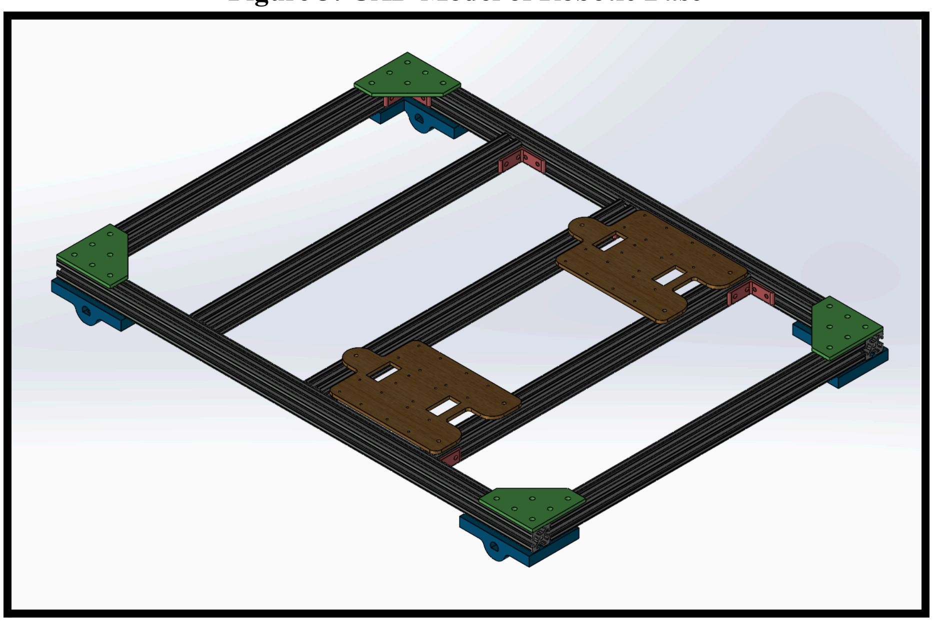

Figure 4: CAD Model of Bottom Plate of Robotic Base

For the Communication system, we initially attempted to use Bluetooth modules to allow the robotic base to be controlled remotely using PlayStation 5 (PS5) controllers. However, this was replaced with a serial communication setup due to time constraints. Currently, the Arduino reads input from a computer, which is communicated using serial commands then the appropriate commands are sent to the ODrive controllers. **Figure 5**, the Communication Setup, depicts the communication flow between the control interface and the robotic base, illustrating how signals are transmitted and processed. This short snippet of code shows the setup and the control of the base.

```
if (Serial.available() > 0) {
  char input = Serial.read();
  if (input == 'A') {
      current_position += POSITION_INCREMENT;
      odrv1.setPosition(current_position);
      delay(10);
      odrv0.setPosition(current_position);
      delay(10);
      odrv2.setPosition(current_position);
      delay(10);
      odrv3.setPosition(current_position);
  } else if (input == 'B') {
      current_position -= POSITION_INCREMENT;
      odrv1.setPosition(current_position);
      delay(10);
      odrv0.setPosition(current_position);
      delay(10);
      odrv2.setPosition(current_position);
      delay(10);
      odrv3.setPosition(current_position);
  }
}
```

Figure 5: Communication Setup

Throughout the project, several challenges were encountered and addressed. One major challenge was finding motors with sufficient torque output. Through extensive research, we were able to identify motors that met the project's requirements. The selected BLDC motors, with ODrive controllers, provided the performance we were tasked to achieve. Another significant challenge was ensuring stability when the robotic arms were fully extended and under full load. Extensive calculations were necessary to make sure the base maintained stability. A distributed weight system was incorporated into the design, with additional weights placed to counterbalance the robotic arms. The motor control setup faced countless issues with documentation and untrackable datasheets and also achieved consistent performance, which was resolved through extensive testing and adjustments in the ODrive controllers.

During the development process, several alternative design choices were considered and tested. Different motor types and controller setups were tested but never met specifications and often never had enough information to be correctly applied. For example, various motors were tested to make sure when we received our final motors we could simply plug them in and the system would work, but the vast majority of motors didn't have easily accessible datasheets making it extremely hard to find necessary information for controlling the motors. As shown in **Figure 6**, we tore apart the robot that inspired the entire design process. We gathered the motor and motor controller, however these parts would be extremely difficult to integrate into the mobile base.

