ECE496 Capstone Final Report - Group 515

Project Name: Remote-Controlled Robot

Team Number: 2022515

Supervisor name: Belinda Wang

Supervisor name: Nick Burgwin

Students:
An Yu 1004797400
Jintao Xu 1003888509
Kevin Liu 1004891165
Hongliang Wang 1003797019

Executive Summary (An Yu)

This report outlines the motivation, design, implementation, and testing of a remote-controlled robot designed to reduce physical travel for individuals with disabilities in large corporate buildings. The project aimed to provide a cost-effective and capable solution for indoor delivery.

The final design met all project requirements, including a remote vision of 480p resolution or higher, a payload capacity of 1 kg, operation for at least 2 hours, and indoor mobility including ramps of at least 10 degrees. The robot was able to deliver items autonomously and stream live video footage to the user interface application.

The software design includes a communication module, user interface, and robot software. Socket programming is used for remote access, and communication is done in a TCP/IP format. The user interface provides options for connecting to the robot, opening the robot camera, choosing the mode of operation, and instructions. The robot software handles connection requests, camera requests, and directional control. The camera module streams live video footage to the user interface application. The hardware includes a Raspberry Pi, a motor driver, a battery, and a camera module. The robot's mobility is ensured with four wheels and four DC motors, controlled by the Raspberry Pi's GPIO pins through a motor driver.

Future work includes improving the robot's design and software to make it more user-friendly, robust, and capable of operating in more complex environments. In conclusion, the project was a success, and the remote-controlled robot has the potential to greatly improve indoor delivery in various other settings, including hospitals, airports, and other large buildings.

Individual Contributions

Jintao Xu

- Conducted extensive research on existing remote delivery robots to inform design
- Developed initial concept and design for the robot, incorporating feedback from team and stakeholders
- Conducted thorough testing and debugging of the robot's functionality, working closely with joystick controller, power control, internet connection, and video transmission to identify and fix issues
- Faced challenges of managing team workload and ensuring effective contribution, addressed through prioritizing tasks and delegating responsibilities based on team members' strengths and availability
- Learned importance of collaboration and communication, thorough testing and debugging, and taking a user-centric approach in design and development

An Yu

- **Software**
    - Desktop app
        - Designed and implemented the desktop interface that allows users to connect to the robot, provide directional input, and access instructions.
        - Implemented socket programming to connect to the remote robot through any wifi network.
        - Implemented APIs to handle commands and receive video, and used multithreading to ensure smooth and simultaneous communication between the robot and the desktop app.
    - Communication protocol
        - Designed and implemented the communication protocol between the robot and the desktop app.
        - Encoded the transmitted data into JSON format strings and decoded them in the robot's software using marshaling and unmarshalling.
        - Transmitted commands to their corresponding locations and functions in the robot's software, and defined the robot's response to each signal.
- **Hardware**
    - Robot control (Raspberry Pi)
        - Developed and wrote the robot control software that allows the Raspberry Pi to receive information and communicate with the desktop app through socket programming
        - Wrote and Integrated the camera module into the robot control software for live video streaming
        - Implemented the first linear version of mapping of directional signal (x-y axis) to the speed of the 4 wheels from -100% to 100% (my teammate did an improved sinusoidal version later)
        - Wrote the first version of GPIO helpers that translate the wheel power signal to pin voltage to control the wheels of the car.
    - Shell and electronics
        - Designed using Solidworks and 3D printed the first version of the robot's shell and electronics in the fall (my teammate did the second version)
        - Conducted cutting, drilling, and the installation of the bottom cap of the robot. Utilized Velcro tapes for attaching the bottom cap to increase maintainability as recommended by the instructor.
        - Connected wires to their corresponding GPIO ports.
- **Communications**
    - Contact person for all admin and supervisor communications and managed meeting & presentation arrangements

Kevin Liu

Kevin is the primary contributor of the team. He accounted for over half of the entire work on the project. He is involved in almost every aspect of the project and was the one that pulled all the pieces together to form a presentable final result.

- **Software**
  Kevin constructed the grand infrastructure and backbone of the software system. Contributed to over eighty percent by fraction of the team's code repository, and enabled everything to work.
  - Wrote majority of GUI.
  - Wrote network connection and server operations code.
  - Wrote camera capturing and remote streaming code.
  - Wrote vehicle control and HID joystick driver code.
  - Wrote user-to-robot network interfacing protocol.
  - Revised vehicle driver, and GPIO operation code.
  - Contributed in writing scripts for Raspberry Pi eduroam connection, and Raspberry Pi run program on startup scripts.

