Design & Assembly of a 3D Printed Humanoid for At-Home Assistive Care

IN PARTIAL FULFILLMENT OF A MAJOR QUALIFYING PROJECT
WORCESTER POLYTECHNIC INSTITUTE

Submitted By:
Shivank Gupta (ME/RBE)
Anna McCusker (BME)
William Michels (ME)
Merel Sutherland (ME/ESS)

Project Advisors:
Prof. Pradeep Radhakrishnan (MME/RBE)
Prof. Dirk Albrecht (BME)
Prof. Derren Rosbach (ESS)

Abstract

The population of U.S. residents above the age of 85 is expected to double within the next twelve years, and triple by 2049. With that, there is a growing distrust of institutional care settings and a strong desire for at-home assistive care. Unfortunately, there is a chronic shortage of at-home assistive care workers coupled with the rapidly growing elderly population. In order to address this gap, robotics and humanoid robotics in healthcare and assistive care are being developed in order to aid in a variety of tasks. The team has developed Finley, a 3D printed, open-source humanoid robot at Worcester Polytechnic Institute. Finley is designed to aid in the home through a variety of assistive applications. The robot is based on Poppy, a French 3D-printed, open-source humanoid developed in 2014.

The Finley project is designed to aid users at-home with a pick and place function for tasks such as putting away groceries and delivering items around the space. This is achieved with the implementation of a versatile gripper hand connected to the body through a modular end effector system. The hand can pick up many objects ranging from a lollipop to a full 500mL bottle of hot sauce. It employs a two-finger pinching hand consisting of one rigid and one compliant finger. This combination allows Finley to grab and manipulate such a wide variety of items. The modular system allows for different hands designed for specific applications to be switched out on the robot without human intervention. This system uses a purely magnetic connection while maintaining electrical continuity to the hand so any included actuators can function. Finley is capable of human interaction through text-to-speech commands to provide information and user entertainment. The robot also has a customizable sensor system in the head so different devices can be used for different applications. These systems allow for easy modifications, lending themselves well to the open-source nature of the project. Finley was designed using CAD modeling software and produced using stereolithography (SLA) 3D printing. Human robot interaction was also implemented into Finley through a speaker and microphone in the head. The robot has also been equipped with Chat GPT 3.5 Turbo artificial intelligence to provide conversation and speech-to-motion capabilities.

The systems implemented on Finley can be useful in at-home assistive care applications. The robot is 3D printed and open source, so it is easily customizable for any setting or function. The team has showcased the potential of these systems through versatile pick and place and human interaction. The ability of Finley to complete tasks around the home on command will reduce the workload for at-home care workers and improve the quality of life of the patient. This report will discuss the detailed design, testing, implementation, and applications of the described Finley humanoid robot system.

Acknowledgements

This project would not have been possible without the help of the following people:

Prof. Pradeep Radhakrishnan
Prof. Derren Rosbach
Prof. Dirk Albrecht
Ms. Barbara Furhman
James Van Milligen (Graduate Student)
Emily Austin (Graduate Student)
Mr. Peter Hefti
The 2023 Humanoid Robot Team
The 2023-24 Humanoid Robot Locomotion Team
Leading Age Massachusetts

Table of Contents

Authorship

Chapter	Author	Editor
1.0 Introduction	Anna	William
1.1 Project Overview and Goals	Anna	William
1.2 Chapter Overview	Merel	Anna
2.0 2023 MQP	Merel	Anna
2.1 Goal	Merel	Anna
2.2 Outline of Components	Merel	Shivank
2.3 Structural Component Design Changes	Merel	Shivank
2.3.1 Head Lid	Merel	Shivank
2.3.2 Pelvis	Merel	Anna
2.3.3 Abdomen	Merel	Anna
2.3.4 Spine	William	Merel
2.3.5 Chest	Merel	Anna
2.3.6 Hands & Forearm	William	Merel
2.3.7 Shin & Feet	Merel	William
2.4 Actuators	Shivank	Merel
2.5 Electrical	Shivank	Merel
2.6 Achievements	Anna	Merel
2.7 Recommendations	Anna	Merel
2.8 2023 MQP Testing	Merel	Anna
3.1 Service and At-Home Care Robotics	Anna	William
3.1.1 The Need for At-Home Care Assistants in Elderly Care	Anna	William
3.1.2 Robotics in a Healthcare and	Anna	William

Chapter	Author	Editor
Service Setting		
3.2 Poppy	Anna	William
3.3 Modularity	Shivank	Anna
3.4 Human Interaction	Shivank	Anna
3.4.1 Artificial Intelligence Model	Shivank	Merel
3.4.2 Speech to Text and Motion	Shivank	Merel
3.5 Human-Robot Trust	Merel	William
3.5.1 Robots in the Workforce	Merel	William
3.5.2 Trust in Humanoid Robots	Merel	William
3.5.3 Inequality in Society Driven by Technology	Merel	Anna
3.6 Sustainability	Merel	Anna
3.6.1 Recycling and Reducing 3D Printed Materials	Merel	Shivank
3.6.2 Increasing Support for Vulnerable Populations	Merel	Shivank
3.6.2.1 Robots in Aging Services	Merel	Shivank
3.6.2.2 Open-Source & OpenAI	Merel	Shivank
3.7 RoboCup@Home	Shivank	Anna
4.1 Pick-and-Place	Anna	Shivank
4.1.1 Grip Design	Anna	Shivank
4.1.2 Pick-and-place Movement	Merel	William
4.1.2.1 Simulated Kinematics	Merel	William
4.1.2.2 Simulated Kinematics in Finley	Merel	William
4.2 Modularity	William	Merel

Chapter	Author	Editor
4.3 Design Changes	William	Merel
4.4 Printing	William	Anna
4.4.1 Resin	William	Anna
4.4.2 Fused Deposition Modeling	William	Anna
4.5 Human Interaction	Shivank	Merel
4.6 Human Study	Merel	William
4.6.1 WPI Community Survey	Merel	William
4.6.2 Residents and Providers Interview	Merel	William
4.7 Relevant Engineering Standards	Anna	Merel
5.1 A-term	Merel	Shivank
5.2 B-term	Merel	Shivank
5.3 C-term	Merel	Shivank
5.4 D-term	Merel	Shivank
6.0 Design Changes	William	Merel
6.1 Structural Redesign	William	Merel
6.1.1 Motor Mounting Pegs	William	Merel
6.1.2 Pelvis	William	Merel
6.1.3 Hips	William	Merel
6.1.4 Forearms	William	Anna
6.2 Quality of Life	William	Anna
6.2.1 Motor Holes	William	Anna
6.2.2 Shin	William	Anna
6.2.3 Motor Wire Access	William	Shivank

Chapter	Author	Editor
6.3 Modularity	William	Shivank
6.3.1 End-Effector Modularity	William	Shivank
6.3.1.1 Magnetic Connection	William	Shivank
6.3.1.2 Electrical Connection	William	Shivank
6.3.2 Head Modularity	Merel	Anna
6.4 Grip Design	William	Anna
7.0 Manufacturing & Assembly	William	Anna
7.1 Printing	William	Anna
7.2 Physical Assembly	Merel	William
7.3 Fastener Reduction	William	Merel
7.4 Material Reduction	William	Merel
7.5 Wiring & Programming	William	Merel
8.1 Hand	Anna	Merel
8.2 Modular Magnetic Connection	William	Merel
8.3 Materials Testing	Merel	William
8.4 Stress Analysis	William	Shivank
8.4.1 Hip	William	Shivank
8.4.2 Pelvis	William	Shivank
8.5 Kinematics	Merel	Shivank
8.6 Human Robot Interaction	Shivank	Anna
9.1 Project Goal and Objectives	Anna	Shivank
9.2 Pick and Place	Merel	Anna
9.3 Modularity	William	Anna
9.4 Redesign	William	Anna
9.5 Human Study	Merel	Anna

Chapter	Author	Editor
9.6 Human Interaction	Shivank	Merel
10.1 Broader Implications	Merel	William
10.1.1 Social Impact	Merel	William
10.1.2 Environmental Impact	Merel	William
10.1.3 Economical Impact and Manufacturing	Merel	William
10.1.4 Political Ramifications	Anna	Merel
10.1.5 Human-Robot Interaction Specific Standards	Anna	William
10.2 Future Work	Anna	Shivank
10.2.1 Wire Management	Anna	Shivank
10.2.2 Object Recognition and Autonomous Hand Swapping	Shivank	Merel
10.2.3 Failsafe Systems	Shivank	Merel
10.2.4 Testing in Assisted Living Facilities	Anna	Merel
10.2.5 Material Reduction and Use	Anna	Merel

List of Figures

List of Tables

List of Abbreviations

Abbreviation	Meaning
FDM	Fused Deposition Modeling
IMU	Inertial Measurement Unit
PLA	Polylactic Acid
CAD	Computer Aided Design
FEA	Finite Element Analysis
AI	Artificial Intelligence
MQP	Major Qualifying Project
SLA	Stereolithography
MME	Mechanical and Materials Engineering
ME	Mechanical Engineering
BME	Biomedical Engineering
RBE	Robotics Engineering
ESS	Environmental and Sustainability Studies
LiDAR	Light Detection and Ranging
IR	Infrared
WPI	Worcester Polytechnic Institute
GPT	Generative Pre-trained Transformer
IFR	International Federation of Robotics
3D	Three Dimensional
PVC	Polyvinyl Chloride
URPS	Undergraduate Research and Projects Showcase
BOM	Bill of Materials
API	Application Programming Interface

Abbreviation	Meaning
FBD	Free Body Diagram

1.0 Introduction

The population of United States residents above the age of 85 is expected to double within the next twelve years, and triple by 2049. With that, there is a growing distrust of institutional care settings and a strong desire for at-home assistive care (Landers et al. 2016). Unfortunately, there is a chronic shortage of at-home assistive care workers coupled with the rapidly growing elderly population. To address this gap, robotics and humanoid robotics in healthcare and assistive care are being developed in order to aid in a variety of tasks. Examples of robots include ARNA, a nursing assistive robot, and Telenoid, a therapeutic humanoid used to help communication and mood (Abubakar et al. 2020; Moyle, Murfield, and Lion 2022). Both demonstrate the benefits of using robots in assistive care.

When considering the widespread need for at-home care assistants and the variety of potential tasks that would be necessary, it is important to create a design that is robust, adaptable, and easily accessible. 3D printing is a simple way to make an open-source robot accessible to large groups of people. It does not require in-depth expertise, and it makes creation and maintenance much quicker compared to commercial manufacturing and shipping. It also allows the user to customize the robot based on the patient's specific need.

During the 2022-2023 academic year, the last humanoid robot MQP team created Ava, an expansion of the Koalby and Poppy projects. The Poppy Project was the original open-source 3D printed humanoid robot project, and the Koalby Project reduced the cost of the robot by over $6,000, as well as introduced batteries to allow for untethered power (*Poppy Project - Open Source Robotic Platform*, n.d.) (Galgano et al., 2022). The Ava team improved structural integrity of the humanoid through the analysis and redesign of parts such as the pelvis and spine. They also increased the voltage of the batteries in order to account for three sensors they integrated into the robot. Lastly, they standardized all the motors into a single brand. Each team has made great strides in the development of this 3D printed, open-source humanoid robot. Below in Figure 1 shows Poppy, Koalby, Ava, and Finley from left to right.

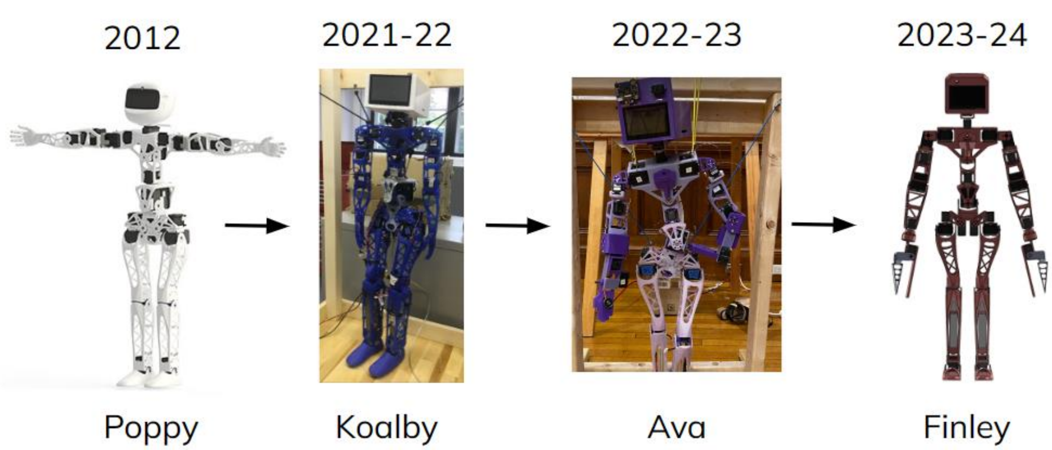


Figure 1: This figure shows the timeline of the project over the years, starting with the Poppy Project in 2012

1.1 Project Overview and Goals

The goal of this project was to develop 3D printed humanoid robots capable of picking and placing small household items and human interaction with residents and providers in aging services. Specifically, the team hoped to develop and implement a pick-and-place function; make a modular end-effector system; redesign parts to improve structural integrity, reduce assembly time, reduce weight, and increase ease of troubleshooting; implement human-robot interaction; and study human-robot trust. The robot designed and produced was named Finley.

In order to achieve this goal, the first objective was to develop a pick-and-place gripper to pick up a variety of objects. A versatile gripping system is beneficial in an at-home assistive care setting with tasks such as putting away groceries. The second objective of the project was to introduce modularity to Finley's wrists, allowing the user to easily swap its hands for different applications. This is done using an electromagnet in each wrist and providing electrical continuity to the hand from the forearm using pogo pins so any included actuators can function. Objective three was to redesign parts in order to improve structural integrity and reduce assembly time. There were several parts that were subject to frequent breakage, causing them to be repeatedly printed and thrown out. Improving structural integrity of parts not only preserved the function of the robot but considers environmental considerations. The fourth objective was to implement systems that allow human interaction with Finley, such as a speaker and microphone. Objective five was to perform a human study to identify how different people feel about humanoid robots to develop a more effective humanoid for use in assistive at-home care. This was done through surveying the WPI community and interviewing residents and providers in aging services.

The previous team made many important decisions and improvements that will allow further development of these robots towards a more specific application. The standardization of motors allows the finalization of specific structural redesigns that are important when considering maintenance and ease of printing. However, it is important to note the change of application from lab assistant to at-home care assistant based on an identifiable need. In summary, the team this year will implement systems that are necessary in order to function in an at-home assistive care setting.

1.2 Chapter Overview

Chapter 2 will discuss the 2023 3D printed humanoid robot MQP team and what they were able to achieve. Chapter 3 will cover the literature review completed, including, at-home care robotics, the poppy project, modular connections, human interaction, human-robot trust, sustainability, and RoboCup@Home. Chapter 4 will include the methodology and project plan for this MQP and Chapter 5 will discuss the project timeline. Chapter 6 will go over design changes in Finley and Chapter 7 will go over the manufacturing and assembly of Finley. Chapter 8 will discuss the testing process of the hands, modular connection, materials, stress analysis, kinematics, and human interaction. Chapter 9 will have the discussion of the project goals and their success in an at-home setting. Chapter 10 will focus on the broader implications of engineering ethics and societal impact. Lastly, Chapter 11 will include the references and Chapter 12 will include the appendices.

2.0 2023 MQP

In this chapter, the Development of 3D Printed Humanoid Robots (2023 MQP) will be discussed, which throughout this chapter will be referred to as the 2023 MQP (Lytle et al., 2023). This includes the goal, component, and design changes as well as achievements and recommendations.

2.1 Goal

The 2023 MQP team built a second robot, named Ava (see below in Figure 2), with design modifications and different electrical components and actuators. The overall goal was "to create Ava, an open source, 3D-printed, humanoid robot that would act as a lab assistant with a focus on lifting objects and assisted walking via pushing a cart." Their key objectives were to improve the structural integrity by redesigning parts to improve the strength of Ava, give Ava walking capabilities by integrating electrical components, add gripping functionality to lift objects and help with assisted walking, and to standardize components to reduce parts and create uniformity.

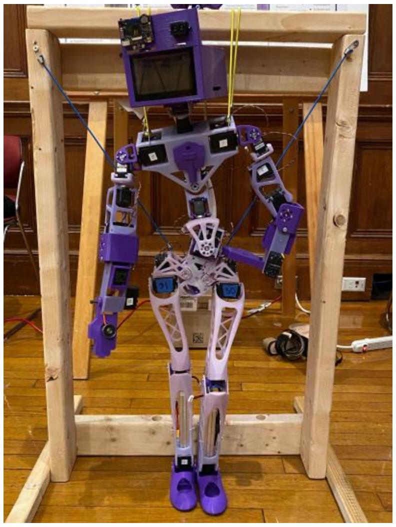


Figure 2: Ava at Project Presentation Day 2023 (Lytle et al., 2023)

2.2 Outline of Components

The 2023 MQP team was also able to reduce costs down from the original Poppy project but had an increase in price from the 2021-2022 Koalby project. Ava was built from 19 resin printed parts, 48 FDM printed parts, and several hundred fasteners. The remaining 4 Dynamixel-MX-64AT motors and 2 Dynamixel AX-12A motors in Koalby were replaced with 29 HerkuleX motors. There are 8 HerkuleX DRS 0601, 19 HerkuleX DRS 0201, and 2 HerkuleX DRS 0101. Two IMUs (MPU-6050 & BNO055), a TF Luna LiDAR, an AI Huskylens Camera, and 2 11.1V batteries were used as well as a Raspberry Pi 4 and an Arduino Mega Clone. A touch screen

LCD was used in the head. The overall cost of Ava was $5,616.18 a reduction from the original Poppy robot costing $6950.06 but more than Koalby, which was $4197.56.

2.3 Structural Component Design Changes

Several design changes and additions were made from Koalby to Ava, including, the head, abdomen, spine, pelvis, hands, chest, shins, and feet. Changes were made to account for motor changes, new functions, and to increase stability in the part and in the overall robot.

2.3.1 Head Lid

The head lid was modified to hold the AI Huskylens Camera and the LiDAR TF Luna. An edge was added where the camera and LiDAR got fastened to and cutouts were added for sensors.

2.3.2 Pelvis

The pelvis was completely redesigned to fit the HerkuleX motors, which replaced the prior Dynamixel motor. The pelvis was designed to hold the motors on a diagonal on top of each other for weight distribution and to centralize the center of mass. There was continuous breakage in the original pelvis, which created the need for redesign. An extrusion to strengthen the servo connection was added and extra reinforcement was added in the back as well as a clamp for the spine.

2.3.3 Abdomen

Adjustments were made to the abdomen to fit the larger HerkuleX DRS-0601 motors. Holes were also widened for extra wire management space. The holes for the servo horn were made smaller to realign the servo horn.

2.3.4 Spine

It was determined that the addition of a spine would be needed to ensure structural stability in the back and pelvis. This would divert some of the load through a rod connected to the pelvis and chest pieces. The spine was designed to rigidly connect to the pelvis and connect to the chest with two degrees of freedom. This way, it could constantly take stress while having enough freedom to move as the robot moves. However, this spine design had a significant interference with the abdomen. In the interest of time, it was never redesigned and tested.

2.3.5 Chest

Several modifications were made to the chest. Motors were added to the shoulders to assist lifting and cuts were made to remove unnecessary mass. An additional cut was made to house the IMU at the center of the chest making it as close to the center of mass as possible. The chest was made as thick and strong as possible to prevent failure without adding unneeded material. A chest plate with Ava's name was also added to protect the IMU.

2.3.6 Hands and Forearm

To allow Ava to be a successful lab assistant, the team needed a grip with the ability to pick up a large variety of objects. Many types of grips were considered, ranging from three-point claw designs to grips that look and perform like human hands. After creating a design matrix, the underactuated three finger robotic grip was chosen as the best. This works with a single worm wheel gear in the middle that controls the position of all three fingers simultaneously through spinning. A place for an electromagnet was also designed in the palm of the hand to help pick up magnetic objects.

In order to account for the new grip addition, the forearm required a complete redesign. Two new Herkulex DRS-0201 motors were added to actuate the gripper and be able to change the angle of the hand. The forearm was split into two pieces: the forearm itself and an elbow. The elbow is essentially a connector between the bicep and forearm. However, where the elbow and forearm meet, they are connected with a clevis pin that can easily be removed. This adds the ability of modularity to the forearms. The user would now be able to attach any hand design they like to the robot with ease. Due to time constraints, the three-point grip was assembled but never implemented in the robot, so a simpler flat hand with a single electromagnet was added in place of it.

2.3.7 Shin & Feet

Ava's shins were printed in two pieces, the top half and bottom half because there was not a big enough printer to print the whole shin and in order to put in the 11.1V battery. Overall, the shin was lengthened to accommodate the 11.1V batteries, the wall lines were thickened to prevent breakage, and to reduce weight the motor mounts in the ankles were removed. L brackets with M2 holes were used to connect to the motor instead.

The feet were widened by 9.8mm to help Ava's balance while walking and holes were cut on top of the feet for the MPU6050 to be securely fastened. Polyvinyl chloride (PVC) sheets were cut and attached to the bottom of each foot for improved traction.

2.4 Actuators

The 2023 MQP team received Koalby with 2 Dynamixel AX-12 neck motors, 4 Dynamixel MX-64 motors in abs and hip, and 21 HerkuleX DRS-0201 motors. The team, upon further evaluation, decided that uniformity in design and programming was an area for improvement that needed to be implemented in Ava. Additionally, an increase in strength was desired considering gripping mechanisms. The motor matrices created by the team can be seen below in Table 1 and Table 2.

Table 1: Ava Upper Body Motor Decision Matrix

Motor Criteria	Weight	Current Situation Herkulex 	Alternative 1 	Alternative 2 
Meet Shoulder Torque Requirement	3	0	1	1
Meet Elbow Torque Requirement	3	0	1	1
Price	5	0	-1	-1
Lead Time	5	0	-1	1
Voltage	2	0	0	0
Compatibility with Resin→ changes needed to implement it	2	0	0	0
Weighted Total		0	-4	6

Table 2: Ava Lower Body Motor Decision Matrix

Motor Criteria	Weight	Current Situation Herkulex 	Alternative 1 	Alternative 2 
Meet Leg Torque Requirement	4	0	-1	1
Meet Hip Torque Requirement	4	0	-1	1
Price	5	0	-1	-1
Lead Time	5	0	-1	1
Voltage	2	0	0	0
Compatibility with Resin→ changes needed to implement it	2	0	0	0
Weighted Total		0	-18	8

The team also conducted Multi-Link Torque Analysis using free body diagrams. These calculations assisted with confirming whether the new motors and various parts of the robot (printed or not) would be strong enough to withstand the current load and any additions. Using the calculations and motor matrix, the team chose to use HerkuleX DRS 0101, 0201, and 0601 motors.

Research and calculations done by the 2023 MQP team established that the Dynamixel MX-64T and AX-12A could be replaced with the HerkuleX DRS 0601 and 0101, respectively. HerkuleX has very similar functionality to Dynamixel in terms of feedback and control as well as stall torque and functionality.

2.5 Electrical

The 2023 MQP team conducted a literature review on the electrical components of Poppy and Koalby. The team understood that distance and force sensors would be required for successful walking, and actions such as picking and placing. Sensors include Infrared (IR), LiDAR (light, distance, and range), and ultrasonic. These sensors define distance, force, orientation, and acceleration of the system.

Of the distance sensors mentioned, IR sensors, which use infrared light to detect objects, are less reliable, and have the shortest maximum measurement length. Meanwhile, ultrasonic sensors, which use sonic waves to detect objects, are not only more reliable, but also have the ability to accurately detect a larger range of materials compared to the IR sensors and have a longer maximum measurement range. However, the LiDAR sensor, which uses laser pulses to detect objects, was found to be the most reliable and versatile as it can measure 3D structures without being inhibited by light interference. Additionally, they tend to have a greater measurement distance than that of the ultrasonic.

2.6 Achievements

The 2023 MQP team made strides in implementing all goals originally set forth for Ava. They planned to improve structural integrity through the analysis and redesign of critical parts such as the pelvis and spine. FEA analysis through ANSYS was used to identify areas of high stress and FBDs were created in order to understand the forces and moments acting on each part. The team also improved the design with the intention of walking. Sensors, such as the LiDAR TF Luna, IMUs, and AI Huskylens Camera, were integrated; parts were changed to accommodate the sensors; and the foot was widened to increase stability. Voltage regulators and 11.1 V batteries were also added to account for the extra sensors. A grip addition that caters to a variety of lab tools was developed, assembled in CAD, and FDM printed. Lastly, all motors were standardized to a single brand (HerkuleX), which further reduced cost by $375. Torque analysis was also done on each motor in order to assess its ability to lift certain lab tools. All these improvements were presented at the WPI Undergraduate Research Project Showcase.

2.7 Recommendations

There were several recommendations that the 2023 team made for the continuation of the project. Because of the last-minute development of the spine and gripping mechanism, implementation and testing were not completed. Specifically, it would be beneficial to test the compatibility of the gripper to pick up objects as well as test the accuracy of the torque values calculated. The 22-23 team also recommended adding pressure sensors in the feet and hands in order to aid in untethered walking. The last recommendation was to look into hazardous resistance solutions so that the robot could operate in a larger variety of locations. Two examples of this would be heat resistance and waterproofing.

2.8 2023 MQP Testing

At the beginning of the 2023-year, Ava and Koalby were found with several breaks and fractures as seen in Figure 3. Virtually every part was breaking or broken on the body of Ava. The pelvis, shoulders, biceps, shins, thighs, every part of them had room for improvements. The team immediately noticed that several parts could be made thicker to strengthen them. Figure 3 below shows how the robots were found at the beginning of the project.

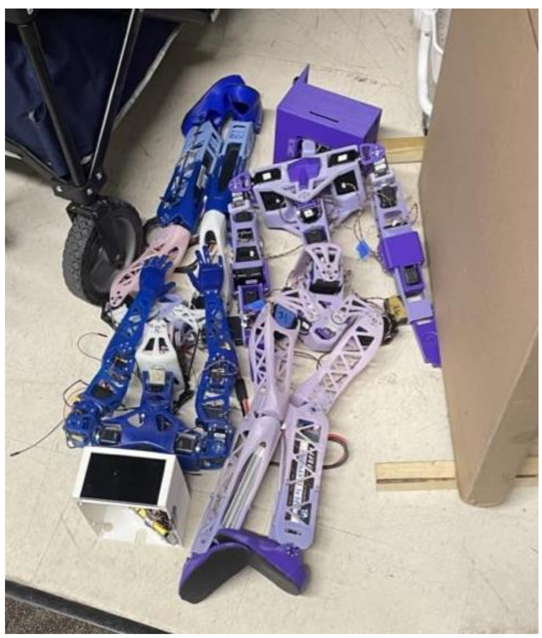


Figure 3: State of robots when they were first found

This chapter provided a general overview of what was accomplished during last year's project. The following chapter will be a summary of the literature review completed in order to complete this year's project.

3.0 Literature Review

The following chapter contains a summary of the literature review conducted in preparation for this project. Sections include information about at-home care and service robots, the Poppy Project, different potential end-effectors, modular connection, failsafe mechanisms, and human-robot trust.

3.1 Service and At-Home Care Robotics

In order to justify the development of Finley as an at-home care service robot, it is important to identify the need for at-home care assistants. Once that need is identified, the team can move forward with deciding the breadth of tasks that could be accomplished. Existing service robots that only have one specified purpose will also be explored in order to establish what has already been done within the industry.

