DEVELOPMENT OF A LOW-COST SOCIAL ROBOTIC PLATFORM

by

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for any proprietary material contained therein.

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Development of a Low-Cost Social Robotic Platform

Abstract

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This thesis presents a social robot named *Woody*. Woody is an upper body robot developed to serve as an interactive learning platform. It uses open-source software, and can be constructed and used for Do-It-Yourself (DIY) projects. In terms of mobility, Woody has two arms, each with five degrees of freedom (DoF), and a head with four DoF between its eyebrows and neck. Woody's hardware is made primarily from laser cut plywood, reducing the cost of fabrication. Embedded electronic components, including two cameras with a microphone, a speaker, and motors, are controlled via a laptop or Raspberry Pi. Interactive functions include face tracking, facial emotion recognition, and several pre-programmed default gestures. Through a graphical user interface (GUI), the user can easily create new gestures via the motion recording function. The GUI also features a way to access instructions for users to build their own Woody, as well as real-time interactions such as recognizing emotions while tracking the user's face.

Chapter 1

Introduction

This chapter introduces the background and goals for the Woody project. Section 1.1 provides a review of the relevant literature in the field of social robotics. Section 1.2 describes prior research conducted in our lab, specifically a previous social robot called Philos as well as software to detect a user's emotions with computer vision. Section 1.3 lists the objectives of Woody, which are affordability, manufacturability, and applicability, towards the goal of developing a low-cost social robot for educational purposes.

1.1 Related Work

Social robots feature unique technical functionalities for interacting with human users in a natural manner using language, gestures, and facial expressions. Several hardware platforms have been developed over the past decades and some are commercially available. Their application domains have been dramatically expanding from entertainment to assistive care, education, and specialized services. This type of robot typically uses social cues provided by human users as control inputs and generates socially acceptable responses.

1.1.1 Design and Appearance of Social Robots

A common theme in social robotics is the use of animal-inspired designs. In the same way that animals are often used in therapeutic applications, a robot can achieve a similar result due to our attraction to animals, and traits like softness and cuteness. Huggable, a robot designed to deal with children, takes the form of a teddy bear [9]. This robot is covered in touch-sensitive material and responds via movement. Paro, meanwhile, was developed to care for the elderly, and is shaped like a seal [10, 11]. Additionally, NeCoRo and iCat are both robots in the form of a cat [12, 13]. Aibo is a robot dog made by Sony that has found success as a consumer product. Aibo has a more robotic appearance than other animal-like robots, featuring a glossy body instead of artificial fur, but features many dog-like mannerisms [14].

Other designs are inspired by the humanoid form. These types of robots have the benefit of familiarity to human-human interaction. For example, generating facial expressions is a way to enhance human-robot interaction (HRI), where a human appearance would be more versatile than an animal appearance. Facial expressions form an important part of human-to-human communication, and the same applies when dealing with a robot. Sparky is a robot that uses four degrees of freedom (DoF) in the face for the purpose of showing various emotions [15]. Sparky additionally has six DoF in its body, allowing it to roll along the ground in several directions, and adjust the position of its head. Feelix is a robot similar to Sparky in that it also has four DoF in the head for facial expression generation [16]. However, Feelix is unique in that it is built on the LEGO Mindstorms platform, giving it the benefits of a Do-It-Yourself (DIY) platform.

Kismet is even more detailed in its ability to demonstrate emotion through its facial expressions [17]. While it is only a head with no body, the head features 21 DoF, allowing for much higher complexity in the facial expressions displayed. Kismet is able to detect user input using a camera and a microphone, and modifies its facial posture in response. Other researchers, meanwhile, have decided not to make a face that changes in the physical world, but instead simply generates it via a digital screen. IROMEC is a robot that features a digital face, and is built to interact with children with autism spectrum disorder (ASD) [18].

Just as it is easier for the user to connect with robots that look like humans, it is also easier to connect with robots that move like humans. An example is NAO, which is a small humanoid robot produced by SoftBank Robotics [19]. NAO is able to manipulate its lower parts with 11 DoF, its upper parts with 14 DoF, record video, and respond to touches on its head. NAO and other social robots show that the way in which a robot moves has a significant effect on HRI. Robots that emphasize degrees of freedom in the face interact very differently than mobile robots. SoftBank Robotics also produces another robot, called Pepper [20, 21]. Pepper features a humanoid torso with a wheeled base. Pepper is equipped with two arms, a face containing sensors, and a tablet on its chest. Pepper functions as a less mobile but more personable alternative to NAO. Another humanoid robot is DARwIn-OP. This robot is similar in size and appearance to NAO. DARwIn-OP has also competed in robot soccer tournaments [22]. Similarly to a robot like Feelix, DARwIn-OP is sold as a kit, which can be assembled by the user and then used as a research or educational platform. This makes it particularly of interest to developers [23].

1.1.2 Functionality and Applications of Social Robots

Social robots' appearance, social capabilities, and technical functionalities are directly related to the target applications and the user acceptance and preference. Sage, Olivia, and Pepper are humanoid robots with embedded vision and voice systems and arms to generate gestures [24, 25, 20, 21]. These robots are well-suited for public service domains, providing information and services to visitors in museums, conferences, or other public events. Social robots have also been used for health care applications.

NAO is often adopted in research studies examining robot-based social and behavioral training [26]. For example, Nao was used for testing robot-assisted social and behavioral therapy for children with ASD [19, 27, 28]. Autom is another upper body platform developed to serve as a robotic weight management coach to help its users lose or maintain their weight and eat a healthy diet [29, 30].

The applications that have been devised for social robots are numerous. Sage is a robotic museum tour guide, with a built-in screen that delivers an educational video to visitors [24]. Olivia acts as a secretary, as well as providing entertainment through her simulated childlike personality. Olivia has demonstrated interaction via speech or a touch screen table in front of her [25]. Autom acts as a weight loss coach, with users inputting their diet and exercise habits on a touch screen and the robot responding with digital facial expressions and words of advice and motivation [29]. Autom has found success in the market and was successfully backed on Indiegogo [30].

Buddy is a small personal assistant that has demonstrated a number of applications, including home security, edutainment, and elderly care [31]. Buddy features a small screen to display either its emotional state, or video content. Baxter is a robot that functions as an industrial worker, designed to be safe, strong, and applicable in a variety of industrial settings. Baxter is able to be easily taught complex motions by a human guiding its arm. It also features a screen display of a face [32]. Sawyer, another commercial robotic platform, is similar to Baxter but has a smaller footprint and longer reach in order to navigate tighter spaces.

Another application of social robotics is long-term engagement with users, particularly those who require degrees of social training. Behavioral control is an important aspect of HRI for this purpose. One theory is that users are more comfortable with robots that display similar personality traits. User-robot personality matching has been proposed and studied by Mataric's research group [33, 34]. The way that robots matched the personality of the human subject was based on the Eysenck model, which identifies three fundamental personality traits: extroversion, neuroticism, and psychoticism. This research group developed a robot called Bandit, in which extroversion/introversion axis was emphasized [35]. Bandit has a humanoid torso mounted on a wheeled platform. Bandit's face is also human-inspired, featuring cameras for eyes and animated facial expression via eyebrow and lip positioning. Notably, however, Bandit was designed not to be too human-like, so as not to raise users' expectations of realism in the robot's behavior.

Considering the critical shortage in the number of caregivers compared to the growing aging population, social robots have strong potential as a long-term, low-cost solution for assisting and caring for older adults. Broad applications range from simple medication control to social and physical interventions [36]. Aibo, Paro, NeCoRo, and iCat are animal-like robots which have been used in several studies for aging populations [12, 13, 37, 38]. For example, Paro has been used as a therapeutic companion for dementia patients. Humanoid robots have been used for this purpose as well. For example, in one study NAO performed cognitive and physical therapy [39], and in another had its therapeutic benefits compared to Paro and a real dog [40]. Bandit is another humanoid robot developed to provide companionship and encouragement to Alzheimer's patients [41].

While previous studies mostly focused on using a single robot for a single user or a group of users, robots can also be used in a multi-robot, multi-user (MRMU) setting. Individual robots may be employed in different classrooms in a school, as well as rooms or houses in a community living facility (e.g., continuing care retirement communities, nursing homes, assisted living facilities, etc.). In this case, the number of robots may vary depending on the application and environment, and each robot must be capable of interacting with its own user(s) independently. To do so, each robot must be able to fully execute the vision and voice systems (at minimum) - which are computationally heavy - to establish HRSI. Previous research has developed various ways that robots can communicate with humans, server, and each other [42, 43, 44]. Darmanin and Bugeja classified six applications of multi-robot systems: surveillance and search and rescue, foraging and flocking, formation and exploration, cooperative manipulation, team heterogeneity, and adversarial environment [45].

1.1.3 DIY Robots and Educational Applications

While applications of social robots for public service and health care domains are significant, the interactive nature of a social robot makes it uniquely suitable to serve as a hands-on learning platform. A social robot is typically equipped with a set of expressive and perceptive functions [46]. These ubiquitous features – while the level of individual functionalities would vary – allow a social robot to provide learning and training opportunities for students. A low-cost yet functional hardware design will also enable a DIY project, encompassing the entire cycle of the robot development from hardware construction to programming [47]. An example in DIY social robotics is Ono, a platform that features a modular face on top of a passive humanoid body in a sitting position [48, 49, 50]. In one study, students were tasked with designing their own robot on top of the Ono platform [51]. Another DIY robot is called TJBot [52]. TJBot is a cardboard robot meant to be built by DIY communities, or by students in order to teach robotics by being simple and fun to build and program.

In addition to platforms being developed for academic research, there are other DIY robotic platforms that are commercially available. Three examples, in order of increasing cost and complexity, are LEGO Mindstorms, Bioloid, and DARwIn-OP (Fig. 1.1). Mindstorms is a platform that uses LEGO components in the construction of robots. It is highly reconfigurable due to the versatility of LEGOs and is meant as an educational tool for children. Many forms of robot have been built with the platform, including humanoids and animal-shaped robots [53, 54]. In one study, a robot dog was built to train autistic children, showing the potential for HRI ap-

Figure 1.1: Commercial DIY robots: Mindstorms [1], Bioloid [2], and DARwIn [3].

plications [55]. Bioloid is another reconfigurable platform, using components meant for compatibility with Dynamixel AX-12A motors. It can be configured into forms such as humanoids, spiders, etc. and has demonstrated vision capability, playing soccer, and instructional robotics [56, 57, 58]. ROBOTIS OP, known in its previous form as DARwIn-OP, is a bipedal humanoid that can be assembled by the user. Its hand is modular and reconfigurable to suit the user's needs. It has been able to play with humans via activities such as bowling, and it can display emotions [59, 60]. A comparison of DIY robotic platforms can be found in Table 1.1.

1.2 Project Background and Previous Prototypes

Previously, the robot "Philos" was developed in the Distributed Intelligence and Robotics Laboratory (dirLAB) [4, 61]. Philos was a small social robot that could be dressed in a penguin suit for a cute appearance, as shown in Fig. 1.2. This familiar animal-like appearance was important for that robot's primary purpose, which was to provide companionship to senior citizens and children, particularly those suffering

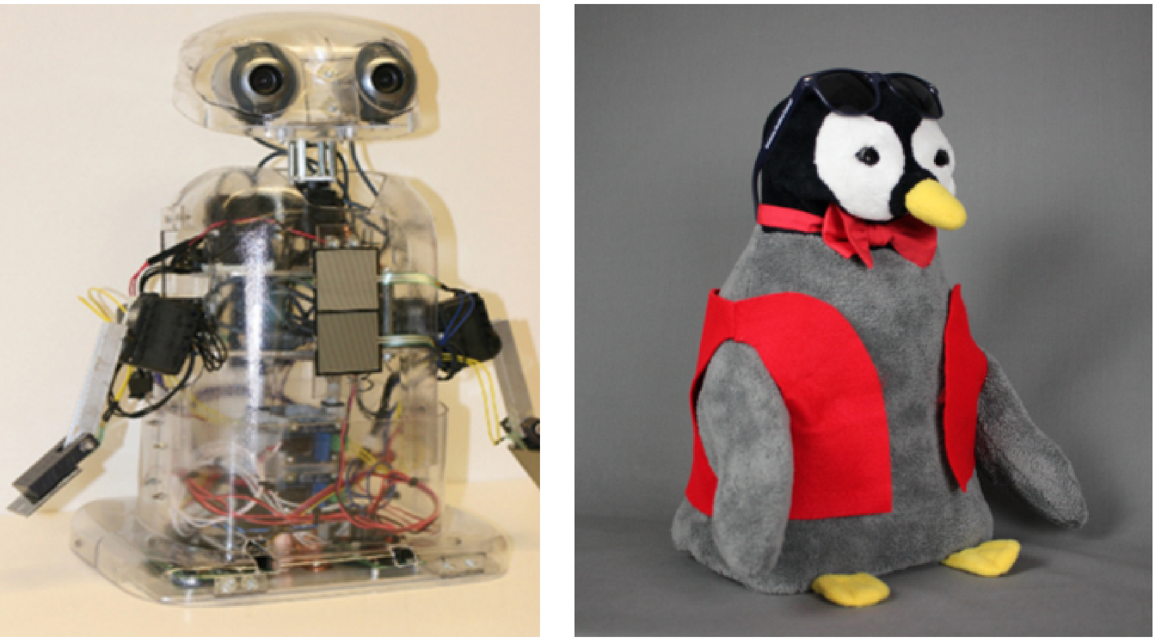


Figure 1.2: Philos, the lab's previous social robot, without and with its cover. Retrieved from [4] and [5], respectively.

from dementia, Alzheimer's disease, autism, and other mental ailments. Since the project is now targeted towards children with interest in engineering, keeping some level of cuteness could be beneficial to making it more enjoyable to put together and see the finished product. However, it is less important to hide the mechanical and electrical components under something like a penguin suit, as students may be interested in seeing the technical aspects of the design. Philos had limited degrees of freedom, and featured unintuitive manufacturing methods such as machining metal and vacuum forming plastic.

As the project moved more in the direction of targeting as an educational tool, having these kinds of complicated manufacturing techniques was less appropriate, as it could be too dangerous or difficult for students to make the robot themselves without significant levels of supervision. A redesign that featured simpler manufacturing methods while having the ability to perform more complicated gestures was desired. Gestures are a crucial component to social interactions and can communicate a variety of emotions. More degrees of freedom are also practical, enabling the robot to grasp objects, which could enable it to play with people. From an educational perspective, students could create their own complicated gestures and movement patterns and thus learn more about programming and controlling robots. Designs based on 3D printing were tested [62]. Another design based on laser cut acrylic with a third degree of freedom in each arm was prototyped as well. Ultimately, however, a design based on laser cut plywood known as "Woody" was created.