- **Hardware**
  Kevin designed the robotic vehicle's onboard systems, selected and bought parts for both the prototype vehicle and the final design. He is the director of vehicle assembly.
  - Designed the 3D printing craft model for final design.
  - Selected motors and wheels based on calculation.
  - Planned and sourced all accessories for assembly, including stand-offs, bolts, nuts, screws, wire, plastic heat-inserts, ribbon cables and more. Had taken care of all nuances of details in hardware assembly.
  - Planned and pre-printed device mounting brackets and all mounting holes.
  - Contributed in processing and submitting 3D files for printing in MyFab.
  - Major contributor in physical assembly of both the prototype and the final design.

Hongliang Wang

- I am mainly responsible for the hardwire of the robot and parts of software.
  - Hardware:
    - Design the final 3D prototype and print it
    - Assemble the robot car together from the scratch
  - Software:
    - Test the robot for moving at the very beginning
    - Enable the speech-to-text module locally (not integrated into UI interface)
- I created the time management spreadsheet to ensure the whole team is moving forward smoothly.
- I created detailed drawings and diagrams to communicate the design to the team and ensure that everyone was on the same page.

1. Introduction

1.1 Background and Motivation (An Yu)

In today's modern world, large corporate buildings have become commonplace for many people to work in. However, traversing these buildings can be a challenge, especially for people with permanent or temporary disabilities. These individuals move slower and often have to follow accessibility paths, making the process of delivering items across rooms even more cumbersome. Even for able-bodied individuals, the time it takes to move from one end of the building to the other can be considerable; for example, a round trip in one of Facebook’s corporate offices takes 30 minutes [1].

We want to address this problem by designing a solution to help people with disabilities and reduce the need for physical travel as much as possible indoors. Currently, off-the-shelf affordable robotic vehicles are mostly incapable of traveling long distances when users don’t have a direct line of sight to them [2]. Additionally, products that satisfy the requirements for such a solution are prohibitively expensive, with typical prices reaching around $170,000 as of November 2021 [3]. Therefore, we aim to design a capable and affordable solution to tackle this delivery problem ourselves.

1.2 Project Goals and Requirements (An Yu)

The goal of this project is to reduce physical travel for the user as much as possible. Some of the tasks users do in the office are lunch, delivering documents, and checking out events in the building.

To achieve this goal, we need to design and construct a means of remote-controlled robot that can see around the building, and also deliver items from one place to another autonomously in an indoor environment, without the need for users to travel to their destinations physically. To achieve this goal, we have established the following requirements.

Table 1. Project Requirements and Metrics

Requirement	Metric
Remote vision	480p resolution or higher
Payload capacity	1 kg (typical office supplies)
Battery life	Operate continuously for at least 2 hours
User friendly interface	UI should be intuitive for easy operation without tutorials.
Cost-effectiveness	Total cost of the project < $400
Mobility	Capable of traveling indoors including ramps of at least 10 degrees

These requirements will serve as the foundation for our design and testing processes, ensuring that the robot we develop meets the needs of our users and operates efficiently in an indoor environment.

2. Final Design

2.1 System-level overview and block diagram (Hongliang Wang)

The details of the system overview are separated into two sections: hardware implementation and software implementation [Figure 1]. In terms of the robot's hardware, the vehicle's primary hull is 3D printed with holes for mounting electronic equipment and routing cables. Regarding onboard devices on the electronic module, a microcomputer platform (with Wi-Fi capability) is utilized to control and execute software on the robot. We use the Raspberry Pi as our microcomputer platform, and all the other components are connected to it. Different ports connect to different hardware devices, such as a camera and motor controllers. Through motor controller circuits, the onboard computer's output will operate the four wheels of the robot. In order to enable safe remote driving, the computer is also connected to a camera and a number of additional sensors. For the power and motorization subsystem, the entire system is powered by an assortment of lithium polymer battery banks.

For the software component, we allowed the robot to move remotely by connecting them to the public internet in a communication module. Coordination between machines utilizes socket programming to establish a TCP/IP connection between the client and the Raspberry Pi server, as well as marshaling and unmarshalling information. Additionally, a new user interface is introduced to the app to make it easier for the user to control the robot. Besides, The software of the robot manages connection requests, camera requests, and direction control.