3.1.1 The Need for At-Home Care Assistants in Elderly Care

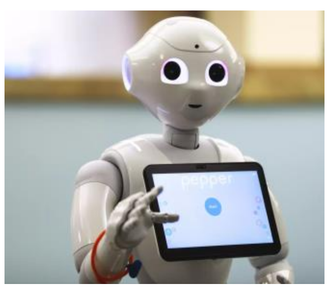
For decades, older Americans have articulated the desire to receive elderly care in the comfort of their own homes. A 2010 survey found that about 75% of Americans over the age of 45 agree, and at home patients tend to have lower cost, higher satisfaction, and equal (if not better) care when compared to inpatients (Landers et al., 2016). Since the COVID-19 pandemic, there is a more prominent distrust of institutional care (assisted living and nursing homes) and preference towards individual at-home care. This is unfortunately coupled with a lack of trained at-home care workers, as well as institutional workers. Elderly care is a physically demanding job, and it tends to have low pay and a relatively high rate of injury (Home Health Care Workforce Shortage, 2023). In one program, wages range between $13 and $15 and half the workers quit within the first year, which happens to be an improvement from the national average of 60% (Galewitz, 2021).

From 2016 to 2036 the population of elderly people over the age of 85 will double, and by 2049 it is going to triple (Landers et al., 2016). Many of that demographic have at least one chronic condition, and if they do not have access to quality care there would be serious consequences (Landers et al., 2016). With that in mind, there is going to be a severe gap in elderly care unless something is done to address it. There is robotics in the service industry already being developed to address this gap and could potentially be an all-encompassing solution for at-home elderly care.

3.1.2 Robotics in a Healthcare and Service Setting

This section will explore three different robots already being developed for a healthcare or service application. These robots include ARNA, a service robot for nursing assistance; Telenoid, a humanoid communications device for older adults; and Hyodol, a socially assistive humanoid robot.

Table 3: Four examples of robotics used in healthcare and elderly service settings.

Name	Picture	Description/Application
ARNA (Abubakar et al., 2020)		Two primary applications, patient sitter and walker. The sitter monitors bedridden patients and can respond to commands (tracking vitals or providing entertainment. As the walker it can have objects attached to it and transport them (IV pole or hospital bed.
Telenoid (Moyle et al., 2022)		Utilizes androgynous features to allow the patient to interpret its traits as they want. This robot is a teleoperated communications device and its sensors are driven by a third-party operator.
Hyodol (Lee et al., 2023)	 	Has embedded sensors with AI capability that the robot uses to communicate with older adults and assist them with daily tasks. Overarching goal is to mimic human social capabilities and lower the frequency of depression in older adults.
Pepper (Institution, n.d.)		Answers commonly asked questions, tells stories, dances, plays games, and offers a generally entertaining experience in nursing homes and assisted living facilities.

According to the International Federation of Robotics (IFR), sales of service robots used in a domestic environment are notably rising. Between 2017 and 2018 alone, the sales for medical robots increased around 50% (Abubakar et al., 2020). As discussed in the previous section, there is also an increasing number of people in need of at-home care. Since the primary focus around elderly care is biomedical, their psychosocial needs tend to be ignored, leading to isolation, loneliness, and even depression. Social robots, or robots that include features related to an animal or human, have proved to have positive effects on older adults (with and without dementia). They have shown great potential in helping with general wellbeing, agitation, anxiety, engagement, and loneliness (Lee et al., 2023). More specifically, one review of twelve studies involving 10 humanoid robots confirmed this potential, with benefits in supporting everyday life, providing interaction/entertainment, and aiding in cognitive and physical training (Moyle et al., 2022).

All three robots discussed in Table 3 serve a relatively specific purpose in their respective healthcare settings. The two humanoid robots are strictly for communication and/or entertainment. While ARNA does seem to have a broader range of capabilities, it is very technical and has no endearing qualities. It would be beneficial to the growing population of people in need of at-home care to develop a robot that has both the endearing qualities of a humanoid robot and the technical qualities needed in order to assist them in daily tasks.

3.2 The Poppy Project

Before moving forward with the project, it is important to understand what each of the three Humanoid Robot MQPs was derived from. Each project is a continuation/development of the Poppy Project, an original open-source, 3D printable humanoid robot that was created in France by Matthieu Lapeyre, Pierre Rouanet, and Jonathan Grizou (*Poppy Project - Open Source Robotic Platform*, n.d.). Poppy had a mass of 3.5kg and was 84cm tall, costing $10,367.59 to produce. The goal for Poppy was to have a variety of applications that range between education, art, and science. For education, teachers could use Poppy to teach students about 3D printing, programming, electronics, and machine learning algorithms, as well as identifying connections between different disciplines such as art and science. In terms of art, users can take creative liberty in the assembly of Poppy and can modify the humanoid for artistic purposes. An example of this is the Comacina-Capsule artists that wanted to explore the junction between robotics and dance through the portrayal of Poppy as an emotional being, shown in Figure 4.

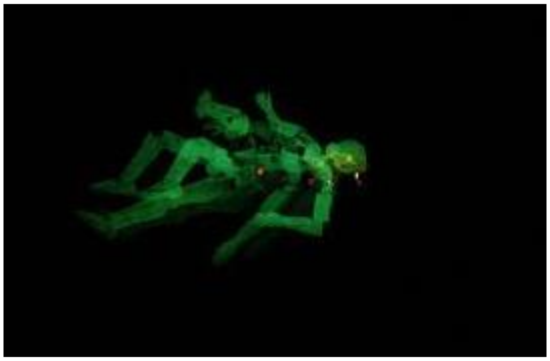


Figure 4: Comacina-Capsule artists' portrayal of Poppy (Poppy Project - Open Source Robotic Platform, n.d.)

There are also several scientific applications for Poppy, including locomotion and the social and emotional response to humanoid robots. On the Poppy Project website, you can find information about the Poppy humanoid, as well as the Poppy torso and Ergo Jr. (*Poppy Project - Open Source Robotic Platform*, n.d.). The Poppy torso is very simply Poppy, but as an apparatus cut off at the torso (top half of Poppy). Ergo Jr is a customizable robotic arm that can be used for educational purposes.

3.3 Modularity

Modularity is a critical aspect of the design philosophy for humanoid robotics, particularly in projects aimed at at-home care. It allows for flexibility, customization, and innovation by enabling different components of the robot to be easily interchanged or upgraded. Not only does this modularity further the adaptability of the robot to various tasks and environments, but also fosters collaboration and community involvement, especially in open-source projects such as this.

In the context of at-home care, where the needs of users can vary widely, modularity becomes particularly valuable. By embracing modular design efforts, the robot can be tailored to specific requirements without the need for extensive redesign or reassembly (Park and Kim, 2020). This empowers end-users, including caregivers and elderly individuals, to customize the robot according to their preferences and evolving needs, enhancing its usability and effectiveness in the home environment.

Moreover, modularity is crucial for pushing forward open-source projects in humanoid robotics for at-home care. By designing robots with interchangeable components, developers can encourage community participation and contributions. Users can adopt and design new features, while easily integrating them into an existing robot ecosystem (Wolf et al., 2023). This collaborative approach fosters innovation and accelerates the development of new solutions to address the diverse challenges in at-home care setting.

Specifically, employing modularity enables the customization of robots to meet the specific needs of elderly individuals, such as assistance with mobility, medication reminders, or household tasks. For example, interchangeable end effectors can allow the robot to perform tasks ranging from simple object manipulation to more complex activities like helping with personal care. Additionally, modularity facilitates the integration of new technologies and sensors, such as fall detection systems or health monitoring devices (Baum, 2024), to enhance the robot's capabilities in providing care and support to elderly users.

Overall, modularity is instrumental in the development of humanoid robots for at-home care, enabling versatility, customization, and collaboration within the robotics community. By embracing modular design principles and encouraging community involvement, developers can create robots that are adaptable, scalable, and capable of meeting the diverse needs of users in the home environment, especially in elderly care settings.

3.4 Human Interaction

To address human interaction within the scope of the humanoid, the team explored various methods to implement physical and verbal interaction capabilities. This included integrating speech recognition and motion control functionalities to enable intuitive communication between users and the humanoid robot.

3.4.1 Artificial Intelligence Model

With the increased academic and industrial desire for artificial intelligence (AI) models, the team found several approaches to introducing an AI model to the humanoid. Firstly, the team looked at pre-trained models such OpenAI's GPT (OpenAI, 2021) and Google's Gemini (Google, 2024). These are neural network machine learning models trained on internet text and public non-curated data. More importantly, these models can be fine-tuned for specific tasks and made available as APIs.

There are also many frameworks and libraries that serve as a solid foundation for building AI models. Open-source frameworks such as TensorFlor (Google Brain, 2015) and PyTorch (Meta AI, 2016) are optimal for deployment on devices facing resource and processing constraints. This could be helpful for integration in the humanoid where tasks are performed on board.

Several platforms such as GitHub host repositories are available to all users. Due to the expanding popularity of AI models and machine learning, many of these available projects contain fully functional models and collections of reinforcement learning environments (GitHub ai-models, n.d.).

Lastly, the deployed model should be optimized for edge devices like the Raspberry Pi. A lightweight model would be ideal for the Pi as it uses smaller architectures, reduces the number of parameters to decrease computational and memory requirements.

3.4.2 Speech to Text and Motion

There is very limited work on controlling the motion of a humanoid using speech commands and AI models. However, splitting this into two separate controls; speech-to-text and motion commands, allows the team to focus on two individual components that will be combined in the future.

There are several speech-to-text recognition options available for integration with the Raspberry Pi-based humanoid. This includes the Python Speech Recognition Library, a popular open-source library for performing speech recognition (SpeechRecognition 3.10.3, 2024), with support for several engines and APIs, online and offline. The Mozilla DeepSpeech is another open-source Speech-To-Text engine, using a model trained by machine learning techniques based on Baidu's Deep Speech research paper (Hannun et al., 2014)

Natural language understanding techniques need to be applied to extract actionable commands from the text. This involves parsing text and mapping key actions to corresponding motion commands. Motion control algorithms interpret the transcribed commands and generate appropriate motion commands for the humanoid robot. These algorithms consider the robot's kinematics, dynamics, environmental constraints, and safety considerations to generate smooth and accurate motion trajectories.

Raspberry Pi integration with the above methods can be done efficiently. The General-Purpose Input/Output (GPIO) pins allow for interfacing with any actuators, sensors, or controls desired. Optimizing the performance of speech-to-text and motion control is essential for achieving responsiveness and minimizing delayed interactions. Due to the limited hardware and processing capabilities of the Pi, the team identified the feasibility of deploying speech recognition models on Raspberry Pi using TensorFlow Lite in hopes of achieving real-time performance suitable for interactive applications.

3.5 Human-Robot Trust

The following section is a shortened version of a report that evaluated the desire for humanoid robots in assisted living facilities. The section outlines robots in the workforce, humanoid robotics, trust in robots, and inequality in society driven by technology. The study was performed with the motivation in mind that engineering design needs the study of human perspectives in it to develop products more acceptable to the user.

3.5.1 Robots in the Workforce

Robots are used in several industries and come in many different forms. They are used in the military, manufacturing, healthcare, dining, education, entertainment, and more. For this project, the team chose to focus on the use of robots in aging services.

Within the military, robots are used in dangerous environments to prevent the need for humans in those fields. “They help reduce labor-intensive tasks and reduce the risk of threats, accidents, injury, and death for their human counterparts.” (*7 Types of Robots Used in the Military*, 2023) Robotic developments have both made warfare safer and more dangerous by completing harmful tasks for soldiers which is to be expected by any technological development in the military. Similar developments in robotics can be seen in manufacturing, as industrial and military robotics share a common history.

Within manufacturing, robots are used to automate processes, relieve load from humans, and make industrial practices safer and less harsh (Li et al., 2020). Manufacturing robots come in many different forms, including robotic arms, cartesian robots, cylindrical robots, and spherical robots. Each form of robot has different responsibilities but a common goal of improving past techniques as well as lifting the load from humans. The introduction of robots in manufacturing has increased productivity, precision, flexibility, and the quality of production. (Li et al., 2020) There has been similar success with the use of robotics in nursing homes.

Within the healthcare industry, robots have been used in surgical applications that allow surgeons to perform complex surgeries and perform minimally invasive surgeries (*Robotics in Healthcare*, 2022). There are also modular robots that support patient rehabilitation efforts through therapeutic exoskeletons and prosthetic limbs that track a patient's progress and monitor their form (*Robotics in Healthcare*, 2022). Lastly there are service robots that lighten the load of healthcare professionals' workloads by doing routine tasks and social robots that interact with patients and visitors (*Robotics in Healthcare*, 2022). Repetitive tasks like prepping patient rooms, tracking medical supplies, and filing purchase orders (*Robotics in Healthcare*, 2022) can all be done by the service robots, leaving healthcare professionals to interact with and heal their patients. The use of these robots are similarly seen in aging services to improve the lives of older adults and to lighten the load of nursing staff as mentioned before in Section 3.1.2.

3.5.2 Trust in Humanoid Robots

Humanoid robots are robots with human-like features and capabilities. They come in a range of human-like attributes, including but not limited to, living skin cells, physical human features, and silicone robot skins. Living skin cells and silicone skin give a robot very human-like appearances but aren't necessary to qualify a robot as humanoid. As mentioned before, many types of humanoids exist including Poppy and the humanoids seen in Section 3.1.2 and 3.2 respectively.

Some humanoids have very human-like features including living skin and silicon skin. Trust of robots with these added humanlike features was studied by the Smithsonian back in 2022. Brian Handwerk stated that, "we view robots as less than human, so making them more human-like may strengthen our relationships." (Handwerk, n.d.) The study is still ongoing to determine if humans trust robots more with living skin. There does exist a scale of how humanlike humanoid robots can be and there's a threshold where humans stop trusting them. To determine if using Finley in assistive care was trustworthy, the human study of "Evaluating the desire for humanoid robots in assisted living facilities" was done.

The team worked to study human-robot trust in humanoid robots and designed Finley to work in assistive at-home care. Results from this study were expected to vary and will be considered in the application and development of the robots.

3.5.3 Inequality in Society Driven by Technology

People have been able to have robots in their homes to do tasks previously done by humans, for example, the robot lawnmower and the robot vacuum. Both are designed to do repetitive tasks with little human intervention and make life easier for consumers (*7 Home Robots You Need In Your House*, 2023). The robotic lawnmower can cost between $650-$5,000 whereas the alternative of a push lawnmower costs around $300. The robotic vacuum can cost between $80 to over $1,400 while the alternative of a vacuum cleaner can cost on the lower end, $20-$30 and a broom and dustpan costing $10. Both actions can also be done by paying people on average $50-$250 to mow a lawn in the U.S. and an average of $20-$50 per hour in the U.S. to clean homes. Using robots instead to do these actions has replaced jobs previously done by humans.

Technological advances like the robotic vacuum and lawnmower are available to everybody but are not accessible to everybody. Spending hundreds of dollars on robotic cleaning machines is not a feasible purchase for everyone and is further increasing inequality in society. Not only is the use of robotics dividing people who can and can't afford it, robots are replacing human jobs.

The technological advances of robotics have impacted jobs significantly. In a study performed in 2017, Massachusetts Institute of Technology Professor Daron Acemoglu and Boston University Professor Pascual Restrepo, found that one more robot per 1,000 workers is predicted to reduce aggregate wages by 0.42% and "one more robot reduces employment by 3.3 workers" (Acemoglu & Restrepo, 2017) To date this means the loss of about 400,000 jobs (Brown, 2020). Job loss as a result of industrial robots is an added driver of inequality. With this in mind, the team has ensured that the 3D printed humanoid robots at WPI are developed to assist humans in their work and not replace their work.

3.6 Sustainability

Sustainability was considered in two ways for the development of the 3D printed humanoid robot Finley. The social dimension and the environmental dimension. Concepts like health and social equity and community development and well-being are integrated using social sustainability (Kosmopoulos, 2024). In order to frame the project, the concept of doughnut economics was applied. Doughnut economics is a vision for how humanity can thrive in the 21st century and helps us find a way to get there (*About Doughnut Economics | DEAL*, n.d.). The doughnut consists of two concentric rings: a social foundation and an ecological ceiling, and in between is a safe and just space for humanity. (*About Doughnut Economics | DEAL*, n.d.) Material reduction and recycling of the 3D printed materials used in Finley will reduce the carbon dioxide emissions and chemical pollution produced from both mining the fossil fuels to make the printing materials and emissions from printing. Reducing the materials used from this project will help it stay under the ecological ceiling. Increasing the support for vulnerable populations with the development of technology for longevity in senior health and well-being will improve social foundations of equity and health.

3.6.1 Recycling and Reducing 3D Printing Materials

Resin printing and FDM printing are used in the development of the 3D printed humanoid robot, Finley. There is ample evidence that resin printing is both harmful to the environment and to the humans doing the printing (Oskui et al., 2016). There are methods to minimize exposure to resin which Grove Labs of the University of California Riverside discusses. They recommend "locating the printer in a well-ventilated space, wearing chemical-resistant gloves and eye protection when adding resin or rinsing a part, and not placing 3D-printed parts in contact with food or drink" (Grover, 2021). To further reduce the use of resin, reducing the material in each part to only use what is necessary to the structure of the 3D printed humanoid robot can minimize as much exposure to the toxic material as possible.

Chemicals evaporate in the process of melting filament in FDM printing, and an unhealthy level of nanoparticles, volatile organic compounds, and gaseous material emissions are produced (Antić et al., 2023). There are dangers involved with using both materials in the development of 3D printed humanoid robots. Similarly precautions to resin printing should be taken for FDM printing. Reducing the material use of parts needing FDM printing will minimize as much exposure to the material as possible.

Waste is created by using both materials. Waste can be reduced by recycling the part's supports or failed parts and turning it into filament to be reused. 3D printer filament recyclers exist, and people can even buy recycled filament to use in their prints.

3.6.2 Increasing Support for Vulnerable Populations

Better attention and care to older members of society in aging services promotes social sustainability. The well-being and health of older adults is an important focus of this project. Longer living and healthier members of society are integral to the social foundation of sustainability. Robots in aging services, as mentioned in section 3.1.2, were developed to better health, and open-source projects and the development of AI increased social equity to enter the safe and just space for humanity.

3.6.2.1 Robots in Aging Services

Within the healthcare industry is a growing need for nurses in elder care. Assistive robots have been introduced around the world to lighten the load on nurses and improve the overall quality of life for residents and patients. Aging services robots include robotic assistants, personal robots, telepresence robots, and robotic exoskeletons (Sawik et al., 2023). A robotic assistant helps with daily tasks, personal robots offer companionship for elderly people, telepresence robots have video conferencing capabilities, and robotic exoskeletons are wearable devices to aid the elderly in mobility (Sawik et al., 2023). Assistive and personal robots have been used for entertainment and completing mundane tasks to lighten the load of nursing staff. Certain humanoid robots tell jokes, tell stories, dance, and have games to entertain nursing home residents (Cox, 2022). They are also able to perform simple tasks that nurses won't have to perform leaving the nurses to do important tasks (Cox, 2022). A variety of robots are found in an assistive care setting, but this study focused primarily on humanoids.

3.6.2.2 Open-Source & OpenAI

There have been strides made to make technology more accessible to humans. OpenAI and ChatGPT for example, are an example of free technology available to everybody. While ChatGPT has led to cases of cheating and misconduct in school and work, ChatGPT doesn't inherently exclude anyone. Before its introduction, students used to pay other students and outside help to do their homework or exams, known as commercial contract cheating (Newton, 2018). Not every student had the option or opportunity to contract someone to do their work for them, which other students had the advantage of. With the introduction of ChatGPT, students can cheat without having to pay someone else, which not all students were able to do before.

ChatGPT has had both positive and negative influences on students, but it has been able to influence all students without exclusion.

Open-source projects and programs is another example of making technology more accessible to humans. Projects and programs that are open source are freely available to everyone and can be easily distributed and modified (Opensource.com, n.d.). People have access to softwares, robot assemblies, and all kinds of technology that they can make their own. The 3D printed humanoid robot team at WPI has been developing an open-source robot that people can freely download, print, assemble, and use to their liking. Robots and complex technology are becoming more accessible to people around the world with open-source projects which gives people the opportunity to make and use something they may not have been able to before.

Open-source and the use of OpenAI in the development of a humanoid robot for assistive care can improve social equity. Making technology available to everyone that can help people is at the foundation of the development of WPI's 3D printed humanoid robots.

3.7 RoboCup@Home

The RoboCup Federation is an "international scientific initiative with the goal to advance the state of the art of intelligent robots (*RoboCup Federation Official Website*, n.d.). When established in 1997, the original mission was to field a team of robots capable of winning against the human soccer World Cup champions by 2050." Since its inception, RoboCup has created various leagues for other applications of advanced robotics including RobCupRescue, RoboCup@Home, and RoboCupIndustrial. The RoboCup@Home league aims to develop service and assistive robot technology with high relevance for future personal domestic applications. It is the largest international annual competition for autonomous robots. Robots are evaluated using a series of benchmark tests, assessing abilities and performance in a realistic home environment setting. Focus lies in the following domains: Human-Robot-Interaction and Cooperation, Navigation and Mapping in dynamic environments, Computer Vision and Object Recognition, Object Manipulation, Adaptive Behaviors, Behavior Integration, Ambient Intelligence, and Standardization and System Integration.

The conducted tests will include the following criteria:

1. Include human machine interaction.
2. Be socially relevant.
3. Be application directed/oriented.
4. Be scientifically challenging.
5. Be easy to set up and low in costs.
6. Be simple and have self-explaining rules.
7. Be interesting to watch.
8. Take a small amount of time.

The team deemed that the listed benchmark abilities and performance tests would be helpful in creating design requirements and evaluating progress in achieving success in an at-home assistive care setting. In doing so, the team will have also set up the future project teams for potential participation in the competition.

This literature review chapter contained a summary of the necessary knowledge needed prior to starting this project, including service and at-home care robotics, the Poppy Project, modularity, human interaction, human-robot trust, sustainability, and RoboCup@Home. The next chapter provides an overview of the methodology and planning that occurred in order to complete this MQP.

4.0 Methodology and Project Plan

This chapter includes the planning and thought process that was put into the development of a 3D printed humanoid robot for assistive at-home care. Sections include picking-and-placing, modular connection, redesign, human interaction, and the human study methodology.

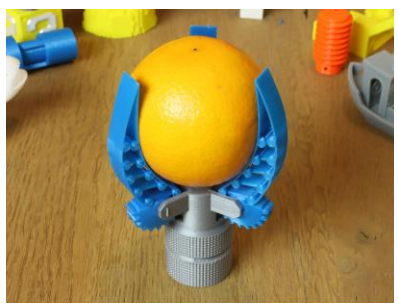
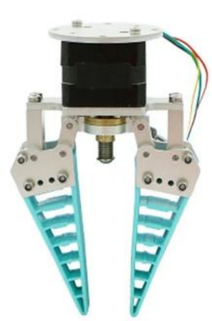
4.1 Pick-and-Place

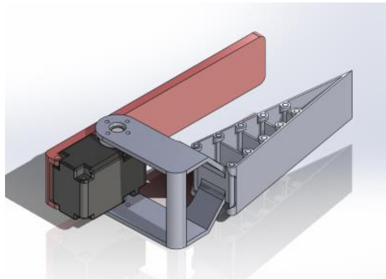
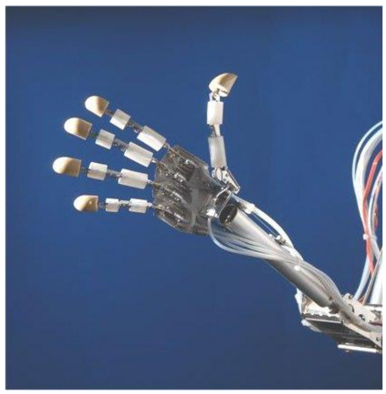
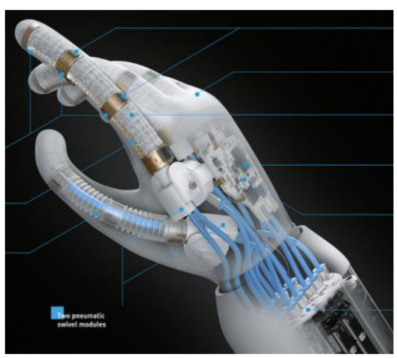
To develop a 3D printed humanoid robot for assistive at-home care, the ability to pick-and-place objects was necessary. In order to accomplish this objective, a versatile gripper hand was developed, and the movement was simulated and transferred to real life.

4.1.1 Grip Design

One major aspect of this project was the development of an end effector capable of picking up and placing a variety of objects. For the purpose of this project, five different hands were considered: the flexible three finger claw, flexible two finger claw, hybrid two finger pinch, wire actuated hand, and pneumatic actuated hand. More information on each of these grips can be found in Table 4.

Table 4: Picture and description of each of the candidate end effectors

Grip Name	Picture	Description
Flexible three-finger claw (*Flexible Gripper by PrintChallenge | Download Free STL Model*, n.d.)		FDM printed three-finger design with flexible fingers. Only requires one motor for full functionality. Fully capable of picking up round objects of a certain size.
Flexible two-finger claw (*Pneumatic Two-Finger Flexible Robot Claw Bionic Hand Robotic Hand Fruit Claw | eBay*, n.d.)		FDM printed two-finger design with flexible fingers. Only requires one motor for full functionality. Capable of picking up a variety of shapes and sizes.

Grip Name	Picture	Description
Hybrid two-finger pinch		This design incorporates one flexible finger and one rigid finger to allow for a more stable gripping ability. Only requires one motor for full functionality. Capable of picking up a variety of shapes and sizes.
Wire actuated hand (*The Best Robotic Hands*, n.d.)		Each individual finger can be actuated using tendon cables together or separately depending on the number of motors being used. Fingers would either have to be constructed using a flexible material or multiple rigid parts. The specific objects this hand can pick up depends on its construction.
Pneumatic actuated hand (DeLaOsa, 2019)		Similar to the wire actuated hand, each finger can be actuated together or separately depending on the design. Pneumatic systems use air or water to activate a piston which can flex the fingers. Fingers would either have to be constructed using a flexible material or multiple rigid parts. The specific objects this hand can pick up depends on its construction.

In order to decide which hand would be the best fit for this project, the team used a decision matrix to evaluate each against a set of design criteria that can be found in Appendix D. According to the decision matrix (Table 5), the hand that most satisfies each of the design criteria is the hybrid two-finger pinch, which earned a score of 24. From here, the team will need to develop tests to determine the best dimensions for the hybrid two-finger pinch. Each iteration will need to pick up a series of objects, and the most successful hands will determine either the width, length or height of the fingers. Thorough testing of each iteration can be found in Section 8.1.

Table 5: Decision matrix in order to evaluate which end-effector is best for this project

Criteria	**Weigh-ting**	**Flexible Three Finger Claw**	*****	**Flexible Two Finger Claw**	*****	**Hybrid Two Finger Pinch**	*****	**Wire Actuated Hand**	*****	**Pnuematic Actuated Hand**	*****
# Actuators	5	1	5	1	5	1	5	-1	-5	1	5
Versatility	4	-1	-4	0	0	1	4	1	4	1	4
Hand Strength	4	0	0	0	0	1	4	0	0	-1	-4
Complexity	3	0	0	1	3	1	3	-1	-3	0	0
Design Time	2	1	2	1	2	0	0	-1	-2	-1	-2
Cost	4	1	4	1	4	1	4	-1	-4	-1	-4
Breakage Risk/ Wear & Tear	4	0	0	0	0	0	0	-1	-4	-1	-4
Modular Compatibility	4	1	4	1	4	1	4	0	0	0	0
Sensor Compatibility	3	-1	-3	-1	-3	0	0	1	3	1	3
TOTAL:			8		15		24		-11		-2

4.1.2 Pick and Place Movement

To develop a 3D printed humanoid robot for assistive at-home care, the movement of picking-and-placing items was important. In order to complete this motion trajectory planning using inverse kinematics was needed to simulate the movement in CoppeliaSim then use the simulated kinematics in the real movement. Testing and adaptations were necessary after applying the simulated kinematics to Finley in real life to make the movement more human-like. Two programs were written, one for simulation of Finley picking and placing and the second for Finley picking and placing in real life.