Additionally, previous work in the lab involved the detection of a human face and real-time tracking, face recognition, and detection of a human's emotional state based on analyzing their face [63, 64]. Facial emotion recognition (FER) is a latest development newly implemented to Woody [65]. By converting a face to a set of landmarks, a computer can detect patterns that indicate various emotions. Emotions can broadly be categorized as sadness, happiness, surprise, disgust, anger, fear, and neutral. Implemented in a study, real-time emotion detection could get insight into a test subject's response that they may not talk about in a survey, for example. When interacting with a robot, the capabilities are even greater. Not only can real-time emotion detection be used to determine the user's response when analyzing data after the fact, but a well-tuned robot could adjust its own behavior to meet the preferences of a user and provide a more satisfying social experience. Based on the success of this software, it was incorporated into Woody and combined with face tracking to be able to gather emotion data while constantly looking at the user's face. Incorporating others' work into Woody is an important goal towards developing an open-source social robot, and can be used as a basis for users to implement their own programs as part of an educational program or for fun.

1.3 Project Objectives

The three main objectives of this thesis project are:

- **Affordability.** The cost for constructing the robot should be affordable for potential DIY applications.
- **Manufacturability.** The robot can be built by two to three students with low-level engineering skills, requiring minimum access to manufacturing equipment.
- **Applicability.** The fabricated robot must have sufficient degrees of freedom and interactive features for a broad range of educational and research applications.

These three factors are significant goals towards the development of a DIY social robot for education and research purposes. First, affordability is important because educators would prefer to spend as little money as possible on classroom resources. This is particularly true if they have many students, and therefore need many kits. Second, manufacturability is useful for teaching construction skills. Robots developed by other companies and research groups can be used to teach students manufacturing through the simplicity of LEGO parts, or more complicated designs featuring nuts and bolts. If this project can teach students yet another manufacturing technique they are unfamiliar with, that would be a success. Third, applicability is important in teaching students about all the things that robots can do. This can inspire students to come up with their own ideas for programs, and if the robot features a user-friendly programming interface, students can learn valuable programming skills while having the fun of developing an application, seeing it through completion, testing it, and finally watching the robot perform it effectively.

Considering the potential educational opportunities a DIY social robot can provide, this thesis presents the design, construction procedure, and graphical user interface (GUI) for a robot, named "Woody" (Fig. 1.3). Woody is a 14-DoF robot with a head, face, two arms, two cameras, a microphone, and a speaker. The controller is a Raspberry Pi, which contains a microprocessor for vision processing and motor

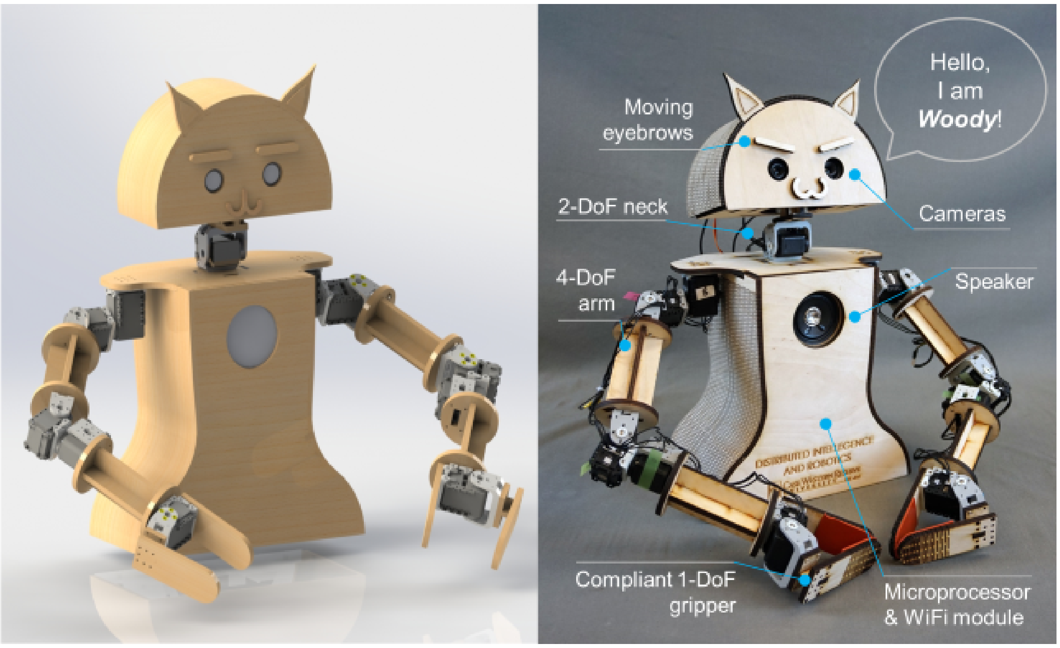


Figure 1.3: CAD model of Woody (left) and fully assembled hardware prototype (right).

control, a Wi-Fi module, and a mini USB port for wireless or wired communication with an interfacing computing device. The entire robot costs around \$700, where the majority of the cost is associated with the servo motors. Replacing the servo motors with less expensive ones will further reduce the cost.

Table 1.1: Comparison of existing DIY robots and Woody

	Commercial DIY robot			Open-source DIY robot		
Robot	LEGO Mindstorm	Bioloid	DARwIn	Ono	TJBot	Woody
Appearance	Customizable	Humanoid (full-body)	Humanoid (full-body)	Humanoid (face)	Abstract	Humanoid (upper-body)
Mobility	✓	✓	✓	x	x	x
Manipulation	✓	x	x	x	x	✓
DoF	3	20	20	13	1	14
Material	Plastic	Metal	Metal	Foam	Paper	Wood
Programming	JAVA	C/Python	C++	Python	Python	Python
Vision Processing	Color detection	Color detection	Color based algorithm	x	x	Fully Programmable
Cost	$539.99	$1,258.95	$9,600	$200	$100	$718.68

Chapter 2

Robot Hardware Development

This chapter describes the hardware design, development, and fabrication. Woody was developed as an open-source based, DIY robotic hardware platform that can be constructed by a couple of college (or high school) students with low-level engineering training. Section 2.1 describes the mechanical design, which is simple and modular for easy construction, customization, and repair. Section 2.2 discusses the electrical design, listing the electronic components used and how they can be controlled using a laptop or a Raspberry Pi. Section 2.3 describes the DIY process, with descriptions of how all the parts are designed, manufactured, and integrated into the robot. Section 2.4 discusses the forward kinematics and inverse kinematics of the arm design using Denavit-Hartenberg (D-H) parameters and geometrical approaches.

2.1 Mechanical Design

Woody uses laser-cut plywood for its mechanical structures which lowers the cost and minimizes the use of fabrication equipment. Woody is comprised of four main subassemblies: the torso, the head, the left arm, and the right arm. A computer-aided design (CAD) rendering of Woody is shown in Fig. 2.1. The torso is the primary housing for the electronic components, apart from the cameras and motors. The head

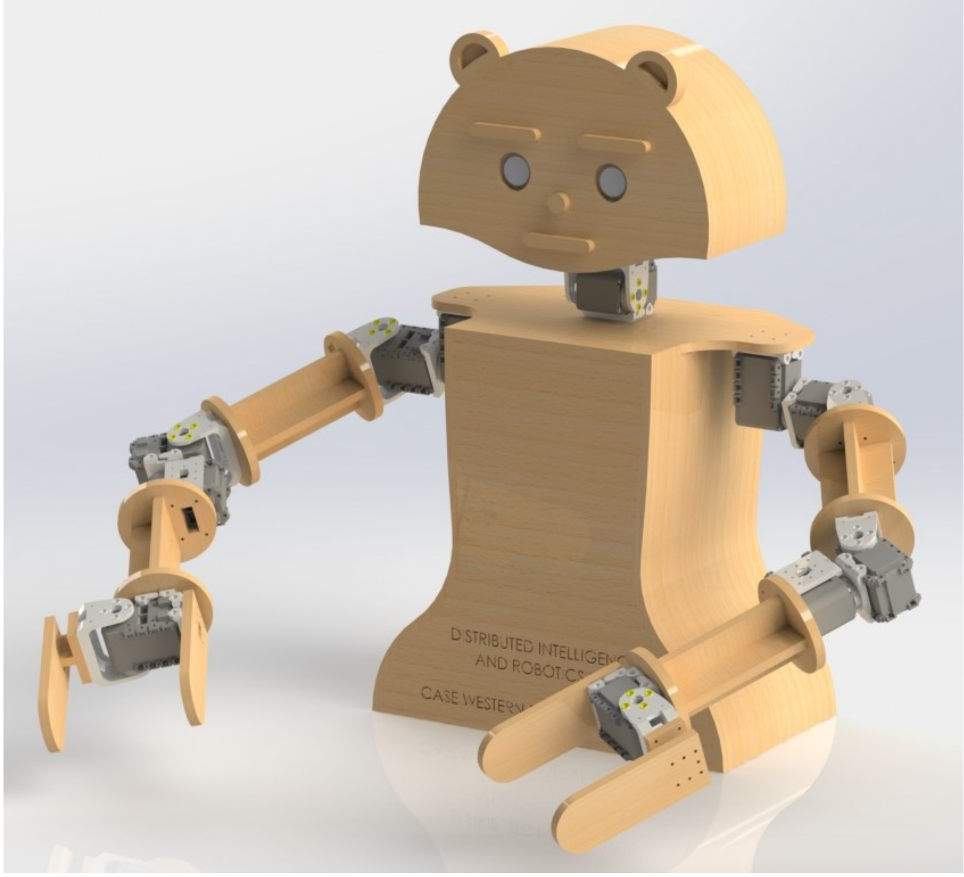


Figure 2.1: CAD Rendering of Woody

is mounted on top, while the arms are mounted to the sides. Most of the assembly is permanently secured using wood glue, though the front and back covers are attached with nuts and bolts for easy access to the internals. For a more interesting appearance, the side panels are cut like a living hinge and contoured around the body.

The head has two DoF in order to produce nodding and shaking motions. Simple facial expressions are generated as well through two small servos controlling the eyebrows. Cameras are installed as Woody's eyes, allowing for a variety of vision applications such as user face tracking, facial emotion recognition, and object detection. As with the torso, the top of the head features a contour design, and the face can be removed. The head features, including the ears, nose, and mouth, are also customizable to fit the user's preference.

Each arm has five DoF: two at the shoulder, two at the elbow, and one for the

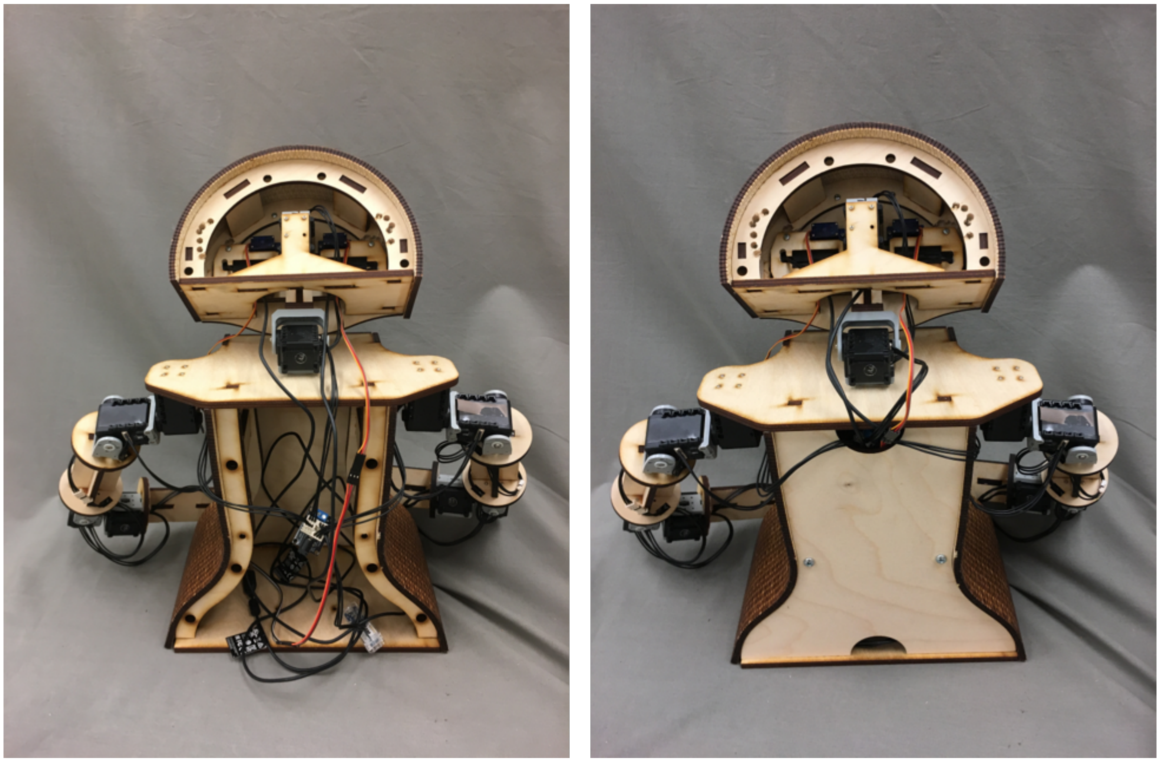


Figure 2.2: Back of Woody's torso, without and with rear cover

gripper. The arm linkages are designed to be as light and rigid as possible. The gripper has two "fingers," each with living hinges and rubber padding on the tip for compliant and secure grasping of objects.

2.1.1 Torso Design

The torso is designed as the base of Woody, both from a mechanical and electrical perspective. It houses most of the electronics, while also supporting the head and the arms, as shown in Fig. 2.2. This necessitates a design that is both robust yet mostly hollow. Additionally, an interesting aesthetic was desired, rather than something blocky – a challenge given the use of laser cut plywood given that it can only be cut in two dimensions and is only .25" thick.

The main structure of the torso houses electronics and keeps the robot upright. Among the wooden components that compose it are a rectangular bottom base, and a top piece representing the shoulder area. Both contain small screw holes for mounting of the motors and electronics. In between these two are long curved pillars. There are four pillars at each corner. They are curved because on the outside of the robot are two side covers. These covers are manufactured with a living hinge pattern, which enables them to be bent around the pillars. Additionally, there are crossbars going between the pillars to keep them upright. The crossbars also support a component that aligns itself with a USB speaker, holding it up against the front cover once the front cover is attached to the main structure.

The electrical components housed in the torso are the Raspberry Pi to control the robot, U2D2 to convert USB to Dynamixel cables, Power hub to power all the Dynamixel motors, and a USB speaker, for which positioning was key in order to produce the best sound while still not being exposed. In order to still have the ability to access to all these components after assembling the robot, the front cover and the rear cover are not glued to the main structure of the torso, and instead are mounted with nuts and bolts. This presented another design challenge, as it was desired for the nuts to not be visible. Therefore, the design uses three layers of wood to make this possible. The bottom layer is flat, the middle layer has a hexagonal hole for the nut to fit into, and the third layer has a smaller circular hole that the bolt can go through but the nut cannot. This is shown in Fig. 2.3 and is what enables disassembly and reassembly of the torso.