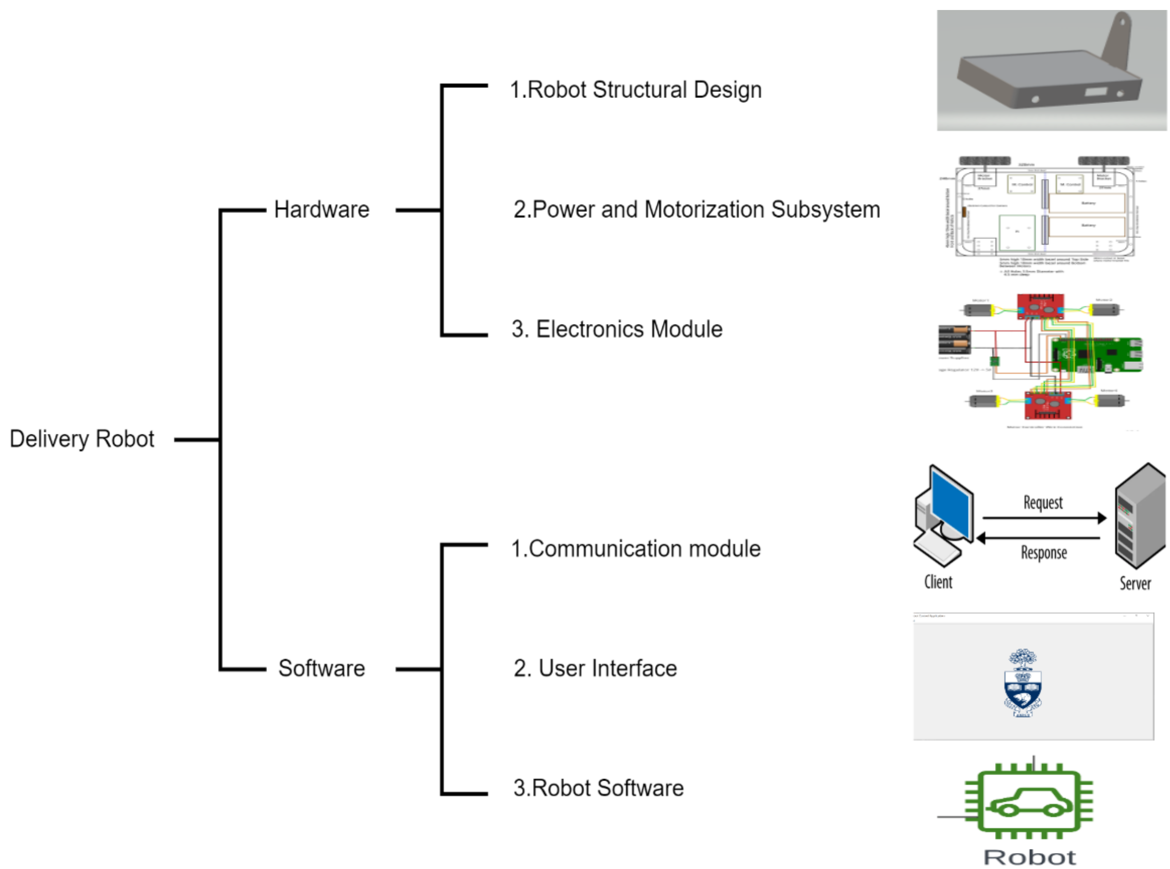

Figure 1 System-level block diagram

2.2 Hardware Descriptions and Designs (Kevin Liu)

The hardware design of the robot includes both the mechanical design of the robot structure and its motorization systems, as well as all the onboard electronic devices. To achieve our goal, a means of indoor cargo transportation without involving physical movement by the user, a robotic car has been chosen as the best design. The car has 4 wheels and is powered by rechargeable batteries. The design of the onboard electronic systems enables the vehicle to be remotely controlled by a user via Wi-Fi. In this section, the detailed approach of designing the robot's hardware will be covered

2.2.1 Robot Structural Design

The hull of the robotic vehicle is printed using a single piece of 3D PLA plastic. Due to the mechanical strength of said material, the thickness of the robot's wall is designed to be 4 mm in width. Printing in a single piece significantly improves the overall rigidity of the hull, and simplifies the assembly.