4.1.2.1 Simulated Kinematics

The locomotion team of this project developed an open-source system utilizing CoppeliaSim to simulate Ava and Finley to replicate their physical actions. Using their open-source software, the movement of Finley picking and placing was simulated in CoppeliaSim using Newton Raphson’s iterative method of inverse kinematics and quintic trajectory planning.

Each trajectory was made by converting millimeter movements of the end effector into radians through inverse kinematics.

Eight coordinates were calculated to make three movements seen in Figure 43 in section 8.5, which required iterative testing to make the movement fluid and accurate. Finley can be seen doing the simulated movement below in Figure 5. Simulating the movement of picking and placing was important for the team because it proved that the system could create movements to be used in assistive care.

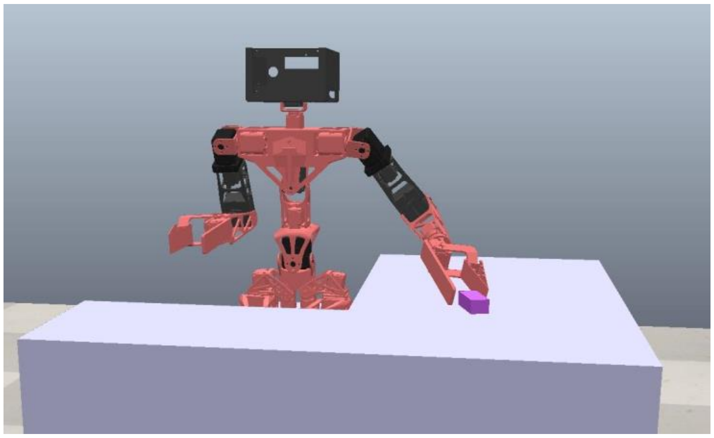


Figure 5: This figure shows Finley picking-and-placing an object in CoppeliaSim simulation

4.1.2.2 Simulated Kinematics in Finley

The code written to run the simulation needed to be tested and adapted when applied to the real-life kinematics. Some of the trajectories were changed to make the movement more human-like and additional code was written for picking and placing objects of variable sizes. There were cases that parts of each trajectory needed to be manually changed or locked because each motor was moving to get to the coordinates making the hand grip in non-human-like manners.

4.2 Modularity

Finley is designed to operate in an at-home assistive care environment, so it is important that a variety of tasks can be completed by the system. Instead of developing one hand that can accomplish many tasks, a modular end-effector system was developed. This system allows for hands designed for specific applications to be easily swapped out. Additionally, modularity was incorporated on the head to allow various sensors to be easily connected.

4.3 Design Changes

While assessing Ava, several redesigns were deemed necessary. Multiple general redesigns were performed across all applicable parts, while others were specific to single components. These changes apply to different categories: structural, quality of life, and aesthetic.

There are also multiple feature additions showcased on Finley. The robot has been outfitted with modular capability with an electromagnetic hand connection. This allows the user to design and swap out different end effectors for different applications. Finley also has a newly designed versatile gripper to showcase this modularity and perform pick-and-place functionality. All these mechanical redesigns and additions were performed using SOLIDWORKS 2023 and produced with polymer additive manufacturing techniques.

While redesigning some parts, areas with extra material not affecting the structural integrity of the part were identified. These areas were cut out to reduce the material cost of Finley. This reduced the overall weight and cost of the robot, as well as the environmental footprint. Additionally, feedback from the study on human-robot trust was considered in redesigns to make Finley more aesthetically appealing.

In each redesign, the material used was reduced to decrease cost and environmental impacts from the project. Additionally, feedback from the study on human-robot trust was considered in redesigns to make Finley more aesthetically appealing.

4.4 Printing

All components of Finley were 3D printed to allow for reproducibility without complex machining. Most parts were produced with stereolithography (SLA) resin printing, and some with fused deposition modeling (FDM) techniques.

4.4.1 Resin

Resin printing is primarily used to obtain highly precise parts with complex geometries. Most components on Finley were modeled to reduce material and weight, leading to increased complexity for printing. Because of this, resin printing is how most parts of Finley were made. Part models were sliced using the Chitubox slicing software. The team chose to use Esun Hard Tough Resin, due to its high strength and wear resistant properties (Hard-Tough Resin, n.d.). Epoxy resin dyes were used to produce different color parts. Three printers were used to produce Finley, namely Mars 2 Pro, Saturn, and Jupiter from Elegoo.

4.4.2 Fused Deposition Modeling

For simpler components and fast prototyping, fused deposition modeling (FDM) printing was utilized with polylactic acid (PLA) filament for a small number of parts. These components were sliced with the PrusaSlicer software and made with a Prusa MK3 FDM printer.

4.5 Human Interaction

After assessing the need for human interaction within an elderly care setting, the team decided to focus on three main components: a trained AI model, speech to motion, and touch screen controls.

The team laid out a plan to achieve the open source and human interaction requirements set. First, the robot needed to be capable of speech to text. This was followed with the selection of a base AI model for training. The model needed to be able to store conversations, perform actions using speech, and demonstrate accurate responses. To supplement this, the robot needed input and output interfaces including a touchscreen user interface, interaction with the Raspberry Pi, and hardware integration with a speaker and microphone. Lastly, the team implemented speech to motion and electronic control. This was done by employing locally stored scripts and movement configurations. The team then gathered user feedback identifying any areas for improvement and usability issues. This involved stress testing models and motion requests, as well as performance optimization.

The human interaction component needed to seamlessly integrate all functionalities of the humanoid and develop the open-source nature of the project while maintaining viability within an at-home assistive care setting.

4.6 Human Study Methodology

A survey and interviews were used to gauge perceptions of humanoid robots for the development of a 3D printed humanoid robot. Past human-robot interactions were researched to develop effective research as well as interview and survey questions.

4.6.1 WPI Community Survey

An online text-based survey was developed and sent out to WPI students, family, and faculty to gauge interest and gather opinions in the development of Finley and Ava at WPI and on humanoid robots. Questions were written using Qualtrics' method on writing great survey questions (Fisher, 2023) and the full survey can be found in Appendix F. All data was kept confidential and WPI community members will only be mentioned as WPI community members.

Data recorded from surveys was analyzed in various graphs and pie charts which can be found in Appendix H. Results were applied to the design of Finley and were used to change the design criteria for the future of this project.

4.6.2 Residents and Providers Interview

Residents and providers of Finley were interviewed to understand user views. The Briarwood Retirement Community and Leading Age organization were identified as interview sites because they responded to interview inquiries. Semi-structured interviews were conducted with Briarwood and members of the Leading Age organization. Semi-structured interviews are in-depth interviews where respondents answer preset open-ended questions and generally cover thirty minutes to an hour (Jamshed, 2014). Data was recorded and kept confidential. Participants did not interact with Finley and Ava but were able to see the robots in videos and photographs. Interview questions can be found in Appendix G.

Data was analyzed by tracking themes through the interviews and emotions of interviewees, for example, excitement, interest, and criticisms. Recommendations and feedback recorded from interviews were applied to the development of the project and to change the design criteria for the future of this project.

4.7 Relevant Engineering Standards

There are several engineering standards that were considered for this project. Firstly, EN ISO 10218-1 addresses requirements for the safe design and construction of robots. As the manufacturers of the humanoid, all of the structural redesigns done were in the interest of ease-of assembly and damage prevention, therefore reducing the risk for harm during servicing. After receiving feedback from relevant industry professionals, wire management is also a safety factor that should be considered in construction, which is further explained in section 10.2.1. Since Finley is developed to function in a professional environment, EN ISO 10218-2 must also be considered. While EN ISO 10218-1 is concerned with manufacturing, EN ISO 10218-2 is focused on safe use and application. This was addressed through Finley's application. Finley is meant to act as an assistant to RNs and caregivers and should not be solely responsible for health-related tasks (Schapoehler, n.d.). Being a pick-and-place aid and providing company and conversation are safe responsibilities for Finley in an at-home care setting. It is also important to note that the manufacturing of Finley must take ISO 13485/9001 into account, as it will be used in a healthcare setting. This means that if the humanoids were to be manufactured for a professional setting, quality assurance testing must be conducted to monitor different aspects of safety (Byrne, n.d.). Another aspect of ISO9001 that can be easily addressed with Finley is identifying and meeting new customer requirements. Finley's modular system will make these adjustments simple and personalized.

This overview of the methodology and project plan serves as the basis on which this project was completed. The next chapter provides a week-by-week summary of each task that was done throughout the 2023-2024 school year.

5.0 Project Timeline

5.1 A-Term Progress

8/24-9/1: For the first week of A term from 8/24-9/1, the team met to review the past projects and brainstorm potential environmental and biomedical applications.

9/2-9/8: From 9/2-9/8, the team read the 2022 MQP report and the 2023 MQP report, made a preliminary decision matrix for the application, reviewed validation & verification requirements, and roped in the Environmental & Sustainability Studies and Biomedical Engineering advisors.

9/9-9/22: From 9/9-9/22, the team got hands on with Koalby and Ava in order to catalog the existing parts and motors. Additionally, the team learned how to do resin printing with a past team member, continued working through the decision matrix for applications, continued application literature review, and began the human interaction proposal. Lastly, the team made a set of quality-of-life design goals to improve assembly and disassembly of the robots.

9/23-9/29: From 9/23-9/29, the team redesigned the shin to remove excess fasteners, integrated biomedical requirements into the project, completed a draft chapter of the previous MQP accomplishments and recommendations. Additional redesigns were made to the bicep and several of Ava’s broken parts were strengthened. Lastly, the application for the project was chosen and an associated literature review was begun.

9/30-10/6: From 9/30-10/6, the team continued to redesign parts to have fewer holes and strengthened motor pegs, a sponsorship email template was created, the application was adjusted to focus on modularity, and a part was printed to test resin with new dyes.

10/7-10/13: From 10/7-10/13, the team created B-Term objectives, deliverables for project presentation day, changes were made to every part in assembly, redesigned was started on the head and the pelvis, and wiring diagrams were obtained for Ava and were analyzed.

5.2 B-Term Progress

10/23-10/29: For the first week of B term from 10/23-10/29, simple changes were made to every part of Finley, including reducing the number of holes, adding material to hole pegs, and adding supports to parts with frequent breakage. RobotShop was emailed to obtain a quote on the required motors as well as inquiring on a sponsorship or discount. The team began redesigning the head and continued to redesign the pelvis.

10/30-11/5: For the second week of B term from 10/30-11/5, all designs were completed except for the head, chest, and neck which require future work. A decision matrix was made to determine grip type. Sponsorship tiers were made as well as a complete company list on who to contact for future sponsorship and an email draft. Lastly, a 5% discount was obtained from RobotShop.

11/6-11/12: For the third week of B term from 11/6-11/12, additional improvements were made to the designs of the foot and bicep. Contacts were found from the previous week’s company list, and biomedical and environmental studies research was begun for literature review. A BME decision matrix was made to decide which vital (heart rate, blood pressure, body temperature, respiratory rate, pulse oximetry) Finley would be able to administer.

11/13-11/19: For the fourth week of B term from 11/13-11/19, design criteria were redone to have sizes and weights. Specifications for objects the gripper can pick up were added, which were the sizes and weights of three objects chosen (glass hot sauce bottle, cardboard mac and cheese box, and a polymer chip bag). A flexible two finger grip was printed, and preliminary tests were done. Male-to-male connectors were worked on with collaboration from the locomotion team. Assembly of Finley in SOLIDWORKS was started and a draft outline for the report was made.

11/20-12/3: For the fifth and sixth weeks of B term from 11/20-12/3, the assembly of Finley in SOLIDWORKS was finished, the design of the pelvis was completed, preliminary designs for the head were made, and printing of completed parts was started. For the human study portion, the consent form was written, and the IRB proposal was started and mostly finished. Lastly, the team met with Chris Nycz from Practice Point lab at WPI to discuss human interaction testing with Finley and testing the robot in a home environment.

12/4-12/15: For the last two weeks of B term from 12/4-12/15, Koalby was disassembled for the team to absorb the working motors. All Koalby's motors were tested, and the motor quote was updated, resulting in a large reduction in required costs. Finley was assembled as much as possible to be presented at the team's Peer Design Review. A hybrid gripper was designed, printed, and assembled to be presented at the PDR.

Lastly, before C term started, the environmental major filled out the IRB application and submitted the proposal for feedback from the board. The CITI program Human Subjects in Undergraduate Student Projects Ethics course was completed as well.

5.3 C-Term Progress

01/10-01/18: For the first week of C term from 01/10/24-01/18/24, sections of the report were written to update literature review and design, most of Finley was printed, the hand testing plan was developed, the electromagnet was tested, and the head was designed.

01/19-01/25: For the second week of C term from 01/19-01/25, pogo pin research was conducted for electrical continuity, the on-board microphone and speaker were chosen, the test method for hand testing was set up, the forearm was redesigned, and head lid options were made.

01/26-02/01: For the third week of C term from 01/26-02/02, the team opted to use a Jira to track tasks, hand iterations were designed, the head was edited to have onboard sensors, the forearms were printed, and assembly of Finley began.

02/02-02/08: For the fourth week of C term from 02/02-02/08, all hand iterations were printed, hand testing setup/methods were finalized, the hip was redesigned, and stress tested, the PCB was finished, more of Finley was assembled, and the human-study proposal was approved.

02/09-02/15: For the fifth week of C term from 02/09-02/15, hand testing began, the modular connection was designed, and the hand and modular connection were added to assembly in SOLIDWORKS.

02/16-02/22: For the sixth week of C term from 02/16-02/22, the survey was developed and distributed for the human study, Gage Repeatability & Reproducibility was done for hand testing, and magnet testing for modularity was done.

02/23-03/01: For the seventh week of C term from 02/23-03/01, the plan for D term was developed for stress testing, the pick-and-place system, analyzing the human study results, modularity, and for project presentation day in April.

5.4 D-Term Progress

03/02-03/12: For the first week of D term from 03/02-03/12, the project was broken up into the pick-and-place system, the modular connection, the human study, and the redesign needed.

03/13-03/19: For the second week of D term from 03/13-03/19, hand testing was finished, and the final hand was chosen, the wiring plan was developed, the final assembly was made, the speaker and magnets were tested, and human-study data was analyzed.

03/20-03/26: For the third week of D term from 03/20-03/26, Finley was assembled fully and a stand for URPS was designed, the head lid was finalized and printed, and the speaker was integrated into the head.

03/27-04/02: For the fourth week of D term from 03/27-04/02, the team simulated the pick-and place movement, built the stand Finley sat on for URPS, the microphone was integrated into the head, and the pick-and-place motion was planned.

04/03-04/09: For the fifth week of D term from 04/03-04/09, the team simulated the pick-and place movement, wrote a speech-to-text program, finished the human study, and developed a high-level presentation for providers in aging services.

04/10-04/16: For the sixth week of D term from 04/10-04/16, the team implemented real pick-and-place motion on Finley, integrated human interaction and speech to motion, and met with people interested in supporting the project.

04/17-04/23: For the seventh week of D term from 04/17-04/23, the team finished pick-and-place movements, human interaction, and demos needed. The project was presented on April 19th, 2024, at the Undergraduate Research and Project Showcase.

04/24-05/01: For the last week of the year, the team finished writing the report and set up the team for next year.

This chapter provided a week-by-week summary of the tasks completed during the 2023-2024 school year. The following chapter will provide an overview of the design changes made to the humanoid, including structural, quality of life, and additional changes.

6.0 Design Changes

Finley has undergone many design changes from Koalby and Ava. These changes and additions can be placed into several different categories: structural, quality of life, and additions. Structural redesigns involve strengthening components on the robot that have been prone to breaking. Quality of life changes have a variety of benefits, such as reducing assembly and servicing time, reducing the number of 3D printed parts, reducing the number of fasteners needed, and reducing material. Lastly, additions include any components or systems that were introduced into Finley. All these changes are described in this chapter.

6.1 Structural Redesign

As previously discussed, many components on Ava were broken at the start of the project. As the locomotion team replaced these parts, they pointed out several parts that broke consistently, signifying that structural redesigns were needed. These redesigns are crucial to the function of Finley, ensuring a long life and allowing for movement without the risk of mechanical failure. Some parts, like the chest, can also take upwards of an hour to replace, so preventing breakage eliminates the need for constant and time-consuming maintenance.

6.1.1 Motor Mounting Pegs

One area of very frequent failure on Ava was the motor mounting pegs. These are small extrusions on the 3D printed parts that allow for motor mounting. The HerkuleX DRS 0101 and 0201 motors have indented screw holes for mounting, shown in Figure 6, that these pegs fit into. These pegs result in very high stress concentrations, as the pegs have a maximum size of 5mm x 5mm x 5mm due to the constraints of the motor geometry. As shown in Figure 7, the previous designs failed to maximize material in these pegs, so failure was common. The pegs were all modified to maximum material per part.

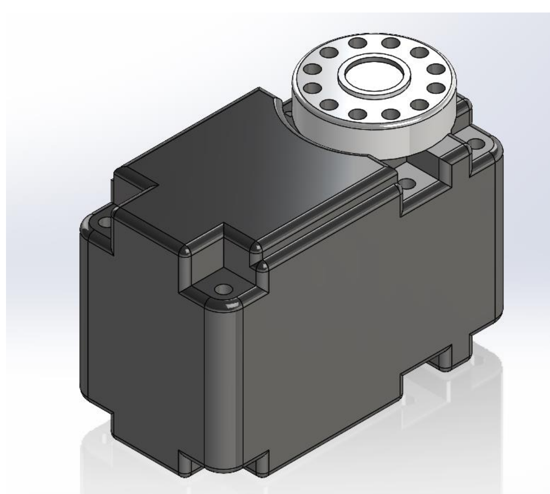


Figure 6: HerkuleX DRS 0201 motor with indented mounting holes

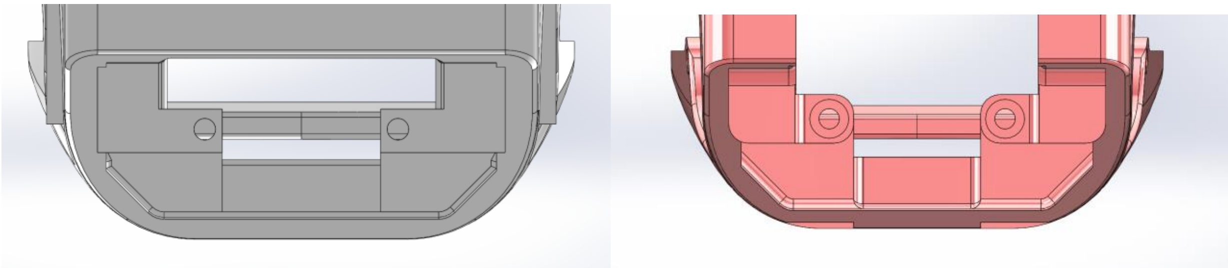


Figure 7: Failure of previous design (left) to maximize motor mounting peg material on bicep with redesigned part (right)

On the shin, the mounting pegs had to be strengthened even more. With the entire weight of the robot resting on it, the shin-foot motor connection pegs continued to break, even after performing the previously described redesign. This problem was solved by extending the pegs perpendicular to the motor and making them more coherent with the rest of the shin material. As seen in Figure 8, the previous pegs were free standing, making them fail easier. The new pegs, shown in Figure 9, are much stronger for this connection.

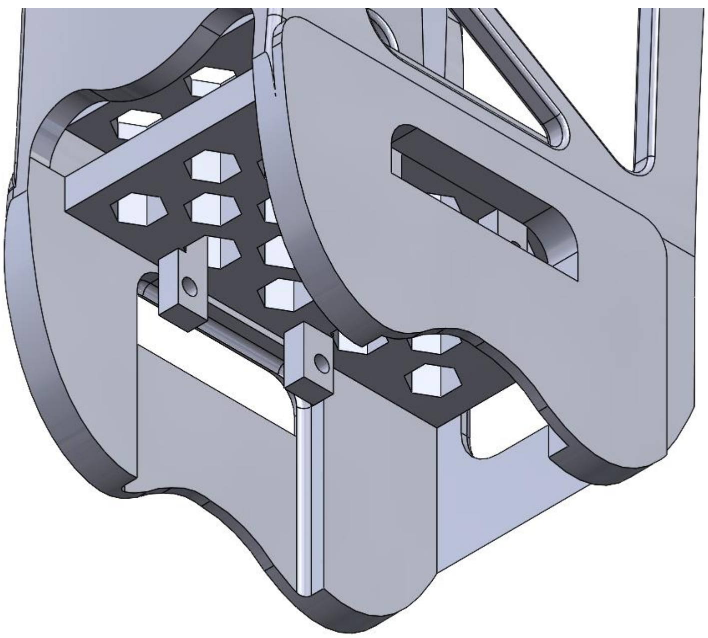


Figure 8: Previous shin design with free-standing motor mounting pegs

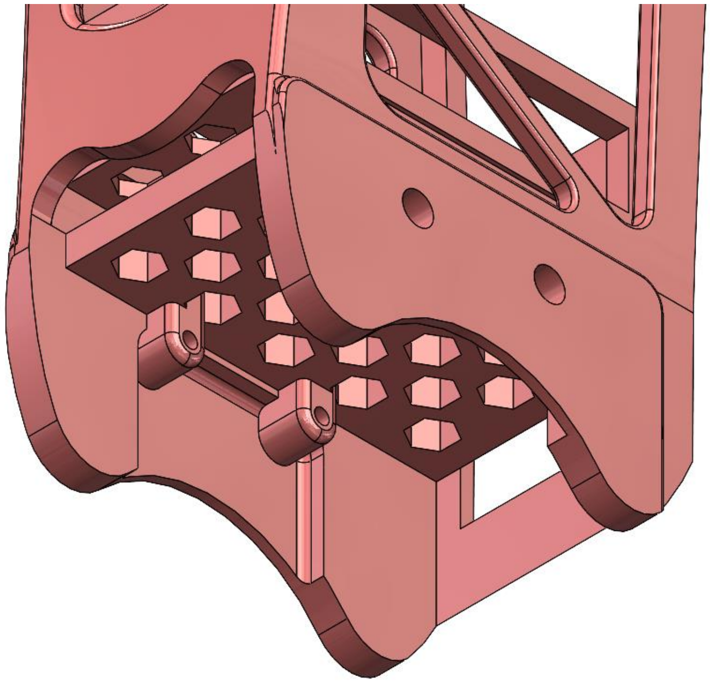


Figure 9: New shin design with stronger motor mounting pegs

6.1.2 Pelvis

The pelvis required more intensive structural redesigns than other parts. The pelvis contains two motors, which were previously stacked diagonally. These motors were attached to the pelvis with four motor adapters that were used initially when replacing the original Dynamixel motors with the new HerkuleX motors on Koalby. This design made for many thin features in the pelvis design, leaving material as thin as 0.5mm. The previous design was prone to failure, so a redesign was necessary. The team decided it would be best to fully redesign the pelvis with simplicity in mind. This new design can be seen in Figure 10, next to the previous pelvis design. The motors were changed to no longer stack diagonally and sit side by side instead. This change meant the two pelvis motors were 10mm closer together horizontally, while still being the same vertical distance from the abdomen connection point. In order to maintain the position of as many motors as possible to not change the kinematics of how Finley moves, the hips were lengthened by 5mm each horizontally. These changes keep the abdomen and hips in the same positions relative to each other, while only slightly decreasing the spacing between the pelvis motors.

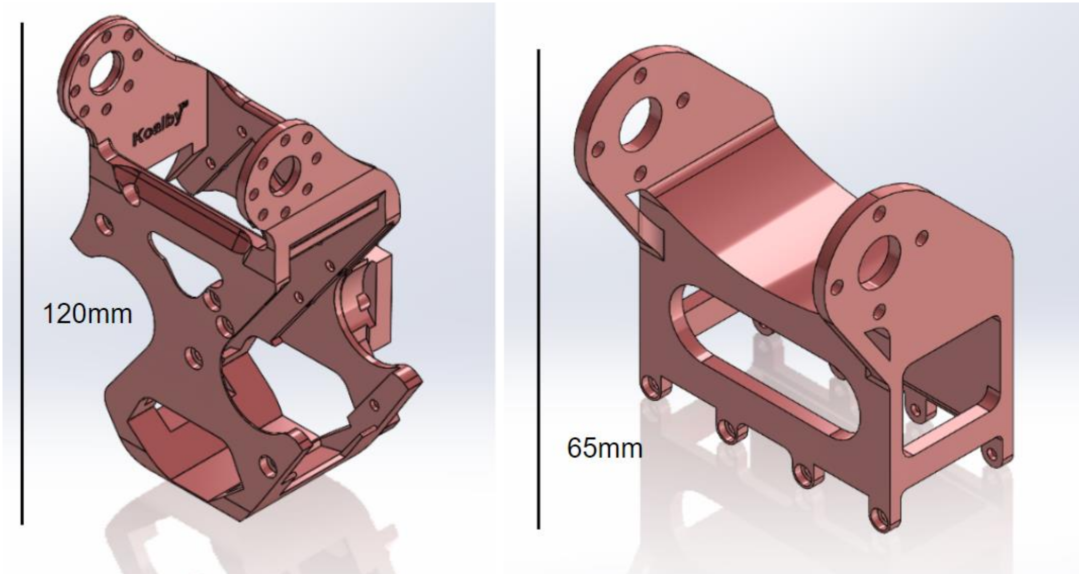


Figure 10: Previous pelvis design (left) and new pelvis redesign (right)

To confirm the efficacy of this redesign, FEA was performed on both the previous and new designs in SOLIDWORKS Simulation. More details on this process can be found in Section 8.4.2. It was found that the pelvis redesign had a 93% reduction in calculated maximum stress.

6.1.3 Hips

In addition to the changes discussed in Section 6.1.2, the hips underwent further redesign. It was noted during assembly that the HerkuleX DRS 0201 motors were very difficult to place in the previous hip design. This was due to the support for the two overhanging motor mounting pegs. These pegs meant that the hip had to be significantly deformed to fit the motor, occasionally causing fracture. A redesign was proposed to remove these two problematic mounting pegs, leaving four remaining. The stress on these remaining motor mounting pegs would inevitably increase from the previous design, so FEA was performed on both designs to determine the new maximum stress. More details of this process can be found in Section 8.4.1. It was found that the new maximum stress on the hip was still well below the yield strength of the Esun Hard Tough Resin, meaning that the redesign was feasible. The new hip design, seen in Figure 11 along with its predecessor, was implemented onto Finley. This change made assembly easier and decreased the risk of fracture when assembling the hip, as well as decreasing the number of screws needed for assembly by two per hip.

