HomeRover

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Abstract—**A system capable of providing a simplistic method of item retrieval for individuals who have found their mobility compromised. Our design will employ a rover with a suction arm capable of lifting items and a user-side control terminal both powered by a software system running on a Raspberry Pi. It is a household friendly product that has a low cost compared to competitors and a low learning curve.**

Index Terms—**Depth camera, kinematics, LiPo battery, motor, NMOS, object detection, printed circuit board, Raspberry Pi, rover, torque**

I. Introduction

ACROSS the United States, approximately 39 million Americans face motor impairments [1]. According to Pew Research and ACS estimates, around 7% of Americans have difficulty walking or climbing stairs, characterized as serious ambulatory difficulties. Increased likelihood of this kind of disability increases with age, with adults aged 75 and older and those aged 65 to 74 as the most impacted age groups [2]. A crucial consequence of these ambulatory difficulties is an increased susceptibility to falls as well as difficulty getting in and out of chairs, with emergency departments seeing 3 million older patients each year due to fall injuries [3]. Thus, these affected individuals face challenges to their autonomy, with their condition potentially getting exacerbated by the need to constantly bend down and pick things up.

Current solutions for object retrieval face three main shortcomings that revolve around the two types of existing solutions. Physical, handheld living aids, such as a grabber arm or claw, have a very limited range due to being capped by the user's arm length. Robotics solutions such as TidyBot can utilize vision models with large language models to automate the room cleanup process [4]. However, this solution only exists in a research capacity, being a joint venture with Google and three leading universities. Thus, these robotics solutions are not commercially available and due to the nature of the research, likely require large amounts of funding as well.

To address these limitations and serve our target audience, we propose a cost-effective, intuitive method of object retrieval for individuals with mobility challenges. Taking the form of a user-assisted autonomous robot, it features an interface for user navigation of the rover to an object's general vicinity, autonomy in operating within the vicinity to pick up the object, and the ability to return the object back to the user. By removing their need to pick things up, we hope to ease their ambulatory difficulties and improve their health and quality of life.

II. Use-Case Requirements

Our device is intended for individuals who find their mobility compromised. For our design to be practical, it must be effective in the home environment. From this use-case, we have determined that the rover we are designing needs to be capable of navigating in a room that is approximately 216 square feet because this is the average living room size in the United States [5]. Based on previous robotic systems that have picked items up around the house and research on user experience we have determined that the device needs to be successful 80% of the time for the best experience [6].

Furthermore, our target demographic is the older population, and we are not aware of their familiarity with modern technology. Because of this we have determined that our device needs a user control side that is very tactile and mechanical feeling. From our research and measuring keys on a keyboard we have determined that the keys on the user side need to be at least the size of the keys on a computer keyboard: approximately 0.75 inch by 0.75 inch [7]. For the best user experience, we also need a display on the user side to allow the user to navigate. We need the latency between the camera on the rover and the user display to be less than 0.1 seconds (100 milliseconds) because this is the time that User-Interface and User-Experience has determined that this is the threshold for seemingly instantaneous interaction with a device [8].

Finally, to meet the requirement of being a household device, we need the rover to be capable of navigating at safe speeds around the house and to be able to navigate on different household terrains. We have determined that hardwood, tile, and carpet flooring are the three main types of flooring that almost every house in the United States has. We have also determined that the rover needs to have an absolute maximum speed of 0.5 meters per second because this is the approximate maximum household speed of the iRobot Roomba [9]. In addition to having safe navigation speeds, we need the electronics to be protected from spills in our design and the total cost of our design to be less than $450. We determined that $450 is the ideal maximum price because this is right around the same cost as the cheapest Roomba model on the market [10].

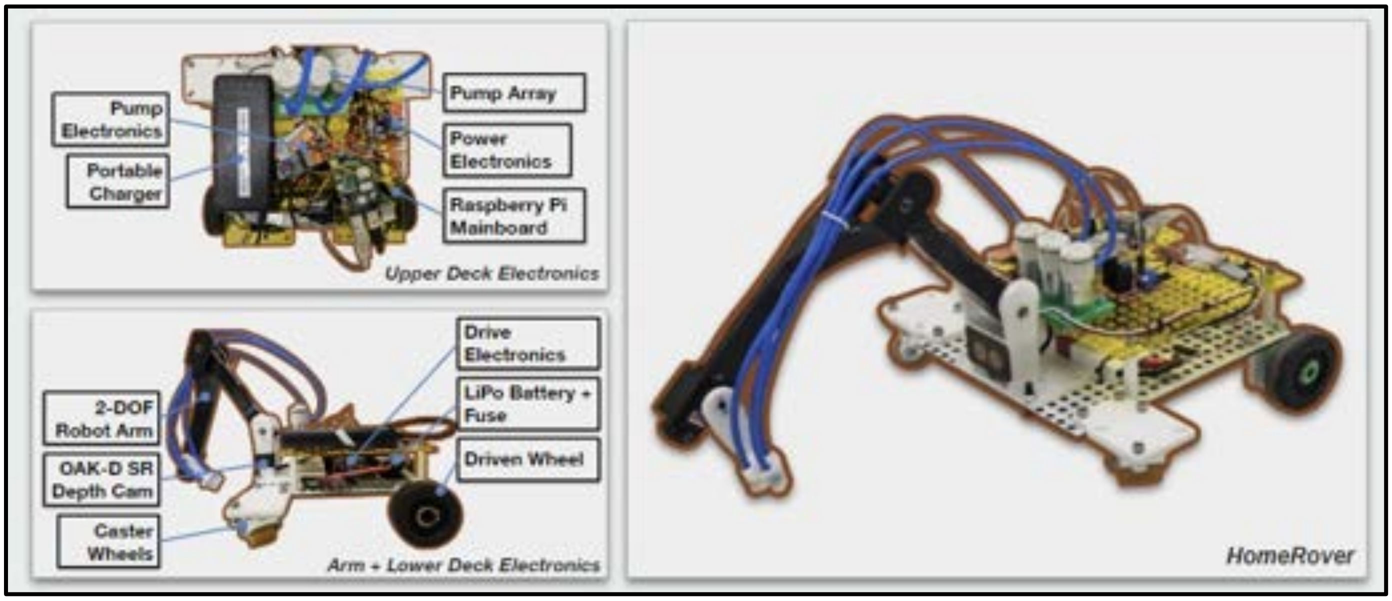


Figure 1. Annotated Picture of Complete HomeRover.

III. Architecture and/or Principle of Operation

A. Changes from Design Report:

The major changes as compared to the design report come mostly from the Rover side. In terms of electronics- The robotic arm parts of the robot have not changed in terms of the electronic mechanism that is used to pick up the objects, other than the power now coming directly from battery voltage. The Pump Array is now powered by a custom Logic-Level and PMOS circuit, that allows for battery voltage to power the pump motors. Additionally, rather than using a Raspberry Pi Pico to drive the Drive Motors, we use an Arduino Nano, for its 5-Volt logic-level capabilities.

Mechanically speaking, both the arm and camera are now centrally aligned. We now use caster wheels in the front of the robot, and the arm design has simplified quite a lot. We'll go much more in depth in the System Implementation section (section VI).

B. Principle of Operation:

The entire system that we design can be surmised in a single, overarching operation, which uses every subsystem on the block diagram on the following page. When the user drives the robot towards the object they desire to pick up and begin the pickup sequence, there are quite a few steps involved.

First, the user must drive towards the object. This involves using the Controller PCB to give controls to the Raspberry Pi, and the Rover responding appropriately. The user can observe the position of the Rover relative to the object of interest, based on live camera feed from the OAK-D SR, which is displayed on the mini-monitor. Once in range (30 cm), the user presses the Pickup button on the Controller to begin the pickup sequence. Once the button is pressed, the robot gathers data from the OAK-D SR to navigate the robot arm to the correct pickup location. Once the end effector of the robot is near the object, the pumps are activated, and the object is retrieved. The user navigates the robot back to themselves, then presses the give button, which extends the arm to the highest point possible, such that the user can pick the object up.

C. Architecture:

The system can be divided into two subparts, as highlighted on the Block Diagram. On the User-Console-Side, the Raspberry Pi serves as the brain of the system, and a portable charger serves as power. It takes in input via a custom-designed control PCB, which is constructed to be simple for our target demographic. The PCB has an integrated Arduino Nano, whose only purpose is to translate the key presses, which are binary switches connected via GPIO, to USB, such that the Raspberry Pi will be able to interpret them in an efficient manner. Additionally present on the Console side is the mini-HDMI monitor, whose purpose is to display the camera feed that HomeRover sees as it moves to the user.

Once the signals from the Controller are interpreted, they are sent via TCP/IP to the Raspberry Pi 4 on the Rover-Side subsystem. Additionally, Rover Signals, such as RETRY and ACK and NAK are interpreted on this board.

Within the Rover-Side subsystem, there are two overarching goals: Rover Movement and Item Retrieval. To achieve Rover Movement, control signals are taken from the User-Console-Side Raspberry Pi 4 and are forwarded to the Raspberry Pi Pico, which offers the necessary opportunity of a low-latency, bare-metal implementation of a control loop to drive the Rover. Achieving the goal of Item Retrieval is a much more complex process. As determined by the user, when it is time for the Rover to attempt retrieval, the arm will move to the closest object detected in its field of view via a series of kinematic instructions. The coordinates for this movement come from the OAK-D SR and are translated to kinematic instructions on the Raspberry Pi 4 mainboard. Controlled by the Raspberry Pi Pico is the Pump Array. The control for the Array is simple - a PMOS transistor is controlled by a GPIO pin of the Pico, which, when the pumps need to be activated, allows for the circuit to be completed. At this time, the object should indeed be retrieved and in the Rover's grasp.