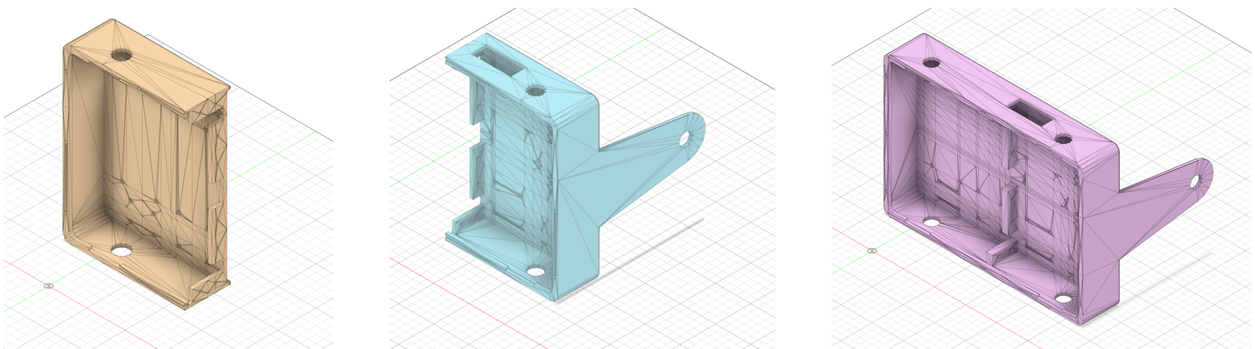

Figure 2. Hull Assemblies of the Robot

However, due to limited 3D printing capabilities, the hull structure had to be printed in 2 separate pieces in our prototype, and be joined together using bolts and nuts connected through prefabricated holes. The onboard devices of the robot will be contained within the cavity of the structure (shown in the forward facing side in Figure 2). The cavity will be covered by a rectangular thin wooden board after the assembly is finished, leaving no internal devices nor wiring visible from outside.

The cargo will be placed on top of the printed robotic hull (shown in the far side in Figure 2). The area of the cargo holding surface is 320x225mm, large enough to accommodate A4, and letter sized paper, iPad Pro (2022), or regular size textbooks. A thin rounded bezel of 0.5mm is raised on the border of the cargo holding surface to prevent items from sliding off.

2.2.2 Power and Motorization Subsystem

The vehicle is driven by 4 active motors for maximized controllability and grip on uneven surfaces. The four wheels are 87mm in diameter, one of the largest sizes we were able to buy. It was discovered in tests that big wheels make driving more stable compared to smaller wheels. The specification of the selected electric motors has theoretical performance of carrying 4 kg of weight on a 10 degrees sloped terrain uphill continuously on full throttle.

Two motor controller l298n is selected as an interface between the onboard computer and the 4 wheels. Each motor controller controls 2 wheels via PWM modulation, and the controller will, as a secondary functionality, output 5V DC as the power for the onboard computer.

To power the motors together with the vehicle's onboard electronics, two 6200mAh lithium polymer batteries are used. This capacity makes the calculated battery life of the vehicle just over 2 hours, assuming full motor power. Since the batteries are rated at 7.4V output power and the motors are rated at 12V, a 100W DC-DC buck-boost converter is used to supply the motors with their specified voltage.

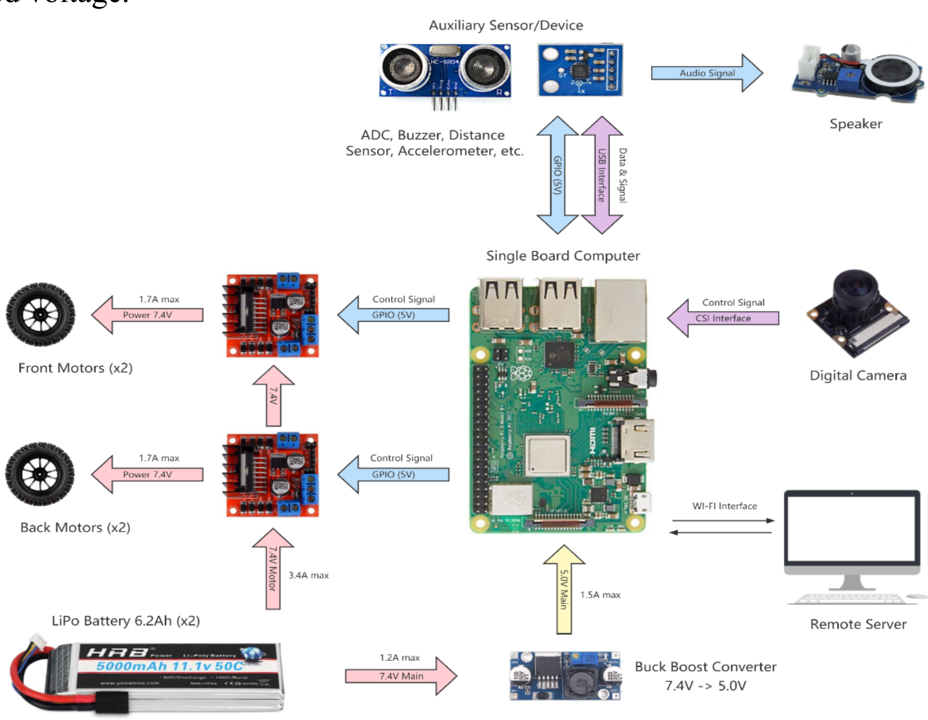

Figure 3 Block diagram

2.2.3 Electronics Module

The vehicle has an onboard single board computer powerful enough for real-time video encoding at 1080p 30Hz, while consuming about 5 watts of power or less. The computer also has a built-in Wi-Fi module for communication. There are a variety of choices of such devices. Due to availability, Raspberry Pi4 model B is used to provide the computation power for the vehicle.