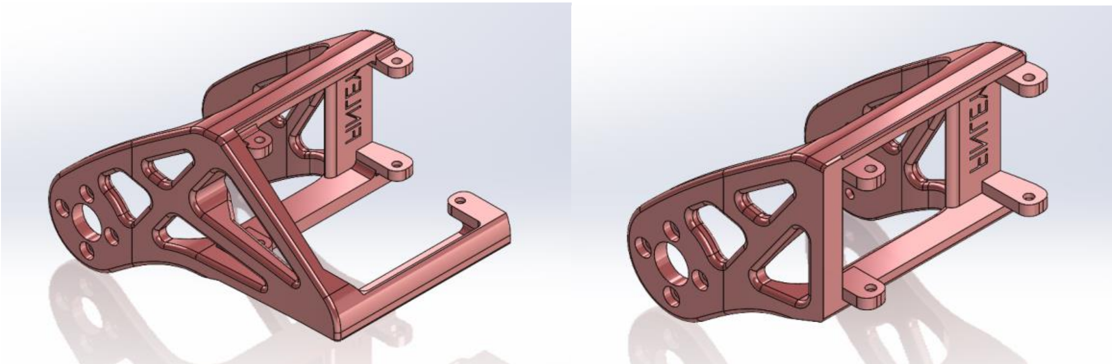


Figure 11: Previous hip design (left) and redesign hip (right)

6.1.4 Forearms

The forearm of the robot was completely redesigned from Ava to provide function to the modular end-effector system and to aesthetically match the rest of the robot. The previous forearms were not rigid and were not compatible with the modular end-effector system on Finley, described in Section 6.3.1. The new forearm features connection points for two motors, one HerkuleX DRS 0601 in the elbow and one HerkuleX DRS 0201 in the wrist. The visual design of triangular cutouts on many main structural components of the robot was translated to the new forearm design. This redesigned forearm can be seen alongside the previous design in Figure 12 below.

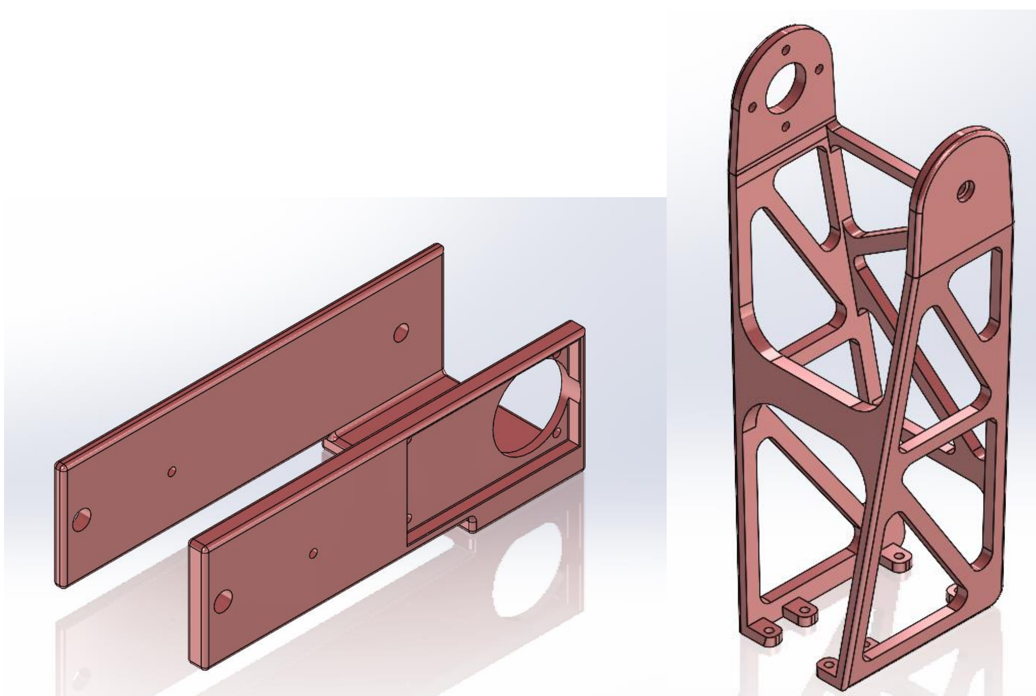


Figure 12: Previous forearm design (left) and redesigned forearm for Finley (right)

6.2 Quality of Life

It is important to consider the user experience of producing and maintaining the robot. Quality of life redesigns are essential to decrease assembly time by reducing the number of 3D printed parts, fasteners needed for assembly, and material costs.

6.2.1 Motor Holes

The HerkuleX motors used all have 12 screws on their motor horns. All parts on Koalby and Ava reflect this, having 12 mounting holes, shown in Figure 13. The team decided that having all 12 holes was unnecessary. There was only 1.5mm of material between the holes. Additionally, the counterbores for the holes overlapped, meaning it was only physically possible to install six screws on each motor horn. The team determined that four mounting holes were sufficient after testing. This change can be seen in Figure 14. This leads to greatly improved assembly and servicing times.

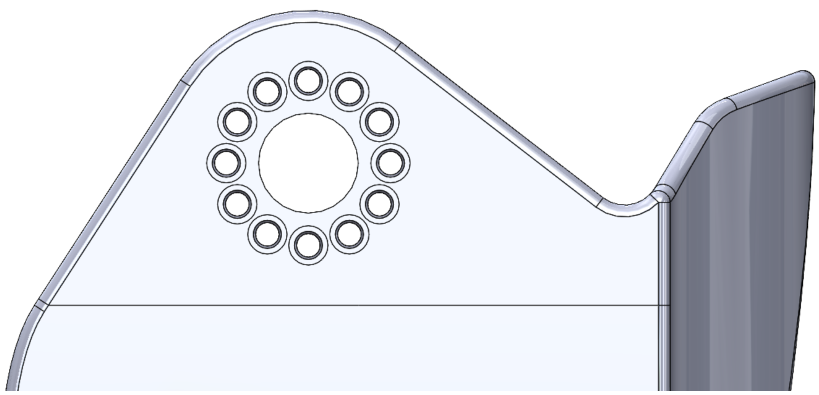


Figure 13: Example of previous 12 hole motor connection on shin

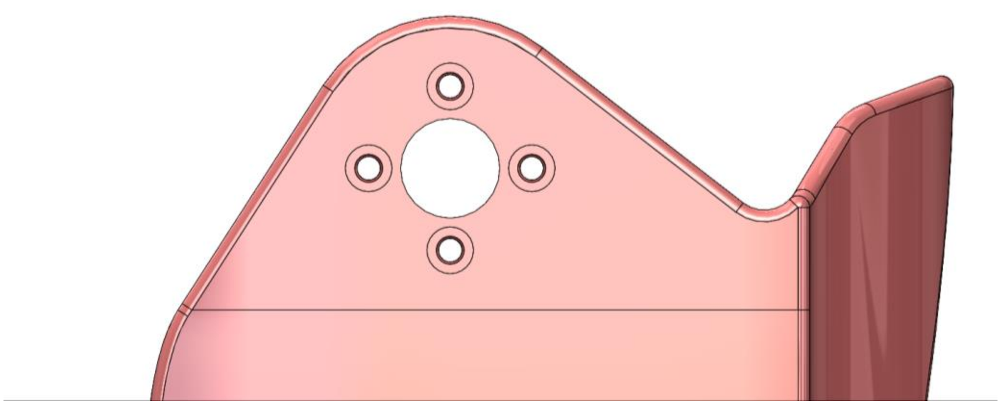


Figure 14: Example of new four-hole motor connection on shin

The size of the screw holes was also changed from the previous design. The robots use M2 screws with a diameter of 2mm to connect the 3D printed components to the motors. All the screw holes for motor mounting had a diameter of 2mm, meaning the screws fit tightly into a newly printed part. This meant that all holes had to be forcefully manually threaded into the plastic pieces, leading to fracture of the motor mounting pegs and hand cramps for the user after screwing together several parts. To fix this, all holes were changed to have a new diameter of 2.1mm. Although small, an increase of 0.1mm made assembly much easier, while maintaining a tight fit.

The previous counterbore size on all the screw holes was too small, measuring 3.35mm across. This meant screw heads would stick out across the robot instead of sitting flush, in some cases causing interference with the motor horns. All counterbores on Finley were increased to a diameter of 4mm to account for this. These changes in hole sizing can also be seen in Figure 14 above on the shin.

6.2.2 Shin

One part of Finley that has undergone a significant number of redesigns is the shin. Previously, the shin was split into two parts due to size constraints with 3D printing. The two parts of the shin were connected with four screws that screwed into small extrusions from the top and bottom pieces. However, the team this year had access to a larger printer, the Elegoo Jupiter, so the shin was consolidated into one piece. The previous and current designs can be seen side by side in Figure 15. Beyond reducing the number of fasteners across the robot by eight, this change also strengthened the shin as it removed possible points of failure.

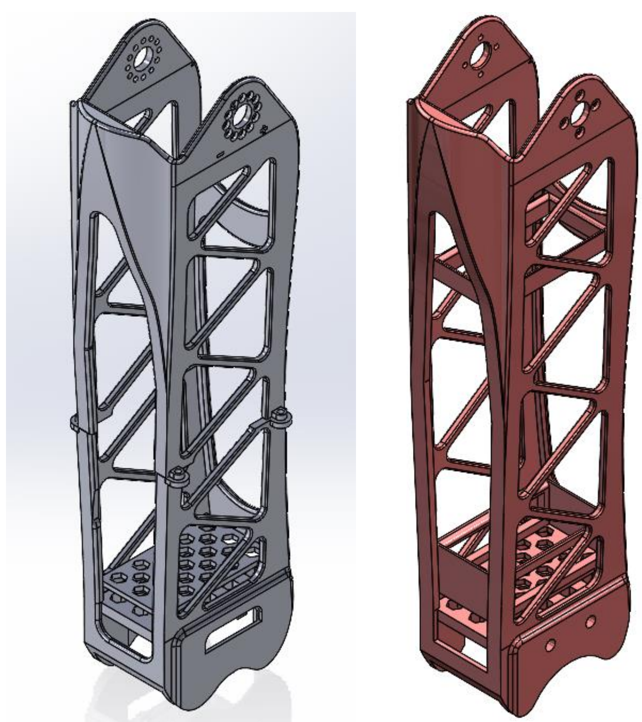


Figure 15: Previous shin design (left) and redesigned shin (right)

Another issue in the shin design was the 11.1V batteries inside having freedom to move. Previously, the batteries sat very loosely in the shin, allowing them to shift around while the robot moved. This is a problem from a locomotion perspective, as a shifting battery will change the robot's center of mass as it walks, possibly leading to failure as the code cannot account for these unpredictable changes. The team decided it was best to constrain the batteries within the shins. This was done by adding two rectangular slots that the battery can slide into, each having internal measurements of 24x48mm. These slots can be seen in Figure 16. These provide a tight fit for the battery, so it can no longer move during use.

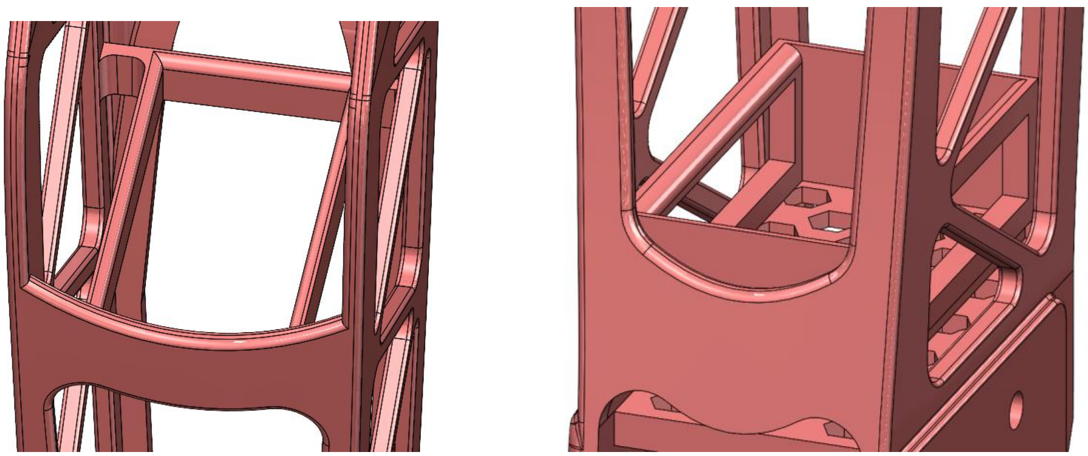


Figure 16: Upper (left) and lower (right) battery support slots

6.2.4 Motor Wire Access

Another issue that was discovered while replacing broken parts on Ava was that in many places, access to the motor wires was blocked by plastic material on the 3D printed part. An example of this can be seen on the thigh in Figure 17. It is important to be able to access the motor connection point without disassembling the robot in case a wire or motor fails. This led to design changes in the back, biceps, chest, thighs, and shins, where material was cut out so the wires can be easily accessed and replaced if needed. One of these changes can be seen in the thigh in Figure 17, with the previous design on the left and new design on the right.

.

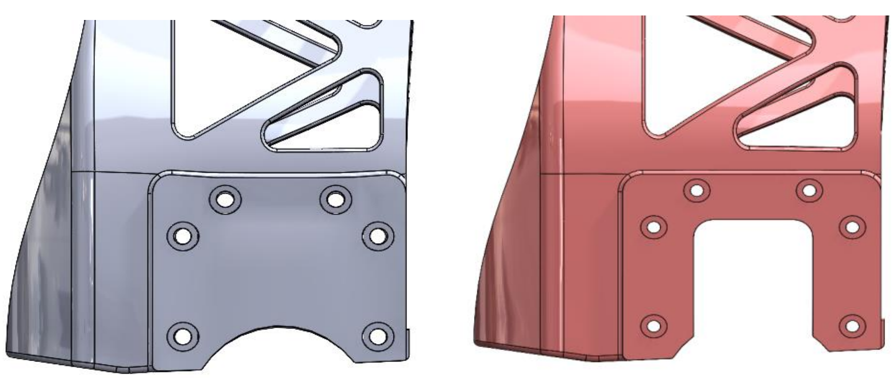


Figure 17: Previous thigh design (left) and new design (right) with cutout for motor wire access

6.3 Modularity

Humanoid robots are designed to execute a wide variety of tasks just like humans. Considering Finley will be operating in an at-home assistive care setting, it is important that he is able to complete different household tasks. Instead of creating one complex end-effector capable of achieving many tasks, the team instead designed a modular wrist system so that hands tailored for specific tasks can be swapped out with ease. The team also implemented modularity in the head so that different sensors for various applications can also be easily switched out. All of this also lends itself well to the open-source nature of the project, so users in the future can customize the robot to whatever needs they have.

6.3.1 End Effector Modularity

The modular end-effector system described in the following sections was designed for ease of use and the ability for hands of different uses to be swapped. The design contains a strong physical connection, while carrying electrical continuity across the wrist.

6.3.1.1 Magnetic Connection

The team decided to use a magnetic connection to achieve modularity in the wrist. This would provide a strong connection while avoiding a complex mechanical latching system. The design utilizes an electromagnet on the forearm side and a permanent magnet on the hand side. The design uses a P25/20 5V electromagnet with a holding force of 5kg. The permanent magnet is a ½’ grade N52 neodymium magnet with a holding force of 7.54kg. Constantly powering the electromagnet would draw a significant amount of power, so this design allows for the hand to be connected without providing power to the electromagnet. When the electromagnet is powered, its magnetic field partially opposes that of the permanent magnet to weaken the connection and allow for easier disconnection. Therefore, the electromagnetic acts as an aid for disconnection; meaning the hand can hold significant weight normally, but easily detach when needed. Testing was performed to determine the ideal separation distance between the two magnets, explained in detail in Section 8.2.

6.3.1.2 Electrical Connection

Any hand attachment design would likely need at least one actuator. This meant that the modular connection also needed to be capable of transferring power and data across it. The connection had to be secure and consistent. Ideally the hand would be perfectly aligned when connected, but this cannot be assumed. If fully static electrical connectors were used, it is possible that the hand could be placed at a slight angle, and one or more of these wires would not make contact. To solve this issue, the team implemented pogo pins. Pogo pins, as shown in Figure 18, are spring loaded wire ends. For a sense of scale, the flat receiving end pin has a diameter of 1.7mm. Using these eliminates the need to connect the hand perfectly, as the springs will ensure a connection even if the separation is larger than expected. Four of these pins and their flat contact counterparts were placed with 90 degrees of separation around the modular device. Four wires are enough to power and communicate with one motor. This set the constraint that any hand designed can use a maximum of four wires. On the body side, these wires can be directly plugged into the motor chain for the arm or wired directly to the Arduino for other applications.

Figure 18: Pogo pins spring side (left) and flat receiving end (right)

6.3.1.3 Mechanical Design

The modular connection has two sides: the forearm side and the hand side. The hand side, shown in Figure 19, connects to the lower forearm motor and houses the electromagnet. The motor and electromagnet are mounted concentrically, so the electromagnet is secured by tightening a 2mm set screw located at the top of the side slot to clamp it in place. The set screw is secured with one M2 nut on the opposite side. This clamping slot also serves as a channel to access the electromagnet wires. On the opposite side, there is a groove that fits the alignment peg on the hand side. Around the top lip of the forearm side are four 1.7mm holes that secure the pogo pins with a press fit.

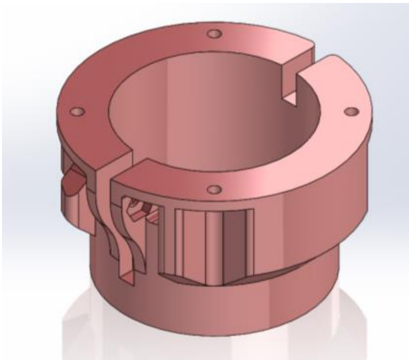


Figure 19: The forearm side modular connection CAD

On the hand side, there is a small circular cutout which the electromagnet fits into to concentrically align both ends. Similar to the forearm side, there are four 2mm holes to house the pogo pin flat contacts. There is a 3mm extrusion which fits into the slot on the forearm side to rotationally align both sides which can be seen below in Figure 20. The hand side also features a thin sleeve which fits over the forearm side to prevent disconnection by lateral impact. For the hybrid two finger gripper hand, there is an attachment point for one motor. This area of the design can be changed for any end effector application.

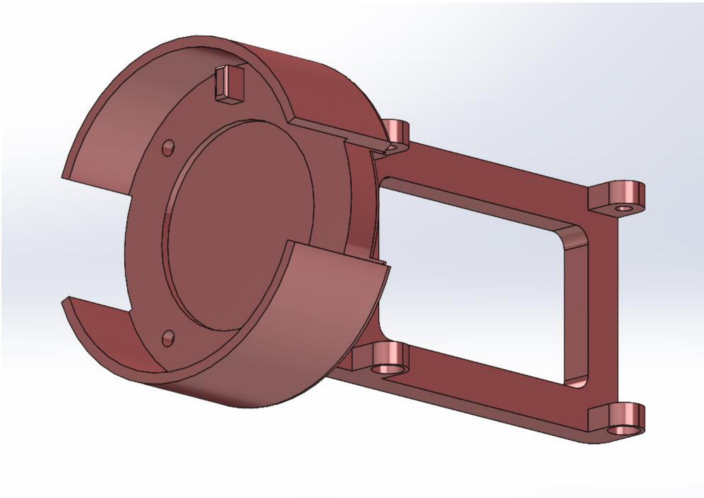


Figure 20: The hand side of the modular connection designed for the hybrid gripper hand

Figure 21 below shows an exploded view of the modular system, including the electromagnet, permanent magnet, and pogo pins.

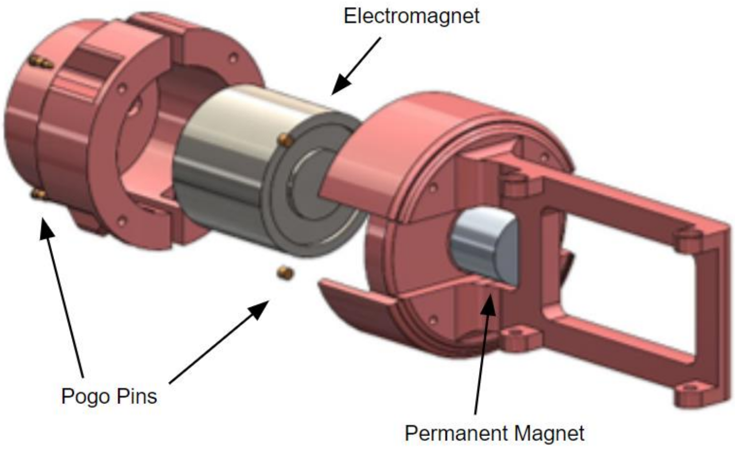


Figure 21: Exploded view of the modular end-effector system

6.3.2 Head Modularity

The team redesigned the head lid to house the necessary sensors onboard for human interaction. The lid can at minimum house a speaker and two microphones to be able to listen from the front and the back of the head which can be seen below in Figure 22. A row of magnets was also added to allow for different sensors to be swapped out easily on the head lid. Any sensor housing can now be designed and attached to the head as long as there is a magnet on the bottom.

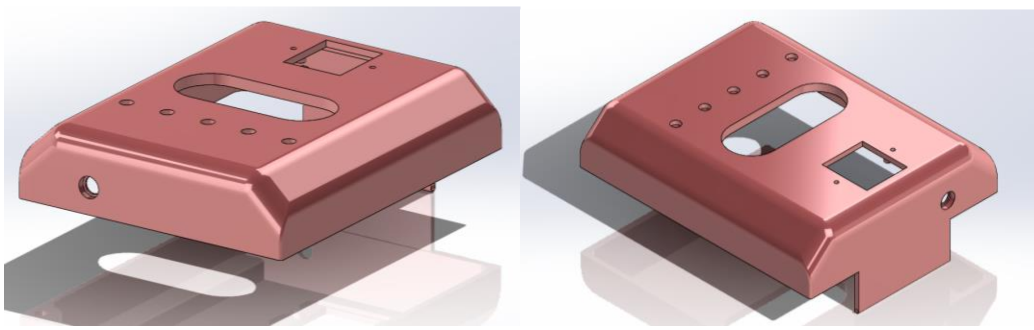


Figure 22: Finley's head lid displays features such as holes for speaker, microphone, and modular connection

From surveying the WPI community and interviewing residents and providers, the team got feedback that visible wires are off-putting which could be integrated better, and some parts were rough around the edges. The image shown of the robot in the survey did not have a lid on the head and had a lot of unintegrated wires. These survey questions and results can be seen below in Appendix F and Appendix H respectively. This feedback influenced the redesign of the head and the head lid to have smoother edges to make it more aesthetically appealing.

6.4 Grip Design

As mentioned in Section 4.1.1, the team decided to design a hybrid two finger pinch gripper for Finley. This hand would consist of one rigid finger and one flexible finger. The rigid finger supplies a large surface area for an object to contact, while the flexible finger utilizes a compliant mechanism to deform around the object. This design would therefore be capable of gripping a wide variety of objects of different shapes and sizes.

The flexible finger used on Finley was inspired by a design by PrintChallenge on printables.com. This system, seen in Figure 23, used three flexible fingers in a radial formation to form a claw grip. While the gripping mechanism and finger formation was not used on Finley, the finger design was adapted. This design makes use of a thin-walled triangle with crossbar supports. These supports are free to rotate independently of the casing, giving the design its flexibility.

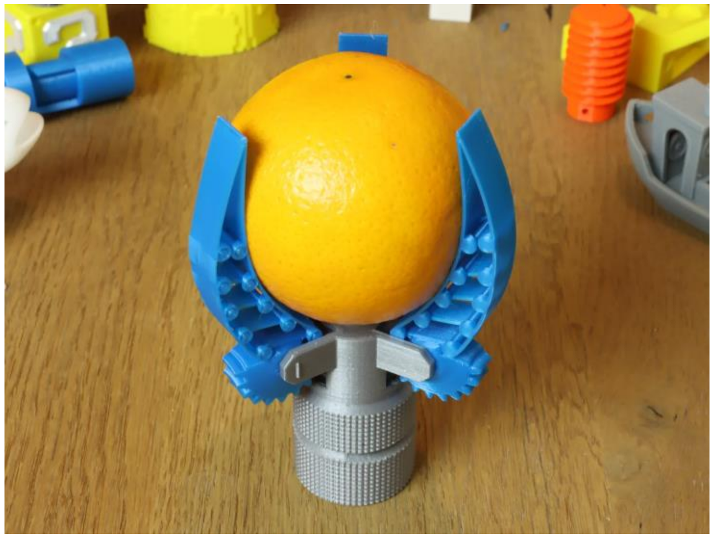


Figure 23: Gripper design that inspired the team's design

The original design uses five crossbar supports, which was reduced by the team to four for Finley. Additionally, the overall dimensions of the design were changed, and the finger was adapted to connect to a HerkuleX DRS 0201 motor. The flexible finger used on Finley has a length of 90mm, a width of 55mm, and a height of 30mm. These dimensions were chosen after testing seven different fingers of varying sizes to choose the ideal design. More details on this testing process can be seen in Section 8.1. The flexible finger was printed from PLA on a FDM 3D printer due to its geometry that contains multiple components in one print.

The rigid finger of the hybrid two finger gripper was printed using Esun Hard Tough Resin to ensure rigidity when gripping objects. Multiple thicknesses were tested for this finger, and it was decided that 5 mm was ideal to reduce bending while keeping material costs at a minimum. The rigid finger spans the length of the flexible finger when fully closed. These two fingers, which can be seen in Figure 24 work well together to allow Finley to grasp a wide variety of objects.

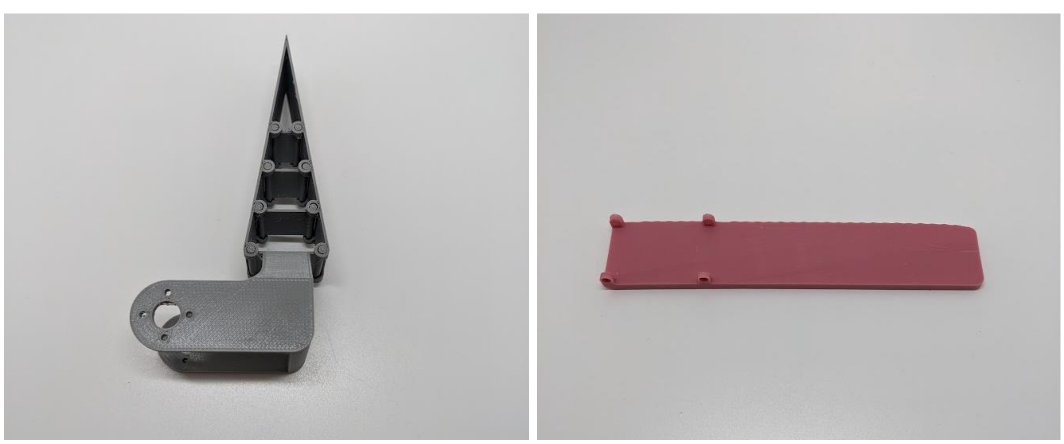


Figure 24: Flexible finger design (left), and rigid finger (right)

As previously mentioned, the hand is actuated by one HerkuleX DRS 0201 motor which rotates the flexible finger. This motor also connects to the rigid finger and the hand side of the modular end-effector system. Both fingers were also covered in silicone to provide more friction when gripping objects of different materials. The full hand assembly can be seen gripping a rubber ball below in Figure 25.

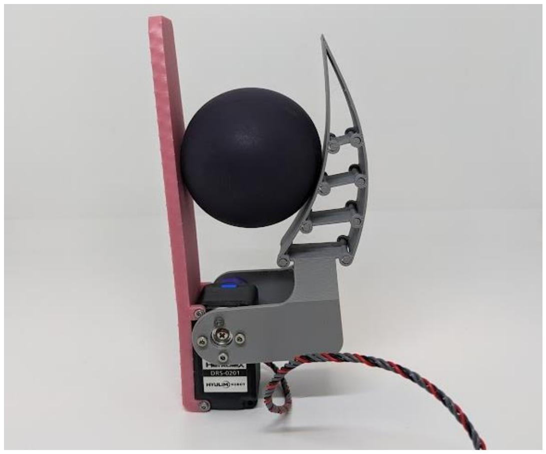


Figure 25: Hybrid two-finger pinch gripper holding a rubber ball

Chapter 6.0 provided a summary of all the design changes that went into the development of Finley. The following chapter summarizes the printing and assembly required to create Finley.