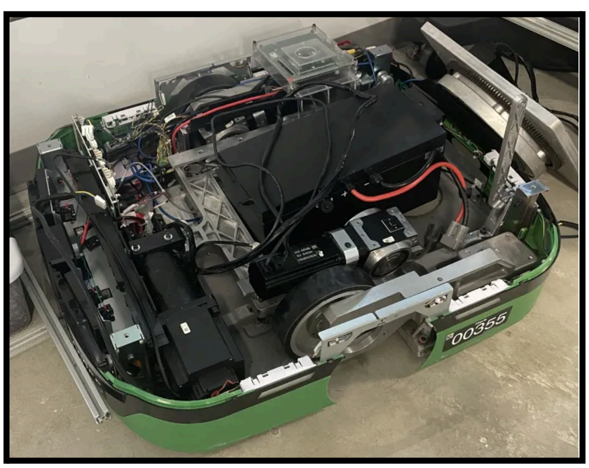

Figure 6: Torn Down Inspired Robot in ARCLab

We finally found a working motor which we could then fine-tune our design around, which was used for our ODrive motor controller as shown in **Figure 7**. When our motors finally arrived, they were hoverboard motors with no datasheet (due to the time constraint of 10 weeks we needed to find already implemented motors and take them apart for our implementation, or else the motors wouldn't arrive in time) however we were able to guess the correct parameters after a long period of guessing the values associated with the motor.

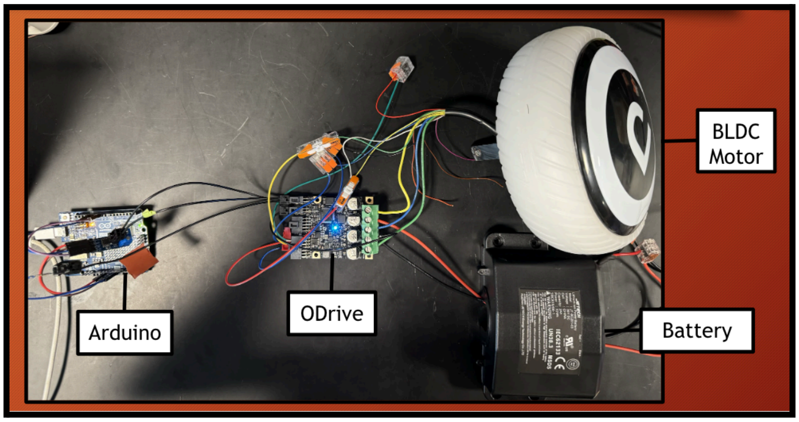

Figure 7: Extensive Motor and Controller Testing

Construction Phases

The frame base was constructed from the design and physics calculations, including stability calculations, which included full and minimal extension considerations, and ensuring ADA guideline compliance. These initial steps ensured that the frame would be stable and capable of supporting the necessary components. **Figure 8**, shows some of the calculations for the base frame and requirements for the component research, the first equation shows the equation for determining the weight of the robot to keep the COM at the center of our robotic base. We realized the weight would need to be 391 pounds to keep the COM the same, so we switched to the 2nd equation to calculate how much the COM would change if we added 130 pounds of weights closer to the back of the base, this resulted in a shift of COM of 3.41 inches towards the arms, from here we can determine the normal force which would results on each wheel due to this shift in the center of mass, for this, we used the 3rd equation along with the knowledge that the total normal force on the wheels must equal to the total weight of the system. From here we found the normal force on each wheel. From the normal force on each wheel, we can find the torque maximum per wheel before the wheels begin to slip. This comes from the 3rd equation which shows the static friction equation. The 5th equation is for wheels we found that would only give the power of the motor, the Torque can then be calculated and the 4th equation shows the relation of torque between the wheel and the force it can output. The last equation shows the equation to find how high of an incline the base can accelerate up before it cannot, this was used to determine the ADA guideline.