The front cover houses six nuts, and the bolts go through the pillars of the main structure for assembly. This means that the front does not have any visible nuts or bolts for a much cleaner appearance. Towards the top of the front cover, at Woody's chest area, is a pattern of cut lines. These are located where the speaker is mounted, reducing muffling of the sound while still covering up the speaker. The back cover, on the other hand, is just a piece of wood with two holes, and the nuts are inside of the main cover. While this does mean that two nuts are visible, they are unobtrusive. It

Figure 2.3: Nut assembly images showing closeup of nut in hexagonal hole, six nuts in the torso cover's second layer, and the torso cover after the third layer is attached.

would have been impossible to mount both the front and back covers from within, as one of the covers needs to be removable from the outside to access the inside in the first place.

The old Philos was first constructed by Kenneth Hornfeck (MS 2011) and Christian Puehn (MS 2015), and later revised by Tao Liu and Yuqi Jiang, who made a robot out of laser-cut acrylic. The first version of Woody's torso was designed and constructed by Alexander Brandt as an outer shell for the second Philos. Therefore, the first Woody built retains a laser-cut acrylic structure on the inside, which was initially meant for support but has ultimately become redundant material. The speaker used in the previous design was not good for the intended use, requiring GPIO input and producing poor quality sound. For the second version of Woody, the goal was to make a robust design that could stand on its own. This meant that adding the bottom base to the original design, which made everything more secure. For the third version, notches were added to all of the pieces so that they fastened together more precisely. A new speaker was also implemented, which required substantial redesigning of the robot's midsection. Looking for a simple solution, a small wishbone-like component was designed that held the speaker in place. A rear cover that was mounted on hinges was planned, but due to a number of factors such as buying the wrong component and not wanting a massive cover to swing out of the robot, the detachable cover that

Figure 2.4: CAD Rendering of Woody's head.

is in the third version of Woody was developed instead.

2.1.2 Head Design

Woody's head is designed to be able to express emotions, generate neck-like motions, and serve as a housing for the cameras, enabling vision-related activities (Fig. 2.4). The head is positioned on top and in the center of the torso. A motor controlling the nodding motion is fastened to the top section of the torso. This motor connects to a small wooden structure that acts as a neck, lifting the head above the torso and extending it slightly forward for improved maneuverability. This structure attaches to a second motor, which controls the shaking of the head. This motor connects to a wooden piece at the back of the head's main structure. Together, these two motors can enable Woody to look around, and perform more complicated social gestures with its head.

The design of the head itself, like the torso, uses several detachable wooden subassemblies. The main structure features a base, a piece that connects to the motors, and two arches which support a contoured top – an aesthetic addition. The face screws into the main structure, acting as a cover for the internals. The back side of the face, which is not visible, is where two Logitech C310 HD cameras and two Tower Pro SG90 motors for the eyebrows are attached. The eyebrow motors feature small holes, allowing them to simply be screwed into the face. The wooden eyebrows are attached to a hub that is compatible with these motors, allowing the eyebrows to be securely fastened but also removable. The cameras, on the other hand, do not have a simple way of being attached. Instead, they are secured between the back of the face and wooden pieces that screw into the face and prevent the cameras from moving. It is also worth noting that the cameras have built in microphones, making the head a crucial component for speech recognition and other recording-based functions

There are several customizable features of the head, enabling the user to truly make Woody their own. The ears slot into holes in the top of the head, while the nose and mouth slot into holes in the face. Several sets of parts have been developed, such as features for a dog face, a man with a mustache, a basic emotionless face, and a cat face. In theory, the eyebrows could also be made customizable, though this has not been done. A user with basic CAD and laser cutter skills could easily develop customizable features of their own if desired. The customizable components of the face have successfully demonstrated Woody's capability as an educational platform. During the summer of 2018, I had the opportunity to mentor two high schoolers, Emily Haag and Hao Qi, and incorporate them into the process of developing the second version of Woody. As part of teaching them Solidworks, I asked them to come up with ideas for face components, and model them with my assistance. Emily created the dog face, and Hao created the mustache face. Next, they were introduced to laser cutting, and they were able to cut out the parts that they had developed. Finally, they were able to glue together their creations, and attach them to Woody's face to see the final result.

Like the torso, subsequent design changes improvements were made after the initial prototype development. One change made was the introduction of the neck. In the previous design, the head was too close to the shoulder section of the torso, which dramatically reduced maneuverability. Additionally, it was too far back. Adding the neck extended the location of the head up and forward, enabling it to perform the gestures that it can now. Another notable change was in manufacturability. The first design introduced the hexagonal cuts to hold nuts for assembly. However, this design featured a separate small wooden piece for each nut. This resulted in a lot of assembly time, where each piece had to be precisely glued to the correct location. The design was modified so that each of these sections was connected into one part. This made assembly much easier for the second and third iterations of Woody, and the only downside was that this part took up more space on a sheet of plywood, leading to more waste.

2.1.3 Arm Design

The purpose of Woody's arms is to grasp and manipulate objects, and perform various gestures for social interaction (Fig. 2.5). The arms are mirror images of one another, and can be thought of as a sequence of motors along with linkages to create distance. The first motor is mounted beneath the overhang of the torso's shoulder area. This motor moves the arm vertically, parallel to the center plane of Woody. The second motor is directly connected to the first motor. This motor moves the arm toward and away from the middle of Woody's body. This motor attaches to a linkage. Linkages are a simple wooden construction of two bases separated by two skeletal pieces connected in a cross or T pattern for rigidity, as shown in Fig. 2.6.

Additionally, a new version of this linkage is in development, as shown in Fig. 2.7. The new design is meant to have identical upper arm and forearm linkages, hide wires

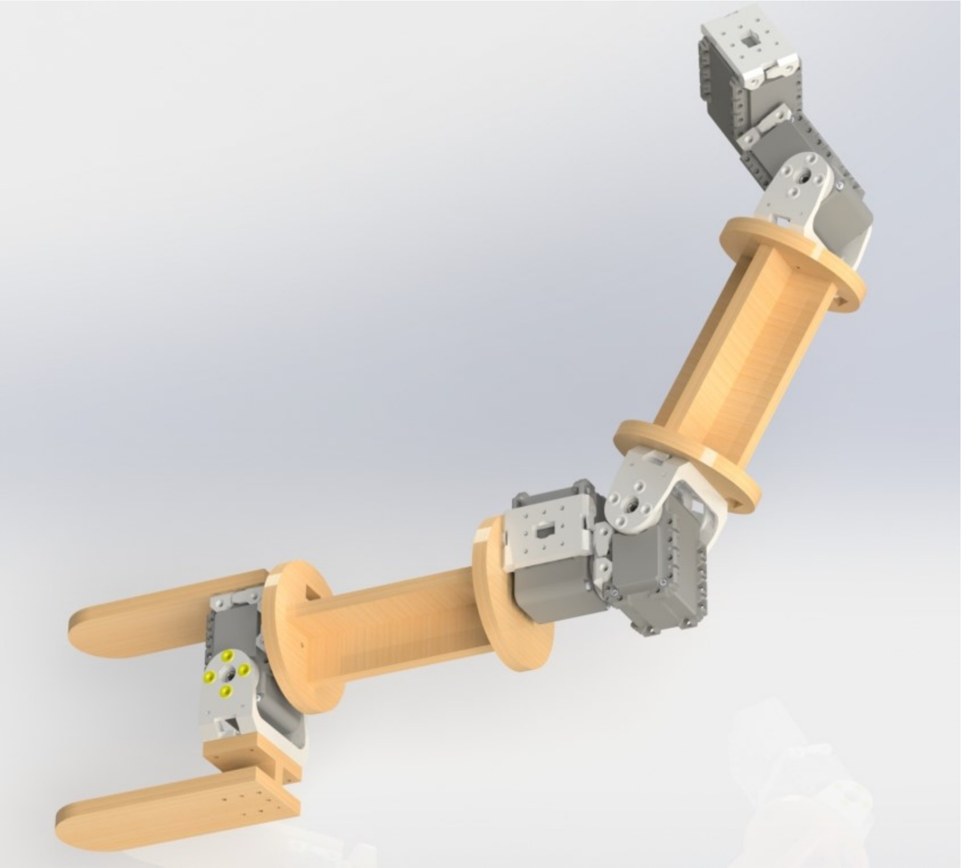


Figure 2.5: CAD Rendering of Woody's left arm.

from view, and maintain the same contoured aesthetic as the head and torso. In order to hide wires, this new design possesses a plywood cover with a living hinge, which is able to bend around the linkage and snap into place, while still being removable in case anything goes wrong with the wire or motor connection underneath. After the upper arm linkage is an elbow motor. The elbow and shoulder movements together enable most of the gestures Woody can perform. The fourth motor mounts directly to the third. Its motion is different from those discussed previously, as it does not work to bend the arm. Instead, it performs the functionality of twisting a wrist. To reduce the moment arm acting on Woody's shoulder, the wrist motion was moved to the elbow as the effect is identical.

After this is the forearm linkage, which connects to the fifth and final motor. This motor actuates the 1-DoF gripper (Fig. 2.8. There are two wooden fingers attached

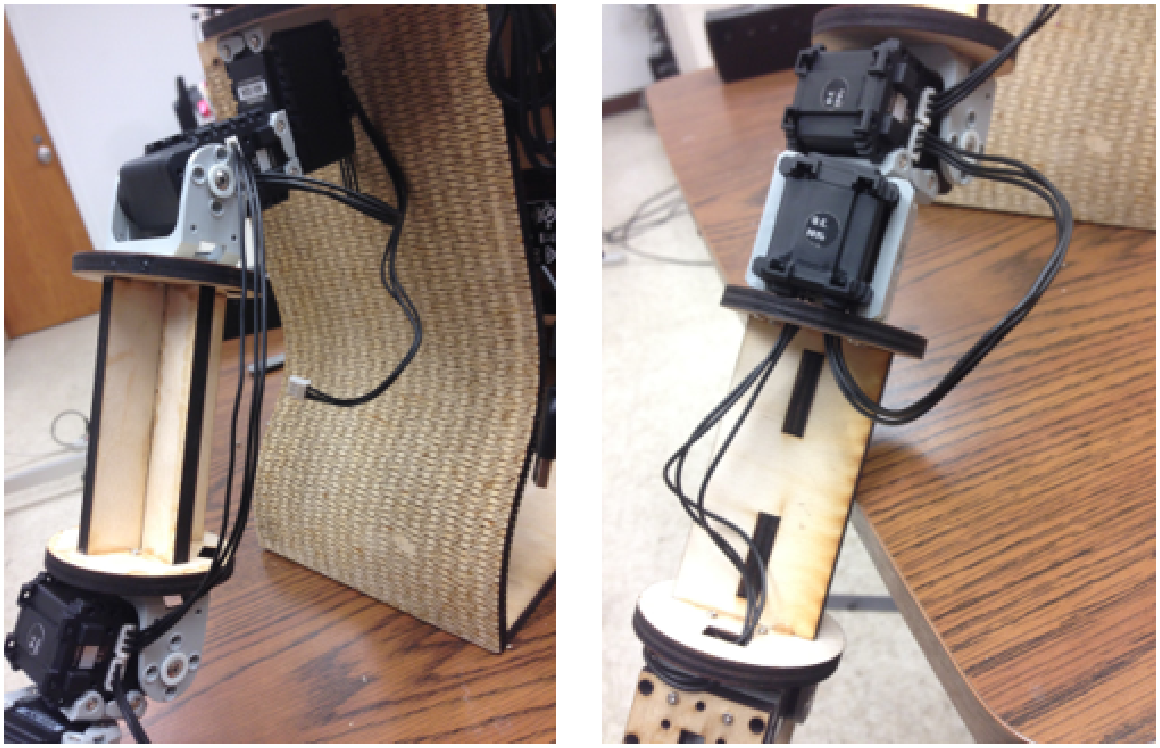


Figure 2.6: Arm linkages for the upper arm and forearm. Note the slight difference in design due to the difference in mounting the forearm motor for twist motions.

to this motor – one stationary, and the other actuated. The actuated finger has a small wooden structure glued to it to offset it from the motor in order for both fingers to meet at the same location when closing the gripper. A pattern of laser cuts was made along the fingers, enabling the gripper to have some compliance when grasping an object. Several versions of this were made to determine what type of cut spacing gave the best strength and malleability without adding stress concentrations that caused the gripper to break. Lastly, rubber padding was added for better grip and increased strength. The padding was cut by hand to form around the finger, etched on the bottom to avoid excessive shear, and glued onto the finger.

Rigidity vs. Compliance

An issue with earlier versions of Philos was the lack of realism in the motion. Specifically, with only two or three DoF, the motion was very robotic and jerky. In addition

Figure 2.7: New arm linkage design from two angles, shown with and without cover.