7.0 Manufacturing & Assembly

The Finley robot is made up of many 3D printed parts that must be fastened together with a slew of screws. The team performed several redesigns that reduced the number of parts, fasteners, and material needed for assembly from Ava. These changes subsequently reduce assembly and servicing time greatly and generally make Finley easier to work with and modify when compared to his predecessors. A full SOLIDWORKS assembly of the robot can be seen in Figure 26.

Figure 26: Fully assembled Finley in SOLIDWORKS

7.1 Printing

All non-electrical components on Finley are 3D printed, either using resin or FDM techniques, as discussed in Section 4.2. Most components are produced from Esun Hard Tough Resin because of its high strength and ability to print complex geometries. Some low-stress components are made from standard PLA to save cost and weight where possible. Finley is comprised of 45 3D printed parts, 40 of which are printed with resin, while the other five are PLA. This is a reduction from Ava’s 50 3D printed parts, where 38 are resin and 12 are PLA. A table in Appendix A shows every 3D printed component of Finley and their respective print times. Note that total printing time can be greatly reduced by fitting multiple parts onto one print bed when printing. A fully assembled robot can be seen below in Figure 27.

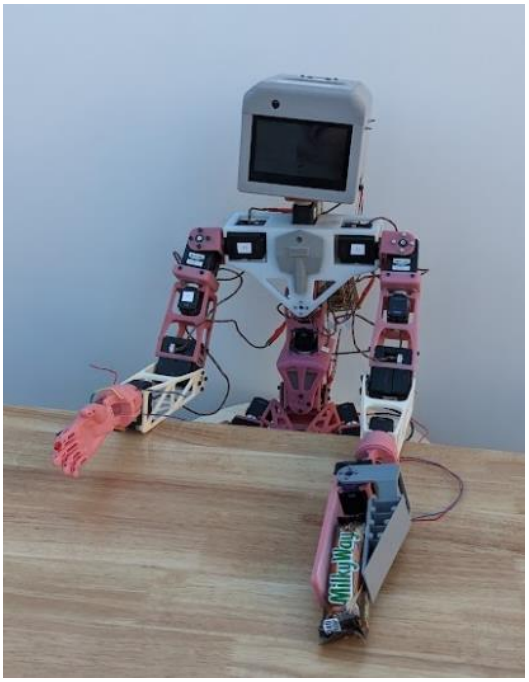


Figure 27: Fully assembled Finley

7.2 Physical Assembly

As seen in Figure 27 above, all design changes discussed in Chapter 6 were produced and integrated on Finley. Every part of the robot was printed and assembled by the team throughout the year. The two-part modular end-effector system can be seen physically in Figure 28 below.

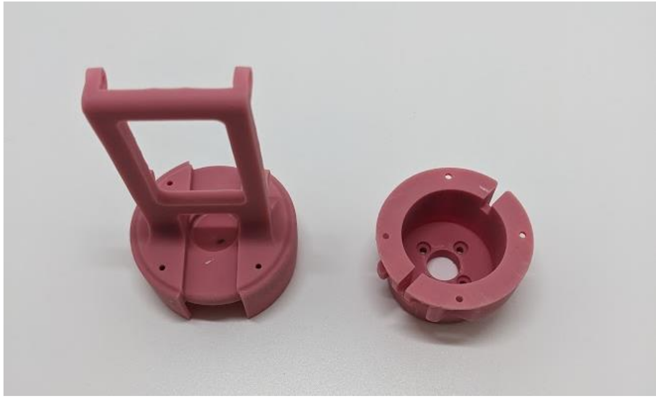


Figure 28: Printed modular end-effector system

The modular end-effector system was also tested on the robot using the hybrid two-finger pinch gripper designed by the team. The system succeeded in completing a pick-and-place task with all parts implemented. Figure 29 below shows Finley with the hand attached through the modular system.

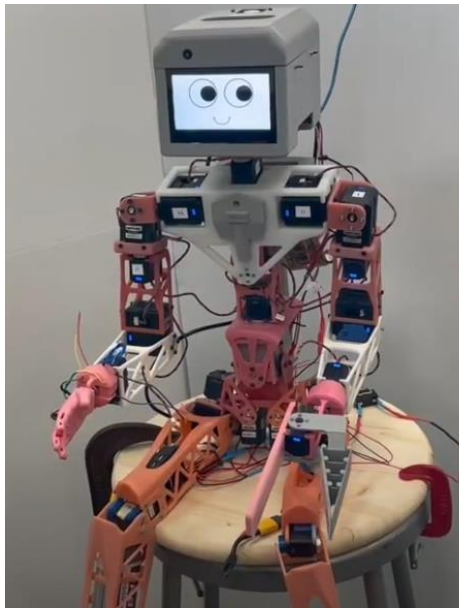


Figure 29: Finley powered with gripper attached

The new head lid design with integrated speaker and microphone was also produced. The head modularity was also successfully included using the row of magnets on top of the head lid. The speaker and magnets can be seen below in Figure 30.

Figure 30: Magnet and speaker included on head lid

An example of a sensor that the team added to showcase this modularity was a Raspberry Pi camera, which can be seen sitting on the head through magnetic connection in Figure 31.

Figure 31: Finley's head with the onboard sensors attached as well as the camera attached on top of the lid using magnets

7.3 Fastener Reduction

Finley has a large reduction in fasteners needed to fully assemble the robot compared to Ava. Most of this reduction comes from the design changes to the number of screw holes in each part to connect to their motor horns, as discussed in Section 6.2.1. Parts that previously had twelve fasteners per motor horn now have only four. Fasteners were also reduced in redesigned parts such as the pelvis and shins as shown in Section 6.1.2 and Section 6.2.2, respectively. These changes led to a 43% reduction in fasteners for assembly from the previous 735 to now 419. A detailed list in Appendix A shows the previous and current number of fasteners needed for each part. These changes make assembling Finley easier than Ava and faster to replace broken parts if need be.

7.4 Material Reduction

While conducting other redesigns, several parts were seen to have excess material that does not add to the structural integrity or functionality of the piece. In these areas, this excess material was cut out to subsequently reduce print times, weight, cost, material, and the environmental impacts of the robot. An example of this can be found in the bicep in Figure 32, where a significant section of the previous design was removed from the front side. Additionally, Table 6 shows select components where material was reduced, the amount of resin saved and resulting cost reduction. A full list of components with material amount, print time, and cost can be found in Appendix A.

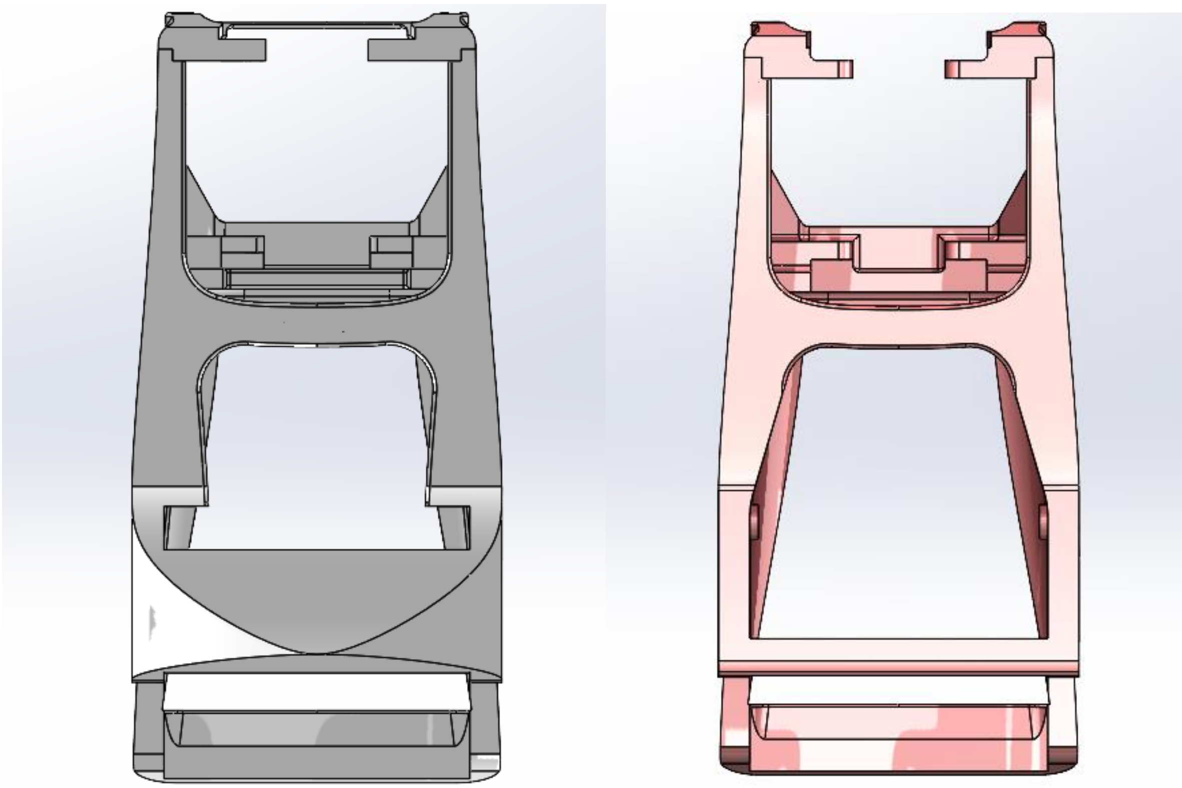


Figure 32: Previous bicep design (left) and new bicep design (right) with excess material removed

Table 6: Material and cost reduction for select parts

Part	Material Reduction	Cost Reduction
Bicep	5.6g (14.29%)	$0.34
Chest	48.2g (13.31%)	$2.89
Foot	5.2g (8.07%)	$0.31
Pelvis	37.7g (55.44%)	$2.26
Hip	6.0g (27.40%)	$0.36

7.5 Wiring and Programming

The upper half of Finley was fully wired to showcase the applications that the robot was capable of. This included the power supply system, motor control circuitry, and electromagnet control for the modular end-effector system. Two 11.1V LiPo batteries provide the power to the system. This power supply splits into two lines: 11.1V to power the HerkuleX DRS 0601 motors and 8.4V to power the HerkuleX DRS 0201 motors. For the applications presented, six HerkuleX

DRS 0601 motors and six HerkuleX DRS 0201 motors were controlled. All motors receive serial communication from the onboard Arduino Mega. The integrated Raspberry Pi completes the processing tasks, while the Arduino Mega sends signals to the motors. This system was developed with help from the 2023-24 Humanoid Robot Locomotion Team.

To account for the added motors in the hand, the team rewrote part of the original Koalby firmware (see Appendix C) to account for “Left_Hand” and “Right_Hand” motors which can be seen below in Figure 33.

```
3   // Left Arm (Wrist to Shoulder)
4   Motor Left_Wrist_Abductor = {6, -160, 150, -95, false, "Left_Wrist_Abductor"};
5   Motor Left_Elbow = {11, -160, 160, -65, true, "Left_Elbow"};
6   Motor Left_Arm_Rotator = {10, -160, 160, 101, false, "Left_Arm_Rotator"};
7   Motor Left_Arm_Abductor = {1, -160, 160, 38, true, "Left_Arm_Abductor"};
8   Motor Left_Hand = {3, -160, 160, -26, false, "Left_Hand"};
9
10  // Right Arm (Wrist to Shoulder)
11  Motor Right_Wrist_Abductor = {25, -160, 160, 27, false, "Right_Wrist_Abductor"};
12  Motor Right_Elbow = {7, -160, 160, 60, true, "Right_Elbow"};
13  Motor Right_Arm_Rotator = {17, -160, 160, 0, false, "Right_Arm_Rotator"};
14  Motor Right_Arm_Abductor = {16, -160, 160, -14, true, "Right_Arm_Abductor"};
15  Motor Right_Hand = {2, -160, 160, 20, false, "Right_Hand"};
16
```

Figure 33: Added motors in line 8 & line 15

Chapter 7.0 provided a summary of the printing and assembly required to create the humanoid. The following chapter will go over the testing that went into each feature, including the hand, modularity, materials, stress analysis, kinematics, and human interaction.

8.0 Testing Process

The purpose of this chapter is to describe the thought process and results behind the testing put into this project. This includes testing the function of each end effector developed, the magnetic modular connection, the performance of Finley involving specified RoboCup@Home tasks, materials testing, and different forms of stress analysis on relevant parts.

8.1 Hand

In order to decide which exact dimensions to use for the hybrid two-finger pinch, seven different designs for the flexible finger were produced to test their ability to pick up and rotate a set of objects of various shapes and materials. The dimensions of each design are described in Table 7, where each finger varies in width, length, and height. Width, length and high is further defined by Figure 34.

Table 7: The dimensions of each hand iteration

Test Number	Length (mm)	Width (mm)	Height (mm)
1	80	60	30
2	90	60	30
3	100	60	30
4	90	55	30
5	90	65	30
6	90	60	25
7	90	60	35

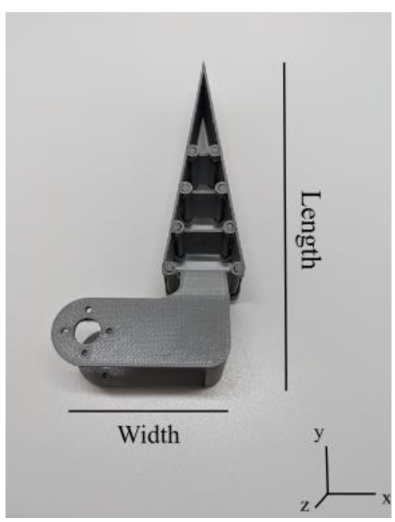


Figure 34: Image defining width and length (height is in the z direction) for each hand iteration

Each candidate was actuated by one motor and controlled using an Arduino that allowed the user to open and close the hand by setting it to a certain angle. In order to maintain reproducibility each object had a set angle for grip and was picked up and rotated in the same manner. The object name, shape, material, and set angle can be found in Table 8.

Table 8:Each object description and grip angle to show variety

Object	Shape	Material	Grip Angle (degree)
Brass Cube	Cube	Metal	30
Thigh Iteration	Varied	Resin	0
Mac and Cheese Box	Rectangular Prism	Cardboard	10
Bag of Chips	Varied	Plastic	30
Hot Sauce	Cylinder	Glass	0
Screwdriver	Cylinder	Plastic	25
Racketball	Sphere	Rubber	-10
Lollipop Stem	Small Cylinder	Cardboard	25
Cell Phone	Rectangular Prism	Metal	N/A

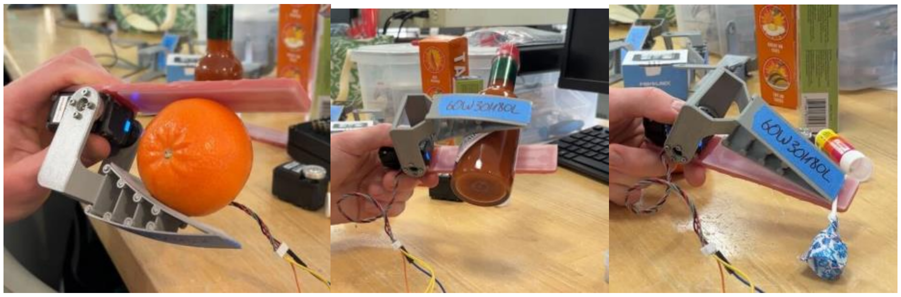


Figure 35: Examples of picking/rotating objects during hand testing

Two team members conducted hand testing in order to account for human error. The ability for each iteration to lift and rotate each object was categorized as “Yes,” “No,” and “Partial,” where “Yes” indicates success, “No” indicates it was unable to lift and/or rotate, and “Partial” indicates that it can lift and/or rotate but not securely. After testing was fully conducted by each of the two teammates, each iteration was scored, where “Yes” scored one point, “Partial” scored zero points, and “No” scored negative one point, making the maximum possible score 16 points. To statistically see the differences between the two teammates’ data sets, the score for each iteration, the mean, and standard deviation can be found in Table 9. Examples of the hand picking up objects can be found in Figure 35, the distribution of each iteration’s score can be found in Figure 36, and the full testing sheet for each team member can be found in Appendix E.

Table 9: Mean and Standard Deviation of Iteriation Trials

Hand Iteration	Teammate 1	Teammate 2	Average Score	Standard Deviation	Variance
1	15	4	9.5	7.8	60.5
2	15	12	13.5	2.1	4.5
3	16	12	14	2.8	8
4	15	15	15	0.0	0
5	14	8	11	4.2	18
6	16	7	11.5	6.4	40.5
7	16	14	15	1.4	2

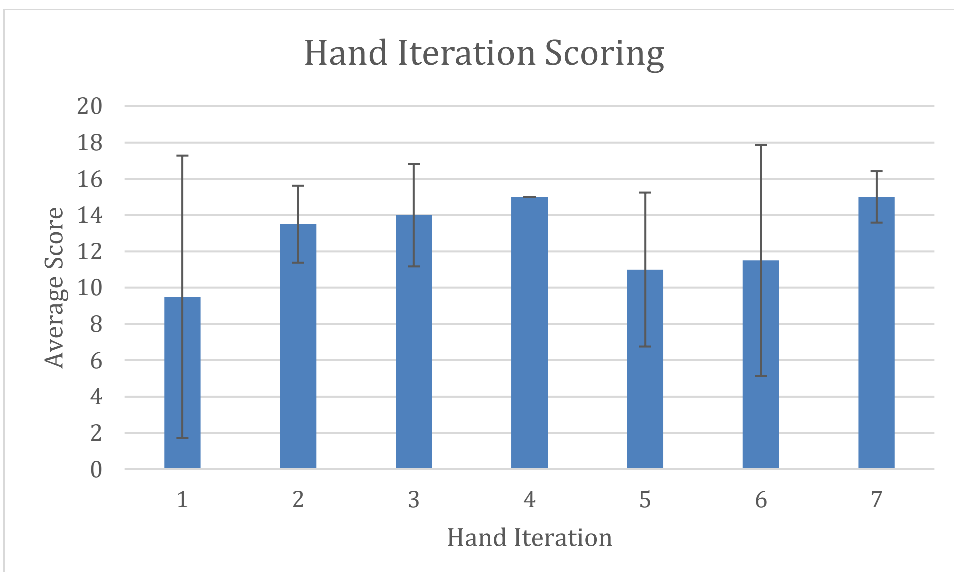


Figure 36: The score for each hand iteration based on testing, where the maximum score can be 16 and error bars representing standard deviation are included

Based on each of the scores, hands four and seven can pick up and rotate the greatest variety of objects. In order to take environmental considerations into account, hand four was ultimately chosen since it uses less material. It is important to note that, based on the average scores for each hand iteration found in table 9, keeping the length at 90 mm was important for performance. For hands four and seven there was a relatively low standard deviation and variance (0/0 and 1.4/2, respectively), suggesting those iterations were also best in terms of reproducibility.

8.2 Modular Magnetic Connection

As discussed in Section 6.3.1.1, the end-effector modular system utilizes a permanent magnet to electromagnet connection at the wrist. In the default state of the system, the electromagnet is off, simply acting as a steel block for the permanent magnet to attract to. When the electromagnet is turned on, its magnetic field partially counteracts that of the permanent magnet, weakening the connection and aiding in disconnection. It was important to study the interaction of these magnets at varying distances of separation to determine the best design. To do this a testing rig was produced where the electromagnet and permanent magnet can pull together with a set distance between them. Masses would then be hung from the electromagnet until the system decoupled. This design of this testing rig can be seen in Figure 37, where each hole has a different separation distance. The side shown fits the electromagnet, while the bottom side has holes for the permanent magnet, each concentric with the top holes.

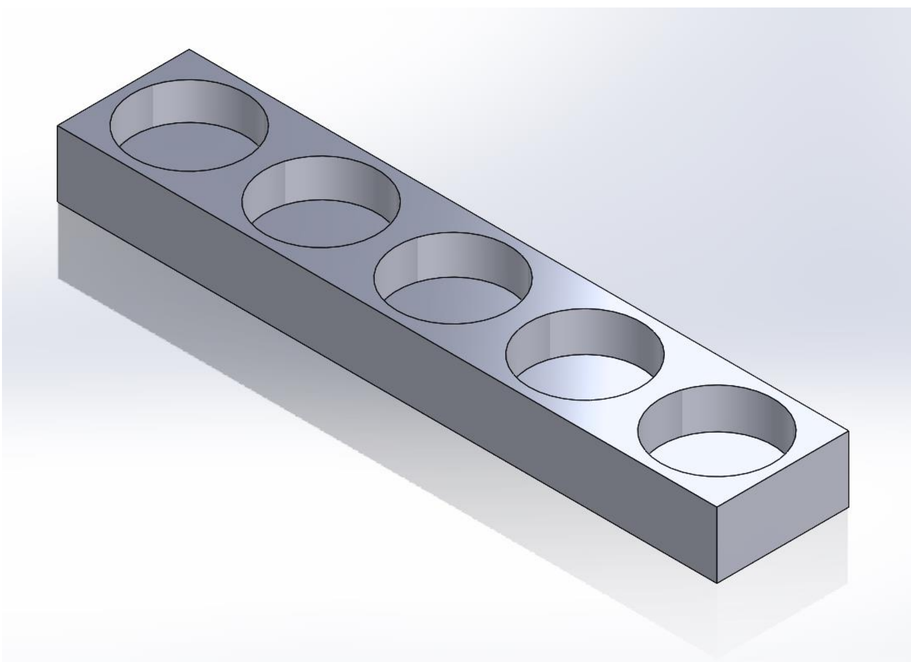


Figure 37: Magnet pull force testing rig with 1.6mm (left) and 0.8mm (right) separation

Data was collected for separation distances of 0.8mm, 1.0mm, 1.2mm, 1.4mm, and 1.6mm of separation between the magnets. The results of this testing can be seen below in Table 10.

Table 10: Test data for different magnet separations

Separation Distance (mm)	Weight to Break with Electromagnet Off (g)	Weight to Break with Electromagnet On (g)
0.8	2086.3	1465.6
1	1725.7	1207.9
1.2	1302.5	1014.7
1.4	918.4	886.2
1.6	729.2	694.9

This data shows an expected increase in the force to break the magnetic connection as the separation distance decreases. It also shows a greater effect of the powered electromagnet as the separation distance decreases. This can likely be explained by the magnetic field of the electromagnet being tighter than that of the permanent magnet. This means the repulsive force of the electromagnet will increase faster than the attractive force of the permanent magnet at increasingly small distances. After this testing, a separation distance of 1.2mm was chosen for the modular system. This distance has a strong enough pull force in the default state (electromagnet off), but still a noticeable repulsion when disconnection, where the electromagnet weakens the connection by 288g. For future work, this design should provide a strong connection while aiding in disconnection enough so that Finley could autonomously swap hands.

8.3 Materials Testing

In order to determine material properties of the Esun Hard Tough Resin used, standard dog bones were printed to be tested. The dog bones were loaded into the MecMesin multitester to be tested for tensile strength. The yield stress (MPa) and strain (%) can be viewed below in Figure 38.

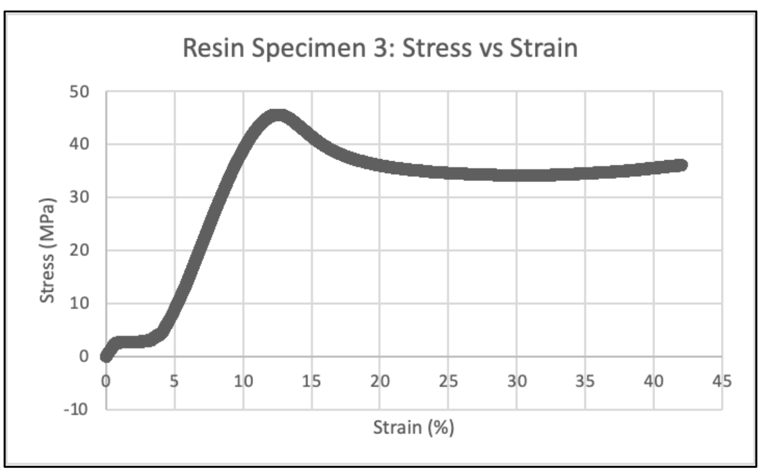


Figure 38: Stress vs. strain curve for Esun Hard Tough Resin

The team found that the average young’s modulus of the dyed resin was 634.43 MPa and average yield strength was 35.22 MPa, which can be seen below in Table 11.

Table 11: Materials testing results

Avg. Young’s Modulus (MPa)	Avg. Yield Strength (MPa)
634.43	35.22

8.4 Stress Analysis

For two parts on Finley, it was deemed necessary by the team to perform Finite Element Analysis (FEA) to determine the stresses experienced under load because they were significantly redesigned. This FEA was performed using SOLIDWORKS Simulation. The redesigns to the hips and pelvis were considered for this study.

8.4.1 Hip

As discussed in Section 6.1.3, the hip piece was changed to make assembly easier. This change involved removing two of the six motor mounting screws, inevitably putting more stress on the remaining four. Before implementation of this change, FEA was performed to evaluate the increase in stress on the component and determine if the maximum stress was higher than the yield strength of the material. An assembly of the hip with the HerkuleX DRS 0201 motor that it connects to was used to more accurately apply the load. For this study, the motor horn holes on the hip were fixed, and a load of 7.34N was applied to the motor vertically upward. This force was calculated by halving the weight of the upper half of the robot to find the subsequent force on the hip. The results of the study can be seen in Figure 39 below, where the equivalent von Mises stress is shown. The calculated maximum stress on the hip was 3.83MPa, well below the 35.22MPa yield strength of the Esun Hard Tough Resin. This analysis proves the redesign was effective, as the new safety factor of the hip component is 9.20.

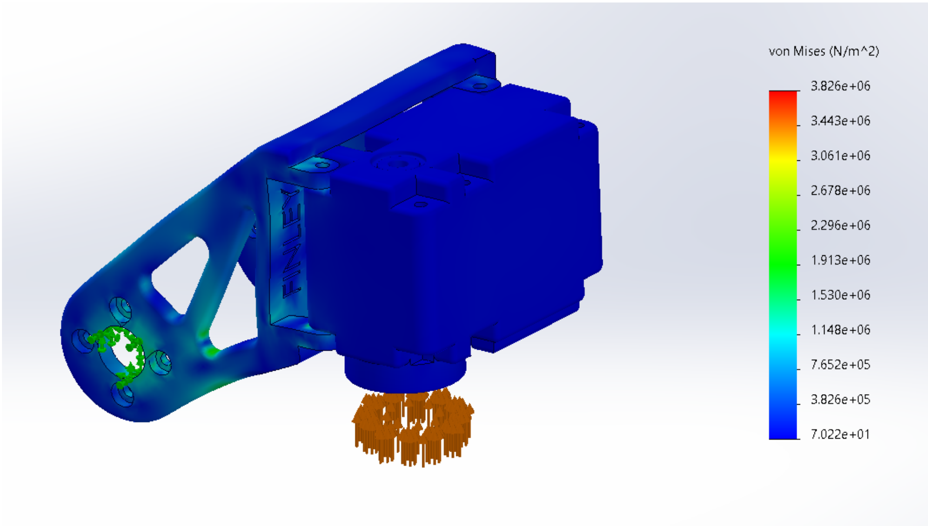


Figure 39: Redesigned hip von Mises stress in FEA

8.4.2 Pelvis

The pelvis redesign discussed in Section 6.1.2 required verification to prove that the change in design led to a stronger part as opposed to a weaker one. The previous and redesigned pelvises were both analyzed using FEA. Similar to the hip stress analysis, the parts were analyzed in an assembly with a motor to accurately apply the loads. Both pelvises were fixed at the screw holes, which connect to the HerkuleX DRS 0201 motors that lead to the hips. A load of 14.05N was applied vertically downward to the upper HerkuleX DRS 0601 motor to replicate the static force of the upper half of the robot on the pelvis. The results of this study can be seen below in Figure 40 with the effective von Mises stress shown. This analysis shows a 93% reduction in maximum stress in the pelvis with the redesign, proving the new design was successful in strengthening the pelvis.