$$\boxed{x_1 m_1 + x_2 m_2 - x_3 m_3 = 0}$$

$$\boxed{N_{\text{front}} \cdot (L - d_{\text{COM}}) = N_{\text{rear}} \cdot d_{\text{COM}}} \quad \boxed{F_{\text{wheelmax}} = \mu \cdot F_{\text{normal}}}$$

$$\boxed{F_{\text{wheel}} = \frac{T}{r}} \quad \boxed{T = \frac{P}{w}}$$

$$\boxed{F_{\text{required}} = m \times g \times \sin(\theta)}$$

Figure 8: Physics Equations / Calculations

Following the stability calculations, the construction of the electronics plate and motor mount began. These components were critical for mounting the various electronics and motors securely to the frame. The electronics plate provided a stable platform for the Arduino Uno R4 WiFi microcontroller, ODrive Pro controllers, and other essential components. The motor mounts were designed to securely hold the high-torque BLDC motors in place. **Figure 9** shows the design of the electronics plate and the motor mount.

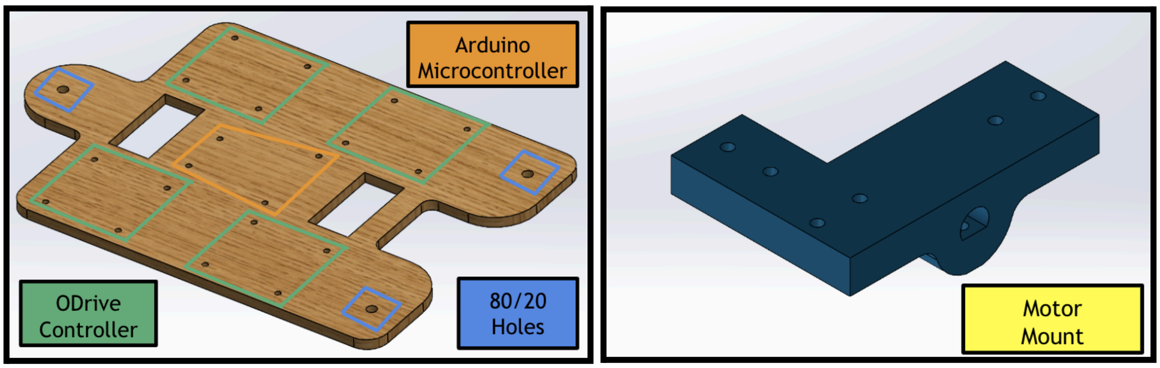

Figure 9: Electronics Plate (Left) and Motor Mount (Right) CAD Model

With the CAD models, starting the construction of the 80/20 frame that is shown in **Figure 4** is required. This allows for the electronic plate and motor mounts to be mounted. This is shown in **Figure 10**. The construction of the frame allows the fabrication of the electronic plate and motor mounts, which are then placed onto the frame with fasteners. Once the electronics plate and motor mounts were attached to the frame, the next step was to add the electronics themselves. This included wiring the Arduino microcontroller, ODrive controllers, and motors. The wiring had to be meticulously planned to avoid interference and ensure reliable communication between components. **Figure 10** shows the process of adding electronics to the frame and highlights the complexity of the wiring setup.

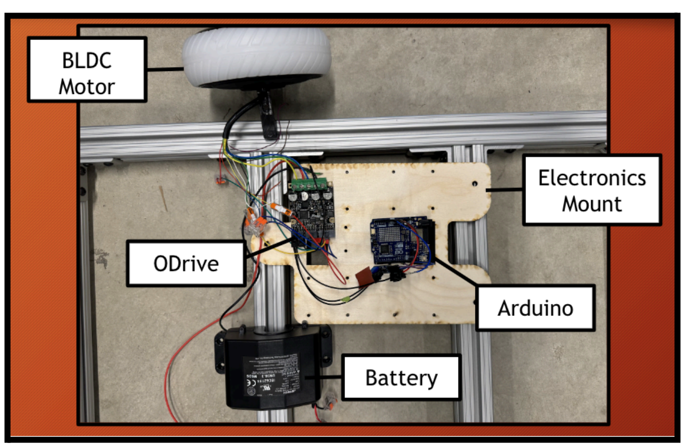

Figure 10: Physical Implementation of One Motor on 80/20 Frame

With the electronics in place, the next phase involved setting up motor control. This was a critical step to ensure that the motors could be controlled precisely and responsively. This is shown in **Figure 11**, which shows the motor velocity and motor position vs time plot during the calibration of the motors. We had issues with Bluetooth connectivity and decided to switch to serial communication for more reliable control. **Figure 12** illustrates the setup for motor control, highlighting the use of serial communication between the computer and the Arduino, and from the Arduino to the ODrive controllers.