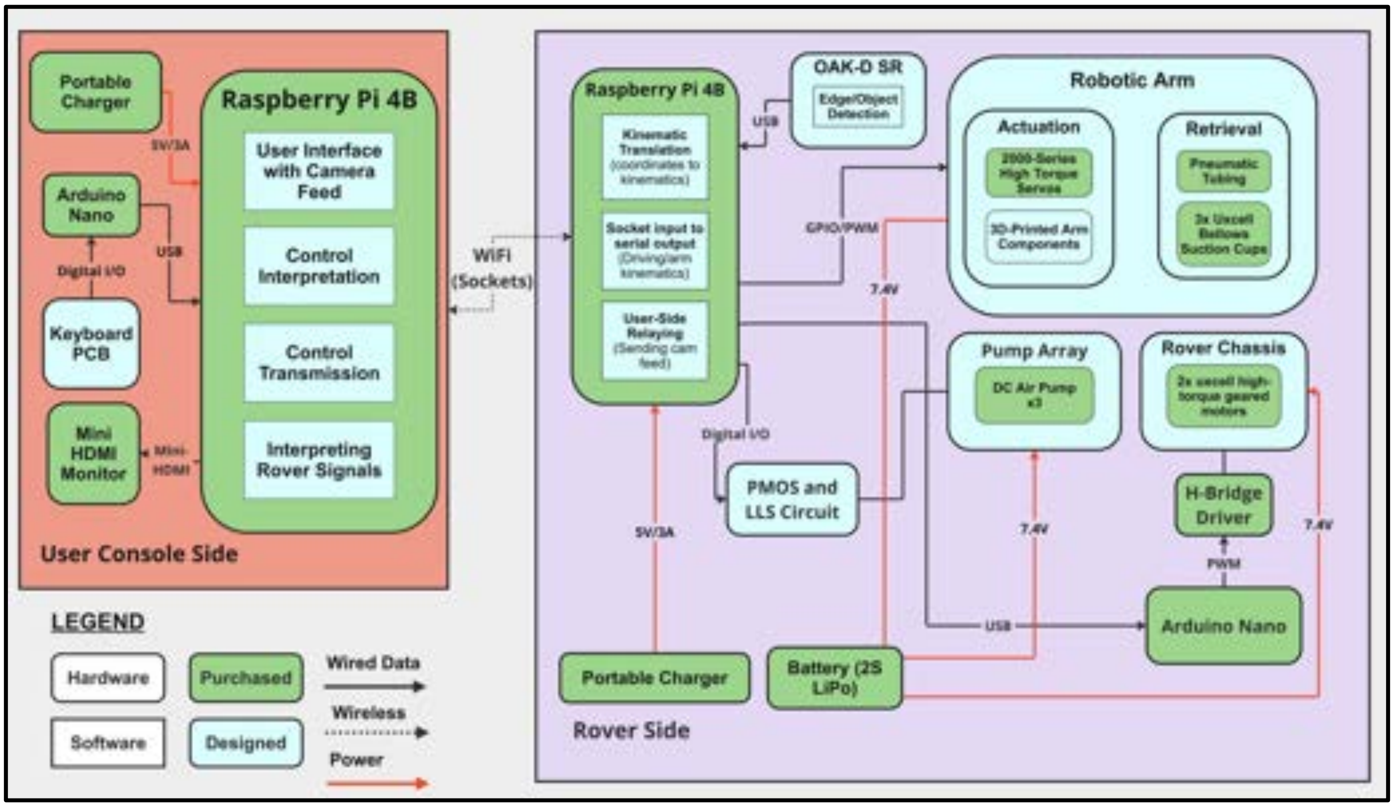


Figure 2. Overarching Block Diagram of HomeRover System.

D. ABET Addition for PI 1-3, 1-4, 1-5

A large principle of engineering used in the HomeRover final product was that of power electronics. The system required adequate power and voltage going to every component such that said component could indeed do the task that was required of it. This required intense planning on our part, where we needed to make sure that certain rails would not over-current the battery onboard. Another principle used in HomeRover was multithreading processes. When we ran our program utilizing the camera script for the first time, we saw that one of the three cores on the Raspberry Pi was being utilized at 100%, which allowed for a very small neural-network frame rate. We were able to multithread this process and ensure that the systems could run efficiently. Additionally, we indeed did use the principle of “breaking down big problems into different components that get implemented separately”. By treating the OAK-D SR coordinate retrieval as a black box, it was trivial to establish the connection between the camera and the arm, to drive the arm to the location given by the camera.

The prime principle that picks up the object of interest is fluid dynamics. The DC pumps on the upper deck electronics of the HomeRover work via a voltage difference that drives the motors. When the impeller of the motor turns three rubber lungs, that rapidly move air into and out of the motor, which then allows for the object to be latched onto. When the air in the pipes is moved out of the pipe, the atmospheric pressure outside of the silicone suction cups allows for grip to be established on the object. With this principle, the arm can lift the object. A principle of mathematics used in this project was inverse kinematics. It allows us to translate the X and Y coordinates given to us by the depth camera to angles at which to rotate the servos and is used in robotics to accomplish the same task with general position. In our case, our kinematics are in two degree-of-freedom, which allowed us to simplify the calculation required to move the arm to the object of interest.

IV. Design Requirements

Our design requirements stem from our use-case requirements of accuracy, usability and being a household friendly design.

Accuracy: We need the object identification, claw positioning and arm suction system to execute with 80% accuracy. When the button is pushed to pick up an item the system needs to position itself and execute the task of picking up within 10 seconds. We arrived at these metrics from the capabilities of a similar but more advanced robot the TidyBot which was developed by a team of engineers at Princeton University [4]. We have established the item pickup range to be between 10 centimeters and 30 centimeters because of the length of the arm we have designed and the capabilities of the OAK-D SR camera. In addition to the accuracy of the picking up mechanism, we need the rover to be capable of detecting and picking up planar objects such as books, tablets and medicine boxes and keeping the suction for the entire time the user is returning the rover to them. Because of the requirement to be able to pick up a tablet we determined that the suction system needs to be capable of picking up 700 grams which is the approximate weight of an iPad with a case [11]. To maintain the suction on an object that weighs this much we have determined that we need to have a pump capable of providing 2.21 pounds per square inch of suction pressure to the suction cup and the subsequent item we are picking up. These calculations come from the area of the suction cups being 0.70 square inches or approximately 4 and a half centimeters squared.

Usability: Another important requirement is the usability of the system. We need the entire system to be user friendly and easy to understand for an older individual who does not necessarily have prior experience with modern technology such as smart phones. We have determined that driving the rover needs to be something that anyone can get comfortable with in under 10 minutes of driving. To achieve this, we have decided to go with a very tactile design with four arrow keys and two buttons for the rover to grab an item and to release the item to the user. In addition to having large buttons, we think that latency is a very important factor for a usable device. From our research on User-interface and User-experience we have found that 0.1 seconds is the time for something to be seemingly instantaneous and less than 1 second for it to feel like the user is interacting with a computer [8]. Because of this metric we have determined that we want the Raspberry Pis to communicate with each other over Wi-Fi in under 100 milliseconds. We have also determined that we need the electrical signals from the buttons being pressed to make it to the user side Raspberry Pi in under 20 milliseconds and for signals being sent out from the Rover side Raspberry Pi to propagate in under 20 milliseconds. The sum of these three paths gives us a critical path of 140 milliseconds between the user pressing the forward button and the rover reacting and moving forward. In addition to latency being important for the user experience, we have determined that we need the user to be able to see what the rover sees for the best navigation. Our design will have a Raspberry Pi screen which will display this to the user and will notify the user when they are within the previously mentioned range of 10 to 30 centimeters. We have also determined that battery life is a very important consideration for the usability of this product. We believe that 1 hour of driving between recharges is the minimum battery life we should achieve. To achieve this our design needs to use a 2S LiPo battery with a minimum of 7000 milliamp hours. We determined this by summing the power consumption of all devices on the rover and found that we needed 10,860 milliamp hours if we were to run the device at full speed, with the suction always on and maxing out the processing capabilities of the Raspberry Pi and the OAK-D SR camera; this is not something that will occur in the usage of the rover so 7000 milliamp hours or greater will suffice.

Household friendly design: Since we are targeting use in a household setting it is very important for our design to be safe while still being capable. To achieve this, we have determined that we need the rover to have an absolute maximum speed of 0.5 meters per second; we arrived at this limit based on the maximum speed of a Roomba [9]. While the maximum speed will be 0.5 meters per second, we are trying to target a slightly slower speed of approximately 0.3 meters per second because this is the speed Roomba's normally operate at within a home. We need this driving speed to be achieved on all three types of flooring we have identified: carpet, hardwood, and tile. In addition to the safety aspect of driving speed we have also determined the rover needs to be made from durable materials that will not cause damage to household objects if it collides with them. Because of this, we have decided to 3D print most of our design and only use metal for the bottom mounting plate which will be the structural basis. Lastly, we need the total cost of our design to be less than $450; this price is close to the cheapest iRobot Roomba on the market [10].

V. Design Trade Studies

For our design we had to consider many factors when choosing how to solve our problem: we had to figure out the pick-up mechanism, we had to figure out the drive train and steering methodology, we had to choose an adequate type of sensing, we had to determine communication protocols and we had to select hardware powerful enough to execute the computations we want the rover to perform.

A. Pick-up mechanism

As previously mentioned, we need our suction pick up mechanism to be capable of lifting 700 grams. Given this metric we know the force acting down on our suction mechanism can be determined by the equation:

$$F = mg \tag{1}$$
$$F = 0.700 * 9.81 \tag{2}$$
$$F = 6.867\ N \tag{3}$$

We get a resulting force of 6.867 Newtons. This result will allow us to calculate the pressure we need to create within our suction tubes to be able to pick up an item and offset the forces of gravity. Furthermore, we know that pressure can be determined by the equation:

$$P = F/A \tag{1}$$
$$P = 6.867/0.00045 \tag{2}$$
$$P = 15260\ N/m^2 \tag{3}$$

Giving us 15260 Newtons per square meter or approximately 2.21 pounds per square inch. From this we determined that a servo powering a syringe to create suction would be capable of achieving the necessary pressure to lift this item; however, we realized that stability would be an issue if we used only one suction cup, so we decided to scale up our design to 3 suction cups in a triangular arrangement to stabilize the arm with larger items. Our design did not have room for the footprint of three large servos so we determined that our best option was to use DC power air pumps which would create the suction directly with a smaller footprint.

B. Drive Train

Safe and efficient navigation is vital to the success of our design. There were 3 main categories we discussed: steering methodology, suspension type and motor layout.

Steering Methodology:

We began by discussing different forms of drive trains for a rover; among these we considered differential steering, tank drive, omnidirectional drive, and Ackermann steering. We immediately ruled out Ackermann steering because we wanted to 3D print modules for the wheels and having a steering axel would complicate our design. We also ruled out omnidirectional drive because the kinematics would be unnecessarily complex for the design we are trying to create. This left us with differential steering and tank drive. Differential steering and tank drive are very similar, both involve different rotations per minute for each side of the rover. Our research led us to believe that tank drive, which is often referred to as skid steering, is bad for driving across carpet. Because we want to be able to drive across all types of flooring, we decided that differential steering is ideal for our setup, and we designed our drive train as such; we eventually modified the drive train to have caster wheels which further enhanced the differential steering.

Suspension type:

After we determined the steering methodology, we began researching different suspension types that would allow us to navigate around a house. We discussed Rocker-Bogey suspension, and dependent suspension. We quickly realized that using Rocker Bogey suspension, while being able to help us balance the rover and offset the weight of the suction claw at the front, would be overly complex and unnecessary for our use-case requirements. We decided that a dependent suspension with 2.5-inch wheels would be able to navigate all the terrains we deem necessary for the success of the rover.