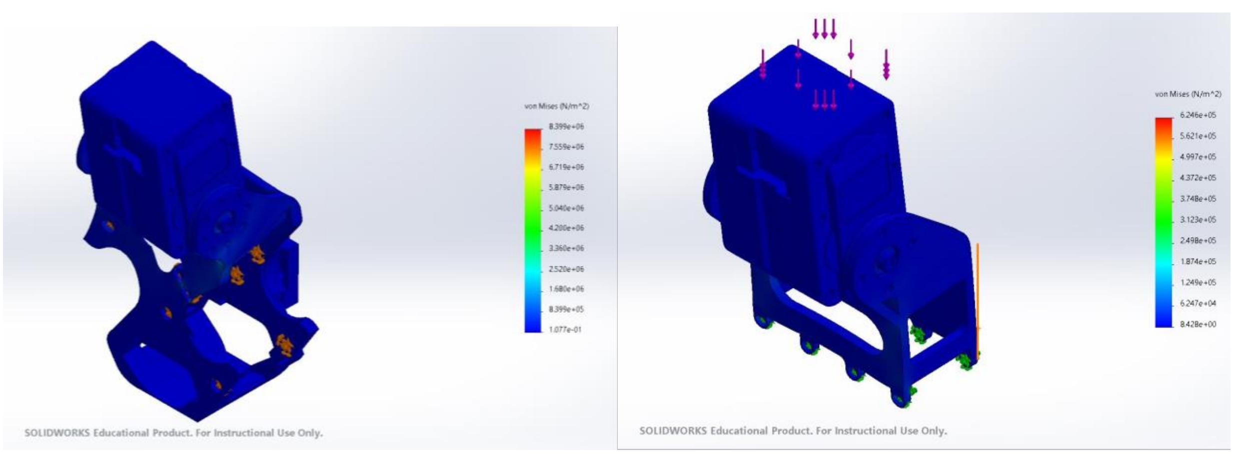


Figure 40: Resolved von Mises stresses on old pelvis (left) and new pelvis (right)

8.5 Kinematics

The pick and place movement discussed in Section 4.5 required several iterations of trajectory planning and testing to make the movement as humanlike as possible. The inverse kinematics needed to develop each trajectory was calculated in MATLAB, which can be seen below in Figure 41 showing the program and Figure 42 showing the outcome. The full MATLAB script can be found in Appendix C. Lines 7-9 are where the team input coordinates for the end effector to move to. This is converted to radians within the program to be used in simulation. This was done for each movement to make up the three trajectories.

Finly_IKinBody.m

```
1   scriptpath = fileparts(mfilename('fullpath'));
2   addpath(scriptpath)
3   addpath('mr')
4   clc;
5   clear;
6
7   deltaX = 175;
8   deltaY = -35;
9   deltaZ = -3;
10
11  %% LEFT ARM
12  Slist = [[1;0;0;0; 8.68; 2.4], ...
13          [0;0;1; -2.4; 425.8100; 0], ...
14          [1;0;0; 0; -1.92; 2.4], ...
15          [0;-1;0;-14.8500; 0; 269.0400], ...
16          [1;0;0; 0; 0; 2]];
17  M = [[1, 0, 0, 451.04]; [0, 1, 0, 2.4]; [0, 0, 1, -8.68]; [0, 0, 0, 1]];
18  T =   [0.000000, -1.000000, -0.000000, 22.830000 + deltaX;
19          0.000000, 0.000000, -1.000000, 141.920000 + deltaY;
20          1.000000, 0.000000, 0.000000, 245.510000 + deltaZ;
21          0.000000, 0.000000, 0.000000, 1.000000];
22  thetalist0 =[deg2rad(0); deg2rad(-45); deg2rad(0); deg2rad(110); deg2rad(0)];
23
24  eomg = 1;
25  ev = 0.01;
26  [thetalist, success] = IKinBody(Slist, M, T, thetalist0, eomg, ev);
27  success
28  thetalist = transpose(thetalist);
29
30  % Print the row vector separated by commas
31  fprintf("Radians: ")
32  fprintf('%f, ', thetalist(1:end-1)); % Print all elements except the last one
33  fprintf('%f\n', thetalist(end)); % Print the last element with a newline character
34
35  thetalist = rad2deg(thetalist);
36  fprintf("Degrees: ")
37  fprintf('%f, ', thetalist(1:end-1)); % Print all elements except the last one
38  fprintf('%f\n', thetalist(end)); % Print the last element with a newline character
```

Figure 41: Inverse kinematics script for Finley’s left arm in MATLAB

```
success =

  logical

   1

Radians: 0.005924, 0.544082, -0.007647, 1.334095, 1.026559
Degrees: 0.339432, 31.173595, -0.438153, 76.438016, 58.817470
```

Figure 42: Results from coordinate input in radians from MATLAB

The radian coordinates calculated by MATLAB were translated into the python script trajectories for picking-and-placing objects like candy as seen below in Figure 43. The movement was done in three trajectories and after testing the length of each movement the team decided to make the first movement 3 seconds, the second movement 6 seconds, and the last movement 3 seconds. For the real movement, velocities and accelerations were kept at 0m/s and 0m/s^2 for the most fluid movements.

```
##first movement to grab the candy
leftArmTraj1 = [
    [[0,0,0,0,0], [1.5,1.5,1.5,1.5,1.5], [3,3,3,3,3]],
    [[0.000000, 1.570796, 0.000000, 1.570796, 0.000000], ##starting position (0,0,0)
     [-0.399673, 0.908213, 0.258504, 1.653297, 0.702046], ## X125, Y0, Z50 : arm left and back
     [-0.266709, 0.697618, 0.206337, 1.413457, 0.890253]], ##X175, Y-3, Z-35: arm more left and align with candy
     [[0,0,0,0,0],[0,0,0,0,0],[0,0,0,0,0]],
     [[0,0,0,0,0],[0,0,0,0,0],[0,0,0,0,0]]]

##second movement to move the candy
leftArmTraj2 = [
    [[0,0,0,0,0],[3,3,3,3,3],[6,6,6,6,6]],
    [[-0.266709, 0.697618, 0.206337, 1.413457, 0.890253], ##X175, Y-35, Z-3: arm more left and align with candy
     [0.121513, 0.669234, -0.101738, 1.342783, -0.905241], ##X175, Y8, Z-20: arm up holding candy
     [-0.804261, 1.486360, 0.088339, 0.689863, -0.122708]], ##X15, Y10, Z120: arm moves right holding candy then drop
    [[0,0,0,0,0], [0,0,0,0,0], [0,0,0,0,0]],
    [[0,0,0,0,0], [0,0,0,0,0], [0,0,0,0,0]]]

#third movement after releasing candy
leftArmTraj3= [
    [[0,0,0,0,0],[3,3,3,3,3]],
    [[-0.804261, 1.486360, 0.088339, 0.689863, -0.122708],
     [0.000000, 1.570798, 0.000000, 1.570796, 0.000000]], ##ending position (0,0,0)
    [[0,0,0,0,0], [0,0,0,0,0]],
    [[0,0,0,0,0], [0,0,0,0,0]]]
###############################
```

Figure 43: Trajectory planning in Python

The simulated movement of Finley picking-and-placing and the real-life movement using the simulated kinematics can be seen below in Figure 44 and Figure 45, respectively.

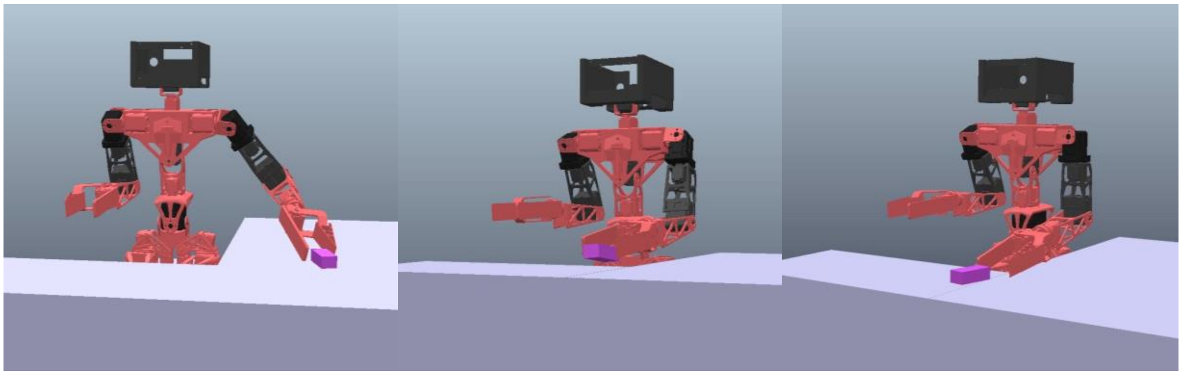


Figure 44: Simulated movements of Finley picking-and-placing

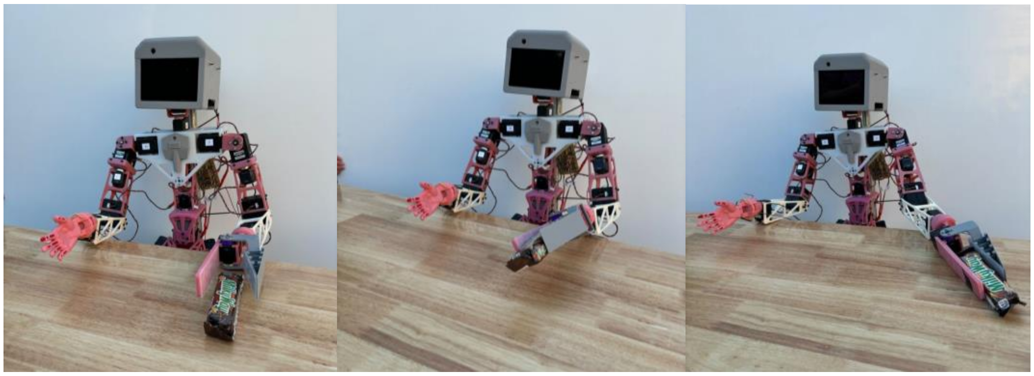


Figure 45: Real life movements of Finley picking-and-placing

8.6 Human Robot Interaction

The team focused on testing and implementing the three components mentioned in Section 4.5. Speech to Motion required speech to text, chat completion, and function invocation. Firstly, the team setup speech to text capabilities by using the Python Speech Recognition Library.

examples > SpeechToText.py > ...

```
import speech_recognition as sr

# Initialize the recognizer
r = sr.Recognizer()

with sr.Microphone() as src:

    # wait to adjust
    print("Adjusting for ambient noise...")
    r.adjust_for_ambient_noise(src, duration=0.2)

    print("Listening for speech")
    #listens for the user's input
    audio2 = r.listen(src, phrase_time_limit=5)

    print("Converting to text...")
    # Using google to recognize audio
    txt = r.recognize_google(audio2)

    print(txt)
```

Figure 46: Example Speech to Text Employing Python Library

As seen in Figure 46, the example text employed the adjust for ambient noise function, listen function, and recognize google function from the speech recognition library. The team adopted this within a listenForQuestion() function in the final ConverseWithFinleyActions.py, which can be found in the TalkToFinley repository on the team's GitHub page (see Appendix C).

Next, the team set up the AI Model. The team selected OpenAI's GPT 3.5 Turbo 0613 as the base model response generation to user input. This model had training data up until

September 2021 and was the most cost effective with 600 API requests costing around one dollar.

Following the creation and setup of the API key, the team implemented the response generation in a python script and tested the generation model, shown below in Figure 43. The team trained the model to store past conversation history, understand the functions it can perform, perform verbal actions before physical actions, and learn information about the team and project.

The next step to consider was the input and output interfaces. This determined how the AI model would interact with the user and access the Raspberry Pi's input and output devices. The team's Raspberry Pi hosts a touchscreen liquid-crystal display (LCD) that serves as the Pi's monitor. Leveraging this, there were many ways to implement a python application that allows users to control different tasks such as PyGame, Flask, or a React JS application. The team selected PyGame as it allowed for touchscreen capability on the Pi and pointers to local python scripts given, they exist in the same folder. The program contained three buttons as seen below in Figure 47.

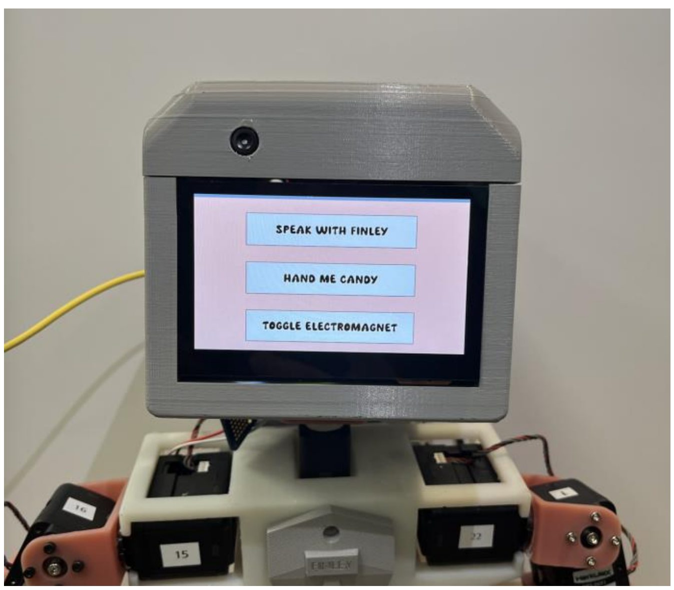


Figure 47: PyGame control screen with microphone

All three buttons featured a pressed state animation, which allowed users to visualize the clicking action. The team also integrated a USB microphone within the head of the robot as seen in the top left of the above figure. The mic features omnidirectional listening with a high sampling rate of 192kHz/24bit and an audio sensitivity of 30dB (MAONO, n.d.). The sleek fit of the lavalier microphone allowed for all wiring to be contained within the robot's head and the screen of the microphone flush with the LCD. The on-board mic, alongside the functional Speech to Text, Chat Completion, and touch screen application, allowed the team to fully set up autonomous speech to motion. This was accomplished by using a feature of the GPT model called tool call invocations (refer to Figures 48 and 49).

```
},{
    "type": "function",
    "function": {
        "name": "lowerRightArm",
        "description": "Lower your right arm",
    },
},{
    "type": "function",
    "function": {
        "name": "handCandy",
        "description": "Hand me a piece of candy",
    },
},{
    "type": "function",
    "function": {
        "name": "toggleElectromagnet",
        "description": "toggle the electromagnet when the user requests you to do so",
    },
```

Figure 48: Tool call setup with prompts

```
# Tool functions Finley can invoke indirectly

def raiseRightArm():
    print("*Lowering right arm*")
    robot.motors[1].target = (math.radians(0), 'P')
    robot.moveAllToTarget()

def handCandy():
    print("*Handing a piece of Candy*")
    finlyPickAndPlaceIRL.main()

def toggleElectromagnet():
    print("*Toggling the Electromagnet*")
    electromagnet.main()
```

Figure 49: Tool call invocations pointing to local scripts

The team created various tool calls that acted as triggers for the functions, as seen in the figures above. The description section of the tool calls found in Figure 48 were used to prompt the GPT model to understand when to perform an action. The robot accomplished handing a piece of candy by directly calling the finlyPickAndPlaceIRL script that contains the trajectories and motor movements explained in the previous section. To call the function, the script had to be imported and the control loop had to be localized in a main function so that the AI model could run it. Furthermore, direct movement within the generative model was implemented by configuring the robot within the script. The raiseRightArm() function (refer to Figure 49) moved Motor 1, the right shoulder, to its home position. Several other functions such as this one were created by the team to control different movements of the humanoid. The robot would successfully provide simultaneous text and speech response before and after its tool call movements.

Lastly, to provide users the ability to easily toggle the electromagnet, the team developed a script to change the state of the pin to which the electromagnet was connected to, shown in Figure 50. A global variable was used to store the previous state so that the toggle would always reverse the current state and thus turn on or off the electromagnet accordingly. This function was called in both the PyGame for the Raspberry Pi touchscreen and in the speech to motion script allowing for users to toggle the electromagnet through the click of a button or a voice command.

electromagnet.py > onExit

```python
from serial import Serial
import RPi.GPIO as GPIO
import time
import signal

pin = 17  # change pin
previous_state = False  # global variable to store previous state

GPIO.setmode(GPIO.BCM)
GPIO.setup(pin, GPIO.OUT)

def main():
    global previous_state  # use the global variable

    signal.signal(signal.SIGINT, onExit)

    # Toggle the state based on the previous state
    if previous_state:
        GPIO.output(pin, False)
        previous_state = False
    else:
        GPIO.output(pin, True)
        previous_state = True

def onExit(sig, frame):  # Remove self parameter
    GPIO.output(pin, False)
    exit(0)
```

Figure 50: Program to Change state of GPIO pin

The structure of the code was such that it can be applied to any modular connection or device by simply changing pin number. An onExit() function was also created to ensure that the pin was set to low, or turned off, after exiting the program to ensure that it did not constantly draw power from the Pi.

This chapter described the testing required in order to finalize final designs and systems for this project. The following chapter will address how each accomplishment addressed one of our design objectives.

9.0 Discussion

In this chapter, the original goal and objectives will be reviewed in relation to at-home assistive care. This is followed by further discussion about the ability of the robot to perform pick-and-place function, modularity, part redesigns, human study, and human-robot interaction components. Each of these components played a major role in expanding on the accomplishments of previous teams.

9.1 Project Goal and Objectives

The overarching goal of this project was to develop 3D printed humanoid robots capable of picking and placing small household items and human interaction with residents and providers in aging services. This was done by successfully completing the following five objectives:

1. Implementing the ability to pick-and-place small household objects.
2. Integrating a modular end-effector system to easily swap hands for various tasks.
3. Redesigning parts to improve structural integrity, reduce assembly time, reduce weight, and increase ease of troubleshooting.
4. Integrating systems that allow human-robot interaction with assistive care patients.
5. Conducting a study to evaluate the desire for humanoid robotics in the assistive care industry.

9.2 Pick and Place

It was important to develop a pick-and-place hand that can pick up any small object that could be found in an at-home assistive care setting. The team did this by using a hybrid two-finger pinch, where there is one rigid finger to stabilize the object and one finger that can bend to the shape of any object using a compliant mechanism. The dimensions for this hand were chosen based on which iteration could pick up the largest variety of shapes and materials, confirming the ability of the hand to pick up and rotate a broad range of small household objects. More specifically, this hand was able to pick up and rotate a variety of shapes and materials, such as a glass cylinder, plastic bag, cardboard box, and metal cube. Larger objects, such as a large, fully filled water bottle and objects that lay flat against a table, such as a cell phone, were outside the scope of the hand's abilities. This induces the restriction of "a broad range of small household objects."

Picking and placing items like groceries, cups, bottles, and medications is a common movement in assistive care tasks. Applying the movement of picking and placing to Finley using simulated kinematics was important for the team because it proved that the system could create movements to be used in assistive care.

9.3 Modularity

Due to the large variety of tasks in an at-home assistive care setting, modular systems were developed for Finley to introduce easy to use customization. A modular end-effector system was designed and successfully implemented. This system allows for hands tailored to specific applications to be easily swapped out. It also provides electrical continuity across the wrist so included actuators can function. Although successful, this system has some room for improvement. The magnetic connection is not strong enough to comfortably lift more than 500g without the hand falling off. Additionally, properly aligning the hand can be difficult. Modularity was also incorporated on the head lid of Finley. Now, various sensors for different applications can be swapped out easily just like the end-effectors. These systems utilize magnets that provide strong mechanical connections while being easy to swap. These systems lend themselves well to the open-source nature of the project, so users can adapt Finley to their specific environment in the future.

9.4 Redesign

All components on Finley were redesigned to improve structural integrity, reduce material, improve aesthetics, and reduce assembly and servicing time. Structural redesigns were effective in making the robot a more robust system that is less prone to breaks. Material reductions make the manufacturing process quicker, as well as reducing weight and environmental impact of the system. Aesthetic redesigns were completed due to feedback from the human study, making users more comfortable when interacting with Finley. Lastly, a significant reduction in fasteners means the robot takes less time to assemble. If a component does break, it will be easier to access and replace. A list of components with printing time, material cost, and number of fasteners can be found in Appendix A.

9.5 Human Study

Performing a human study to identify how different people feel about humanoid robots helped the team to develop a more effective humanoid for use in assistive at-home care. Doing market research, community surveys, and user interviews was important for the team because engineering design needs the study of human perspectives in it. Surveying the WPI community was important in learning that trust in humanoid robots varies for different people which impacts people’s opinions on them. Results from the survey can be found in Appendix H.

The team found that there is a lot of interest in using Finley. Providers responded that Finley would be able to reduce stress on assistive care workers and ultimately increase human-human interaction between providers and residents in Aging Services. Additionally, results from market research and interviews with residents and providers were considered in the development of new design criteria for the future of 3D printed humanoid robots at WPI. Respondents and interviewees indicated they wanted Finley to be able to do more like fall detection, measure vitals, predict and prevent falls, and use object recognition to manipulate objects. The new design criteria for the future of the project are to further develop Finley to do its current applications as well as implementing object recognition, detect falls of residents, and to integrate wires in a safe and aesthetic manner.

Overall, from conducting a study on human-robot trust it was found that people have varying levels of trust in robotics, especially in humanoid robots. There is a lot of interest in this project and in using 3D printed humanoid robots in assistive at-home care.

9.6 Human Interaction

Finley was successfully able to hold a conversation with users, perform actions upon speech commands, interact with electronic devices via GPIO pins, and host a touch screen application for controls. In doing so, the team completed the objectives set for the human interaction component of the project. The link to the TalkToFinley GitHub repository, which contains all human interaction code, can be found in Appendix C.

The team was able to gauge Finley's interaction through various demonstrations. Throughout the construction of the humanoid, students and faculty at the university would interact with the robot by asking it questions and having it perform motions. The team noticed that the delay in response, associated with the API call and on-board processing, as well as inconsistent responses dissuaded users from being overly communicative with Finley which would translate to the robot in an at-home assistive care setting. The team marked this as an area of improvement.

The integrated microphone responded well in noisy environments indicating a strong use for it in various situations in an elderly care setting. Additionally, the touch screen allowed for users to choose a physical interaction or verbal interaction, and the UI including font and button animation was well received by users.

The human interaction compounded to the open-source nature of the project as all the code used was made available on the project GitHub and can be adapted by users to suit their needs going forwards. The basic script to toggle any GPIO pin allowed for the team to swap any electronic device and perform actions.

This chapter described how the team successfully addressed each design objective for at-home assistive care. The following chapter will cover the broader implications of this project in society, the environment, and the economy, as well as future work that the team recommends for the next team.

10.0 Conclusions

Overall, the team successfully designed and assembled a 3D printed humanoid robot named Finley to pick-and-place objects and conduct human interaction for assistive at-home care. A pick-and-place system and pick-and-place movement were developed in simulation and in real life. Next, a modular connection was developed at the wrists where different hands can be attached for different applications with electrical continuity. A human study was performed to identify how different people feel about humanoid robots to develop a more effective humanoid for use in assistive at-home care. Lastly, Finley is capable of human interaction through speech-to-text and speech-to-motion using OpenAI. All completed objectives were showcased at the Undergraduate Research and Projects Showcase (URPS) at WPI.

10.1 Broader Implications

The development of Finley has had impacts beyond the technical achievements made by the project. This chapter will cover the social, environmental, and economic impacts that this project has had.

10.1.1 Social Impact

The nature of this project was to develop an open-source humanoid robot for assistive at-home care. Anyone with the right tools and general engineering knowledge can build and use their own 3D printed humanoid robot. With it being open-source, customers can design new hands for different applications if it fits with the modular connection developed in this project.

There is a pressing need for assistance in aging services around the United States, and the team was able to develop an assistive care robot to address that need. The team stressed that Finley was designed to help providers spend more time with residents, not to replace human interaction and replace jobs. Finley was developed to improve the health and the wellbeing of seniors both by lightening the load on workers and being able to interact with residents and providers using OpenAI.

Lastly, this project incorporated human perspectives into the engineering design of Finley by conducting a human study that collected user and community views. Finley was reassessed and redesigned after surveys and interviews to be more acceptable and better address the needs of residents and providers in aging services.

10.1.2 Environmental Impact

Unfortunately, resin and PLA are toxic materials that negatively impact the environment through sourcing and use. To address this, each part of Finley went under structural redesigns and material reductions to increase strength and prevent breakage. This decreased the amount of resin used to reduce the negative environmental impacts from this project.

10.1.3 Economical Impact and Manufacturability

Competitor aging services humanoid robots like Pepper, sell starting at $32,000 while Finley would cost $6931.10. More residents and more aging services facilities will be able to afford an assistive-care robot with the development of Finley. Finley also helps with decreasing the stress that assistive-care workers feel by being able to do repetitive tasks which the team found will decrease the high turnover rate and high burnout rate in nursing. Increasing job retention is a positive economic impact that this project has proven.

The project is open source, meaning anyone can download the necessary programs, parts, and instructions to build and use their very own 3D printed humanoid robot. The drawbacks with the project being open source are that customers would need a resin printer costing $890, a FDM printer costing $750, all components needed to build the robot costing $6931.10, as well as enough engineering knowledge to assemble and troubleshoot the robot. The Esun Hard Tough Resin costs $60/kg and PLA is $26/kg. The full cost of the robot considering everything required to manufacture comes out to be $8571.1 which is still less than other humanoid robots in the market. A full Bill of Materials (BOM) can be found in Appendix B.

10.1.4 Political Ramifications

While this project can potentially be used all over the world, there are several aspects to this project that make this difficult. The growing need for at-home assistive care in this project, while not solely a U.S. problem, is centered around statistics based in the United States. Ordering certain parts, such as motors or resin printers in general, can be difficult due to having to import these from specific countries. This limits access to essential aspects of this project and can be problematic in countries with strict import laws and high shipping prices.

10.1.5 Human-Robot Interaction Specific Standards

In addition to the standards discussed in 4.7, there are at least two human-robot interaction specific standards that would need to be considered if Finley and other humanoids were to be used in an at-home care setting, IEEE SA P7017 and P3107. P7017 describes the methodology and application of “compliance by design” surrounding socially assistive robots. This includes risk assessments, methods for compliance, conceptual frameworks, etc. (IEEE Standards Association, n.d.). P3107 describes general terms surrounding human-robot interaction for a variety of applications (IEEE Standards Association, n.d.).

10.2 Future Work

The team was successful in implementing multiple systems to benefit the future of this project. However, there are significant areas that can be added or improved upon next year. This chapter will describe potential improvements in wire management, object recognition and autonomous hand swapping, failsafe mechanisms, testing in residential facilities, and material reduction and use.