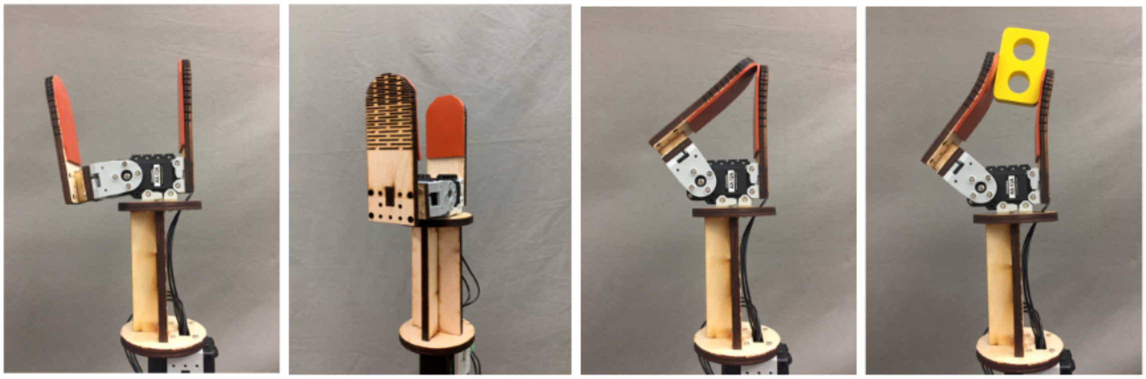


Figure 2.8: Gripper images taken from different views in open position, closed position, and bending around an object.

to adding more DoF to the arm, new linkages for the arm were developed with springs in order to test increased compliance. The first iteration of this design, shown in Fig. 2.9 was a predecessor to the arms that are currently on the robot. There were two

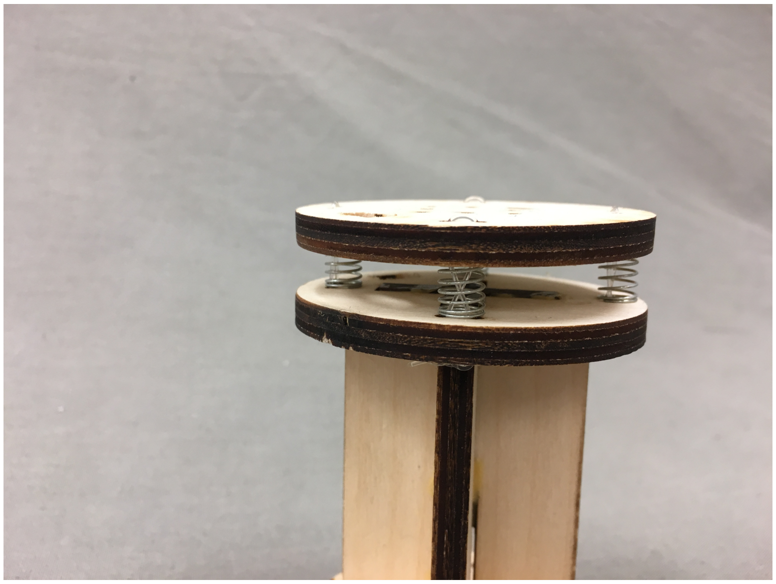


Figure 2.9: Closeup of old arm linkage showing springs for compliance.

skeleton pieces connected to two bases. Each base was circular for even spacing of springs, which is why they remained circular until the recent redesign. At each end of the arm were two more circular pieces. These pieces were not rigidly connected to the arm. Instead, the base pieces and free pieces each had small holes for strings to pass through, and etchings in the wood to prevent the springs from moving around. There were four spring/wire groups evenly spaced around each side. However, once this design was actually implemented into the robot, the problems became apparent. Rather than making the design more lifelike, it became extremely jerky. Subsequently, the design was modified to not include the springs any longer, and just have a rigid wooden assembly. However, it is worth noting that this rigid piece was longer than on previous versions of the robot, which in itself generated some damping to make the motion a bit smoother.

A radically different concept for the arm was also tested. This arm concept was a series of panels with a rigid bar going through them, with wires passing through to actuate movement. A prototype was constructed out of laser cut acrylic, as shown in Fig. 2.10. For the rigid bar in the prototype, several high strength springs found

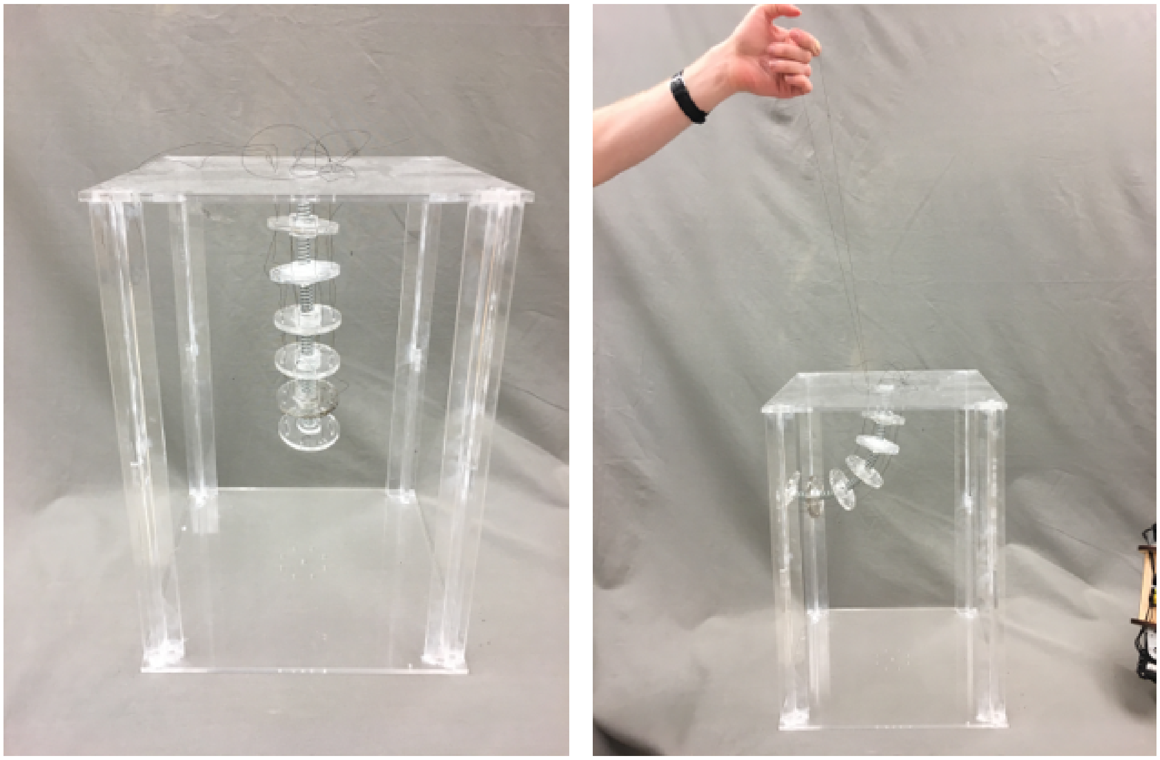


Figure 2.10: Prototype of compliant arm in stationary and bending positions.

in the lab were attached to the acrylic pieces using super glue. At one point hot glue was tested as a replacement for super glue, with the theory being that it could do a better job filling the space in the springs, but this design was weak and almost instantly fell apart. To make the design less wobbly, the spacing between the acrylic pieces was modified by using bolt cutters to cut the springs in half. Fishing line was threaded through the sections and connected into a loop using a uni-knot.

A testing platform was built allowing this arm to be suspended in the air, which featured a base, four legs, and a top section that the arm was connected to. Next, the design was tested for its capability to support and lift weights. Clamps were used to secure a 1/10 lb weight to the bottom of the arm, and then pulled up to various angles using a force gauge. This was done at the front and back of the design (while it was symmetrical in appearance, the prototype had a noticeable skew towards one direction). Results are shown in Table 2.1. Although the design was able to bend towards various angles while being weighed down, one problem immediately emerged. The weight would keep the arm relatively centered, so even though it could point in different directions it would be much harder to extend itself in the horizontal plane as an arm should. Ultimately, the complexity of this problem resulted in it being dropped from the project, and the focus of the research returned to the old rigid arm design.

Table 2.1: Compliant arm test results

	Unweighted: Front	Unweighted: Back	Weighted: Front	Weighted: Back
45 deg	2.6 N	4.4 N	4.0 N	5.2 N
90 deg	6.4 N	8.0 N	7.0 N	10.0 N
135 deg	9.2 N	10.0 N	10.0 N	14.0 N
180 deg	11.2 N	11.6 N	14.0 N	14.0 N

2.2 Electrical Design

Woody can be centrally controlled by either a laptop or a Raspberry Pi, depending on the target application. For purposes of testing, a laptop is often easier. There are two downsides to using a laptop over a Raspberry Pi, however. The first is that a laptop is not small enough to be hidden inside of the robot. This ties the robot down, and makes it less autonomous and portable. The second downside is the lack of GPIO ports. The majority of the electronics that Woody uses are powered and

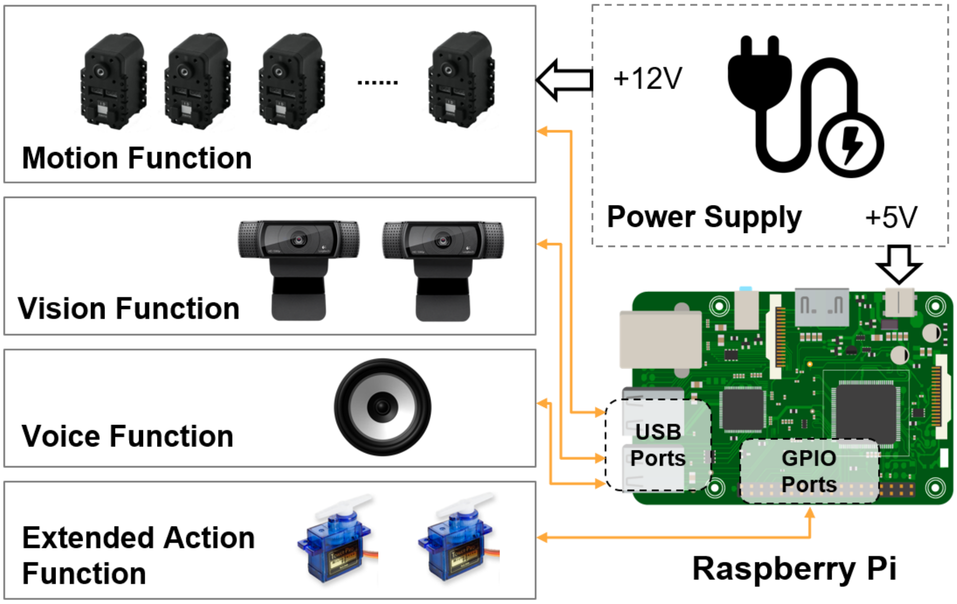


Figure 2.11: Circuit diagram with various function connection.

controlled by USB, but the notable exception is the Tower Pro SG90 servo motors. These motors can only be controlled by the Raspberry Pi's built-in GPIO ports, and are impossible to control with a traditional laptop.

A Raspberry Pi requires a monitor, mouse, and keyboard to be set up, making it less portable and reducing the benefits of its small size during the initial process. However, for practical applications, the Raspberry Pi is very effective. Once setup is complete and the monitor and keyboard are no longer required, it becomes much more portable and autonomous. The robot can simply be placed in front of a user with no monitor or laptop in sight, and either run autonomously or wirelessly through VNC viewer. The robot itself is designed to be semi-autonomous with basic embedded functions, such as data transmission and motor control. The portable control board (i.e., Raspberry Pi 3 model B) has a relatively high computational capability compared to other processing boards for embedded applications. It is sufficient to handle the low-level image processing on board. It also has a Wi-Fi module to communicate within a local area network (LAN). Fig. 2.11 shows all electronic components embedded in Woody.

The inputs of Woody are the two Logitech webcams installed at the location of the eyes. These webcams also feature built-in microphones, enabling visual and auditory input. Additionally, some applications of Woody, as well as programming the robot, require interfacing with a computer monitor via a keyboard and mouse.

Woody's outputs are the motors and speaker. For the arms and head, Dynamixel AX-12A motors are used. Dynamixel AX-12A motors possess several advantages making them desirable. First, they are easy to program. The Pypot library in Python is able to access and use many of the internal capabilities of the motors, such as setting and getting position, setting and getting velocity, as well as dealing with more complex variables (i.e., forces, temperatures). From a hardware perspective, the motors have several built-in points where nuts can be inserted, making them easy to install into a mechanical design. Two frames are available for sale, as shown in Fig. 2.12. The smaller frame is great for securing the motors to a location on the robot, as well as transmitting twist motions. The larger frame, meanwhile, is useful for transmitting bend motions. Additionally, the wiring is very easy. The cables used by the motors carry power, input data, and output data. Each motor possesses two ports. This allows the motors to be daisy-chained together, vastly reducing the wire clutter.

While most of the electronic components can be powered via USB from the laptop or Raspberry Pi, the Dynamixel motors require a separate power source of 12 V and 5 A. An AX/MX Power Hub is used to convert from the power cable to the cables that connect the motors. This hub features six ports for Dynamixel cables. Three connect to motors on the robot, specifically to the left shoulder, right shoulder, and the base of the neck. The fourth connects to the U2D2, which is a device that converts USB input from the computer to Dynamixel cable.

The Dynamixel motors offer accurate motor position control and feedback. They are used to generate the motion of the neck and two arms with grippers. The Dy-

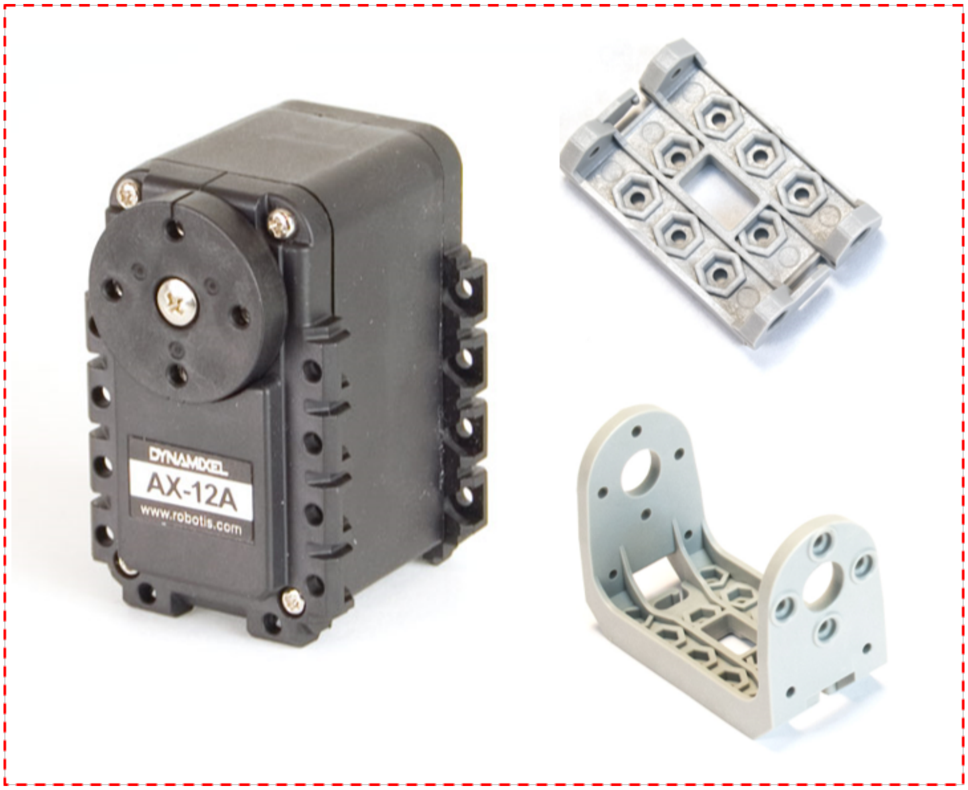


Figure 2.12: Dynamixel AX-12A motor and two frames for mounting components. Retrieved from [6, 7, 8].

namixel motor can provide maximum torque at 1.5 N·m. According to Woody's mechanical design, motors on its shoulder carry the largest torque at 0.64 N·m. In other words, Woody can still lift things up to 240 g at the maximum torque on its shoulder. The Tower Pro motors are used for moving the eyebrows to generate simple facial expressions. The robot can be battery powered or plugged into a continuous power source. The control board has extra serial ports for potential extension in the functionality.

The speaker is powered and controlled by USB and plugs into the control computer, and can be used for a variety of audio applications such as text-to-speech and playing music. The Tower Pro SG90 servo motors control the eyebrows, and are powered by the GPIO ports on the Raspberry Pi.