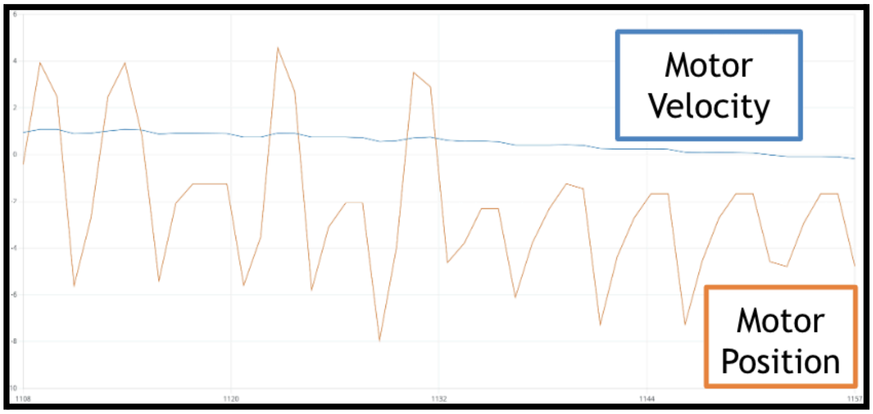

Figure 11: Plot of Motor Velocity and Motor Position vs Time of Hoverboard Motors

```
if (Serial.available() > 0) {
  char input = Serial.read();
  if (input == 'A') {
      current_position += POSITION_INCREMENT;
      odrv1.setPosition(current_position);
      delay(10);
      odrv0.setPosition(current_position);
      delay(10);
      odrv2.setPosition(current_position);
      delay(10);
      odrv3.setPosition(current_position);
  } else if (input == 'B') {
      current_position -= POSITION_INCREMENT;
      odrv1.setPosition(current_position);
      delay(10);
      odrv0.setPosition(current_position);
      delay(10);
      odrv2.setPosition(current_position);
      delay(10);
      odrv3.setPosition(current_position);
  }
}
```

Figure 12: Setup of Motor Control Serial Communication from Arduino to ODrive

The final design of the mobile robotic base is a robust and flexible platform capable of navigating various terrains and performing precise movements. The system is designed for rapid deployment in emergencies, providing reliable performance in rescue operations. Key features of the system include stability and maneuverability, achieved through the use of high-torque motors, precise control systems, and a well-balanced frame design. Remote control is enabled through serial communication, allowing operators to control the base from a safe distance. Additionally, the power management system ensures a continuous and stable power supply, which is critical for maintaining performance during extended operations.

Challenges and Solutions

The development of the Mobile Robotic Base for Human Rescue involved extensive iterative testing to refine the system and overcome various challenges. One significant hurdle we encountered involved the extensive testing required for the motors and controllers. We did not have access to the correct headers and wires for our controllers with limited time to source them. As such we had to use less-than-ideal connections for our motors which made configuring them more difficult. These connections were measured using an oscilloscope. Ideally, the reading should just be a voltage reading from 0 to 1 and then back to 0, which shows a bit has been transmitted, however, that is not the case as shown in **Figure 13**. There was a lot of noise in these readings which led us to issues properly connecting our motors to the controller and microcontroller. Lack of documentation and incorrect documentation were major issues we encountered. Without proper documentation of the motors, we were unable to calibrate the motors with the motor controllers. We eventually found a motor with the correct documentation and were able to successfully get a motor running. After getting the motor configured we ran into issues controlling them due to incorrect documentation. The documentation for our Arduino stated the TX and RX pins were in different locations than they were. This information lead take apart our entire system before realizing the documentation was incorrect. Additionally, logistical issues such as order delays for components posed challenges, impacting the project timeline. Despite these hurdles, we were able to persist and systematically test our components to create a robust and reliable system, ready to be further developed into the overall rescue system.