Motor Layout:

After we had settled on a suspension and a steering methodology, we were able to determine the motor layout we wanted to employ. When we were designing this part of the drive train we used to methods of analysis: calculations for the rover speed and cost analysis. To start we needed to determine the necessary rotations per minute to achieve 0.5 meters per second; from this we would be able to find a motor and a gearbox and finish designing our drive train. The equation we used to calculate the rotations per minute necessary is:

$$v = \frac{(\pi D)x}{60} \tag{1}$$

Where v is the velocity of the rover, D is the diameter of the wheels and x is the resulting rotations per minute we need to achieve our velocity. Plugging in our requirements we get:

$$0.5 = \frac{\pi 0.0635x}{60} \tag{2}$$

$$x = 150 \text{ RPM} \tag{3}$$

And when we solve for x, we determined that the necessary rotations per minute we need for our design is 150. After we determined this speed, we were able to look for motors and we found the uxcell Gear Motor with Encoder DC 12V 201RPM Gear Ratio 21.3:1 which was perfect for our design. Given the cost of $20 we determined that purchasing two motors was more than sufficient and then we designed a drive train that included an inline timing belt which would keep the driving kinematics simple. We placed the motors at the back of the design going with a Rear-Wheel Drive system to offset the weight of the claw at the front.

C. Sensing

Arguably one of the most important subsystems crucial to the success of our design is the concept of sensing, particularly of camera choice. Being able to both detect an object in the general vicinity of our rover as well as being able to output useful information to dictate our arm movement is of utmost importance to achieving our mission and serving our use case.

When choosing an adequate camera, we considered numerous types of cameras before choosing the OAK-D SR camera, each with their own set of limitations that shied away from the OAK's advantages. The first main difference between the OAK and other cameras was the presence of on-device capabilities. Using the OAK's RVC2 chip, it is capable of running custom AI models, object detection, video/image encoding, 3D edge detection, and 3D feature tracking, to name a few [13]. According to the Luxonis documentation, RealSense stereo cameras do not have any of these capabilities on-device [12]. Due to the constrained timeline of the project and managing a reasonable scope, we thought the presence of these on-device features would make the software and detection more achievable while remaining a challenge in figuring how to correctly establish a pipeline and interface with these different features.

Another main difference between the cameras was the method each camera used to perceive depth. For an OAK-D, this takes the form of passive stereo depth perception, which uses "disparity matching to estimate the depth of objects and scenes" through the usage of a stereo camera pair [14]. The reason this is favorable for our application was because disparity matching is unsuitable for blank, featureless surfaces, making its highest efficacy occur in the contrast of an object and its blank surrounding, our proposed use case. On the other hand, most commercial cameras utilize lasers to determine depth, specifically through 2D LiDAR. One such example is the suite of projects made by LSLIDAR, whose 2D LiDAR "is designed to emit only a single beam onto the target object" [15]. What this means that through this single 2D sweep and resulting 2D plane, if we were to use these cameras, we are limited by the height of our object, and it could be less effective on irregular shaped objects that flit in appearance with the 2D plane. Thus, using the OAK and its stereo depth perception, we can scan more effectively for a specific object.

D. Communication Protocols

To achieve full interconnection with the various parts of our system, such as transmitting control signals from the user side to the rover side, sending ACK/NAK/RETRY signals from the rover to the user to establish fault tolerance, and sending the camera live feed from the rover to the user, we need a robust wireless communication paradigm. The specific aspects we identified as the advantages of interest are the throughput and range of the protocol.

Protocol [16]	Throughput	Range	Latency
Wi-Fi	11 Mbps	32m indoors	150ms
Bluetooth	800 Kbps	5-30m	200ms

Table I: Table showing analysis of Wi-Fi and Bluetooth Protocols

Because of our requirement of sending a live camera feed, our most emphasized category is throughput/bandwidth. As shown in the graph, the data rate for Wi-Fi is much higher than that of Bluetooth, which was a primary factor in influencing our design decision in enabling our mini-HDMI camera on the user side. In addition, the increased range in Wi-Fi is significant in that it will allow for a good signal throughout our user space of a typical living room. This has the additional effect of enabling a high data rate because with a consistent, high signal, there will be less timeout and retry periods. Additionally, in a noisy environment, being able to broadcast a strong signal will lead to increased communication strength, which is especially important in RF-heavy areas. Lastly, we also observe that Wi-Fi has lower latency than that of Bluetooth, which highlights how Wi-Fi better suits our latency metrics in our design requirements by aiming for a more responsive experience for the user with the faster message passing within our full system.

E. *Hardware*

When choosing hardware for the design we knew we needed a computer that could receive the camera footage processing an object detection algorithm and calculating the kinematics for the suction claw. Because of this requirement we determined we needed a single board computer rather than a smaller device such as a microcontroller. When we were determining what type of computer we would need we were choosing from a Jetson Nano, a Raspberry Pi 4 and the AMD KRIA KR260. When choosing from these computers we considered the factors of cost, performance, and power consumption.

Computer	Cost	Performance	Power Consumption
Jetson Nano	$149	Middle	+5V, 2A
Raspberry Pi 4	$55	Worst	+5V, 3A
AMD KRIA KR260	$350	Best	+12V, 3A

Table II: Table showing analysis of Single Board Computers

Overall, all these boards would have been capable of running the software interface on the rover side, but we determined that the Jetson was overkill because we do not plan on utilizing its machine learning and artificial intelligence capabilities. We also determined that the power consumption of the AMD KRIA was too much for our design and that the price was significantly out of our range; we also would not be using nearly enough of the processing power of the AMD KRIA to justify the cost or the increased power consumption. This led us to the Raspberry Pi 4 which would be sufficient for our design with 4GB of ram and the Broadcom BCM2711, Quad core Cortex-A72 (ARM v8) 64-bit SoC. After we decided on this board on the rover side of our design, we determined that putting the same board on the user side would make interfacing the design much easier. We determined that the Wi-Fi capabilities and the price-point of the Raspberry Pi 4 justified using it on both ends of our system.

On the user side, we determined the USB protocol was the easiest protocol to connect the buttons from the user input to the Raspberry Pi. From our experimentation we determined that using an Arduino on our PCB will allow us to convert an analog high or low signal to a USB signal that is meaningful for the Raspberry Pi. Due to size constraints, we will be employing an Arduino Nano on the user side PCB.

When implementing hardware on the rover side we are employing GPIO because it allows for a fast control loop. This will allow us to reach our target latency of 20 milliseconds from the Raspberry Pi to the motors. The Raspberry Pi has an operating system meaning it is too slow for the encoder feedback in our control loop. The encoder quadrature style which means it sends two square waves offset from each other; the Raspberry Pi would not be able to check its GPIO pins fast enough for the waves when the encoders are detecting if the voltage is 90° out of phase because of its GPIO sampling frequency of 40 Hertz when the encoder is sampling at 201 Hertz [17][18][19]. To solve this problem, we decided that employing a Raspberry Pi Pico will allow us to implement our control loop on bare metal which will allow us to interpret encoder feedback faster.

VI. System Implementation

To better describe the HomeRover System Implementation, this section will be split, as it is in our Block Diagram, into the Rover-Side and Controller-Side subsystems.

A. *User-Console-Side Implementation*

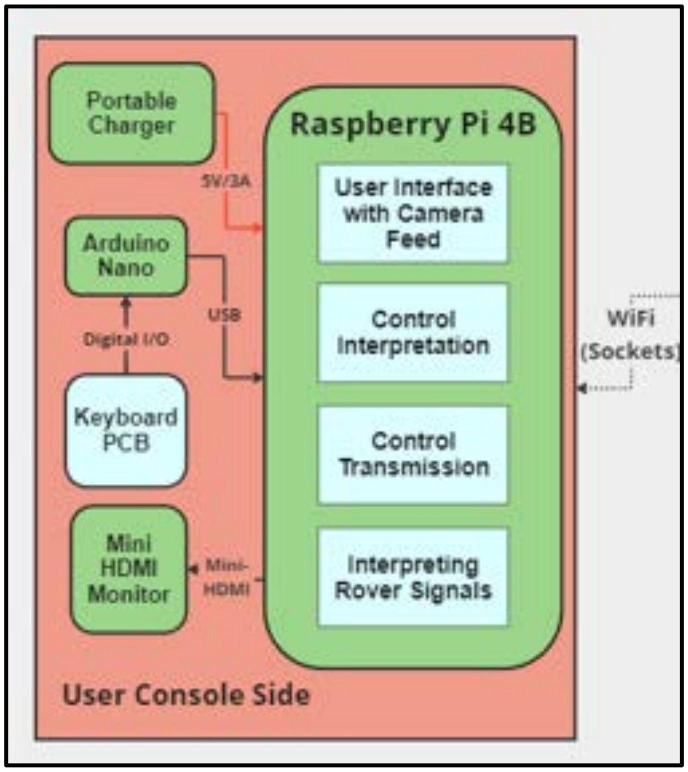


Figure 3. Cropped User-Console-Side Section of the Overarching Block Diagram.

Originally, the User-Console-Side Implementation was to be powered by a 2S Lithium Polymer battery, which was to be buck converted down to 5 Volts. In the interest of the safety of the user and the ease of development of the controller side, we elected to use a portable charger to power the Raspberry Pi at 5 Volts.

The input to the entire system, and the way that the user can interact with the system, is through our Controller. Aiming to achieve the most compact implementation possible, we have elected to design the PCB by ourselves, with an integrated Arduino Nano on the PCB translating the binary keypresses to USB, such that the Raspberry Pi can process the keystrokes efficiently. The Controller will be comprised of six buttons: Forward, Backward, Left, Right, and Give and Pickup. When the Forward and Backward keys are pressed, HomeRover will move forward and backward accordingly. When the left and right keys are pressed, HomeRover will turn in place. The Give button, as mentioned prior, will extend the robot arm such that the user will be able to retrieve the object from it.

A nontrivial quality-of-life aspect of the User-Console-Side is the mini monitor. The mini-HDMI monitor will allow for the camera feed coming from the Rover to be displayed to the user, such that they can better navigate the Rover from farther distances, and to be able to figure out when to begin the pickup sequence.