A single wide-angle camera is mounted at the front of the vehicle on top of a rig structure. The camera is 23 cm away from the ground at its position. With a 160 degree field of view, the camera will enable the user to clearly observe the surroundings of the vehicle to drive safely. The robot has 60 frames per second capturing capability. However, due to bandwidth limitations, to achieve the best visual experience, a capture rate of 30fps is used instead for better picture quality.

2.3 Software Descriptions and Designs (An Yu)

The software design of this project can be divided into three parts: robot software, user interface application, and communication protocols.

2.3.1 Communication module

For communication, we developed an app that acts as the client and the Raspberry Pi as the server. Socket programming is used for the connection between the client and server, which allows for remote access. Communication is done in a TCP/IP format and involves a three-way handshake when a connection is made. To avoid congestion, video transfers from the camera are done in another port.

To transmit information and commands in a binary format, we defined a communication content protocol for a JSON format string for both the client and server. Information and commands are marshalled into a binary string when transferred over the internet and unmarshaled and parsed after the receiver receives them.

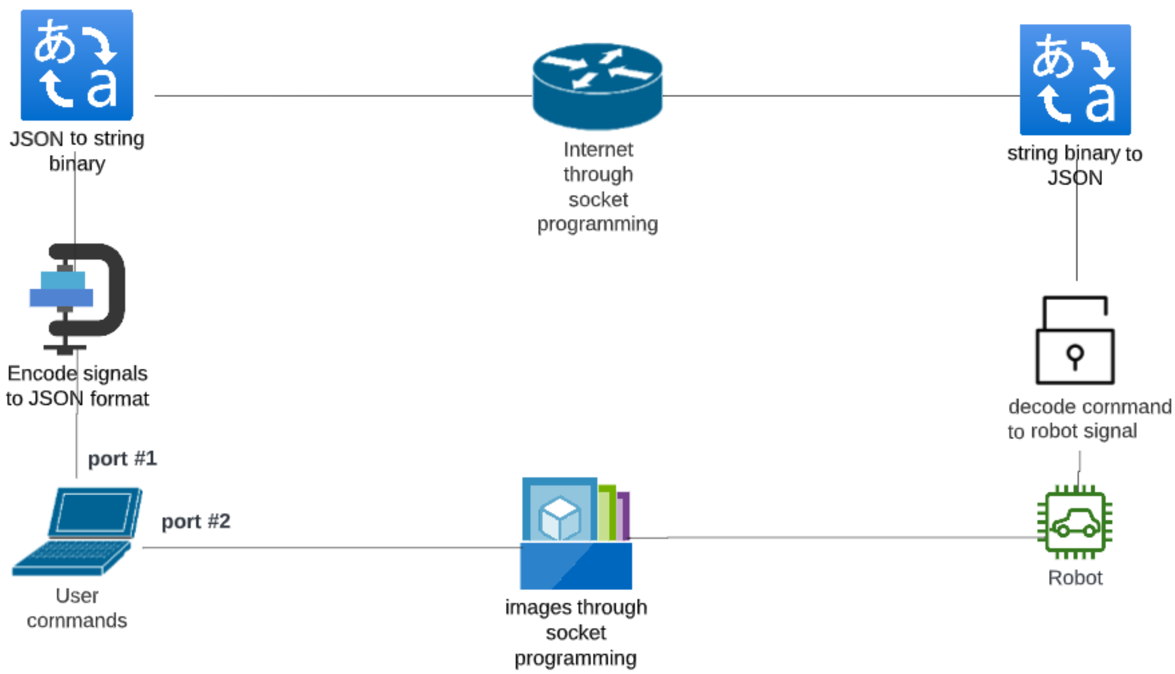

Figure 4. Communication module between user application and robot software

2.3.2 User interface

Our interface provides the user with options to connect and disconnect with the robot, open the robot camera, choose the mode of operation, and instructions. To allow for precise control of the robot, we enabled the user to plug in a joystick for analog precise directional control and gradual power increase. Joystick input is read by the user interface app using the pygame module. The app then parses the joystick input values, which are analog in two axes, and fine-tunes them to a formula to convert them into corresponding motor signals so that the turn and power are as desired.