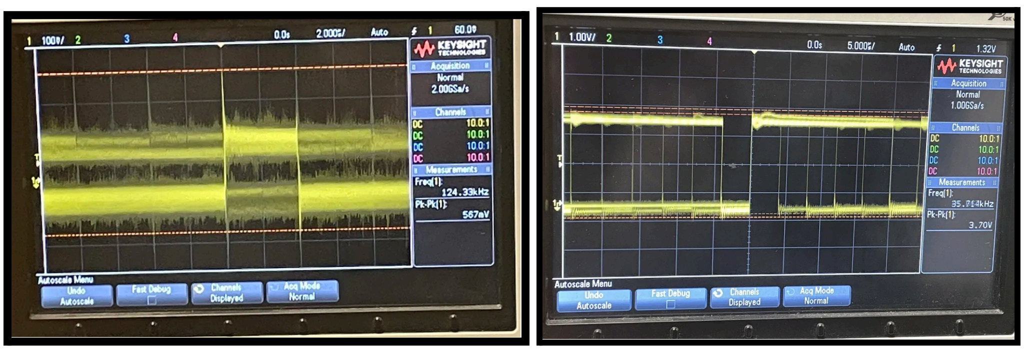

Figure 13: Oscilloscope Readings of Serial Communication Terminals (RX, TX Pins)

Results

Prototype Development

We successfully developed a functional prototype shown in **Figure 14**, integrating all our components with control capability through a computer connection. The only specification we were unable to attain was the full remote control for the base. The microcontroller we selected advertised Bluetooth capabilities, but the Bluetooth libraries for the controller are still being developed, and there is little documentation regarding its Bluetooth integration. This problem was exacerbated by the late arrival of our motors which made us unaware of the issues with the microcontroller and unable to pivot to another solution. Our mentors and ourselves are still wildly enthusiastic about our finished prototype. Our comprehensive design considerations and choices guided our construction and produced a base that is ready to be further developed into the overall rescue system being developed by ARCLab.