B. Rover-Side Implementation

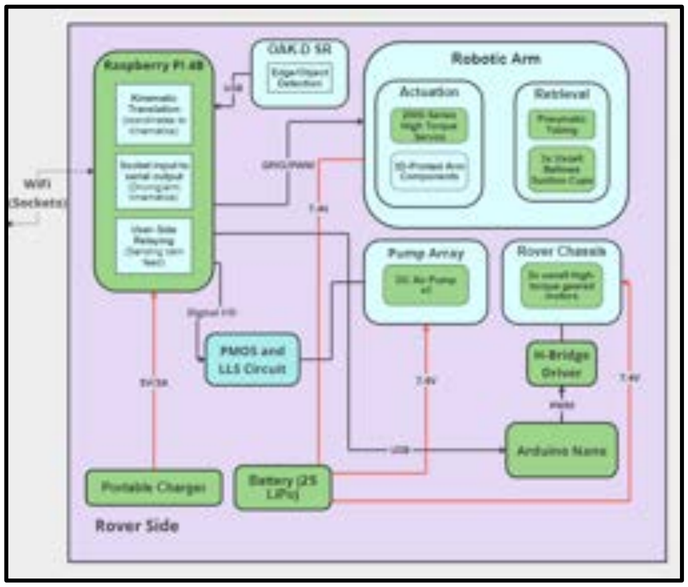


Figure 4. Cropped Rover-Side Section of the Overarching Block Diagram.

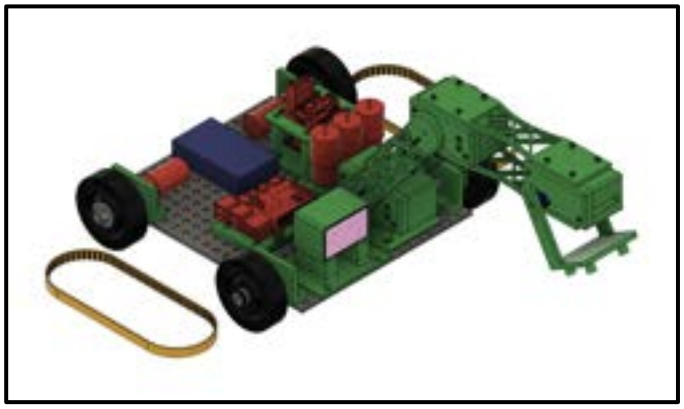


Figure 5. Isometric View of the old version of the Rover Assembly. Power elements are in Blue, 3D-Printed elements are in Green, and electronics are in Red.

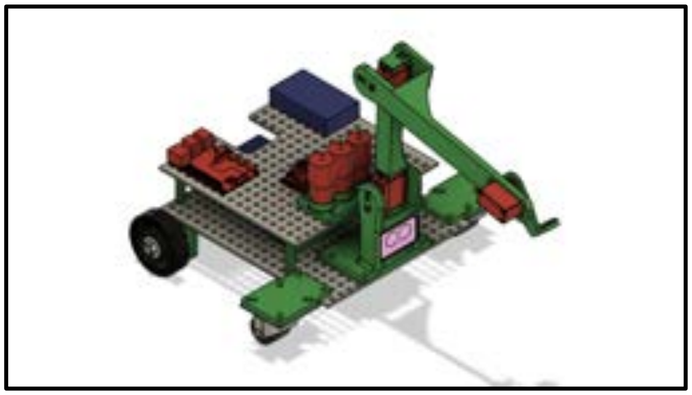


Figure 6. Isometric View of the new version of the Rover Assembly. Power elements are in Blue, 3D-Printed elements are in Green, and electronics are in Red.

HomeRover is powered by a 2S Lithium Polymer battery for the motor function, modeled by the blue rectangular prism near the back of the robot, and the Raspberry Pi computing unit is powered by an independent portable charger because of its 5V 3A power requirement. The weight of the battery acts as a counterweight for the weight being picked up at the end of the robotic arm. The perforation/holes in the main chassis plate are to allow for more agile development; if components need to be repositioned, they can be, without needing to redesign and re-print objects.

As mentioned before, the overall design of the Rover can be split into two goals: Movement and Item Retrieval. The Raspberry Pi 4 Single Board Computer, pictured in the image above, acts as the onboard computer for the Rover, taking inputs from the User-Console-Side and operating the rover accordingly.

i.) Movement:

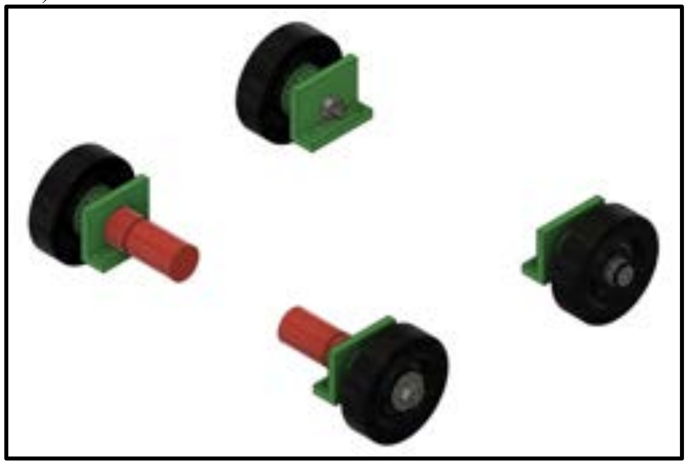


Figure 7. Isometric View of the Old Drive System. 3D-Printed elements are in Green, and electronics are in Red.

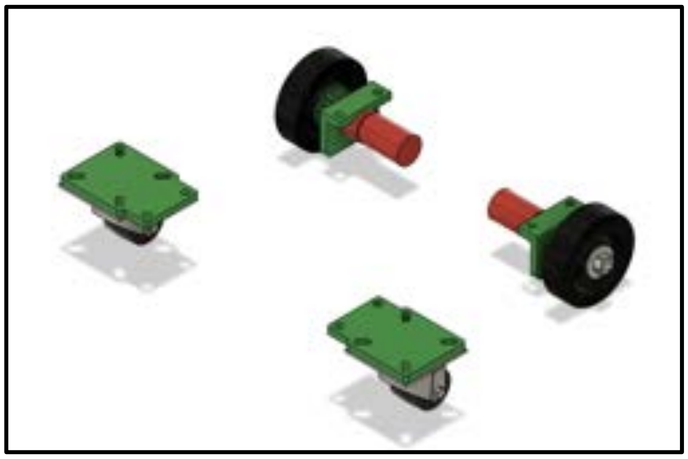


Figure 8. Isometric View of the New Drive System. 3D-Printed elements are in Green, and electronics are in Red.

The Rover's drive train is designed in an effective manner, which pushed towards our goal. The front two motors sat on a dead shaft, where they spun directly on the bolt which holds them. This would have allowed for the rover to drive from the back two wheels, and the front two wheels to be driven by a timing belt pulley system. Unfortunately, in practical testing, we realized that the Rover, while being powered by 7.4 Volts, did not have enough torque to turn while driving with the timing belts at a speed that we deemed acceptable for the home level. To make the driving smooth, we switched to using caster wheels in the front of the robot, to enable smooth turning. Additionally, the initial idea was to use encoding on the motors for alignment purposes; however, with the addition of the caster wheels, encoding was no longer possible or practical, as caster wheels change the trajectory of motion in a complicated fashion.

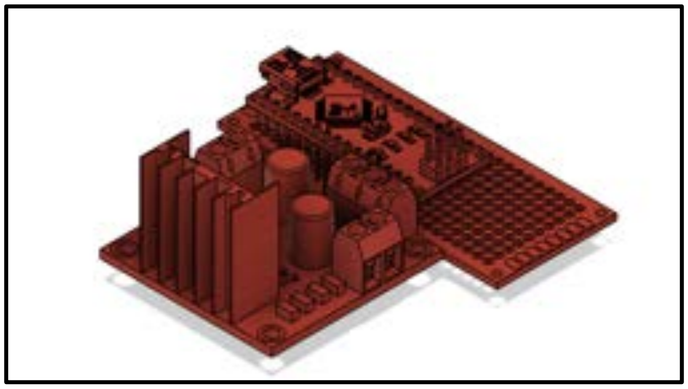


Figure 9. Isometric View of the Drive Electronics. Electronics are in Red.

The Arduino Nano drives the motor driver board with Pulse-Width Modulation to a connection on the driver board, which then applies the appropriate voltage across the motor terminals, moving the motors and thus the Rover. This arrangement, though not as neat as our original plan of a 3D-printed electronics enclosure would have it, saves space on the Rover for other electronics.

ii.) Item Retrieval:

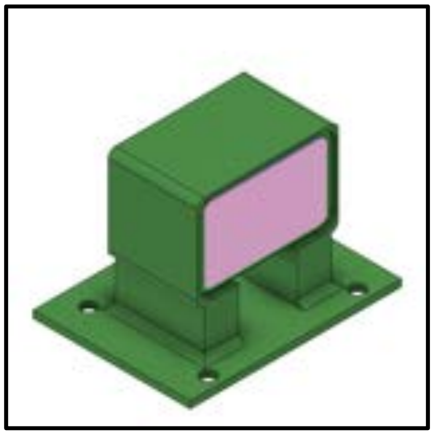


Figure 10. Isometric View of the old OAK-D SR Mount. 3D-Printed elements are in Green.

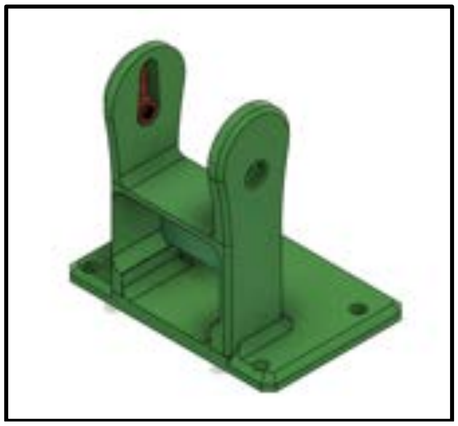


Figure 11. Isometric View of new OAK-D SR Mount. 3D-Printed elements are in Green.

The detection and retrieval process has not changed since the design report; however, the mounting is now central and in line with the arm, such that our calculations to align the arm with the object of interest could be simplified.

The first step in the process of retrieving the item is the process of detecting it, and determining where it is relative to the robot. For this, we chose the OAK-D SR camera, the mount for which is pictured above. The camera comes with the ability to do onboard ML processing, and we used an onboard machine learning algorithm (MobilenetSSD) that it comes with to determine the distance (X, Y, and Z) from the camera. A sample output of the camera is shown below.