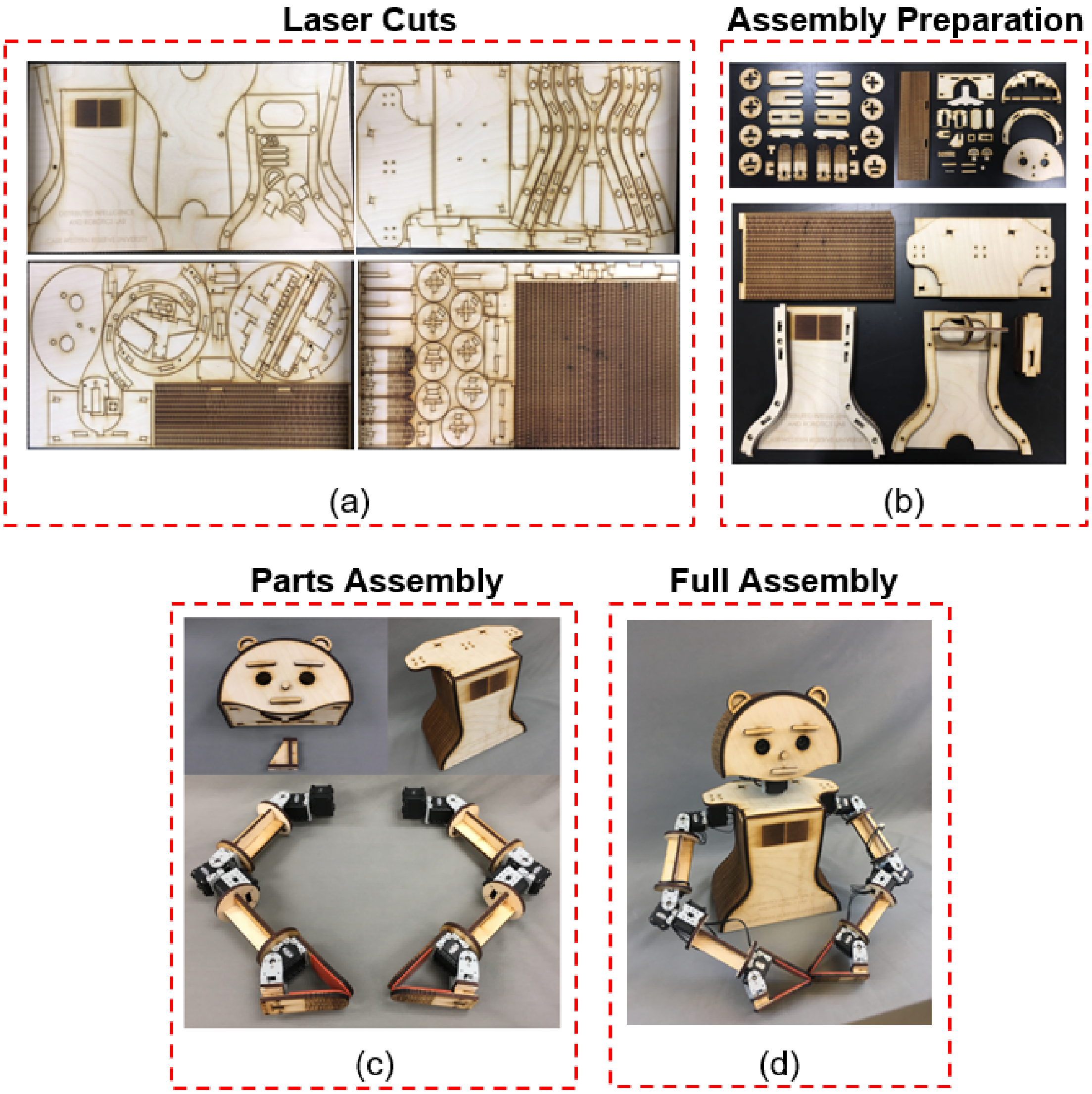


Figure 2.13: Basic assembly guide: start with wooden sheets, laser cut (a), remove pieces (b), glue subassemblies, fasten together (c), add electronics and fully assemble Woody (d).

2.3 Hardware Construction Procedure

The wooden components of the robot's body can be cut from four sheets of 12" × 24" × 1/4" plywood on a laser cutter, and assembled with glue and screws. Two primary design criteria were the cost and ease of fabrication, so that it can be used by DIY communities. To do so, requiring more than one large piece of equipment for prototyping is not desired. While 3D printing has become more inexpensive and accessible, building the entire robot structure via 3D printing can be quite costly and time consuming. 2D-based design has its own limitations in the types of the design when assembled in a 3D configuration. However, it is typically cheaper and faster. Therefore, plywood sheets and a laser cutter were selected for fabrication of Woody. Table 2.2 lists the components of the robot and associated costs.

Table 2.2: Materials and parts list for Woody fabrication

	Parts	#	Cost ($) / #	Tot. Cost ($)
Hardware	Plywood	4	6.50	23.00
	Rubber sheet	1	8.00	8.00
Electronics	Dynamixel AX-12A	12	224.50 / 6	449.00
	Tower Pro Servo	2	11.81 / 2	11.81
	Logitech Webcam	2	27.36	54.72
	USB Speaker	1	12.50	12.50
	Power Hub	1	7.95	7.95
	Dynamixel U2D2	1	49.90	49.90
	Power Cable	1	15.84	15.84
Connectors	Bioloid Frame F2	7	1.49	10.43
	Bioloid Frame F3	12	1.49	17.88
	M2x6 Bolt	400	3.90 / 400	3.90
	M2x10 Bolt	50	1.90 / 50	1.90
	M2x12 Bolt	50	1.90 / 50	1.90

The construction of a single robot may take about a day or two for two to three persons, as listed in Table 2.3. First, the designs of mechanical structures in DXF files are downloaded and imported to CorelDraw, where they are fit to the size of the wood sheet. Cutting of the CorelDraw files uses a laser cutter (i.e., a Universal ILS12.150D), as shown in Fig. 2.13a. Once the wooden pieces are cut, subassemblies are created by gluing the pieces following a manual created for the Woody construction [66]. Fig. 2.13b shows the parts sorted into their respective destinations, and Fig. 2.13c shows the assembled subassemblies. Some of the subassemblies require bolts and nuts for assembly. The grippers have rubber sheeting to be cut and attached using super glue.

Table 2.3: Summary of fabrication and assembly steps shown in Fig. 2.13

	Step A	Step B	Step C	Step D
Production /connection method	Laser cutting	Wood glue	Screw	Screw
Material and parts	Plywood	Plywood	Rubber, Electronics	Electronics
Number of Pieces	4	60	5	1
Production time (hours)	4	2 (glue), 24 (dry)	1	1

For the eyebrows, several wooden pieces are cut and attached on the back of the face piece for easy installation of the servos.

The main body frame is constructed by assembling 20 wooden pieces. Screwing in the front and rear covers completes the torso assembly. For the head, there are several wooden pieces mounted on the back side of the face piece for easy installation of the servos. Once done, the face is attached to the main head structure: a wooden skeleton structure which is covered on top by a curved wooden sheet. Servo motors for the eyebrows are screwed in, and cameras are positioned and fastened using the camera holders. Two Dynamixel motors separated by the neck extension connect the head to the torso, making sure their range of motion satisfies the head's workspace. 3-pin wires are daisy-chained from the power hub to the neck motors, while the cameras and eyebrow servos are directly wired to the USB ports and pins of the Raspberry Pi, respectively.

Woody's two arms are mirror images of each other, with the same material and manufacturing requirements. As with the head, each motor's workspace should be verified before attaching. Two motors are used to control Woody's shoulder movement. These are connected to an upper arm subassembly. Next are two motors at the elbow, for elbow joint movement and wrist rotation. The wrist rotator is connected to the forearm, which has the gripper motor at the end. The two grippers static and moving are mounted to opposite sides of the gripper motor. From the power hub, wires are daisy-chained between the motors along the arm. All these steps are repeated for the second arm, but mirrored. Finally, the arms and the head are fastened to the top of the torso and the rear cover is attached to complete the assembly (Fig. 2.13d).

2.4 Kinematics

This section describes calculation of the forward and inverse kinematics of Woody's left arm. As the right arm is a mirror image, kinematics for the right arm would in turn be a mirror image of these calculations.

2.4.1 Forward Kinematics

Each arm of Woody is a 4-DOF RRRR manipulator. Forward kinematics of the arm, from the shoulder to the end-effector, is derived using D-H parameterization. For simplification, c_i represents $\cos\theta_i$, $\cos(\theta_1 + \theta_2)$ by c_{12}. Two arms are identical but mirrored, and therefore, the left arm of Woody is used for both forward kinematics and inverse kinematics derivation. Table 2.4 lists the D-H parameters for the left arm. Note that the D-H parameters of the link 1 in table 2.4 only represent the rotation of the base frame because of the hardware installation. Reference frames attached to the arm and the parameters are also illustrated in Fig. 2.14 (a).

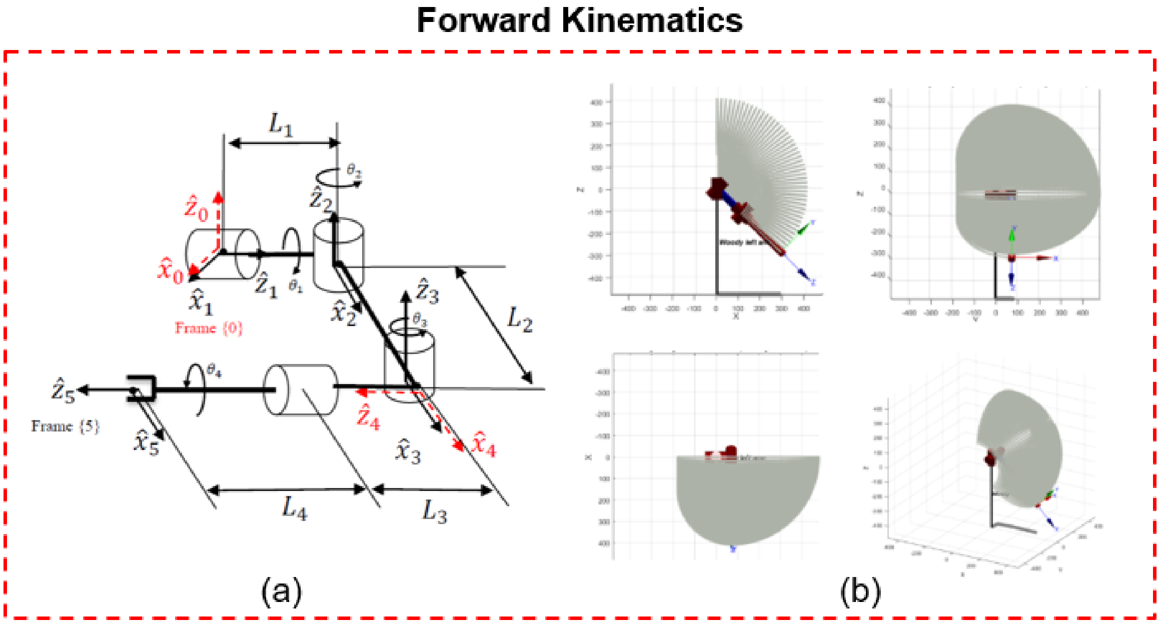


Figure 2.14: Forward Kinematics of Woody's Left Arm: (a) D-H coordinate frame assignment for the manipulators; (b) workspace shown by forward kinematics trajectory of end-effector

Table 2.4: D-H parameters for 4-link Woody left arm

link	θ_i	d_i	a_i	α_i
1	0	0	0	$-\pi/2$
2	θ_1	l_1	0	$\pi/2$
3	θ_2	0	l_2	0
4	θ_3	0	0	$\pi/2$
5	θ_4	$l_3 + l_4$	0	0

Based on this parameterization, the rigid-body transformation from the frame {0} to the frame {5} is calculated as:

$$T_5^0 = \begin{bmatrix} s_1 s_4 + c_4 c_1 c_{23} & c_4 s_1 - c_1 s_4 c_{23} & c_1 s_{23} & d_x \\ c_4 s_{23} & s_4 s_{23} & -c_{23} & d_y \\ c_1 s_4 - s_1 c_4 c_{23} & c_1 c_4 + s_1 s_4 c_{23} & -s_1 s_{23} & d_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2.1}$$

$$\begin{aligned} d_x &= c_1 s_{23}(l_3 + l_4) + l_2 c_1 c_2 \\ d_y &= l_1 - c_{23}(l_3 + l_4) + l_2 s_2 \\ d_z &= -s_1 s_{23}(l_3 + l_4) - l_2 c_2 s_1 \end{aligned} \tag{2.2}$$

After frame transformation, d_x, d_y, and d_z showed the end-effector pose in the 3D Cartesian space referring to the base frame. Note that d_x, d_y and d_z are only determined by joint angle θ_1, θ_2, and θ_3, therefore, the workspace of the robot arm can be illustrated by plotting the trajectory of the end-effector within a particular angle range of $joint_1$, $joint_2$, and $joint_3$. For Woody's left arm, the angle ranges for $joint_1$, $joint_2$, and $joint_3$ are -$\pi/2 \sim \pi/3$, 0$\sim \pi/2$, and 0$\sim \pi/2$ based on specific mechanical designing and assembling of the robot arm. Thus, the workspace for both Woody's left and right arm can be plotted in 3D simulation space. (Fig. 2.14 (b))

2.4.2 Inverse Kinematics

Inverse kinematics of the arm is solved by geometric approaches. As shown in Fig. 2.15 (a), given the two frames $\{0\}$ and $\{5\}$, the values of θ_1, θ_2, and θ_3 can be solved geometrically as illustrated in Fig. 2.15 (b), (c). Given end-effector pose, $[d_x, d_y, d_z]^T$,

$$\theta_1 = \tan^{-1}(\frac{-d_z}{d_x}) \tag{2.3}$$

Then, consider seeing the robot arm along the direction of the arrow in Fig. 2.15 (b), the left arm appears to be a typical two-link planar manipulator. Geometrically, define $d'_x = \frac{d_x}{cos\theta_1}$ and $d'_y = d_y - L_1$, θ_3 is given by

$$\theta_3 = cos^{-1}(\frac{-{d'_x}^2 - {d'_y}^2 + {L_2}^2 + (L_3 + L_4)^2}{2L_2(L_3 + L_4)}) - \frac{\pi}{2} \tag{2.4}$$

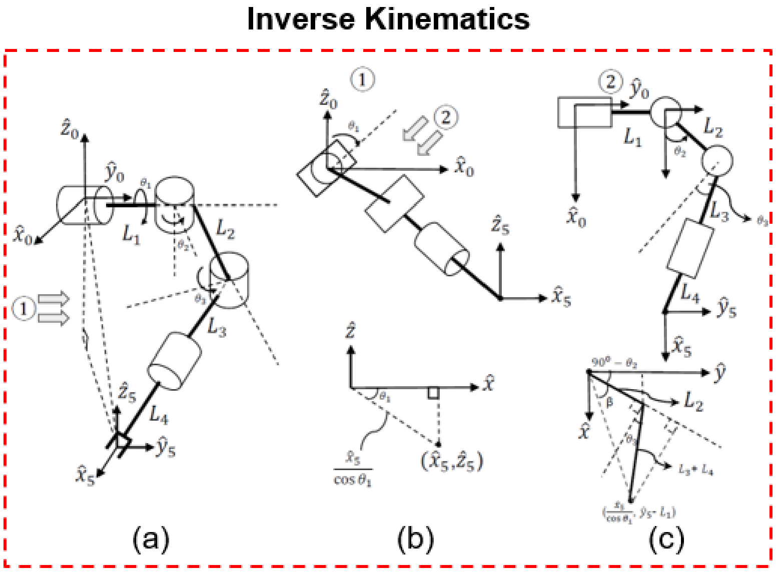


Figure 2.15: Inverse Kinematics of Woody's Left Arm: (a) geometric model (pointing downwards) with base frame {0} and end-effector frame {5}; (b) geometric model seen from the side view; (c) geometric model seen from the top view.