10.2.1 Wire Management

Based on experience and feedback received from interviews, wire management would significantly improve the humanoids both functionally and aesthetically. Throughout the year, wire breakage was common that can cause shorting, safety concerns, and constant troubleshooting in order to identify the problem. It would also generally make the robot look better, as interviewees found the wires unappealing. Identifying possible solutions for wire management and choosing the most applicable option for a humanoid with multiple degrees of freedom would significantly aid in taking this project to the next level.

10.2.2 Object Recognition and Autonomous Hand Swapping

Eventually, Finley should be able to function independently in an at-home assistive care setting. In order to do this, object recognition and autonomous hand swapping would be necessary. With the addition of a magnetic modular system on the head, any sensor necessary for object recognition, such as the HuskyLens AI camera or TF Luna LiDAR (sensors that have been purchased in the past), can be easily incorporated into the humanoid. Object recognition can allow patients to tell Finley to grab certain objects and complete specific tasks.

If Finley can complete a variety of tasks there may be several different end-effectors that could be in use. After constructing an easily swappable universal modular design this year, the team hopes that Finley will eventually be able to swap hands on his own after being told to complete a task that requires a different end-effector. This may look like a docking bay with a set number of hands oriented for that universal connection, allowing Finley to simply stick the current end-effector into a compartment, detach it, then move to a different compartment to attach another hand. This could be accomplished using methods of localization and calibration such as April Tags (*AprilTag*, n.d.). Both this and object recognition would allow Finley to operate more independently as an at-home care assistant.

10.2.3 Failsafe Systems

From testing, the team deemed it necessary to incorporate failsafe systems into the humanoids in case of a fall to minimize damage and reduce the frequency of reprinting and servicing. This can include both passive safety features and emergency shutdown procedures. Passive safety features can include impact absorbing materials or deformable structures in case of fall. Emergency shutdown procedures occur when the humanoid experiences power loss or critical failure and can involve self-righting or stabilization maneuvers.

10.2.4 Testing in Assisted Living Facilities

Based on feedback received during interviews, it would be necessary to eventually bring Finley to actual residential facilities to interact with both the surroundings and patients. Finley must be capable of navigating in a residential/at-home setting and interacting with patients, both of which can be accomplished through reaching out to the facilities that the team has made connections with this year.

10.2.5 Material Reduction and Use

Resin and PLA printing produces a lot of wasted material. Failed prints or broken parts made of PLA can be recycled to be used again, similarly failed prints or broken parts made of resin can be repurposed into something else or ground down into bricks. Parts made from PLA can be made using recycled PLA which can be sourced from various companies to make the project more environmentally conscious. Sourcing recycled PLA for parts that require it and recycling old PLA and resin used by the project should be considered for next year.

10.2.6 Human Interaction

Throughout the various demos and testing of Finley's interaction capabilities, the team found plenty of room for changes and improvement. The team noticed the latency during conversations and after making motion requests. This can be attributed to the numerous API requests being made alongside serial communication with the motors. The team suggests looking at ways to reallocate memory and optimize the performance of the Raspberry Pi. Additionally, the AI model requires more tuning and training to deliver consistent and accurate chat completion. This is an ongoing process as AI models require iterative training and constant adaptation. The possibility of self-learning models to auto-create tool call functions and motor movements would also provide more autonomy in the elderly care environment and reduce the need for developers to create a function for every possible movement. Lastly, improving the input and output interfaces such as the on-board speaker and touchscreen application would better the user experience and make Finley's interaction more robust to different environments.

11.0 Reflections

11.1 Merel Sutherland

This project posed an interesting challenge for me being a ME and ESS double major because I got to integrate the social side of engineering into the development of Finley. I learned about how much trust plays a factor into how we perceive robots and how important market research, and user perspectives are in engineering. Additionally, I learned how to use CoppeliaSim, trajectory planning, inverse kinematics, as well as troubleshooting the necessary scripts in Python and MATLAB. Learning that this project could help real people was my biggest takeaway.

11.2 William Michels

A major challenge of this project was taking on a project that had already been worked on for multiple years. It took a lot of time not only to understand what had been done and why, but also in fixing issues with CAD, wiring, etc. However, my experience from many design projects and courses prepared me well to work on such a complex system. From this project, I learned more about 3D printing and troubleshooting, wiring, and smart motor control. I believe this year's team has set up the project well for future development and applications of Finley.

11.3 Anna McCusker

As a BME major, it was exciting to see the transition of this mechanical/robotics project to more of a healthcare application such as at-home assistive care. Throughout the year, there was exposure to a variety of tools that would not have necessarily been used during the BME curriculum, and it was an incredible opportunity to expand one's skill set and aid in the development of a project that could one day change lives.

11.4 Shivank Gupta

This project pushed me to employ my learnings from the project-based curriculum at the university. With the interdisciplinary nature of the project, I was able to work on electrical, mechanical, and software components satisfying my ME and RBE requirements. I learned from the incredible project team and faculty, who helped me hone my skills and introduced me to new facets of engineering. I enjoyed the application of the project and the positive direction it took with respect to the elderly care and human-robot interaction.

References

7 Home Robots You Need In Your House. (2023, September 14). ECOVACS US. https://www.ecovacs.com/us/blog/home-robot-design

7 Types of Robots Used in the Military. (2023, January 6). ADS, Inc. https://www.adsinc.com/news/7-types-of-robots-used-in-the-military

About Doughnut Economics | DEAL. (n.d.). Retrieved April 2, 2024, from https://doughnuteconomics.org/about-doughnut-economics

Abubakar, S., Das, S. K., Robinson, C., Saadatzi, M. N., Logsdon, M. C., Mitchell, H., Chlebowy, D., & Popa, D. O. (2020). ARNA, a Service robot for Nursing Assistance: System Overview and User Acceptability. *2020 IEEE 16th International Conference on Automation Science and Engineering (CASE)*, 1408–1414. https://doi.org/10.1109/CASE48305.2020.9216845

Acemoglu, D., & Restrepo, P. (2017). *Robots and Jobs: Evidence from US Labor Markets*. National Bureau of Economic Research.

Antić, J., Mišković, Ž., Mitrović, R., Stamenić, Z., & Antelj, J. (2023). The Risk assessment of 3D printing FDM technology. *Procedia Structural Integrity*, *48*, 274–279. https://doi.org/10.1016/j.prostr.2023.07.132

AprilTag. (n.d.). Retrieved April 29, 2024, from https://april.eecs.umich.edu/software/apriltag

Baum, S. (n.d.). *A novel elderly care robot could soon provide personal assistance, enhancing seniors' quality of life*. Retrieved April 29, 2024, from https://techxplore.com/news/2024-02-elderly-robot-personal-seniors-quality.html

Brown, S. (2020, July 29). *A new study measures the actual impact of robots on jobs. It's significant. | MIT Sloan*. https://mitsloan.mit.edu/ideas-made-to-matter/a-new-study-measures-actual-impact-robots-jobs-its-significant

Byrne, J. (n.d.). *ISO 9001 vs ISO 13485. What's the difference?* Retrieved April 29, 2024, from https://www.cognidox.com/blog/iso-9001-vs-iso-13485-what-is-the-difference

Cox, P. (2022, July 7). *Nursing home robots entertain, watch for trouble signs*. MPR News. https://www.mprnews.org/story/2022/07/07/nursing-home-robots-dance-sing-and-watch-for-signs-of-trouble

DeLaOsa, J. (2019, March 4). *Pneumatic Robot Hand Uses a Digital Twin and Artificial Intelligence*. Design World. https://www.designworldonline.com/pneumatic-robot-hand-uses-a-digital-twin-and-artificial-intelligence/

Fisher, S. (2023, April 1). *Survey Questions: Tips & Examples in 2022*. Qualtrics. https://www.qualtrics.com/blog/writing-survey-questions/

Flexible Gripper by PrintChallenge | Download free STL model. (n.d.). Printables.Com. Retrieved April 29, 2024, from https://www.printables.com/model/398296-flexible-gripper

Galewitz, P. (2021, June 30). With Workers In Short Supply, Seniors Often Wait Months For Home Health Care. *NPR*. https://www.npr.org/sections/health-shots/2021/06/30/1010328071/with-workers-in-short-supply-seniors-often-wait-months-for-home-health-care

Galgano, A., Fournet, D., Lehman, A., Engdahl, W., & Beazley, R. (2022). *3D Printed Humanoid Robot Project*. https://digital.wpi.edu/concern/student_works/dr26z168n?locale=en

Gemini—Chat to supercharge your ideas. (n.d.). Gemini. Retrieved April 29, 2024, from https://gemini.google.com

GPT-3.5 Turbo. (n.d.). OpenAI Platform. Retrieved April 29, 2024, from https://platform.openai.com/docs/models/gpt-3-5-turbo

Grover, W. H. (2021, June 13). *The rise (and risks) of resin-based 3D printers*. Grover Lab: Department of Bioengineering, University of California, Riverside. https://groverlab.org/hnbfpr/2021-06-13-3d-printer-risks.html

Handwerk, B. (n.d.). *How Humanlike Do We Really Want Robots to Be?* Smithsonian Magazine. Retrieved January 13, 2024, from https://www.smithsonianmag.com/science-nature/how-humanlike-do-we-really-want-robots-to-be-180980234/

Hannun, A., Case, C., Casper, J., Catanzaro, B., Diamos, G., Elsen, E., Prenger, R., Satheesh, S., Sengupta, S., Coates, A., & Ng, A. Y. (2014). *Deep Speech: Scaling up end-to-end speech recognition* (arXiv:1412.5567). arXiv. http://arxiv.org/abs/1412.5567

Home Health Care Workforce Shortage. (2023, June 9). Penn LDI. https://ldi.upenn.edu/our-work/research-updates/home-health-care-workforce-not-keeping-up-with-community-needs/

Institution, S. (n.d.). *Smithsonian Launches Pilot Program of "Pepper" Robots*. Smithsonian Institution. Retrieved April 28, 2024, from https://www.si.edu/newsdesk/releases/smithsonian-launches-pilot-program-pepper-robots

Jamshed, S. (2014). Qualitative research method-interviewing and observation. *Journal of Basic and Clinical Pharmacy*, *5*(4), 87–88. https://doi.org/10.4103/0976-0105.141942

Kosmopoulos, P. (2024). Chapter 10—The way forward for sustainable development. In P. Kosmopoulos (Ed.), *Planning and Management of Solar Power from Space* (pp. 173–189). Academic Press. https://doi.org/10.1016/B978-0-12-823390-0.00001-6

Landers, S., Madigan, E., Leff, B., Rosati, R. J., McCann, B. A., Hornbake, R., MacMillan, R., Jones, K., Bowles, K., Dowding, D., Lee, T., Moorhead, T., Rodriguez, S., & Breese, E. (2016). The Future of Home Health Care. *Home Health Care Management & Practice*, *28*(4), 262–278. https://doi.org/10.1177/1084822316666368

Lee, O. E. K., Nam, I., Chon, Y., Park, A., & Choi, N. (2023). Socially Assistive Humanoid Robots: Effects on Depression and Health-Related Quality of Life among Low-Income, Socially Isolated Older Adults in South Korea. *Journal of Applied Gerontology*, *42*(3), 367–375. https://doi.org/10.1177/07334648221138283

Li, M., Milojević, A., & Handroos, H. (2020). Robotics in Manufacturing-The Past and the Present. In *Technical, Economic and Societal Effects of Manufacturing 4.0: Automation, Adaption and Manufacturing in Finland and Beyond* (pp. 85–95).

Lytle, T., Austin, E., Van Milligan, J., Alarcon, Z., & Alag, A. S. (2023). *Development of 3D Printed Humanoid Robots*. https://digital.wpi.edu/concern/student_works/br86b7141?locale=en

Moyle, W., Murfield, J., & Lion, K. (2022). Therapeutic use of the humanoid robot, Telenoid, with older adults: A critical interpretive synthesis review. *Assistive Technology*, *0*(0), 1–8. https://doi.org/10.1080/10400435.2022.2060375

Newton, P. M. (2018). How Common Is Commercial Contract Cheating in Higher Education and Is It Increasing? A Systematic Review. *Frontiers in Education*, *3*. https://doi.org/10.3389/feduc.2018.00067

Opensource.com. (n.d.). *What is open source? | Opensource.com*. Retrieved March 26, 2024, from https://opensource.com/resources/what-open-source

Oskui, S. M., Diamante, G., Liao, C., Shi, W., Gan, J., Schlenk, D., & Grover, W. H. (2016). Assessing and Reducing the Toxicity of 3D-Printed Parts. *Environmental Science & Technology Letters*, *3*(1), 1–6. https://doi.org/10.1021/acs.estlett.5b00249

Park, H., & Kim, D. (2020). An open-source anthropomorphic robot hand system: HRI hand. *HardwareX*, *7*, e00100. https://doi.org/10.1016/j.ohx.2020.e00100

Pneumatic Two-Finger Flexible Robot Claw Bionic Hand Robotic Hand Fruit Claw | eBay. (n.d.). Retrieved April 29, 2024, from https://www.ebay.com/itm/364412089141

Poppy Project—Open source robotic platform. (n.d.). Retrieved April 28, 2024, from https://www.poppy-project.org/en/

PyTorch. (n.d.). PyTorch. Retrieved April 29, 2024, from https://pytorch.org/

RoboCup Federation official website. (n.d.). Retrieved April 29, 2024, from https://www.robocup.org/

Robotics in Healthcare: Past, Present, and Future. (2022, February 10). AdventHealth University. https://www.ahu.edu/blog/robotics-in-healthcare

Sawik, B., Tobis, S., Baum, E., Suwalska, A., Kropińska, S., Stachnik, K., Pérez-Bernabeu, E., Cildoz, M., Agustin, A., & Wieczorowska-Tobis, K. (2023). Robots for Elderly Care: Review, Multi-Criteria Optimization Model and Qualitative Case Study. *Healthcare*, *11*(9), 1286. https://doi.org/10.3390/healthcare11091286

Schapoehler, M. (n.d.). *Robot Safety Standards 101: Developing a Safe Environment with Industrial Robots*. Retrieved April 29, 2024, from https://blog.airlinehyd.com/robot-safety-standards-101-developing-a-safe-environment-with-industrial-robots

TensorFlow. (n.d.). Retrieved April 29, 2024, from https://www.tensorflow.org/

The best robotic hands. (n.d.). Retrieved April 29, 2024, from https://mindtrans.narod.ru/hands/hands.htm

Topic: Ai-models. (n.d.). GitHub. Retrieved April 29, 2024, from https://github.com/topics/ai-models

Wolf, S., Hofmann, C., Bahls, T., Maurenbrecher, H., & Pleintinger, B. (2023). Modularity in Humanoid Robot Design for Flexibility in System Structure and Application. *2023 IEEE-RAS*

22nd International Conference on Humanoid Robots (Humanoids), 1–7. https://doi.org/10.1109/Humanoids57100.2023.10375175

Zhang (Uberi), A. (n.d.). *SpeechRecognition* (3.10.3) [Python; MacOS :: MacOS X, Microsoft :: Windows, Other OS, POSIX :: Linux]. Retrieved April 29, 2024, from https://github.com/Uberi/speech_recognition#readme

Appendices

Appendix A: Printing Time, Material Costs, Fasteners for Assembly

Part	Quantity	Print Time (hr)
Abdomen	1	7:10
Abdomen Motor Connector 1	1	2:22
Abdomen Motor Connector 2	1	2:37
Back	1	3:45
Bicep	2	3:54
Chest	1	7:36
IMU Cover	1	1:09
IMU Holder	1	1:23
Chest Motor Connector 1	1	1:07
Chest Motor Connector 2	1	1:34
Foot	2	3:31
Forearm	2	3:33
Head	1	16:45
Head Lid	1	11:04
Hip	2	2:50
Hip Connector	2	1:03
Motor Adapter	6	0:37
Neck	1	1:55
Pelvis	1	3:20
Shoulder	2	2:15
Shoulder Connector	2	1:15
Thigh	2	13:05
Flexible Finger	2	4:53
Modular Forearm Side	2	1:55
Modular Hand Side	2	2:59
Rigid Finger	2	1:07
Shin	2	13:41

Part	Quantity	Resin Volume (mL)	Unit Cost ($)	Cost Reduction ($)
Abdomen	1	58.69	3.876	-0.042
Abdomen Motor Connector 1	1	6.16	0.408	0.024
Abdomen Motor Connector 2	1	11.39	0.75	-0.006
Back	1	25.68	1.692	0.054
Bicep	2	30.5	2.016	0.336
Chest	1	285.3	18.828	2.892
IMU Cover	1		0.31148	0.40732
IMU Holder	1	5.69	0.378	0
Chest Motor Connector 1	1	3.93	0.258	0
Chest Motor Connector 2	1	5.25	0.348	0
Foot	2	53.81	3.552	0.312
Forearm	2	32.01	2.112	-1.52258
Head	1		4.17144	0.57564
Head Lid	1		2.85662	-1.0504
Hip	2	14.42	0.954	0.36
Hip Connector	2	8.07	0.534	-0.024
Motor Adapter	6	3.66	0.24	0
Neck	1	6.66	0.438	0.006
Pelvis	1	27.52	1.818	2.262
Shoulder	2	10.63	0.702	0.018
Shoulder Connector	2	18.78	1.242	-0.396
Thigh	2	71.74	4.734	0
Flexible Finger	2		0.94276	N/A
Modular Forearm Side	2	11.98	0.792	N/A
Modular Hand Side	2	15.64	1.032	N/A
Rigid Finger	2	30.28	1.998	N/A
Shin	2	102.46	6.762	N/A

Part	Ava Screws	Finley Screws	Fastener Reduction	Quantity	Total
Abdomen	36	12	24	1	24
Abdomen Motor Connector 1	12	12	0	1	0
Abdomen Motor Connector 2	6	6	0	1	0
Back	32	16	16	1	16
Bicep	10	10	0	2	0
Chest	40	24	16	1	16
IMU Cover	1	1	0	1	0
IMU Holder	4	4	0	1	0
Chest Motor Connector 1	12	12	0	1	0
Chest Motor Connector 2	6	6	0	1	0
Foot	24	8	16	2	32
Ava Lower Forearm	4	0	4	2	8
Head	21	21	0	1	0
Head Lid	4	0	4	1	4
Hip	30	12	18	2	36
Hip Connector	16	8	8	2	16
Motor Adapter	60	36	24	1	24
Neck	9	9	0	1	0
Pelvis	40	16	24	1	24
Shoulder	36	9	27	2	54
Shoulder Connector	8	8	0	2	0
Thigh	36	20	16	2	32
Elbow Connector	16	0	16	2	32
Hand	13	0	13	2	26
Shin Top	28	0	28	2	56
Shin Bottom	4	0	4	2	8
Shin	0	12	-12	2	-24
Spine Clamp	2	0	2	1	2
Finley Forearm	0	14	-14	2	-28
Modular Forearm Side	0	5	-5	2	-10

Part	Ava Screws	Finley Screws	Fastener Reduction	Quantity	Total
Modular Hand Side	0	4	-4	2	-8
Flexible Finger	0	8	-8	2	-16
Rigid Finger	0	4	-4	2	-8

Appendix B: Bill of Materials

https://docs.google.com/spreadsheets/d/1vNgo_gJMDSlnh2p_JXGI3isvdwswHQfm9-zYc49q1OI/edit?usp=sharing

Component	Unit Cost	Quantity	Total Cost
Parts			
3D Printed Parts (PLA)	$9.23	1	9.23
3D Printed Parts (Resin)	$83.09	1	83.09
Motors			
HerkuleX DRS 0101	$70.00	2	$140.00
HerkuleX DRS 0201	$154.00	17	$2,618.00
HerkuleX DRS 0601	$335.00	10	$3,350.00
Electronics			
HRB 11.1V 5000mAh Battery (pack of 2)	$33.99	2	$67.98
DRA-0007 / Harness (300mm) Motor Wires	$8.00	15	$120.00
5V 5 kg Electromagnet	$9.95	3	$29.85
Waveshare 4.3 inch DSI LCD Display	$38.50	1	$38.50
Raspberry Pi 4 Mobel B	$80.00	1	$80.00
Ribbon cable for Raspberry Pi	$1.90	1	$1.90
Arduino Mega 2560 Rev3	$48.90	1	$48.90
BNO055 IMU	$9.99	1	$9.99
Adafruit Perma-Proto Half-sized Breadboard PCB	$4.50	1	$4.50
Electret Microphone - 20Hz-20KHz Omnidirectional	$0.95	2	$1.90
Electret Microphone Amplifier - MAX4466 with Adjustable Gain	$6.95	1	$6.95
6pcs Speaker 3 Watt 8 Ohm Mini Speaker 8 ohm 3w Loudspeaker	$2.33	6	$13.99
Pi Camera	$10.99	1	$10.99
D86-N52 - Neodymium Disc Magnet	$3.08	8	$24.64
CONN SPRING TARGET 1POS SMD	$0.59	25	$14.70
SURFACE MOUNT SPRING-LOADED PIN	$0.86	25	$21.42
Silicone Rubber Sheet, 50A 1/16 x 9 x 12"	$9.99	1	$9.99

Component	Unit Cost	Quantity	Total Cost
JST Connectors	$9.99	1	$9.99
LM2596 DC-DC Buck Converter (pack of 10)	$16.99	1	$16.99
Hardware			
"18-8 Stainless Steel Socket Head Screw M2 x 0.4 mm Thread, 8 mm Long"	$8.10	2	$16.20
Alloy Steel Socket Head Screw Black Oxide, M2.6 x 0.45 mm Thread, 6 mm Long (pack of 25)	$11.18	4	$44.72
18-8 Stainless Steel Socket Head Screw M4 x 0.7 mm Thread, 6 mm Long (pack of 100)	$7.63	1	$7.63
18-8 Stainless Steel Hex Nut M2 x 0.4 mm Thread (pack of 100)	$6.14	1	$6.14
18-8 Stainless Steel Socket Head Screw M2 x 0.4 mm Thread, 8 mm Long (pack of 100)	$8.10	2	$16.20
Adjustable Clevis Pin, Zinc-Plated 1004-1045 Carbon Steel, 3/16" Diameter, 2.5" Long (pack of 10)	$6.59	1	$6.59
Zinc-Plated Alloy Steel Socket Head Screw, M2 x 0.4 mm Thread, 12 mm Long (pack of 100)	$16.63	1	$16.63
Unused			
TF-Luna LiDAR	$28.59	1	$28.59
Huskeylens - AI Camera	$54.90	1	$54.90
Total Cost			
			$6931.1

Appendix C: Access to CAD and Software

Link to the full GitHub for all software and CAD files: https://github.com/KoalbyMQP
Link to the GitHub where all of the scripts and simulation can be found in the design branch: https://github.com/KoalbyMQP/RaspberryPi-Code_23-24/tree/design & https://github.com/KoalbyMQP/Arduino-Code_23-24/tree/finley

GitHub Link to Finley Interaction Repository:
https://github.com/KoalbyMQP/TalkToFinley/tree/motionTest

Instructions can be found on what to download and how to download the various programs in the GitHub.

Appendix D: Design Criteria to Determine Hand Design

This appendix contains the design criteria used to evaluate the hands described in section 4.4.

Criteria Name	Description	Ranking Specifications
# Actuators	Limited number of actuators is ideal in terms of cost and simplicity	-1: More than 2 actuators 0: 2 actuators 1: 1 actuator
Versatility	What the hand can grab and how effective it is.	-1: can only work with a specified object 0: can grab more than one kind of thing 1: can grab more things (within limits)
Hand Strength	Strength of the hand itself to not break under load.	-1: Fragile 0: Won't break under normal loads 1: Very strong
Complexity	Number of parts and likelihood to fail.	-1: Very complex, lots of parts 0: Moderate amount of parts 1: Very few parts
Design Time	Time/Work to design.	-1: Too much for what it's worth 0: Can do 1: Easy as pie
Cost	Low cost of materials.	-1: Multiple high cost parts 0: Not bad 1: Cheap parts/already have parts
Breakage Risk/ Wear & Tear	Ability for hand to be used over time without breaking.	-1: Fails after a few uses 0: Works but needs replacements after a while 1: Lasts long periods of time
Modular Compatibility	How easy is it to attach the end effector to the robot & provide power & send and receive data.	-1: Complicated attachment. 0: Most users have the capability to swap the end effector. 1: The average user can easily swap the end effector.
Sensor Compatibility	Can we add other functions onto the hand (vitals, paint brush).	-1: Complex and no space for other functions. 0: Minimal space for other functions. 1: Space for other functions that can be easily applied.