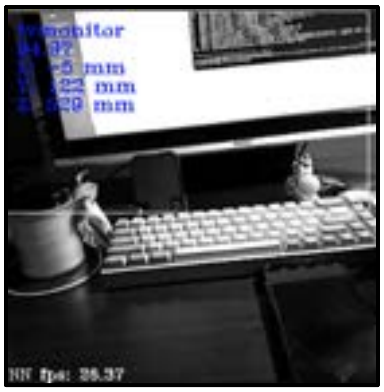
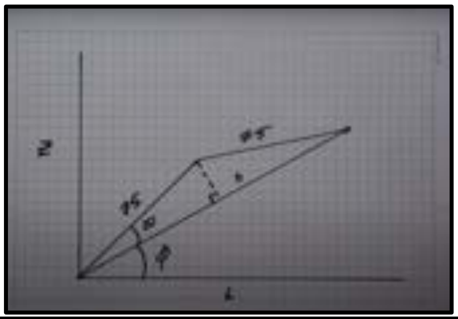
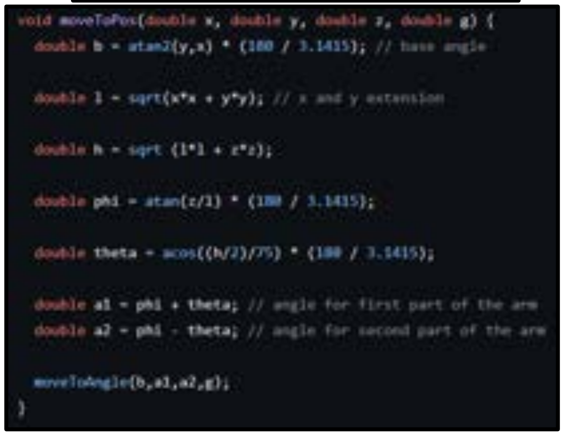


Figure 12. Sample Depth Camera output from OAK-D SR.

As is visible in the image above, the camera comes with the ability to run programs to identify objects; however, the scope of our project is limited to only pick up objects with one object being in the frame of the camera. Also visible is the X, Y and Z distances to the center of the object, whose numbers the Raspberry Pi 4 mainboard will process and generate the kinematic scheme for the robotic arm.





```
void moveToPos(double x, double y, double z, double g) {
  double b = atan2(y,x) * (180 / 3.1415); // base angle

  double l = sqrt(x*x + y*y); // x and y extension

  double h = sqrt (l*l + z*z);

  double phi = atan(z/l) * (180 / 3.1415);

  double theta = acos((h/2)/75) * (180 / 3.1415);

  double a1 = phi + theta; // angle for first part of the arm
  double a2 = phi - theta; // angle for second part of the arm

  moveToAngle(b,a1,a2,g);
}
```

Figures 13 and 14. Sample Diagram and Code for limited DOF kinematics.[21]

Because of the deliberately degree-of-freedom-limited nature of the robot arm (pictured below), the kinematics are rather simple, and can be calculated with the simple script shown above. A factor that we thought we may have needed to consider is the center of rotation of the arm- however, with the central mounting of the arm and the camera, the center of rotation did not matter after all, and the motion of the arm was quite standard.

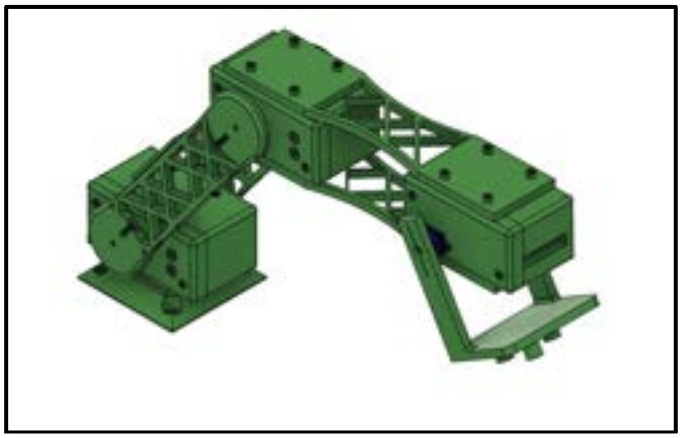


Figure 15. Old Robot Arm Assembly. 3D-Printed elements are in Green.

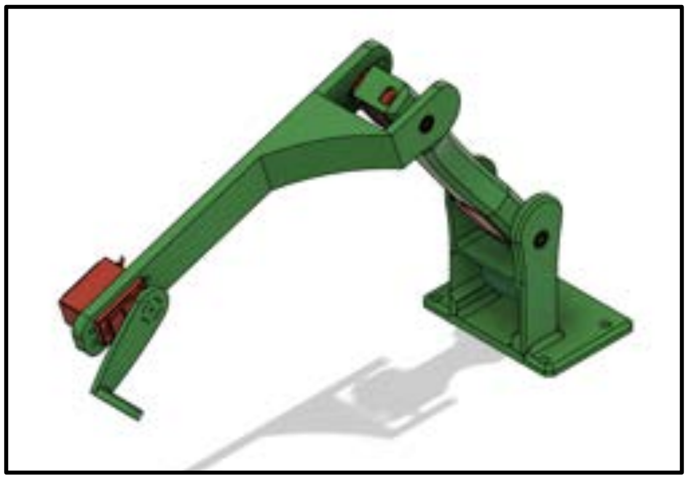


Figure 16. New Robot Arm Assembly. 3D-Printed elements are in Green.

The new robot arm assembly, pictured above, sits on the Rover in the configuration shown in a previous picture. Each leg of the arm is controlled by a 2000 Series servo, each with enough torque to carry its respective leg. The 2000 Series Servo has a stall torque (25.2 kg.cm), which is enough to hold our maximum weight up at the end of the arm. The range of our arm is 30 cm, and our max mass at the end of the arm is 0.7 kg, which leads to an eventual final torque of 21 kg.cm. As the calculated stall torque will be less than the servo's stall torque, the servos are able to hold the arm at a constant orientation and navigate its end effector to the correct position. Initially, the goal with the (old) modular arm shown above was to limit the printing time of any part to be about 1 hour, should the part need to be adjusted; however, the 3D printers in Roboclub were quite fast, allowing for the entire new arm to be printed in about 5 hours. The servos are controlled by Pulse-Width Modulation, a common technique seen in many different applications to use a single binary connection to send, essentially, analog signals.

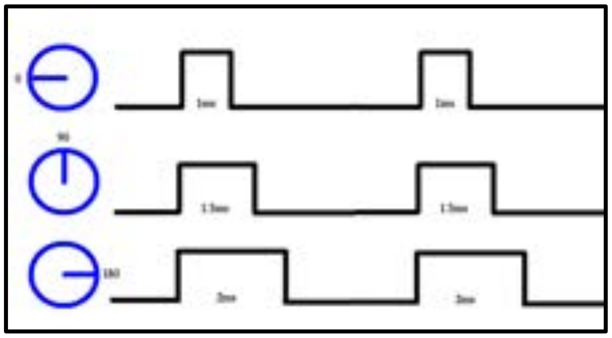


Figure 17. Diagram detailing Pulse-Width Modulation.[22]

With the ability to drive the servos to degree-accurate positions, we can accurately move the end-effector to the position slightly above the object of interest.

Figure 18. Bellows Suction Cups, made of silicone.[23]

Pictured above are silicone suction cups present at the end effector of the arm, seen above in the CAD rendering. Their shape and material allow for their deformation around irregularly shaped objects; however, we did not add irregular objects to our scope, and decided instead to focus on honing the precision of our robot with the planar objects that we had in mind.

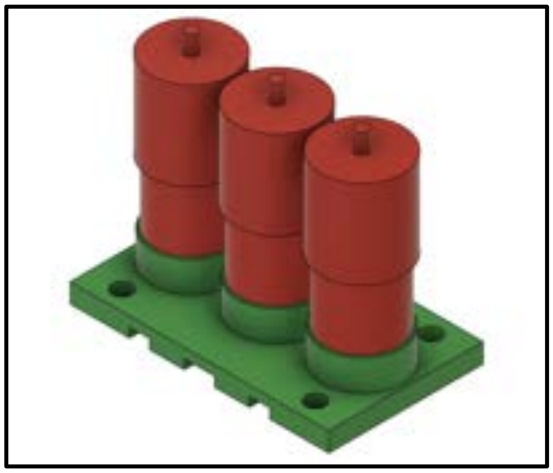


Figure 19. Pump Holder. 3D-Printed elements are in Green, and electronics are in Red.

To pick up objects, we elected to use DC motor pumps, which provide adequate pressure to pick up the requisite planar objects.

iii.) Control Scheme

To better describe the modus operandi of the rover, a state machine is shown below.

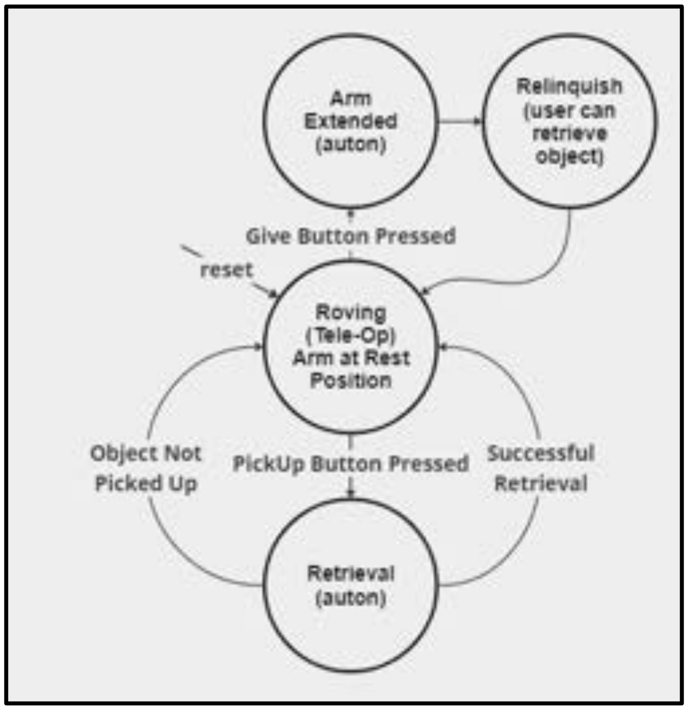


Figure 20. Simple State Machine Describing Rover Architecture

As you can see, the rover has three main states, roving (driving), retrieval (pickup) and relinquish (giving the item). Each of these states are independent and contain signals to all the components of the rover to ensure that no unnecessary actions are taking place that could take away from the user experience or increase the rover's power consumption.