Additionally, the user interface app utilizes multi-threading to handle user commands and accept messages and video signals from the server. This means that the user can control the robot and receive video feedback at the same time without any delay or interference. We have also designed the interface to be user-friendly, eliminating unnecessary options for the user and only displaying mandatory options such as connect, open camera, and modes of operation.

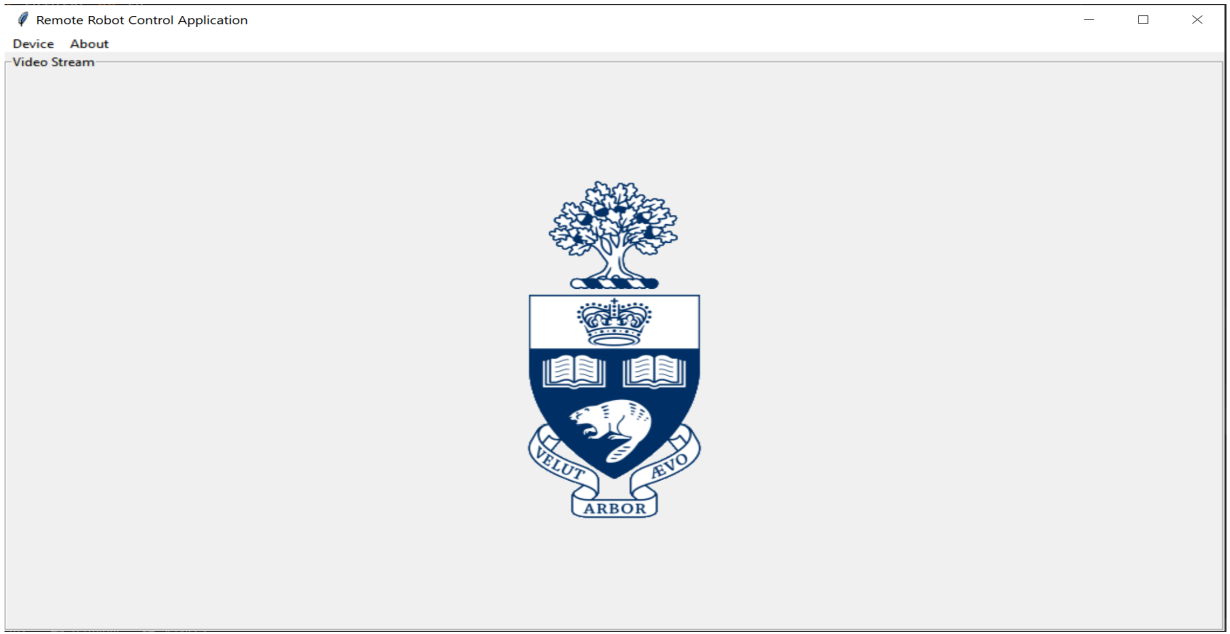

Figure 5. Remote Control User Interface

2.3.3 Robot software

The robot software is responsible for handling connection requests, camera requests, and directional control. The user inputs directional commands, which can be analog in two axes. These inputs are fine-tuned using a formula to convert them into corresponding motor signals so that the turn and the power are desired. The robot software then outputs these motor signals in analog format (0-100%) to the corresponding 12 GPIO ports, which control the motors.

The robot software also manages the camera module, which streams live video footage to the user interface application. The robot software provides a programming interface to the camera module, allowing the user interface to request and display video. The camera module captures the video feed using an onboard camera and streams it to the user interface application via a separate port to avoid congestion with other communication data.

2.4 Assessment of final design (An Yu)

After iterating the design multiple times, we were able to create a final design that met all project requirements. We made several changes, including swapping out wheels that were not suitable for the weight, changing the motors for increased payload capacity, and modifying the 3D-printed shell to ensure the stability of the motors.

Overall, we are pleased with the final design, which successfully addressed the problem of reducing physical travel for individuals with disabilities in large corporate buildings. However, there is always room for improvement. For instance, we noticed that users still need to connect to the robot when it starts, which could be streamlined in future versions.