For deriving θ_2, β is calculated from θ_3:

$$\beta = tan^{-1}(\frac{(L_3 + L_4)sin(\frac{\pi}{2} - \theta_3)}{(L_3 + L_4)sin(\frac{\pi}{2} - \theta_3) + L_2}) \tag{2.5}$$

Therefore, θ_2 is given by

$$\theta_2 = \begin{cases} tan^{-1}(\frac{d'_y}{d'_x}) + \beta & d_y \geq 0 \\ \beta - tan^{-1}(\frac{d'_y}{d'_x}) & d_y < 0 \end{cases} \tag{2.6}$$

Note that Fig. 2.15 (a) only includes the situation which d_y is positive, when d_y is a negative value, d'_y should be changed as $d'_y = -d_y + L_1$, the joint angle θ_2 should also be updated according to eq. (2.6).

In the previous section, joint range for each joint angle is fixed, all different poses of the robot arm have been considered. The above solutions are the general form. For Woody's right arm, the solution is essentially a mirror of the left.

Chapter 3

Software Development

This chapter discusses the development of software that can be run by Woody. Section 3.1 describes interactive software, listing expressive functions, perceptive functions, and how they are combined to create human-robot interactions. Section 3.2 describes the graphical user interface, which is designed to be user-friendly and to run many of the interaction functions.

3.1 Interactive Features

This section presents Woody's interactive features enabled through expressive and perceptive functions. Woody's embedded expressive functions include simple facial expressions, various built-in gestures, and speech/sound/music generation; perceptive functions include face detection, facial emotion recognition, and speech recognition. As Woody is developed as an open-source based platform, it is configured to utilize existing open-source algorithms. Our own algorithms, such as facial emotion recognition, will be also shared publicly.

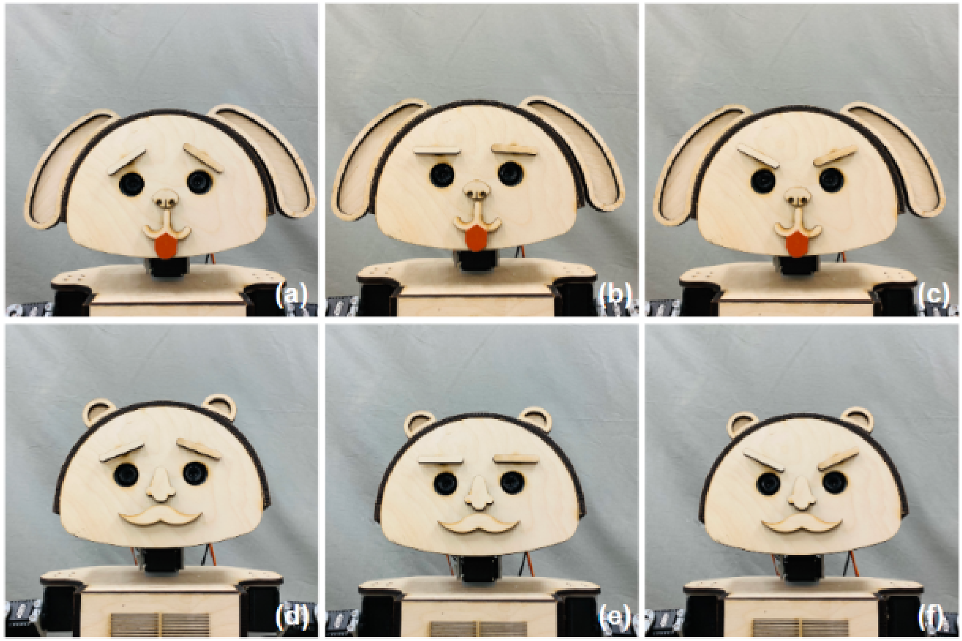


Figure 3.1: Woody's head features with varied eyebrow movements. (a)∼(c) show "dog" head features with eyebrow movements from sadness to anger; (d)∼(f) show "man with mustache" head features with corresponding eyebrow movements.

3.1.1 Expressive Functions

Human facial expressions are highly complicated, involving 30 action units of describing facial muscle movements [67]. Therefore, a robot's facial expressions are often simplified to just use eyebrows, mouth, or both [68]. Some robots show higher flexibility in exhibiting facial expressions by using a screen displaying an animated face. For a robot a with mechanically designed face, however, generating facial expressions is still challenging. Moving eyebrows can be a simple yet effective method for creating simple facial expressions without adding highly complex mechanisms into the hardware design.

Two small servos mounted inside of Woody's head above two cameras actuate the eyebrows. They can generate discrete angles, representing different facial emotions, or generate continuous movements. Combined with varied head features such as ears, nose, and mouth, Woody can demonstrate both positive emotions (e.g., happiness) and negative emotions (e.g., anger or sadness). Fig. 3.1 shows some of the face examples assembled with two different sets of customizable components and three eyebrow angles. Each column represents positive, neutral, and negative facial expressions generated by Woody. The head fixtures, including the ears, nose, and mouth can be further customized based on individual preferences and target users.

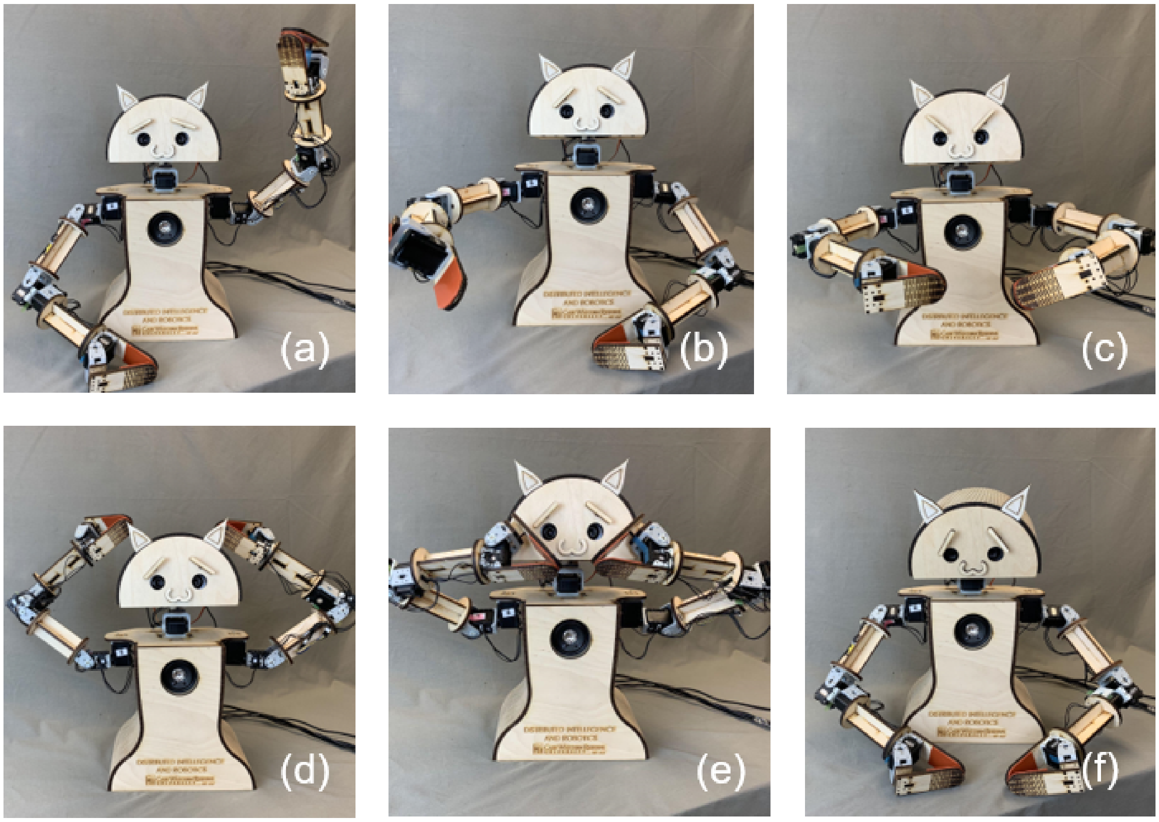


Figure 3.2: Woody's recognizable gestural cues: (a) shows "wave" gesture, (b) shows "shake hand" gesture, (c) shows "angry" gesture, (d) shows "afraid" gesture, (e) shows "surprised" gesture, and (f) shows "sad" gesture.

Woody also features several built-in gestures which can be combined with facial expressions for affective communication with users. Fig. 3.2 demonstrates some examples of recognizable gestures that Woody can perform in its interaction with users. Fig. 3.2a is Woody waving to the user by performing a basic greeting gesture, Fig. 3.2b shows "hand shaking" gesture. Fig. 3.2c∼f illustrates the gesture of Woody being "angry", "afraid", "surprised" and "sad" as the responses to user emotional states input. In addition to these built-in gestures, users can record new gestures and motions.

Woody can be programmed to generate speech or other types of sound/music. It can also play a user-recorded voice or sound sources. Additionally, Google Text-to-Speech is a useful Python library with a very lifelike voice that can be used for custom sayings [69]. Sound files can be easily converted to MP3 and played using Python's OS library with mpg321.

3.1.2 Perceptive Functions

Woody's perceptive functions may vary significantly depending on its user and application. The embedded functions include face detection, facial emotion recognition (FER), and speech recognition. These functions may be simultaneously or selectively used. Additional functions can also be added as the user customizes the system for their own use. The built-in FER function is based on our own algorithm for reliable and efficient performance based on geometric facial features combined with support vector machines (SVMs) [70, 71]. Integrated with other vision algorithms, Woody is able to achieve face tracking and user emotion detection aiming to improve quality and quantity of HRI.

Speech recognition is realized by Python's SpeechRecognition library [72]. This system allows the user to create his or her own library, which is compatible with several open-source speech recognizers, such as Google's Cloud Speech-to-Text When a user speaks a word, the software will produce a list of possible matches sorted by confidence. If one of these words is the same as an answer option, the response is recorded and the next question is asked.

3.1.3 Interacting with Woody

To truly interact with Woody, it is beneficial to have both expressive and perceptive functions active at the same time. This enables Woody to directly respond to the behavior of a user. Two examples of interaction functions are gesture recording and face tracking.

Gesture Recording

Gesture recording was developed as a way for users to manually create their own gestures for Woody even if they do not have substantial programming experience themselves. This ties directly into the goal of making Woody an educational platform, as it is a fun way to introduce the student to controlling the robot, before later introducing them to more complex software. Briefly, gesture recording involves manually moving Woody's motors to desired positions, and the software automatically saves the poses and later replays a series of poses as a gesture. Gesture recording was also created to simplify the process of developing gestures for live demonstrations. Before gesture recording, the process of finding a gesture required moving all the motors to a desired location, running a program that listed where they were, and recording the relevant numbers. This needed to be done for every pose in the gesture, and then all numbers had to be manually entered into a separate function. The time it would take to reach a target destination needed to be estimated, generally just using a pause of 1 or 2 seconds between poses.

Gesture recording simplified this process significantly. For the gesture recording function, the robot first moves all the motors to a predetermined start pose, which is the head facing forward and the arms on the ground in front. Next, torque is disabled for all motors. This enables the user to manually reposition the arms or the head without resistance. In the first version of gesture recording, the pose was recorded every three seconds until there was a keyboard interrupt. When the gesture is saved, only the motors that have moved more than 5 degrees are adjusted. This is done because the user moving the robot around will inherently be somewhat imprecise, and this reduces unwanted movements. Additionally, this helps to conserve power, as the Dynamixel motors sometimes fail when too many of them are being operated at the same time. If no motor has moved more than 10 degrees, the program continues until it detects significant change, and then stores that information.

In order to play back the gestures created through recording, it would have been inconvenient to define a new function for every single gesture. Instead, a universal gesture player was created. This player takes as its input a list of motor ID vectors, a list of position vectors, and a vector of times. These three lists will all be the same length, as they each refer to a specific pose in the gesture. The function iterates through these lists, each time calling the same subfunction. The subfunction takes as input the vector of motor IDs, the vector of positions, and the time. Speed in Pypot is in degrees per second, so determining each motor's speed is done by taking the absolute value of the difference between the current position and target position, and dividing by the time. This is done for each motor. The result is that the motion is very smooth and synchronized compared to if speed were manually set in an individual function, as each motor is moving at the exact speed it needs to for all the motors to finish their motion at the same time.

Over time, several additions were made to improve the process even more. Rather than saving a gesture every three seconds, the program now waits until the user begins moving the robot. This is done by simply checking if any motor is more than 5 degrees from where it was before. At this point a timer begins, and the program starts checking to see if motion has stopped. This is detected by checking that all motors have not moved substantially since the last iteration. At this point, assuming the motion of at least one motor has exceeded 10 degrees, the pose is saved and the process repeats. The timer stops as well, which is how the duration is set during playback, enabling the user to set the desired speed by moving the motors over more or less time.

Lastly, a feature was added where the data generated through the gesture recording process was converted to a Python dictionary and saved to a text file. By having the user input a name for each gesture, it was possible to recall a gesture by having the user type in the name of the gesture they want to play. From there, the program would read each line of the text file, convert the text back into a dictionary, and check if the name in the dictionary matched the name the user requested. Once a match was found, the universal gesture player took the motor IDs, poses, and times that were all stored in the dictionary as inputs, allowing it to play the desired gesture. Storing the gestures to a text file has benefits for modifying the gestures as well, as one does not have to go through the process of rerecording every time a change is desired. Instead, values can be slightly modified in the text file allowing of precise tuning. Undesired poses can be easily deleted. Also, copying and pasting elements of the dictionary can be done if, for example, a gesture loops between several poses and the user wishes to run multiple loops.