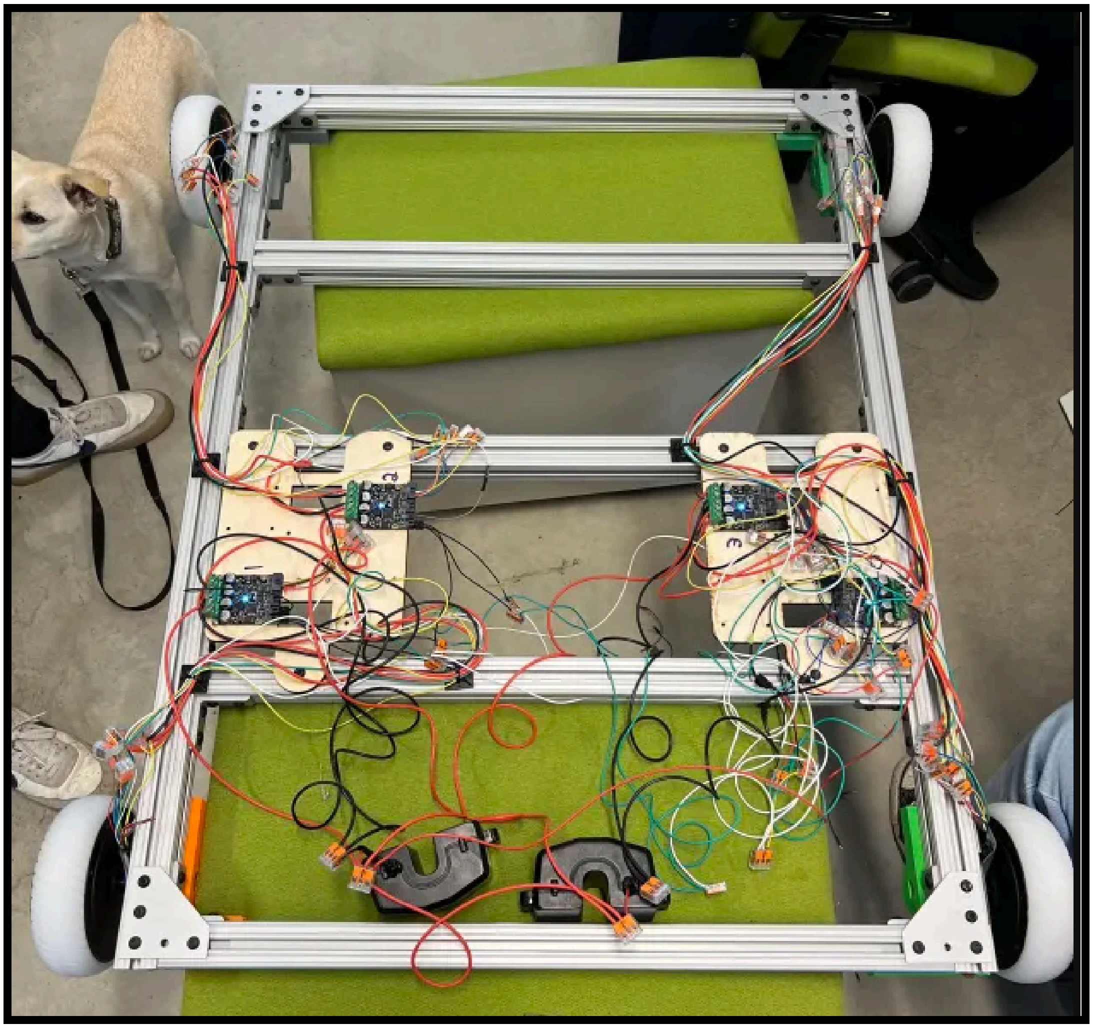

Figure 14: Finished Product

Testing and Validation

Extensive testing was conducted on our motors to ensure proper functioning. **Figure 11** shows readings of the motor position and velocity which we used to ensure proper motor behavior with our control inputs. The iterative testing process was performed for all four motors and motor controllers. This testing was crucial as the motors we were given had no documentation, and as such we had to rigorously calibrate and test them to make our system robust and responsive to our controls.

Project Impacts

Social and Economic Impact

The main impacts of our project lie in the economic and social spheres. Human-robot interaction is a newly developing field that has promise in redefining many aspects of life. For the field of human-robot interaction to grow systems like ours that are safe and serve a great purpose must continually be developed and deployed into their use cases. Specifically related to our project, there is only one system that is comparable to the robot being developed by ARCLab[2]. This system does not consider the safety and biomechanics of the person being rescued, has cost millions of dollars to develop, and hasn't been worked on for over a decade. We have developed a base that can be constructed with relatively cheap components while being robust and replicable. Systems like ours have the potential to open the door for cost-effective systems to be developed and expand the field of human-robot interaction.

Conclusion

Accomplishments

We were successful in developing a mobile robotic base. We were able to configure four separate motors, integrate them into the frame of our base, and control them via a computer connection. The base can move in any direction and is a helpful proof of concept for the future development of this project. Besides remote control which could have been addressed if our motors arrived on time, our prototype meets the design requirements we were originally presented with. Our team's efforts in designing and integrating components and controls through extensive testing and problem-solving have resulted in a functional and effective robotic system.

Social Impact

As previously mentioned, our project has the potential to greatly impact society. A fully developed system capable of rescuing individuals impacted by combat, natural disasters, or other tragedies spotlights the potential of robots to improve efforts such as search and rescue along with sparking conversation of what other applications of robotic systems could be applied to improve our quality of life.

Future Work

Future teams should focus on refining the prototype and enhancing its capabilities. More advanced control systems could be developed including a fully remote controlled implementation or algorithmic pathing. Improved steering systems, like Ackermann steering, could improve the mobility of the base, and adding a suspension system to the base would improve its performance in adverse conditions.

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Appendix A

List of Parts

This appendix includes all of the hardware components chosen for this project.

- ODrive Pro (motor controller)
- Arduino UNO R4 WiFi (microcontroller)
- SN65HVD230 CAN Board (CAN transceiver)
- WAGO (wire connectors)
- Jetson Pixel Hoverboard (motors and batteries)
- 80-20 T-slot aluminum extrusions (base frame)
- Motor mounts (3D printed)