3. Testing and Verification (Jintao Xu)

Table 2. Verification and testing results

Requirement	**Verification Method**	**Verification Result and Proof**
Video resolution rating (480p@30Hz)	The video quality will be measured with one app SpeedTest, and the latency will be checked for 1 hour during the robot's working condition. The test will pass if the resolution rate is kept the same or exceeds 640x480p@30Hz, and the latency is always less than 500 ms.	PASS, Verified, The robot is capable of transmitting at a resolution of 640x480p@60Hz with an average latency of approximately 450 ms.
Payload capacity (can carry 1 kg cargo of A4 paper size, flat)	Fully charge the vehicle's battery before the test. With an empty vehicle, test its controllability in a typical indoor environment: drive in straight lines in a hallway, turn left and right around corners under full speed, parking to full speed transition, and full speed to break transition. The vehicle should be responsive to the user's command and without the danger of tilting or flipping over. Then, load the vehicle with 1 kg of cargo (a stack	The robot can carry up to 1 kg of cargo, but it is not designed for straight-line movement due to changes in the vehicle's balance caused by the shifting cargo.

	of A4 printing paper/ notebooks/ iPads, etc.). Repeat the test described in the previous paragraph, and check for the controllability and stability of the vehicle. Additionally, the payload must not be endangered by the frisk of falling off the vehicle. As a stretched objective, taller and less stable cargo, with 1 kg mass in total will also be tested. This may include coffee cups with liquid, water bottles with a lid on, etc.	
Battery capacity and longevity (2 hrs of operation at max speed)	Fully charge the vehicle, then place it upside down with 4 wheels free to spin. Ramp up the motor speed to 100% and start a timer. After the first hour, do the following check every 10 minutes: place the vehicle upright on its wheels and load 1 kg of cargo onto it. Then, check if the vehicle is able to drive under the load. If affirmative, flip the vehicle to the upside-down position again and keep running the motor at 100%. Repeat the check until the vehicle is no longer capable of driving at half of its speed at full charge. Then the time of the last checking prior will be the effective battery life. The test shall be repeated at least 2 times and results averaged.	PASS, Verified, the robot is capable of functioning at its highest speed setting for a period of two hours without stopping or malfunctioning.
User friendly interface	“click depth” test: Evaluate the number of clicks to reach for any command on the app interface	PASS, Verified

	less than or equal to two	
Mobility · Driving speed rating (walking speed, or 5 km/hr). · Terrain slope rating (can climb uphill 10° slope)	After a full battery charge, load the vehicle with 1 kg of cargo. Put down a start and a finish line in a straight indoor hallway, 10 meters apart. Move the vehicle to 1 meter before the start line (distance for initial acceleration). Start the vehicle and drive it across the start and to the finish line. Use a stopwatch and a recording camera to independently measure the duration and cross-validate measurement results. For the climb testing. Place the vehicle on a 10° sloped surface. Rotate the vehicle to face 4 different directions and check to verify the vehicle will stay in place (and not slide down) when parking on the ramp.Then, the vehicle is placed downhill off the ramp. Start the vehicle and drive it uphill. Verify if the vehicle can climb the 10° slope for at least 5 meters in horizontal distance. The robot's speed will be measured with a velocimeter on different types of floor conditions (carpet, wooden floor, cement floor) in the working condition. The test will pass if the speed reaches the same level.	PASS, Verified, Actual speed is 5.4 km/hr under the wood floor condition, and it has been tested and demonstrated the ability to climb a 10-degree incline.