VII. Test, Verification and Validation

A. Tests for Accuracy

To ensure the success of our full system in the sphere of accuracy, we need our separate subsystem components to execute with 80% accuracy, as described in the design requirements. The first sphere, object identification, requires utilizing object detection on the Oak D-SR camera. Once this pipeline is created, to achieve our desired accuracy, it must be tested and achieve greater than 95% success against a thorough and complete dataset of 50+ test pictures, which will consist of 7+ objects in various orientations and poses to mimic the variability of a real-world scenario. In addition, this dataset will have image augmentation performed on it to further increase the completeness of our testing dataset. The second and third spheres of full system accuracy are claw positioning and arm suction, which will be tested in tandem in integration tests. These tests will, following specific instructions and amounts representing camera output calculations, measure the offset and difference in distance between the observed target area and the theoretical, golden target area. This golden target area will be determined through calculations of kinematics to determine the correct landing location of the arm and end effector. Success will be measured by a maximum of 1 centimeter offset on any side of the real and theoretical overlap. To meet our other full-system accuracy requirements, such as the 10 second requirement for the system to position itself and pick up the item, the item pickup range of 10 to 30 centimeters, and the suction lifting capacity of 700 grams, it would require procedural tests where we incrementally measure a specific metric to make sure we can reach the respective threshold.

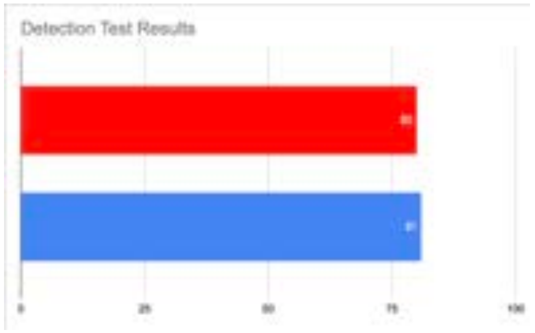


Figure 21. Detection accuracy results as a percentage. (red) target, (blue) achieved.

From our proposed tests, since the Oak D-SR has the capability of utilizing pre-trained models on chip, individual testing of our chosen object detection model we felt unnecessary since the model was pre-trained. Instead, we focused more on integration testing in conjunction with the claw positioning and arm suction. Thus, our final testing strategy painted successes as full system success and failure as an inability to navigate and pick up the object. To achieve the metrics visible on the graph, we conducted a cumulative 120 trials, with an ultimate result of 97 successful trials observed. When compared to our design specifications, our test outputs were ultimately underperforming our theoretical predictions at first, so we had to tune our model, once we tuned our model our accuracy increased from 64% to 81%. In various other pickup robots, the camera is mounted in a higher position, allowing the arm to gauge the depth of an object. In our case, we utilize z offsets which cannot optimize for a variety of objects due to the lack of uniformity in their shapes and depths. Our first 50 trials were performed with cardboard boxes, the next 50 were performed with cell phones and the last 20 were performed with a deck of cards, we saw significant improvement to the pickup accuracy when we modified our kinematics equation slightly and switched to objects that were lower to the floor such as a cell phone or a deck of cards. Since our design requirement was scaled to pick up planar objects, we excluded further tests from our data set but we had a 0% pickup rate of round objects such as water bottles, but we had a 95% item detection rate of irregular shaped objects; this showed that the suction mechanism was likely the limiting factor in our design when it comes to irregularly shaped objects.

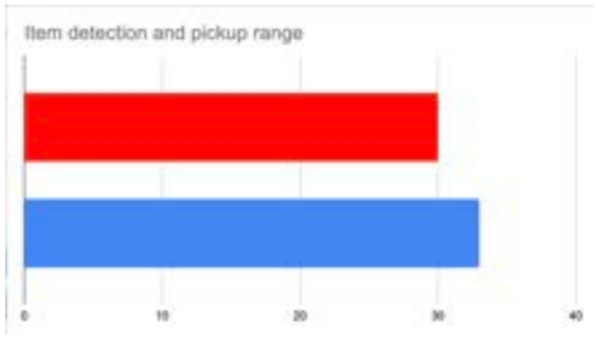


Figure 22. Item detection results in cm. (red) target, (blue) achieved.

For our item detection results, as stated previously, we measured through placing objects varying distances and finding the maximum bound. Compared to our theoretical predictions from our design specifications of a 10cm – 30cm range, we can achieve a maximum of 33cm, meeting and exceeding this requirement. Since in our reposition adjustment checks we can alter the depth range that we consider to be a “found” object, having a wider range allows us to be more flexible in our arm movements, allowing for us to better meet our use case requirements through increased range of the arm and pickup accuracy that results.

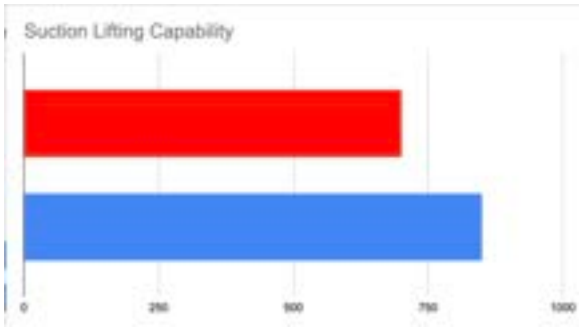


Figure 23. Suction capability results in grams. (red) target, (blue) achieved.

Initially, when performing the tests for suction, we found that our pumps were only capable of lifting 600g at 5V. To achieve a better value that more closely matches our theoretical predictions, we increased the voltage of our pumps to 8.3V, the maximum voltage of the LiPo battery, and this change allowed us to obtain a new upper bound of 850g, surpassing our design requirement, effectively serving our use case.

B. *Tests for Latency*

Latency in our system is represented in multiple facets, those being transmission latency, control center latency, receiver to motor latency, and receiver to suction claw latency. Regarding the transmission latency, this mainly takes the form of communication between the two Raspberry Pi’s. In this case, our testing method will take the form of recording the time of data transmission between the two using system timers and subtracting the time difference with a target of less than 100 milliseconds. For the control center latency, which takes the form of communication between the user-console output and Raspberry Pi retrieval, our testing plan is to record the time between pressing a button and observing its response in a terminal window on the Raspberry Pi side, with a goal of less than 20 milliseconds. To record the time, we plan on using slow motion iPhone camera video taken at 240 fps, where we will be able to clearly see the terminal response. Receiver to motor and receiver to suction claw latency are similar in that both originate through signals sent through Raspberry Pi, with the difference being which mechanical subcomponent experiences the stimulus. We plan on testing using slow motion iPhone camera video as well, with target latencies of less than 20 milliseconds.

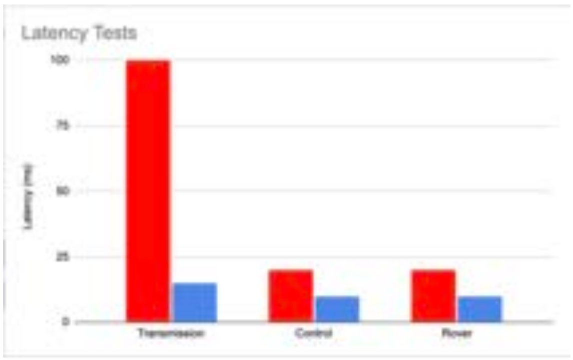


Figure 24. Latency tests results in ms. (red) target, (blue) achieved.

Utilizing the testing method of timing with a slow motion, high framerate camera, we were able to collate results on user side latency, transmission latency, and rover side latency. For each running 5 trials, we see a 10ms response for the user side, a 15ms response for the transmission side, and a 10ms response for the rover side. These results both meet and exceed our theoretical requirements established as part of our design requirements, meaning that for our achieved use case purpose of the response of our system being instantaneous to the user, we achieve on all fronts.

C. *Tests for Battery Life*

Another sub-aspect of the user experience, battery life, will be tested using the discharge battery capacity testing method, where we charge and discharge the battery fully and time how long it takes to discharge. We will have the system turned on with periodic instructions to pick items up to model real-world current levels and real-world usage. Our testing target will be greater than 1 hour between recharges.

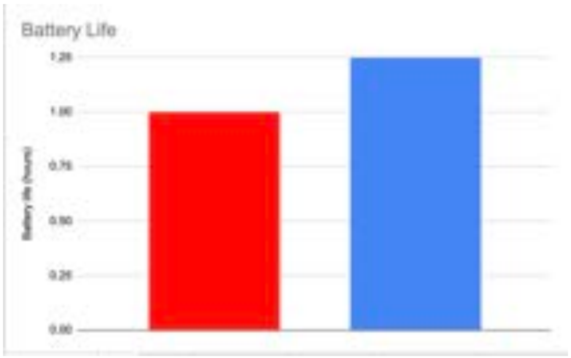


Figure 25. Battery life results in hrs. (red) target, (blue) achieved.

Going from a full charge to discharging fully, under real-world usage and intensive usage of performing tasks like driving and pickup, we saw our battery life capacity maximize at 1.25 hours. This meets and exceeds our design requirement, highlighting how for our use case of user-experience, a user will have the battery life as promised to deliver this capability for an adequate period of time.

D. *Tests for Versatility*

The last main concept we highlighted in our design requirements was the ability of our system to navigate any household setting, whether it be carpet, hardwood, or tile. Success in navigation is defined as being able to reach and maintain our established 0.3 meters per second travel speed, measured through taking the time elapsed to travel between two points on any of the varied surfaces, and dividing by time to get meters per second.

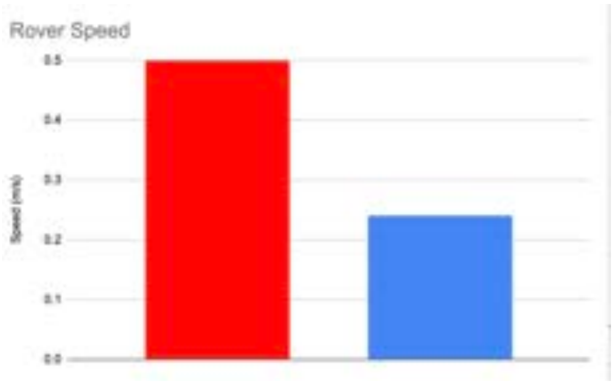


Figure 26. Speed tests measured in m/s. (red) target, (blue) achieved.

Measuring the drive time across one meter for five trials, we observe, compared to our design requirement of 0.5 m/s according to safe operating speeds of commercial, household robots, we achieve a driving speed of 0.24 m/s, achieving our targeted speed goal, which translates to achieving our use case requirement of safety. Additionally, regarding versatility, we were able to achieve these speeds on hardwood, tile, and smooth concrete. Unfortunately, we were unable to find a testing environment with carpet, resulting in our substitution for smooth concrete, a common household floor material in garages. This substitution was made with our use case and target user in mind due to the new floor material still being popular in households.

VIII. Project Management

A. *Schedule*

Figure 27 showcases our schedule and Gantt chart broken up in terms of individual responsibility. Without delineating between individual members, the main categories in our schedule involved design, specifically regarding the control booth, arm, and chassis, as well as fabrication of the respective subsystems. The other main spheres of our schedule involved designing and implementing the kinematics scheme for our rover as well as communication schemes between the user console and the rover. Additionally, the schedule included tasks to tackle the software/vision part of the project, including everything from software setup, depth camera experimentation, and writing the pipeline. Towards the end of the semester, before the final presentation and final demo, we budgeted a period of three weeks for slack time, meant for integration and full system tuning and testing. We were conscientious of major breaks like spring break when making our schedule, and the impacts were reflected in the schedule. Lastly, major course milestones were highlighted so we can see how our progress fits into the bigger picture.