Face Tracking

Another way interaction has been achieved is via face tracking. Since the head has embedded cameras, and is actuated by a 2-DoF neck, this design enables the robot to maintain eye contact with the user by determining the location of the user's face and having the motors move accordingly to line itself up in both the vertical and horizontal planes. Face tracking uses a haarcascade to train Woody on how to recognize a human face. OpenCV generates a rectangle that bounds the face. From there, it is possible to determine the location of a user's face when they stand in front of Woody by calculating the average location. Woody will then attempt to adjust the position of its two neck motors such that the face ends up in the middle of the display. This required a significant degree of parameter tuning, as the motor speed, target motor position, and time between recalibrating the position of the face all have an impact on the smoothness of the motion. Ultimately, the new position would be set to 0.04 times the distance from the center, the speed would be set to the distance from the center divided by 4, and the pause before recalibrating the position of the face was set to 0.01 seconds. For quick calculation without sacrificing video quality, a resolution of 320 x 240 was selected. This was particularly significant when adding emotion detection, as that decreased the processing speed significantly. If Woody does not detect a face for over half a second, it enters scanning mode. In this mode, Woody's head continuously moves from side to side until a face is detected. This is accomplished by continuously checking whether the motor has arrived at its destination, and whether it sees a face. Arriving at its destination causes it to switch direction and repeat the process. Seeing a face immediately ends scanning mode and sets the positions and speeds based on the previously listed parameters.

Other Interactions

By using the threading module in Python, it is possible to use face tracking along with other forms of interaction. Real-time emotion detection based on facial expressions can be performed while following the user's face as it moves. After filtering, Woody can then perform a gesture that matches the user's emotional state (i.e., dancing for happiness, weeping for sadness, and more). Dialogue is another feature that can be implemented. By combining speech recognition with text-to-speech, Woody can carry out simulated conversations with users. For example, Woody can administer a psychological assessment or ask the user permission to play music. These simulated conversations are key to HRI because they are a way to establish communication from the user to the robot and from the robot to the user. Additionally, simulating a conversation while running face tracking simultaneously makes the conversation feel even more real, bringing it closer to a conversation between humans that look each other in the eye when speaking.

3.2 Graphical User Interface

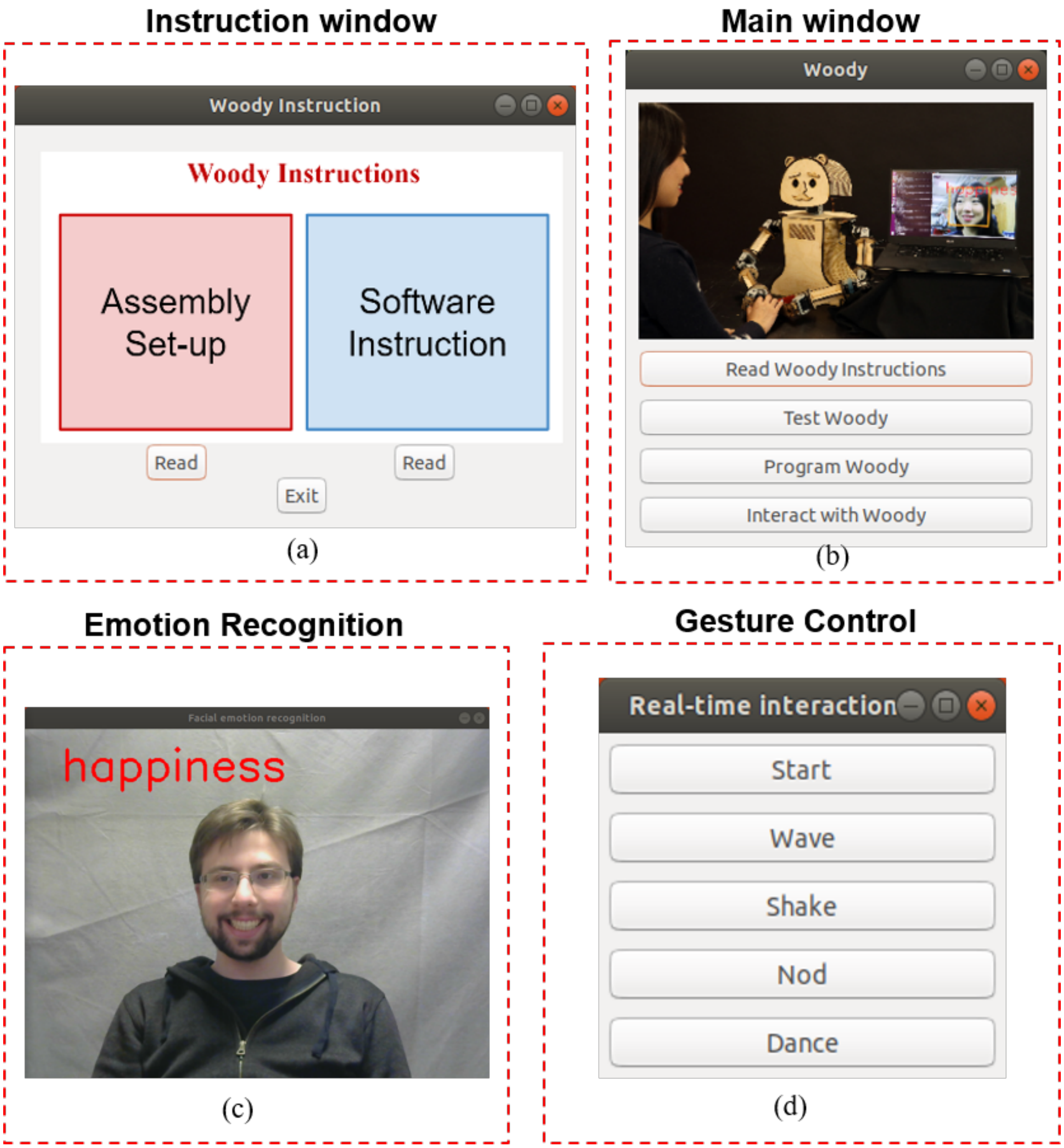
To offer improved ease of use, a GUI was developed using Python. The GUI's main menu, shown in Fig. 3.3b, has four buttons which contain the basic and most important functions of this system. The buttons are designed using the "box container" feature from the GTK+ library and are vertically packed together.

The first button on the main GUI is "Read Woody Instructions" with the Woody construction manual which contains mechanical assembly procedure and electronic set-up process, shown in Fig. 3.3a. The instructions are written in detail with pictures, informing users of all aspects of the construction and set-up processes. The instruction consists of 9 sections, including all needed pieces, assembly of each part of Woody and descriptions of electronic components in detail. Each section of the instructions begins with a list of the required components and a corresponding picture, followed by step-by-step instructions also with pictures. After construction, there are instructions on electrical setup detailing the wiring of all the components, and software setup detailing all the libraries that must be installed and links to helpful documentation. The second button "Test Your Woody" is designed for testing if the motor functions of the robot are correctly set-up and whether camera connections are normal. A dialogue appears if something is not right for initialization.

The third button allows the users to "Program Woody." When this button is clicked, another window will open with two buttons, one for "Enter the Programming Window" and "Record New Gestures." The first option allows the users to program the robot themselves by accessing the actual programming layer of Woody in Python. Not all users, however, are familiar with programming languages. The second option allows the users to program new gestures or arm/neck movements by physically moving the body parts and directly recording the positions from the servo motor encoders. When the "Record Gesture" button is clicked, the robot returns to its start pose, and torque is disabled. The user manually moves the motors to a desired location, and then stops so the program can detect that movement has completed. Next, the program saves the motor IDs that were moved, their new position, and the time taken before stopping. This is repeated indefinitely until the user stops recording. The user can name the gesture, and each pose is saved to a text file. The next time the list of gestures is opened in the GUI, this newly recorded gesture will appear at the bottom of the button list as shown in Fig. 3.3d. The gesture can be performed by clicking the button, and can also be programmed in Python by calling its name from the text file.

The fourth button is “Interact with Woody”. When a user clicks the button, two separate windows pop up next to each other. Fig. 3.3c presents the result of real-time facial emotion recognition (FER), and Fig. 3.3d presents a series of buttons named for user generated gestures. The vision processing and motor controlling functions can run at the same time by using the threading package in Python.

Therefore, in HRI scenarios, Woody can integrate FER with making corresponding social gestural cues to match its emotional state to that of the user. Additionally, the easy-to-use GUI is helpful in many occasions. For example, this can benefit parents monitoring their kids’ emotional states, as they can make the robot perform gestures to improve human-robot social interactions. For another example, administrators of clinical psychological trials can use this GUI and system to make participants more engaged during tests.



Instruction window

Main window

Emotion Recognition

Gesture Control

(a)

(b)

(c)

(d)

Figure 3.3: Woody GUI: (a) Instruction window for Woody set-up; (b) GUI main menu; (c) real-time emotion detection; (d) real-time interaction function interface.

Chapter 4

Potential Applications

This chapter discusses further potential applications of Woody. Section 4.1 describes how Woody can be used for personality assessment. There is an overview of the literature in personality, specifically how it relates to robotics, followed by a description of Woody's ability to administer a personality test using speech recognition, and lastly future goals involving Woody adjusting its behavior to best suit the user's personality. Section 4.2 discusses events where Woody was demonstrated to the public. A variety of age groups have responded to Woody, and a number of different demos have been created, which show the versatility of the robot.

4.1 Use of Woody for Personality Assessment

4.1.1 Background and Motivation

An area of interest in HRI is customizing the personality of a robot. This was an initial goal of the Woody project. There is still much work to be done on this in the future, thus this section presents a literature review to be used as a starting point for future work in this area.

The most widely used personality metric in psychology today is the Big Five [73].

The Big Five refers to five personality parameters that have been scientifically shown to be the most common ways that people categorize each other. These parameters are extraversion (E), agreeableness (A), conscientiousness (C), neuroticism (N), and openness to experience (O). There are several versions of the Big Five test, such as the BFI-44 with 44 questions [74], the BFI-10 which uses 10 questions from the BFI-44 for a shortened test [75], and the NEO PI-R, which is a much more detailed version [76]. There are other metrics as well, such as the Myers-Briggs Type Indicator (MBTI). The MBTI is an older test that scores people on four axes. These are extraversion/introversion (E/I), sensing/intuition (S/N), thinking/feeling (T/F), and judging/perceiving (J/P). Unlike the Big Five which simply assigns a percentage for each variable, the MBTI sorts people into types, such as INTP and ESFJ. There is some correlation between the parameters of the two tests [77]. Both tests share an extraversion parameter. Agreeableness correlates with feeling. Openness correlates with intuition, as well as feeling and perceiving to a lesser degree. Conscientiousness correlates with judging, as well as sensation and thinking to a lesser degree. Neuroticism has a low correlation with introversion. These correlations could be used to apply research that uses the MBTI, translating it into Big Five so that Woody's parameters remain consistent.

A review article discussed the role of personality in a variety of HRI studies [78]. The Big Five was found to be the dominant personality metric, appearing in 31% of studies. Interestingly, the extraversion/introversion dimension on its own was used in 26% of studies. A process for developing a robot's personality has been developed [79]. In this process, a personality profile was developed from user feedback of which traits they would like to see in a robot. Actors would perform these behaviors, which were then translated to robot expressions, animated for visualization, and evaluated. Gestures were inspired by film animation, of which the most cited are the 12 principles of Disney Animation. Another study also generated robot gestures based on personality [80]. Specifically, the extraversion/introversion axis of the MBTI was used to adjust the size and velocity (higher for extraversion) of gestures, as well as the thinking/feeling axis to adjust the frequency (higher for feeling).

Big Five personality parameters can be used as a basis for natural language generation (NLG) [81, 82]. Their software is called PERSONAGE, for PERSONAlity GEnerator. Elements of language are affected by the personality traits, particularly the extraversion dimension. Applying the software used in this research could be used to program how a robot behaves, and would be a useful part of a multidimensional robot personality. A separate study developed a corpus of over 88,000 utterances relating to discussions about restaurants. PERSONAGE was used to have personalities discuss the subjects in different ways. Personality types were associated with different aggregation and pragmatic operations [83]. Another paper provides a list of other NLG systems used in HRI, including CRAG [84]. However, CRAG differs from PERSONAGE in that it uses the PEN model of personality (psychoticism, extraversion, neuroticism).

Personality has been applied to robot facial expressions [85]. The article discusses the relationship between emotion (neutral, happiness, surprise, fear, sadness, disgust, anger), mood (PAD: pleasure, arousability, dominance), and personality (Big Five). Probabilities for pleasure and arousal are calculated from the O, E, A, and N Big Five traits. Basic emotions are mapped onto axes of pleasure and arousal. The emotion that is generated causes the robot to change its facial expression, demonstrated both by a digital display and a physical robotic head. Another study used Big Five and NEO PI-R to map to emotion and facial expression, again via the PAD model for mood [76]. The typical equations are used for mapping personality to mood were originally developed by Mehrabian [86] and are commonly used. NEO PI-R is a more detailed version of Big Five that gives six facets to each of the five personality traits, and equations were developed for each emotion. For enhanced realism, the researchers incorporated an additional “resistant” parameter.

The effects of personality similarity on interaction have been studied [87]. Extraverts and introverts do better interacting with the same type, but disagreeables do not benefit from interactions with other disagreeables. While this paper focuses on human-to-human interaction, the same principles could be applied to HRI. Additionally, this paper provides an overview of social behaviors demonstrated by each of the personality metrics. Extraversion predicts amount of talking, personal self-disclosure, and smoothness. Agreeableness predicts warmth and positive affect (smiling, laughing, eye contract). Conscientiousness predicts attentiveness and responsiveness (eye contact, verbal acknowledgments, nonverbal acknowledgments). Neuroticism predicts forced, awkward, and strained interactions. Openness predicts more conversation sequences and topics introduced, and an inclination towards intellectual topics.

4.1.2 Technical Approach

Woody can get to know its user by administering the Big Five personality test to them. This is done via text-to-speech and speech recognition. Woody begins by presenting the user with instructions on how to answer the questions. A simple version has the user respond the questions with a number between 1 and 5, representing their agreement or disagreement with the prompt. A more complicated version listens for more natural word patterns, and converts to a numerical value. In this version, there is a dictionary of words representing “agree” (i.e. “yes”, “correct”, “support”), “disagree” (i.e. differ, oppose), “strongly” (i.e. “greatly”, “very”), and “not” (i.e. “don’t”). From there, combinations of words generate the desired response, where “agree” and “disagree” return 4 or 2, respectively; “strongly” modifies them to a 5 or a 1, and “not” inverts the response (i.e. 2 becomes 4, 1 becomes 5, and vice versa).