Figure 6. Testing Driving speed rating under the wood floor condition

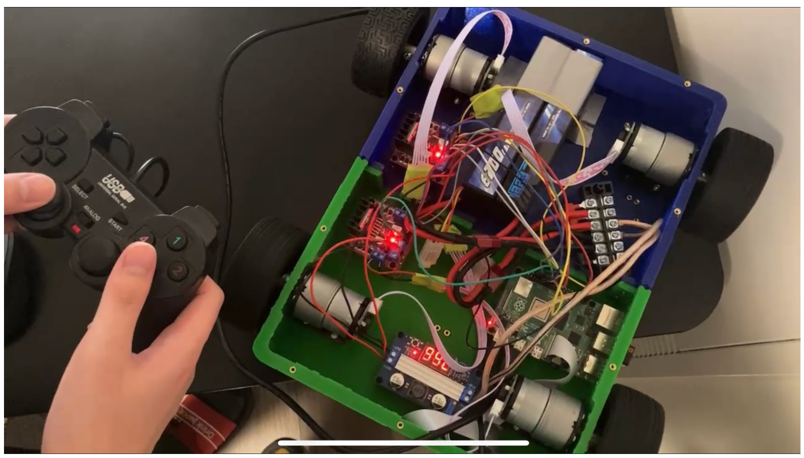

Figure 7. Motor power control & Internet environment evaluation

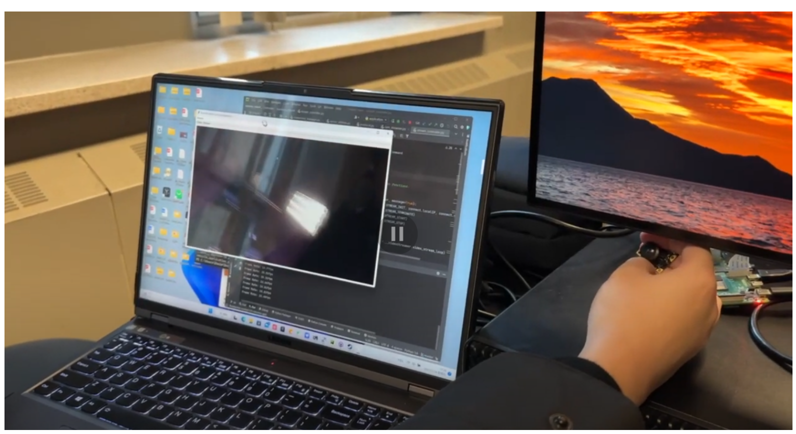

Figure 8. Video Transmission & Video resolution rating

Robot testing can involve testing the robot's ability to operate under different network conditions, including Internet connectivity, as well as joystick control and video transmission.

Internet connectivity testing can include assessing the robot's ability to operate and communicate with other devices over various network conditions, such as slow or unreliable Internet connections. This is important for ensuring that the robot can continue to operate effectively even in areas with poor network connectivity. Joystick control testing can involve assessing the robot's ability to respond to user commands and movements, and ensuring that the joystick controls are responsive and intuitive to use. This is important for enabling operators to control the robot effectively and efficiently. Video transmission testing can involve assessing the robot's ability to capture and transmit high-quality video feeds of its surroundings to a remote location. This is important for enabling remote monitoring and control of the robot, and ensuring that the operator has a clear view of the robot's surroundings.

Overall, testing the robot's ability to operate under different network conditions, joystick control conditions, and video transmission conditions etc. It is important for ensuring that the robot can perform effectively and reliably in a range of scenarios.

4. Summary and Conclusions

Our Remote-Controlled Robot addresses the problem of reducing physical travel for individuals with disabilities in large corporate buildings, by providing a cost-effective and capable solution for indoor delivery. The robot was designed to have a remote vision of 480p resolution or higher, a payload capacity of 1 kg, operate continuously for at least 2 hours, and be able to travel indoors including ramps of at least 10 degrees.

The project goals and requirements were met as demonstrated through testing and validation. The robot was able to travel indoors, climb ramps of at least 10 degrees, and deliver items autonomously. The robot met the 480p remote vision requirement, with the ability to stream live video footage to the user interface application. The robot also met the 1 kg payload capacity requirement and operated continuously for at least 2 hours. The robot was cost-effective, with a total project cost of less than $400.

The ideas presented in the project worked out as the robot successfully addressed the problem of reducing physical travel for individuals with disabilities in large corporate buildings. However, future work can be done to improve the robot's design and software to make it more user-friendly, robust, and capable of operating in more complex environments.

The key conclusion to be drawn from the project is that a cost-effective and capable solution can be developed to tackle the problem of reducing physical travel for individuals with disabilities in large corporate buildings.

Future work can be done to improve the robot's ability to navigate complex environments, such as using machine learning algorithms to help the robot recognize objects and avoid obstacles. Additionally, the robot can be made more versatile by adding features such as voice control and autonomous navigation. Other potential applications of this work include indoor delivery for hospitals, airports, and other large buildings.

5. References

[1] R. Brustein, "What these photos of Facebook's new headquarters say about the future of work," The Washington Post, Nov. 30, 2015. [Online]. Available: *https://www.washingtonpost.com/news/the-switch/wp/2015/11/30/what-these-photos-of-facebooks-new-headquarters-say-about-the-future-of-work/. [Accessed: Apr. 5, 2023].*

[2] “RC Car Motor, 2 set DC motor wheel kit 6V 280rpm high speed electric motor + toy car tire wheel + mounting base + set screw for Smart Car Robot Arduino raspberry pi,” *Amazon.ca: Toys & Games*. [Online]. Available: https://www.amazon.ca/Electric-Plastic-Mounting-Arduino-Raspberry/dp/B088FR7LST/ref=sr_1_1?crid=3KKZ5VNG5BTX7&keywords=raspberry%2Bpi%2Bwheel%2Bmotor&qid=1663619848&sprefix=raspberry%2Bpi%2Bwheel%2Bmotor%2Caps%2C228&sr=8-1 . [Accessed: 26-Oct-2022].

[3] “Delivery and service robots,” *Segway Robotics*, 21-Oct-2022. [Online]. Available: https://robotics.segway.com/. [Accessed: 26-Oct-2022].