Some notable changes from our original schedule to the final schedule we ended up following were the extended period we spent working on fabricating the chassis and the moving of camera feedback and tuning to the slack period. We spent a lot of time fabricating and redesigning the rover to fit our use case which set us back a few weeks when the interim demo rolled around but we were able to get caught up afterwards and make simplifying design decisions to get back on track. We ended up frontloading a lot of the electronics and design and then spent the majority of the last 3 weeks debugging our code, tuning the rover control system and movement, and verifying our design.

B. *Team Member Responsibilities*

Mimicking the design and delineation of our schedule, our division of responsibility is as follows.

Varun's main tasks were to design both the robotic arm we used for our rover as well as the rover itself. This entailed fleshing out all the required components, power calculations, mechanical calculations, and testing to make sure the rover is structurally and electrically sound. Additionally, he was primarily in charge of designing, building, and testing the suction mechanism. He also played a major part in fabrication of the rover in making sure the interconnects and communication is sound. Varun was also responsible for developing the state machine that controlled the rover's actions and debugged a lot of the rover code in a joint effort with Hayden.

Hayden's main tasks were similar in that he played a major part in designing the control booth/user console as well as aspects of the rover, including all the requisite calculations and parts sourcing as stated above. Overall design and fabrication of the rover is mainly a two-person joint effort between Hayden and Varun. In addition, Hayden took ownership of the kinematics scheme in translating our camera output to rover movement. Hayden was also responsible for researching and developing our serial and socket protocol that allowed the user to communicate with the rover.

Nathan's primary tasks revolved around the software side, particularly in the space of object recognition with the depth camera. This entailed experimenting extensively with the depth camera, developing the pipeline utilizing its onboard tools, setting up the Raspberry PI and setting up the interfacing in that respect as well as enabling communication between the user side and rover side as far as pipelining the camera feed onto a web page. Because it is intimately linked, Nathan also assisted Hayden and Varun in fleshing out the kinematics.

No tasks were fundamentally disjoint and isolated from the others, and we all played a part in every aspect of our system. For integration and testing, we were all present for tests and made observations.

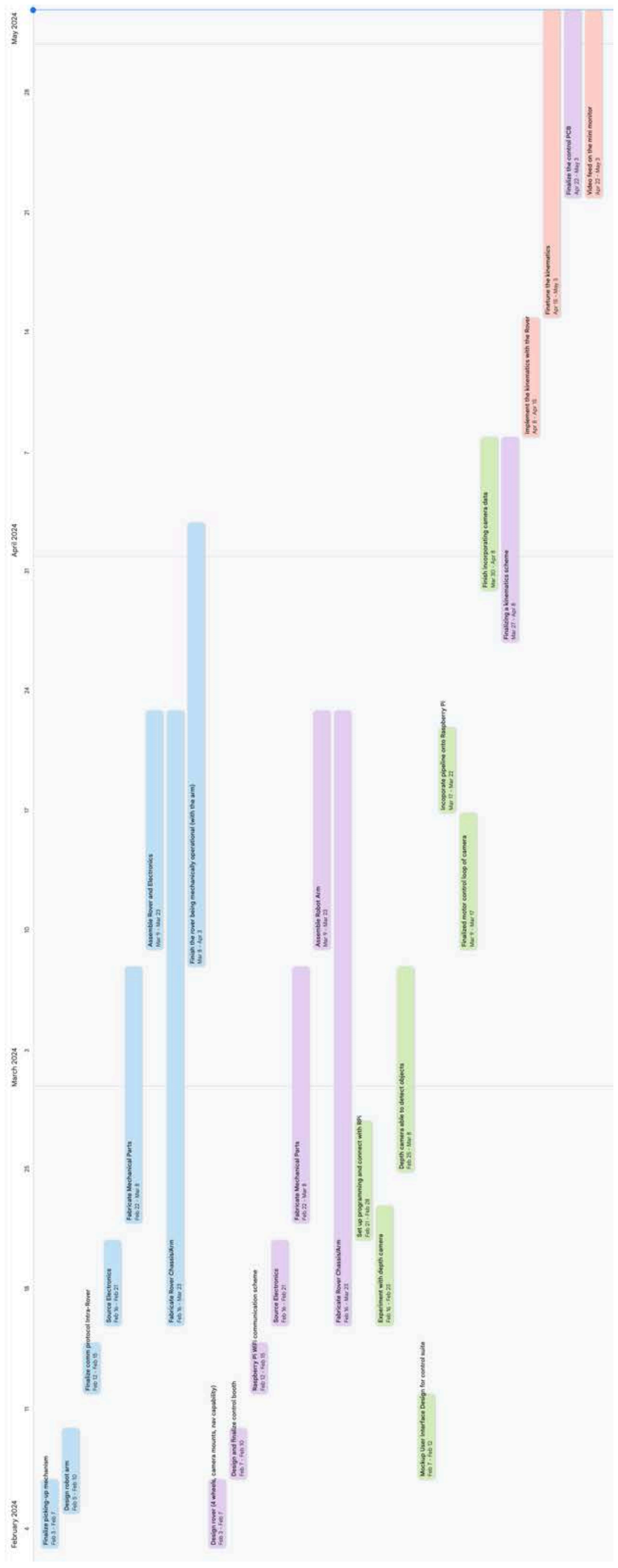


Figure 27. Schedule example with milestones and team responsibilities

C. *Bill of Materials and Budget*

Table III at the end of the report highlights our bill of materials and resulting budget. We aimed to take advantage of the ECE inventory as best we could, utilizing our own equipment and even finding communal equipment to bring costs down. A lot of the stuff we originally planned to buy, like timing belts, shoulder screws, Raspberry Pi Picos and nuts and bolts we did not end up needing.

D. *AWS Usage*

No AWS credits requested/used.

E. *Risk Management*

Regarding our most pressing risks, this will take the form of our vision system and the resulting communication to the robotic arm. The primary expertise on our team does not lie in the sphere of computer vision and object detection, so our primary risk is getting accurate depth data from the camera and successfully detecting objects. If we find that detecting objects through edge and feature detection is proving to be inaccurate and not meeting our desired metrics, a potential solution is to utilize the onboard capabilities of the camera to run machine learning algorithms and AI models to hopefully achieve a better result. If this were to happen, we would need a risk mitigation strategy that measures the new power draw of the camera from running a higher intensity workload and makes sure the battery is capable of successful function.

With our final product, we handled this project risk both from the standpoints of design and schedule. Regarding the design, we indeed utilized the onboard ML capabilities of the camera to run the MobileNetSSD model for the purposes of object detection. Specifically, we incorporated both StereoDepth nodes as well as a SpatialDetectionNetwork node to be able to receive detections from our camera frame, thus allowing us to calculate regions of interest, bounding boxes, and our final x-y-z coordinates to pass to the arm controller. However, another risk we found after using this method was that our pickup accuracy was not entirely meeting our accuracy requirements at 80%. To mitigate this risk, we edited many of the attributes of the nodes, using median filters in our depth node and lowering the confidence threshold as well as the bounding box scale factor in our detection node. Ultimately, this allowed us to better identify objects by sacrificing accuracy in label detection because label detection was never a requirement of our system, so these tradeoffs were made through cognizance of our system requirements. From a scheduling standpoint, in order to budget more time to flesh out a functioning ML pipeline, a change we made to the schedule was to push back getting the camera feed of the rover to the week before demo in order to prioritize main functionality. We had to conduct a priority assessment in determining the crucialness of certain tasks to our overarching system requirements and proceeded from there.

Regarding the end effector, we previously stated that if we observe that our method of suction cannot fully lift the objects as stated in our design requirements, whether through pure pressure or because of irregularities, we can brainstorm and research new end-effectors that could provide a better job adhering to irregular shaped objects. If we find that translating camera coordinates to kinematic instructions are resulting in inaccurate arm movement, we plan on adding ample integration time towards the end of the semester for calibration to work out the most accurate offsets from the camera location and coordinates to the arm's starting location.

With our final product, we handled this project risk firstly through a scheduling perspective. During the last few weeks before demo, our risk mitigation plan was successful in that through ample integration testing time, we were able to finetune our kinematic offsets from the camera location and coordinates to the arm, adjusting for the type of object we were aiming to pick up and the nature of how the suction cups worked with the arm. During testing, we noticed that with the path the arm was taking to arrive at an object, it would sometimes fold over the suction cups. Thus, through a design change, we altered the way it covered the z distance and then the y distance, allowing for minimal potential to fold the cups.

IX. Ethical Issues

The ethical issues that relate to our product revolve both around the supply chain in how we source our products as well as edge cases that result in failure or misapplication. Such examples of edge cases revolve around concerns of privacy, specifically regarding invasive usage of the camera. In addition, this concern is only exacerbated by the uncertainty users face with the underlying technology of the product. Despite the live camera feed of a user's living room being visible only during operation of the system and not saved to any sort of memory, users may be concerned that there is internal processing of their living room. The mere potential of users to speculate that an outside party can view their home could result in widespread panic. In addition, malicious actors could contribute to invasive usage of the camera through snooping on the local network and interfering with our serial connections and web app hosting to potentially route the video feed elsewhere, a dangerous harm to safety and privacy.

Failure or misapplication is significant in this case specifically in that the population that is most vulnerable in these cases are those individuals who face ambulatory difficulties but have the additional challenge of not having a support system at home. This group is vulnerable because since our project provides a capability to ease their daily life, having this ability compromised without any outside support could be damaging with no recourse. Some approaches to mitigate these adverse impacts are two-fold, relating to the potential paranoia as well as danger to safety and privacy. Firstly, we would aim to promote transparency on the main control loop and inner functionality of our project as well as emphasizing the open-source nature of our camera. In addition, we could provide accurate reporting on the life cycle of their user stimulus data, tracking exactly where it gets read and used to where it gets discarded. Regarding safety, we could refactor our design with security in mind, following design principles rooted in security, which could include checking policies, memory barriers, and encryption.