Appendix E: Hand Testing Data for Gage R&R

Team Member 1 Data and Scores:

Hand 1	Picks up	Rotates	
Racketball	Yes	Yes	
Peter's Brass Cube	Yes	Yes	
Old Thigh	No	No	
Mac and cheese	Yes	Yes	
Chips	Yes	Yes	
Hot sauce	No	No	
Screwdriver	No	No	
Lollipop Stem	Yes	Yes	
Score	2	2	4

Hand 2	Picks up	Rotates	
Racketball	Yes	Yes	
Peter's Brass Cu	Yes	Yes	
Old Thigh	Yes	No	
Mac and cheese	Yes	Yes	
Chips	Yes	Yes	
Hot sauce	Yes	Yes	
Screwdriver	Yes	Partial	
Lollipop Stem	Yes	Partial	
Score	8	4	12

Hand 3	Picks up	Rotates	
Racketball	Yes	Partial	
Peter's Brass Cu	Yes	Yes	
Old Thigh	Yes	Yes	
Mac and cheese	Yes	Yes	
Chips	Yes	Yes	
Hot sauce	Yes	Partial	
Screwdriver	Yes	Partial	
Lollipop Stem	Yes	Partial	
Score	8	4	12

Hand 4	Picks up	Rotates
Racketball	Yes	Yes
Peter's Brass Cu	Yes	Yes
Old Thigh	Yes	Yes
Mac and cheese	Yes	Yes
Chips	Yes	Yes
Hot sauce	Yes	Yes
Screwdriver	Yes	Partial
Lollipop Stem	Yes	Yes
Score	8	7
		15

Hand 5	Picks up	Rotates	
Racketball	Yes	Yes	
Peter's Brass Cube	Yes	Yes	
Old Thigh	No	No	
Mac and cheese	Yes	Yes	
Chips	Yes	Yes	
Hot sauce	Yes	No	
Screwdriver	Yes	Partial	
Lollipop Stem	Yes	Partial	
Score	6	2	8

Hand 6	Picks up	Rotates	
Racketball	Yes	Yes	
Peter's Brass Cu	Yes	No	25
Old Thigh	Yes	No	
Mac and cheese	Yes	Yes	
Chips	Yes	Yes	
Hot sauce	Yes	Partial	
Screwdriver	No	No	
Lollipop Stem	Yes	Yes	
Score	6	1	7

Hand 7	Picks up	Rotates	
Racketball	Yes	Yes	
Peter's Brass Cu	Yes	Yes	
Old Thigh	Yes	Partial	
Mac and cheese	Yes	Yes	
Chips	Yes	Yes	
Hot sauce	Yes	Yes	
Screwdriver	Yes	Yes	
Lollipop Stem	Yes	Partial	
Score	8	6	14

Team Member 2 Data and Scores:

Hand 1	Picks up	Rotates	
Racketball	Yes	Yes	
Peter's Brass Cube	Yes	Yes	
Old Thigh	Yes	Yes	
Mac and cheese	Yes	Yes	
Chips	Yes	Partial	
Hot sauce	Yes	Yes	
Screwdriver	Yes	Yes	
Lollipop Stem	Yes	Yes	
Score	8	7	15

Hand 2	Picks up	Rotates	
Racketball	Yes	Yes	
Peter's Brass Cu	Yes	Yes	
Old Thigh	Yes	Yes	
Mac and cheese	Yes	Yes	
Chips	Yes	Partial	
Hot sauce	Yes	Yes	
Screwdriver	Yes	Yes	
Lollipop Stem	Yes	Yes	
Score	8	7	15

Hand 3	Picks up	Rotates	
Racketball	Yes	Yes	
Peter's Brass Cu	Yes	Yes	
Old Thigh	Yes	Yes	
Mac and cheese	Yes	Yes	
Chips	Yes	Yes	
Hot sauce	Yes	Yes	
Screwdriver	Yes	Yes	
Lollipop Stem	Yes	Yes	
Score	8	8	16

Hand 4	Picks up	Rotates
Racketball	Yes	Yes
Peter's Brass Cu	Yes	Yes
Old Thigh	Yes	Yes
Mac and cheese	Yes	Yes
Chips	Yes	Partial
Hot sauce	Yes	Yes
Screwdriver	Yes	Yes
Lollipop Stem	Yes	Yes
Score	8	7
		15

Hand 5	Picks up	Rotates	
Racketball	Yes	Yes	
Peter's Brass Cube	Yes	Yes	
Old Thigh	Yes	Yes	
Mac and cheese	Yes	Partial	
Chips	Yes	Partial	
Hot sauce	Yes	Yes	
Screwdriver	Yes	Yes	
Lollipop Stem	Yes	Yes	
Score	8	6	14

Hand 6	Picks up	Rotates	
Racketball	Yes	Yes	
Peter's Brass Cu	Yes	Yes	
Old Thigh	Yes	Yes	
Mac and cheese	Yes	Yes	
Chips	Yes	Yes	
Hot sauce	Yes	Yes	
Screwdriver	Yes	Yes	
Lollipop Stem	Yes	Yes	
Score	8	8	16

Hand 7	Picks up	Rotates	
Racketball	Yes	Yes	
Peter's Brass Cu	Yes	Yes	
Old Thigh	Yes	Yes	
Mac and cheese	Yes	Yes	
Chips	Yes	Yes	
Hot sauce	Yes	Yes	
Screwdriver	Yes	Yes	
Lollipop Stem	Yes	Yes	
Score	8	8	16

Appendix F: Survey Questions

https://docs.google.com/document/d/10aD5MHSqsk7t1IvI4BJWNCNhJrttxzDKswhhJwFj7Uo/edit?usp=sharing

Appendix G: Interview Questions

https://docs.google.com/document/d/1JIk-uhffCfa_BniMEwe3j489C4T1iA8q8b1r-JxZN04/edit?usp=sharing

Appendix H: Survey Results

Raw Survey Data:
https://drive.google.com/drive/folders/1kFXaHaz0J_qcQWFjzOP_xrlA8twttYA7?usp=drive_link

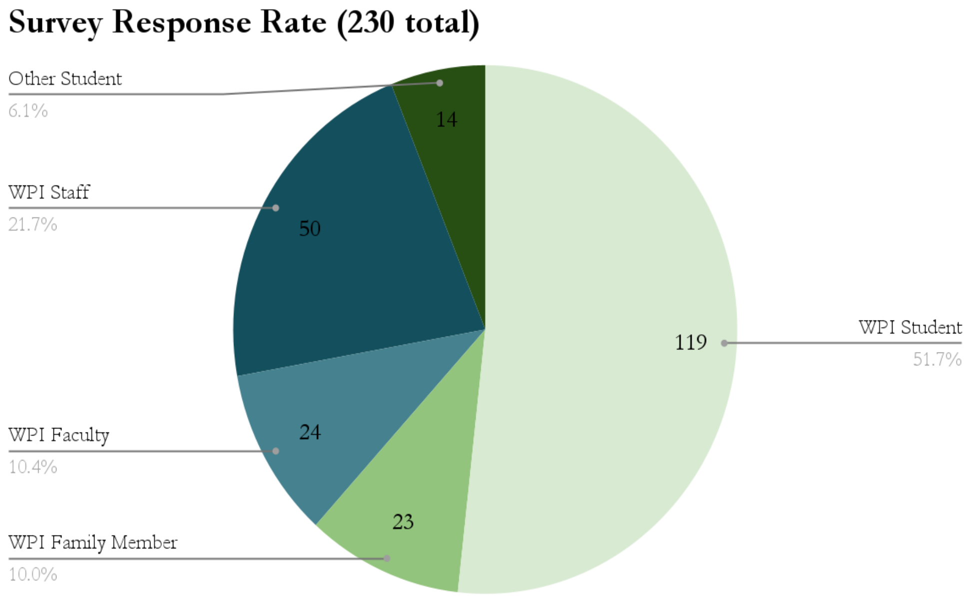


Figure A: Question 1 WPI Community Survey Response Rate

Survey responses were distributed as follows; 119 WPI students, 14 non-WPI students, 50 WPI staff members, 41 WPI faculty members, and 23 WPI family members.

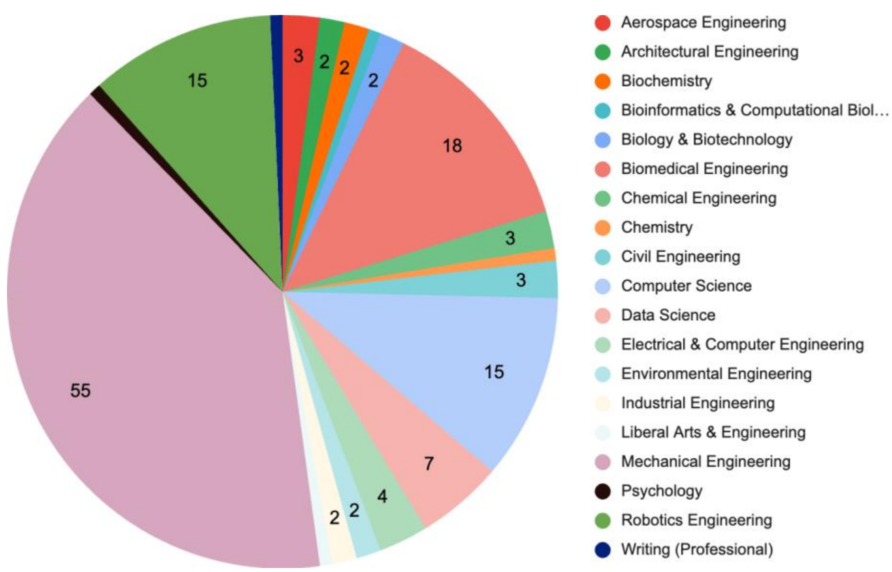


Figure B: Question 2

WPI students' majors were reflected as follows; 55 'Mechanical Engineering', 18 'Biomedical Engineering', 15 'Robotics Engineering', 15 'Computer Science', 7 'Data Science' and the remaining majors were 4 students or less.

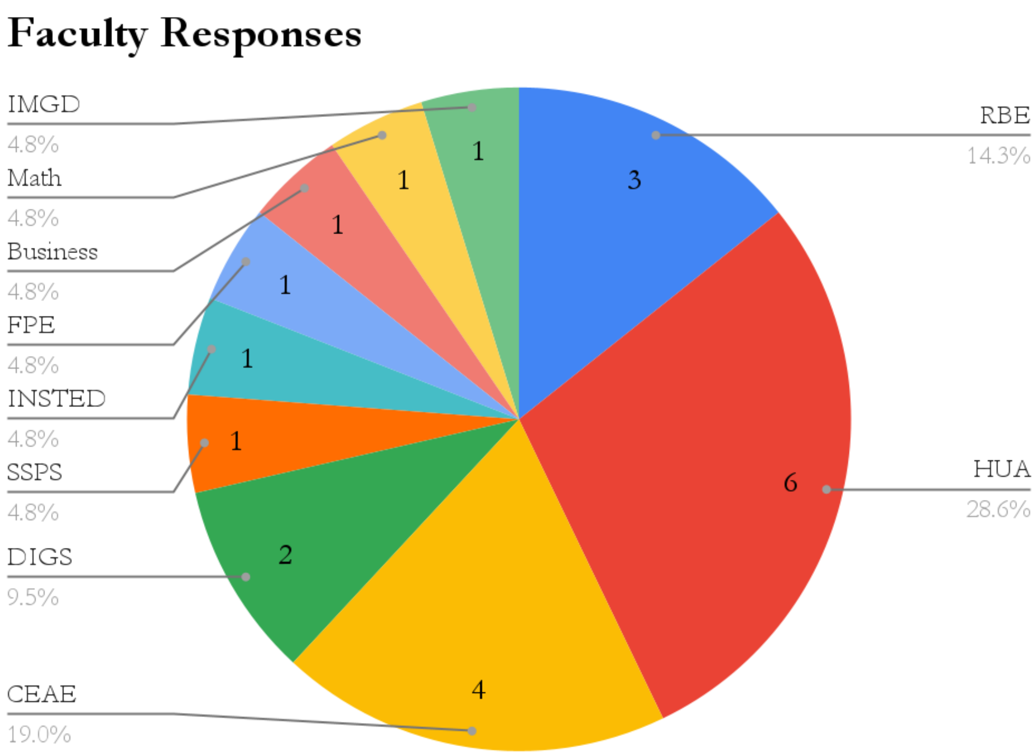


Figure C: Question 3

The following faculty departments were recorded, 6 'Humanities', 4 'Civil, Environmental, and Architectural Engineering', 3 'Robotics Engineering', and the rest were 2 responses of fewer.

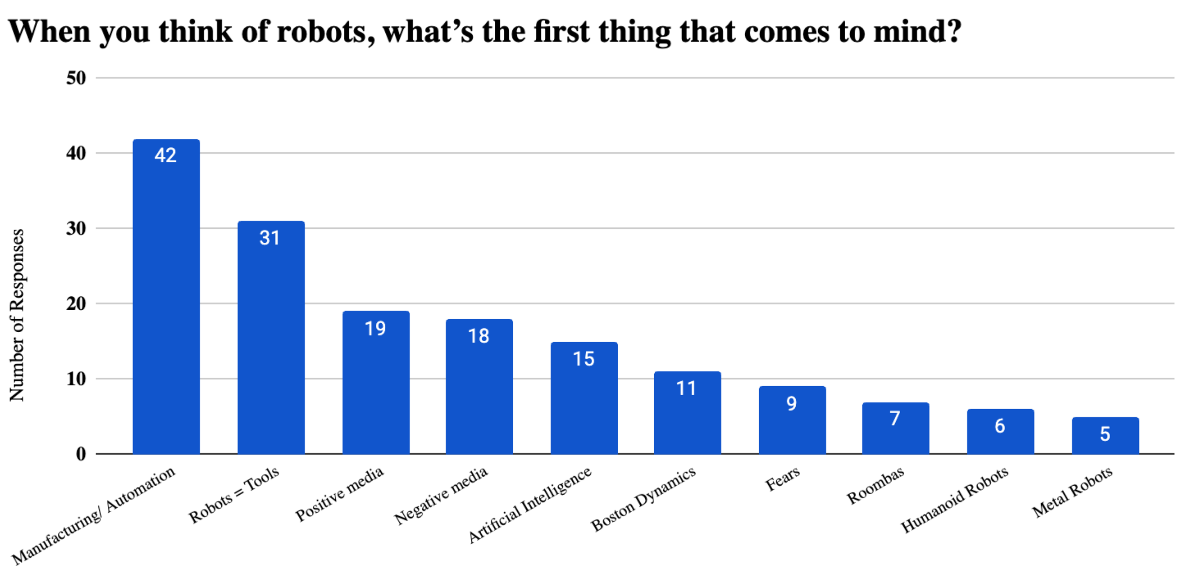


Figure D: Question 4

Responses to Q4 include: 42 of 'Manufacturing/Automation', 31 of 'Robots are tools', 19 of positive media, 18 of negative media, 15 of 'Artificial Intelligence', 11 of 'Boston Dynamics', 9 in fear of robots, 7 of 'Roombas', 6 of 'Humanoid Robots', and 5 of 'Metal Robots'.

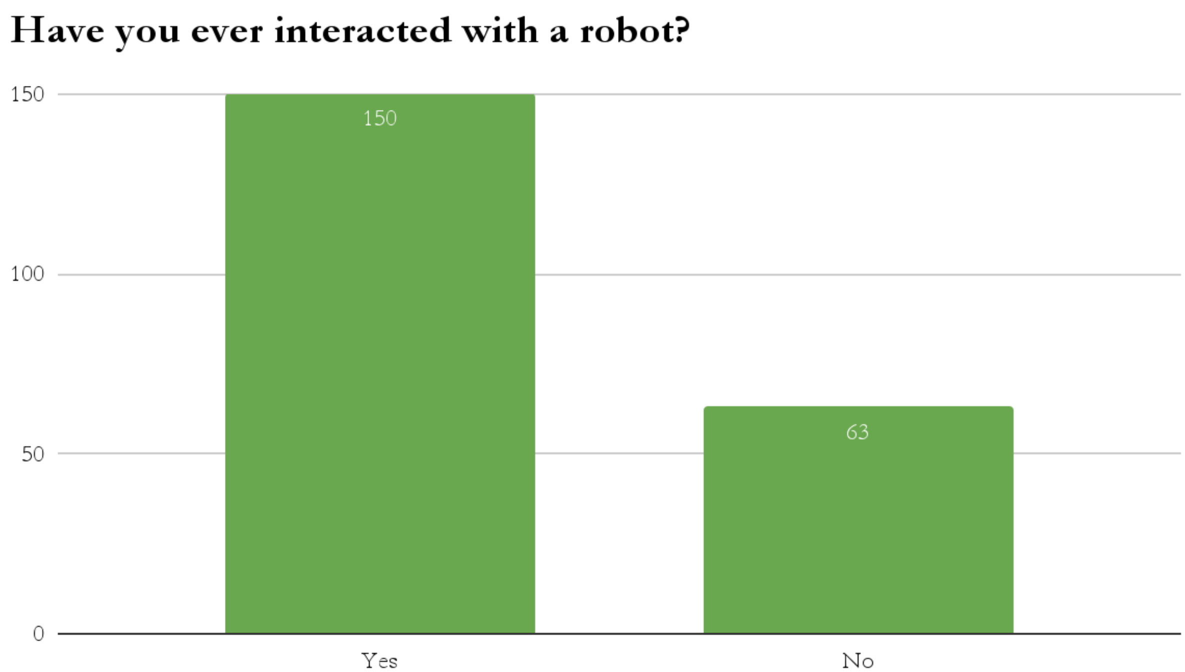


Figure E: Question 5

150 of the respondents responded 'Yes' and 63 responded 'No'.

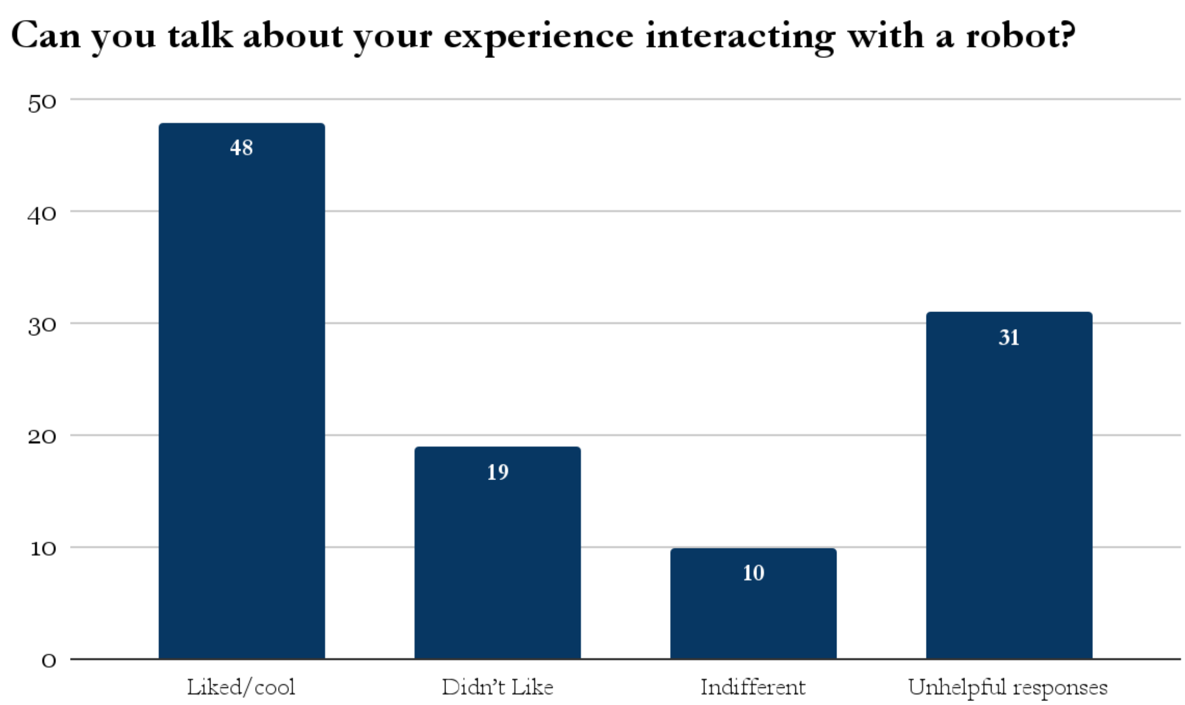


Figure F: Question 6

From the 150 that responded 'Yes' to Q5, 48 responded that they 'Liked/ Thought it was cool', 19 responded that they 'Didn't Like' the experience, 10 were indifferent, and 31 gave unhelpful responses.

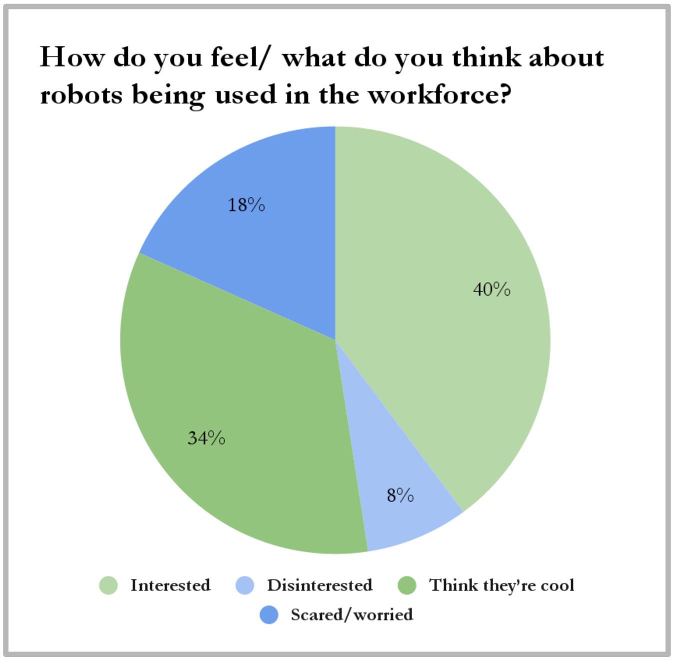


Figure G: Question 7

From the 230 responses, 40% were 'Interested' in robots being used in the workforce, 34% 'Think they're cool', 18% were 'Scared/worried', and 8% were 'Disinterested'.

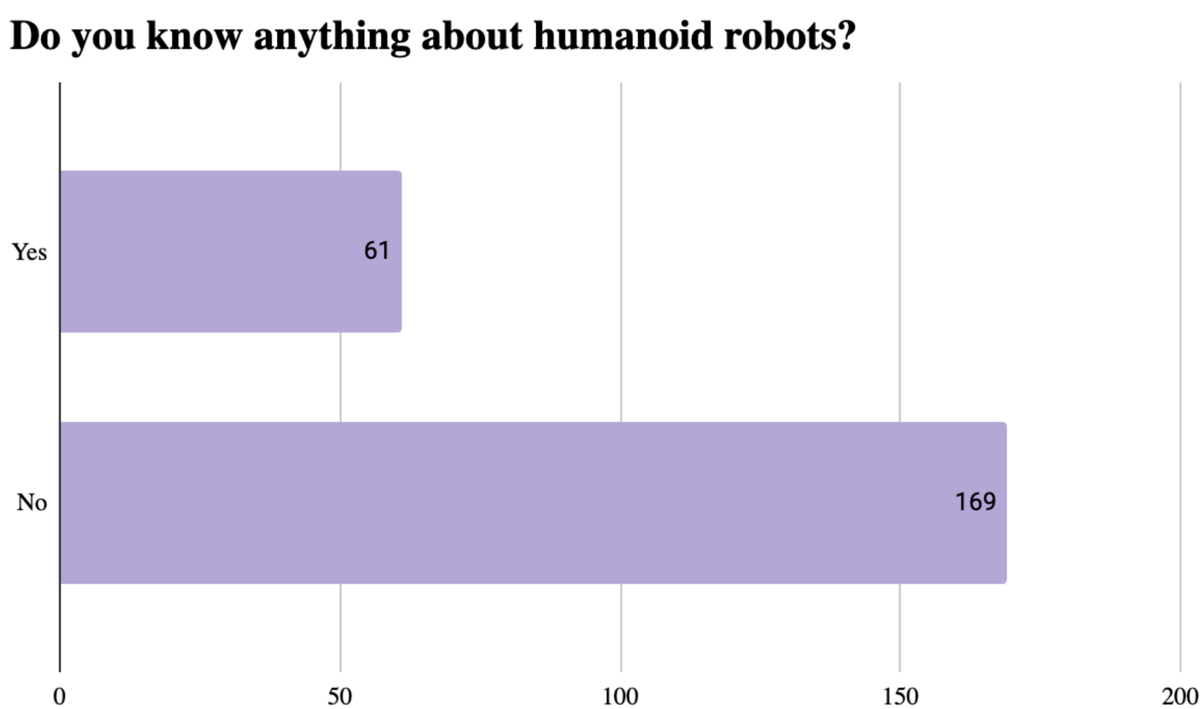


Figure H: Question 8

61 of survey respondents responded 'Yes' to knowing anything about humanoid robots and 169 responded 'No'.

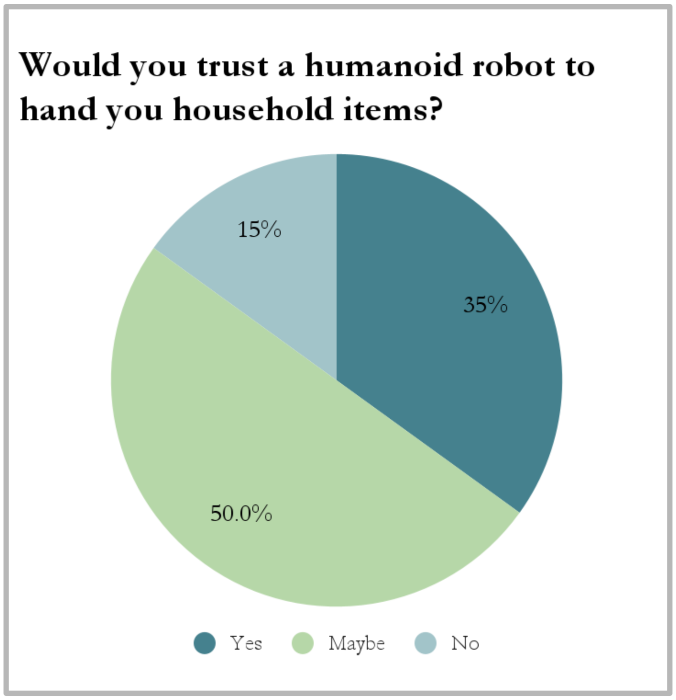


Figure I: Question 9

186 people responded to this question, 50% answered 'Maybe', 35% answered 'Yes', and 15% answered 'No'.

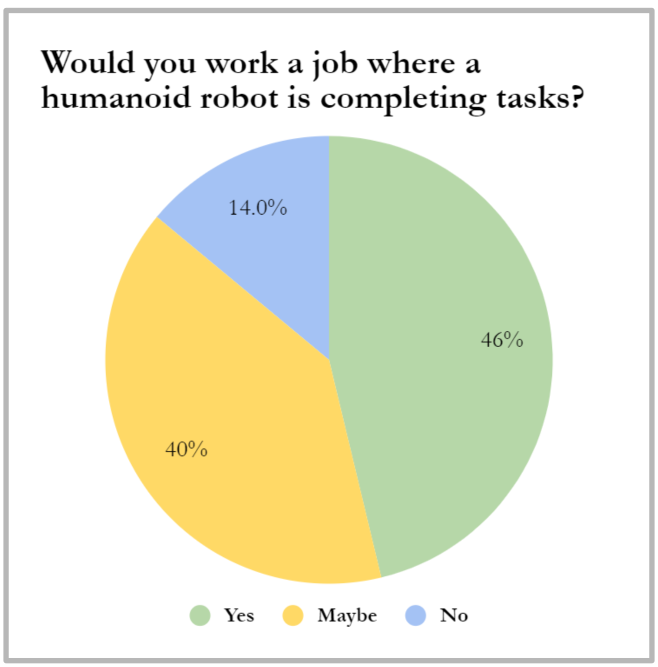


Figure X: Question 10

46% answered 'Yes' to working a job with a humanoid robot, 40% answered 'Maybe', and 14% answered 'No'.

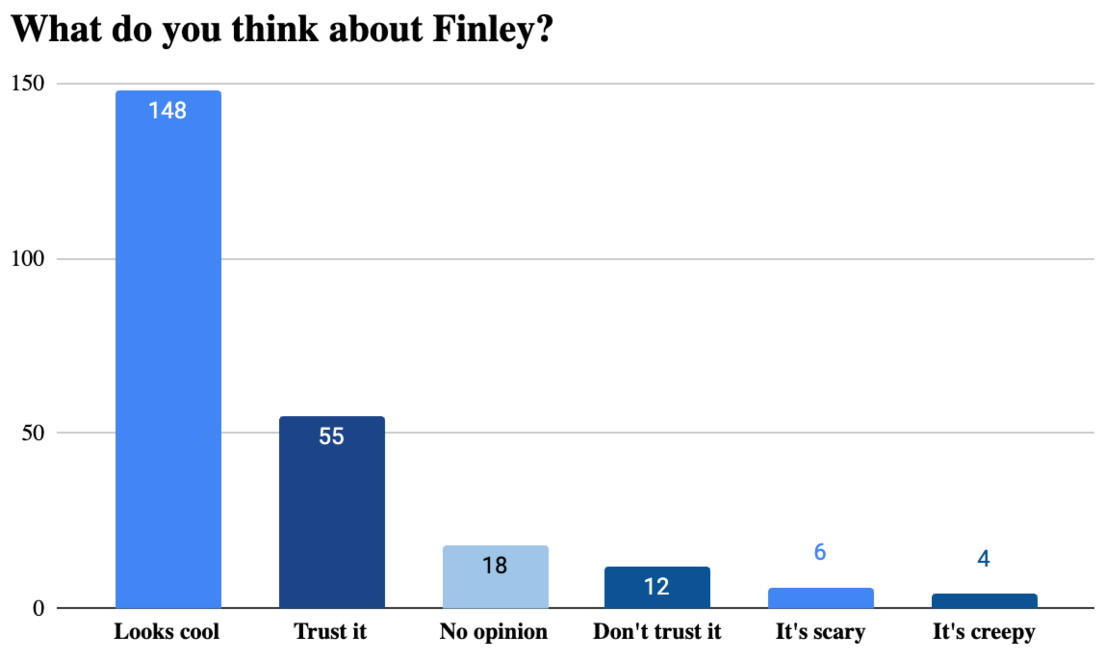


Figure G: Question 11

148 of respondents responded that Finley 'Looks cool', 55 responded that they 'Trust it', 18 had no opinion, 12 responded that they 'Don't trust it', 6 responded 'It's scary', and 4 responded 'It's creepy'.