Regarding the concerns with our product's relation to the ethical sourcing of materials, an extremely important issue arises focusing on these materials' origin throughout the supply chain. This is particularly important for our lithium batteries, which require an element called cobalt. According to Siddharth Kara, "roughly 75 percent of the world's supply of cobalt is mined in the Congo," and despite a large majority of mines being licensed and regulated, there exist mines held up by the hands of child labor [29]. If we are not aware of the origins of the cobalt that goes into our batteries, we are directly supporting these brutal mining practices that are causing human catastrophe through the exploitation and exhaustion of the natural resources of the Congo land. An approach we can take to be more cognizant of our materials is through analyzing the sources of our parts simultaneously with developing our bill of materials. For instance, for our Hoovo batteries, their website states that "from raw material procurement, sample testing, production process management to product output, every step is strictly in accordance with industry standards for production, high standards, strict requirements, to ensure that each battery can be reliable, stable performance" [28]. Thus, through our judgement, we determined we could proceed with such a battery, and we can apply this process throughout our bill of materials.

X. Related Work

As mentioned in the introduction, there are several physical and robotics solutions to the problem described earlier. In terms of similarity to the project we were finally able to put together, the existing robotics solutions align closer than the physical solutions. The first solution of interest is TidyBot, the joint research project with Princeton and Google. The main aim of TidyBot is to leverage large language models to personalize physical assistance [4]. Personalization occurs through determining people's preferences in where to pick up objects and store them away [4]. Rather than provide mechanical assistance to the act of picking things up, as in HomeRover's controller-guided movement and suction arm, TidyBot aims to remove the user entirely, automating the entire process. Thus, the targeted user group varies significantly in that TidyBot is not operating with the underlying mission to assist those with ambulatory difficulties. With HomeRover's specialized mission, we developed features that restore autonomy and empower independence in living alone.

Another solution is created by Kinova, and it is a "safe, lightweight robotic arm with a three-fingered hand" that can attach to a wheelchair [24]. The user group that is assisted through this device is "people with upper-body disabilities", and this arm enables them to "perform tasks like picking up objects and opening doors" [24]. Similar in concept to HomeRover, the ultimate use case appears to be more for a mobile application rather than from an immobile, sitting position. To increase the potential pickup radius of the arm, rather than put the arm on a remotely controlled rover like in HomeRover, the arm relies on user movement through its attachment to a wheelchair, thus achieving a similar result from a different approach. Major differences from our final product lie in the specification of their arm, which has 9 degrees of freedom as well as custom software and a custom computing and control system, where our final product has an arm capable of 2 degrees of freedom, with adapted DepthAI software and control system based on inverse kinematics. Like TidyBot, this project mainly exists in a research capacity, meaning it is extremely expensive to acquire, at $50,000 currently for the research version [24]. Thus, other solutions currently exist on the market with advanced proprietary technology, but in the near future, the prospect of having a device that can provide physical assistance that is cost effective and achieves a similar function is uncertain, thus providing the space that we hope HomeRover can fill.

XI. Summary

Our system was able to meet the overarching design specifications at the end of the semester; the Rover drives towards an object, can be aligned, and pick up said object at the push of a button. There are some limits of the system- if the object to pick up is too small, often the precision of the arm is not enough to get full pump coverage on the object of interest, which leads to an accurate travel to the object, but not a successful pickup. Additionally, with any sort of irregularity on the surface of the object, the suction system fails relatively quickly. If given more time, we would improve the consistency of the algorithm, and optimize it for a more crowded network environment and have it be able to pick up more irregularly-shaped objects. We could also improve the align feature of the Rover, which currently relies on user input to adjust- by improving the power of the drive motors, we can drive them slowly and still have enough power to move the full rover around.

A. Future work

We will continue to work on this Rover beyond the semester. There are several large, sweeping improvements we can make to the Rover, including accelerating any ML with an FPGA-SOC. We met AMD during the final demo, and they selected us to receive their AMD Kria KR-260 board, on which we'll develop in future semesters. For student groups that may want to address this application, some advice- begin by figuring out your object detection algorithm thoroughly before completing your design, ensuring that your eventual hardware design can easily support the software that runs the project.

Glossary of Acronyms

CAD	Computer-Aided Design
DOF	Degree of Freedom
FPS	Frames per second
GPIO	General Purpose In/Out
PCB	Printed Circuit Board
RPi	Raspberry Pi
SoC	System on Chip

References

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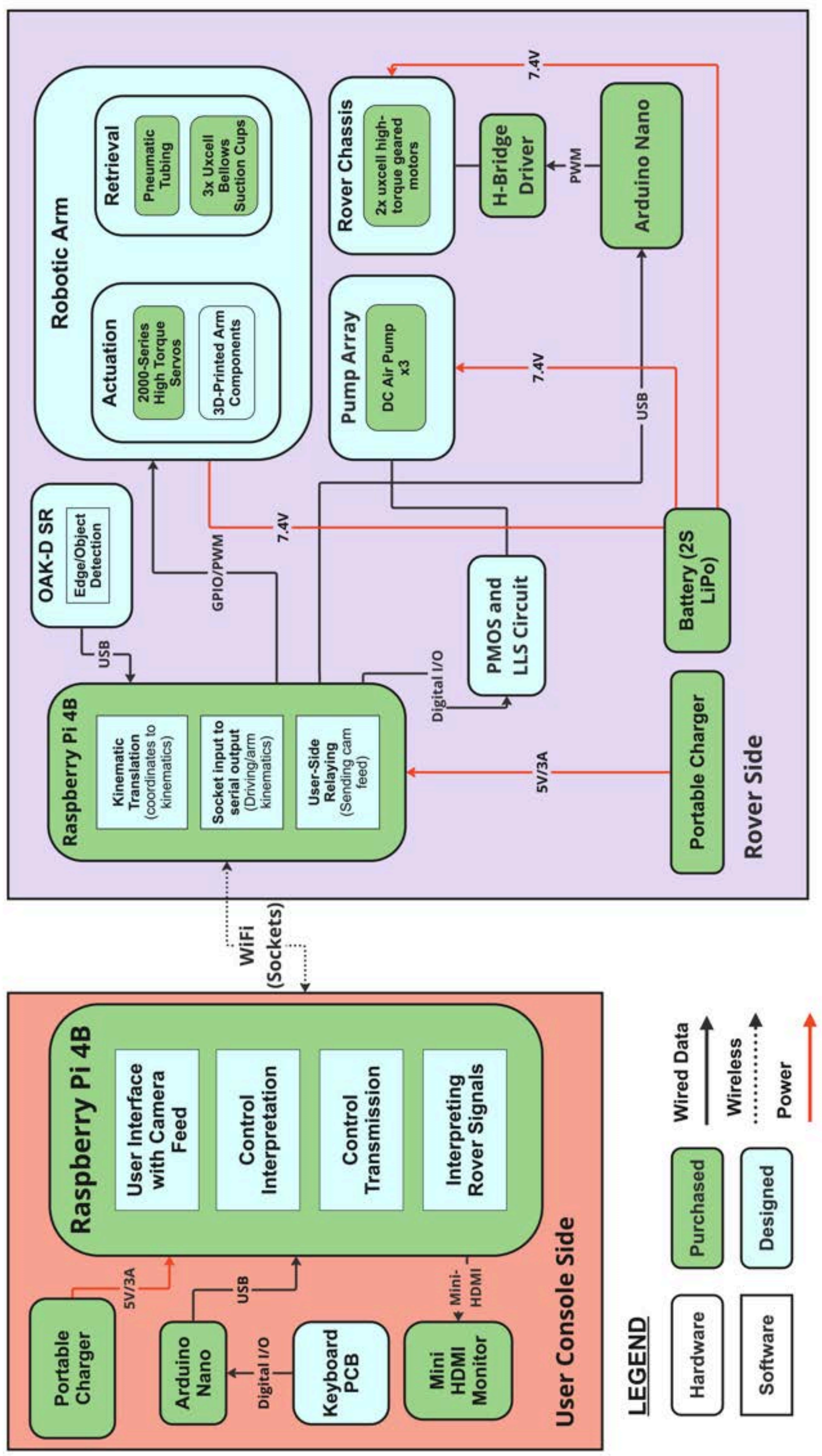
Rover Side
Robotic Arm
Actuation
2000-Series High Torque Servos
3D-Printed Arm Components
Retrieval
Pneumatic Tubing
3x Uxcell Bellows Suction Cups
Rover Chassis
2x uxcell high-torque geared motors
H-Bridge Driver
PWM
Arduino Nano
7.4V
Pump Array
DC Air Pump x3
7.4V
USB
OAK-D SR
Edge/Object Detection
USB
GPIO/PWM
7.4V
PMOS and LLS Circuit
Digital I/O
Battery (2S LiPo)
Raspberry Pi 4B
Kinematic Translation (coordinates to kinematics)
Socket input to serial output (Driving/arm kinematics)
User-Side Relaying (Sending cam feed)
5V/3A
Portable Charger
WiFi (Sockets)
User Console Side
Raspberry Pi 4B
User Interface with Camera Feed
Control Interpretation
Control Transmission
Interpreting Rover Signals
Portable Charger
5V/3A
Arduino Nano
USB
Digital I/O
Keyboard PCB
Mini HDMI Monitor
Mini-HDMI
LEGEND
Hardware
Software
Purchased
Designed
Wired Data
Wireless
Power

Table III: Bill of Materials

Description	**Model #**	**Manufacturer**	**Quantity**	**Cost**	**Total**
Drive Train Motor	a17092900ux0541	uxcell	2	19.99	39.98
Arm Servos	B0CDWPL9QZ	FXDLSERVO	2	24.99	49.98
Arm Bearings	a19121700ux0034	uxcell	10	8.99	8.99
Suction Tubing	a13080200ux0301	uxcell	1	8.99	8.99
Suction connectors	a18092200ux0610	uxcell	10	6.99	6.99
3D printer Filament	P-PETG-Black	YOOPAI	1	12.99	12.99
Suction cups	a18110600ux0302	uxcell	4	8.49	8.49
Air Pumps	X2019050306	Hxchen	3	15.99	15.99
Arm Bearings	608ZZ	Sackorange	20	8.79	8.79
Servo Horn	CS981	ShareGoo	2	8.69	8.69
Depth Camera	Oak-D Short Range	Luxonis	1	199	199
Metal mounting plate	Aluminum plastic composite	RoboClub	1	0	0
Single Board Computer	RAS-4-4G	Raspberry Pi	2	55	110
Wheels	T81P-296BB	BaneBot	2	3.5	7
USB to GPIO	Arduino Nano	Arduino	2	25	50
Caster Wheels	4778T51	McMaster-Carr	2	18.86	37.72
Washer for live shaft	94051a230	McMaster-Carr	2	3.57	7.14
Screw for live shaft	92620a621	McMaster-Carr	50	16.15	16.15
Mounting bolts	800600	Everbilt	100	22.32	22.32
Mounting nuts	802582	Everbilt	100	8.98	8.98
Batteries	B0BRKG5FBH	HOOVO	2	49.99	49.99
PCB		JLPCB	1	9	9
				Total Cost	687.18