Upon explaining the instructions, Woody will ask the first question, and listen for a response. If no clear response is heard, Woody will say “I didn’t catch that. What did you say?" and listen again. If a response is recognized, it will be compared to the dictionary of acceptable responses. If there is a match, the response is saved and the next question is asked. Otherwise, Woody says "Invalid response" and listens again. Woody will ask the user either 10 or 44 questions depending on the version of the test being used. At the end, the scores are calculated and told to the user.

4.1.3 Potential Extension

A long-term goal of the Woody project is to be able to match Woody's personality to the user to facilitate positive interactions. Ultimately the project moved in a more educational direction, but there was progress that can be built on in the future. Extraversion/introversion and thinking/feeling are two personality traits that manifest themselves in gestures [80]. However, due to its prevalence in the literature, most of the personality-related work in this thesis deals with the Big Five. Therefore, Big Five's extraversion and agreeableness were used as substitutes for MBTI's E/I and T/F. Extraversion has an impact on the size and velocity of gestures, and agreeableness impacts the frequency. These parameters are fairly easy to add to Woody's gesture functions, and a program was created to enable this, specifically by having Woody wave to the user in a way that varies size, velocity, and frequency. The program begins by asking the user to input an extraversion value between 1 and 5, which the user does by typing into the terminal. This could theoretically be done using voice control as well. Next, this is repeated for agreeableness. From there, the program calls a "wave" function, which takes the extraversion and agreeableness parameters as inputs. The motor speed is changed based on the agreeableness function, and so is the time that the robot pauses between poses. This results in an overall faster or slower gesture. For size, it is first noteworthy that waving cycles between two positions. The starting position for the wave does not change regardless of the extraversion parameter. The destination position is modified to a value plus the extraversion parameter times a constant. The greater the extraversion parameter, the greater the distance traveled between poses, and therefore the larger the gesture. There are two ways to implement variable frequency. The first is by having a static value for a pause between gestures, which is a function of the extraversion variable. The second is by repeatedly iterating a random number, and if this number is in a specific range the gesture is performed. By expanding the range, there will be a greater frequency. This method can be thought of as the more realistic version, as there is randomness to it rather than just having the same length of pause every time. This program was developed prior to the creation of the universal gesture function created in conjunction with gesture recording. Therefore, these parameters were not implemented in that function, but doing so would be straightforward in future research. Changing the speed would be even easier with universal gesture. Each individual speed would not need to have a parameter assigned. Instead, the duration variable could be modified by an agreeableness parameter value, and all the speeds would change accordingly. Manipulating gesture size would be slightly less straightforward, but could be done by treating every pose as a distance from a base pose, and multiplying or dividing those distances by an extraversion parameter. Manipulating frequency would not change, as frequency is simply based on the gaps between gestures rather than the specifics of how a gesture function operates.

Another potential extension is emotion matching. This type of extension would build on both personality matching and facial emotion recognition, to try to have Woody behave in a way that would be conducive to positive interaction with the user. Woody has been shown to display emotions through use of gestures with its arms and head as well as moving its eyebrows, but the lack of a mouth reduces some of its expressive ability. Implementing personality matching into a robot with a mechanical mouth or a digital screen display would allow for greater emotional range, but adding these features was deemed out of scope due to cost and the fact that the

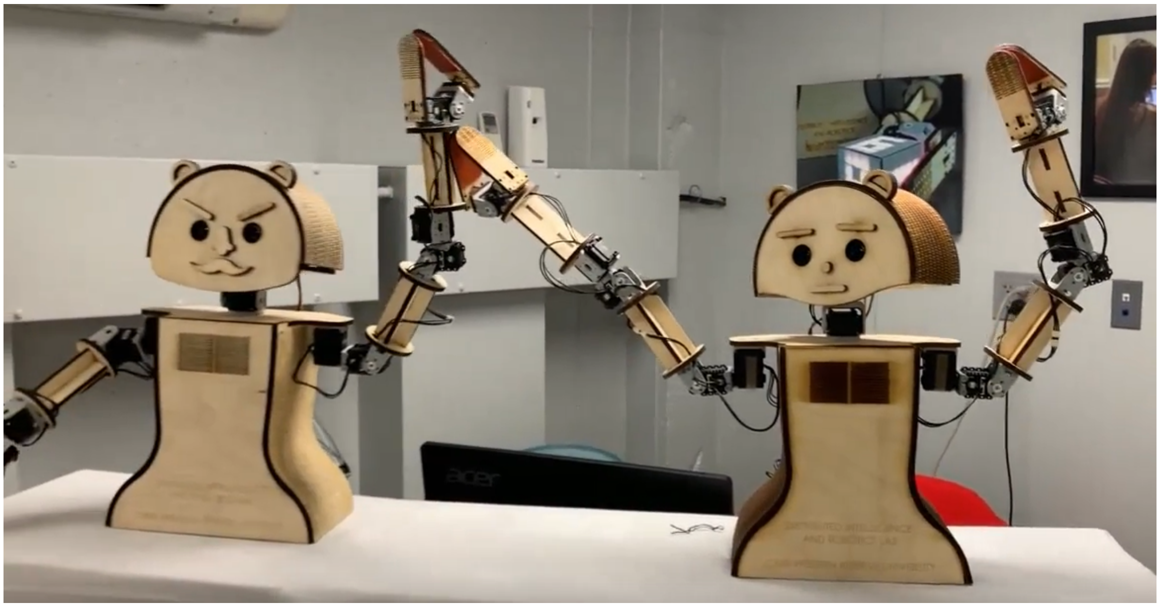


Figure 4.1: Two Woodys performing gestures at the Living Lab.

existing design was satisfactory for most purposes. Incorporating natural language generation is also an interesting possibility, but this too was deemed to be out of the scope of the project due to unforeseen difficulties with implementing PERSONAGE. Implementing personality-based NLG would have been an entire project on its own, so it was not pursued further.

4.2 Public Social Engagements

As part of the dirLAB's social outreach, Woody has been demonstrated to the public in a variety of settings, for a variety of age groups and audiences. First, at the Living Lab, Woody was demonstrated to seniors at an assisted living community. Second, at CWRU's Research ShowCASE, Woody was demonstrated to university students, as well as faculty, staff, and families. Third, Woody was demonstrated to middle school students who visited the lab as part of a field trip.

4.2.1 Living Lab

Woody has been successfully demonstrated at the Living Lab in Ohio Living's Breckenridge Village, an assisted living community (Fig. 4.1). The senior residents responded positively to Woody's cute appearance and ability to perform a variety of social gestures. Two Woody robots were active for this demo, and cycled through a series of gestures, including waving, hugging, and dancing. Each gesture also had a corresponding pre-recorded voice message, such as saying "hello" while waving. While dancing, Woody would also play music. At this earlier point in Woody's development, text-to-speech had not yet been implemented, so the conversations were simulated to demonstrate what they could look like in the future. To do this, a lab member would ask a prepared question knowing what Woody's next gesture and dialogue line would be, and Woody would appear to respond.

4.2.2 Research ShowCASE

Woody has also been successfully demonstrated at CWRU's annual Research ShowCASE (Fig. 4.2). Two demos were developed, and each was performed on one of the Woody robots (the third was disabled, but in view of the public so they could still see the extent of Woody's customizability). In the first demo, Woody used speech recognition to talk to a user. Woody would ask if the user wanted to hear Woody's favorite song (retrieved from [88]), and play it if the user said yes. If not, Woody would simply say "Nice to meet you" and wait for the next user. In the second demo, Woody performed face tracking and emotion detection. If no user was detected, Woody moved his head side to side until finding someone. Then the user could see what their emotion was on a laptop next to Woody. For added interactivity, Woody waved to the users every few seconds. Both demos were pleasing to the spectators, some of whom interacted with Woody for several minutes. The demo that seemed to please audiences the most was the emotion recognition. People from a variety of

Figure 4.2: Woody at Research ShowCASE displaying face tracking and emotion detection.

age groups and backgrounds attempted to modify their facial expression to appear as having a particular emotion. Many children had to be pulled away from the demo by their parents, as they found the face tracking and emotion detection fun.

4.2.3 Summer Lab Visitors

More recently, students from a local camp visited the lab on a field trip. Several of the lab's projects were available for demonstration, including two active Woodys. One was used to demonstrate basic emotional gestures. The other demonstrated grasping capability. First, it picked up and moved a small object between predetermined locations on the table. Next, it tore its own ear off (made possible by the fact that the ears are secured by friction and gravity for purposes of customizability). This shocked and entertained the students. A noteworthy aspect of these two demos is that they were created by two new students, Jesse Feng and Khai Ngo, respectively.

Neither student had any experience with Woody until several weeks prior, and yet were able to develop their own demos. This shows the intuitiveness of Woody, and its capability as an educational platform.

Chapter 5

Discussion and Future Work

This chapter is an overview of the research, and a description of what could potentially come next. Section 5.1 is the conclusion, describing Woody's success as a low-cost social robot. Section 5.2 is an overview of potential applications. Section 5.3 presents ideas for future work, such as a more detailed study and changes to the hardware.

5.1 Conclusion

As stated in the introduction, the goals for Woody were:

- **Affordability.** The cost for constructing the robot should be affordable for potential DIY applications.
- **Manufacturability.** The robot can be built by two to three students with low-level engineering skills, requiring minimum access to manufacturing equipment.
- **Applicability.** The fabricated robot must have sufficient degrees of freedom and interactive features for a broad range of educational and research applications.

This section describes how each of these goals was met.

5.1.1 Affordability

Woody was developed as a relatively low-cost DIY platform that can be reproduced for educational and research projects. Table 1.1 compares several commercially available DIY robots and existing open-source platforms with Woody in terms of their mechanical structures, software applications and cost. The prices of commercial DIY robots vary significantly depending on the number of DoF, types of actuators, and embedded capabilities. Bioloid and DARwIn have the same number of DoF, while DARwIn uses higher performance servo motors. LEGO Mindstorms contains three motors that can be used for customizable designs, though its applications for human-robot social interaction may be limited. Among the three open-source platforms, Woody stands out for its upper-body humanoid configuration featuring two arms with manipulation capabilities. While being more expensive than the other two open-source robots, Woody can be reproduced at a relatively low cost and its interactive features are highly customizable with potential room for further improvements.

5.1.2 Manufacturability

Woody has been shown to be easy to manufacture, as three different versions have all been constructed with increasing efficiency. Different people have been involved in the construction as well, including high schoolers, which demonstrates the potential for Woody as an educational tool for manufacturing. The design was straightforward to build, and users unfamiliar with the robot were able to do it with minimal supervision. In an educational setting, it would be possible for two students to build a Woody with an instructor occasionally stepping in. The only piece of advanced machinery required is a laser cutter, which can be found at Sears think[box] and other design centers assuming the user does not own one. There are four main sections of the robot: the head, torso, and both arms. The majority of the components are made of plywood, which is simple to cut on a laser cutter, and then attached together with wood glue. From there, it is just a matter of using nuts and bolts to fasten all the wooden subassemblies and motors together. Finally, the wires and electronics are added, and the robot is ready for use. In terms of construction time, users can expect about 3 hours for laser cutting, 2 hours to glue parts together, 24 hours to let glue dry, and less than an hour each on attaching the rubber and electronics.

5.1.3 Applicability

Woody possesses 14 total degrees of freedom, which enable it to perform a variety of social and practical tasks. Each arm possesses 2-DoF at the shoulder, 2 at the elbow, and 1 for the gripper. The head has 2-DoF in the neck, as well as two eyebrows that can rotate up and down for purposes of displaying emotions. The Dynamixel AX-12A motors are sufficient for the practical applications of Woody, aside from the eyebrows where smaller servos are used. The wooden structure of the arms is lightweight and compact yet rigid enough to support itself without interfering with any motions. For potential use of Woody for learning robotic manipulation, forward and inverse kinematics of the arm have been calculated and provided in section 2.4. These degrees of freedom are complex enough for versatility in the type of movements that can be formed, but simple enough that users can understand what is happening, and learn about robotic manipulation that way.

Woody has demonstrated its ability to perform a variety of interactive functions, with still the potential for more. These functions are enabled by its inputs via cameras, microphones, and internal motor sensors, as well as outputs via motors and speakers. Woody can express emotions via its degrees of freedom. Gestures can be used to display activities such as weeping or dancing to communicate sadness or happiness respectively, and the eyebrows can move to reflect Woody's emotional state. These gestures can be modified to reflect variances in perceived personality. Woody can also grasp and manipulate objects. The cameras have been used for two primary purposes: face tracking and emotion detection. These can benefit interaction by maintaining a connection with the user through something resembling eye contact, and by gathering real-time data on the user's emotional state, which can be used for data collection or to modify the robot's behavior. Through speech-to-text and text-to-speech, a variety of conversational features have been created. These include simple demos such as asking permission to play music and then playing it, and more complex activities such as running a personality assessment by asking questions from the BFI10 and storing the responses to provide the user with their personality metrics. A GUI has been developed to facilitate many of these interactions, and provide a way for users to easily figure out how Woody operates. Lastly, as part of Woody's role as an educational device, students could learn about robotics not only through existing interaction behaviors, but by developing their own.

5.2 Potential Applications

Woody's GUI has great educational potential. Students can learn a variety of things about manufacturing, robotics, and programming. This begins with students constructing their own Woody using the provided instructions. From there, they can begin to learn programming, starting simple and getting more complex over time. At the beginning, they would simply use the provided gesture recording function. This would enable them to generate their own social gestures, as well as training Woody to perform physical tasks such as object manipulation. Over time, students could go deeper into the code and start writing their own programs in Python.

The GUI also has applications in facilitating social interactions. Woody can be remotely controlled to interact with a user such as a hospital patient. Woody could administer personality tests, ask users questions, or play games with them. Real-time emotion detection along with face tracking can be used for immediate feedback on the user's mental state and response to Woody.

5.3 Future Work

The next step on this project is to organize a human subject study. In it, users would be invited to manufacture Woody themselves using provided instructions, program Woody themselves, and interact with it. Real-time emotion detection will be used as well as a survey to gauge their feedback. Learning what users like and don't like about their experience building, programming, and interacting with Woody will enable further development of the project based on received feedback.

In terms of hardware, there are several areas for improvement. There have been issues with the motors leading to jerky motion at times. Possible modifications include smoother control with gradual acceleration, regular lubrication of motor gears, and using new motors. Bringing the cost down even further would also be beneficial. As the bulk of the cost comes from the motors, using a cheaper motor is a goal. However, we must account for the fact that the rest of the hardware will then need to change around the new motors, and wiring could become more difficult due to the lack of daisy-chaining capability that a replacement motor is likely to have. Additionally, the number of motors could be reduced depending on the required DoF for a certain task. Certain tasks may only require the arms or the head, but not both. Even arm-related tasks may not require every joint to be active. One arm could be removed entirely, and Woody dressed like a pirate to explain the missing limb. Another potential hardware change is the integration of the mouth into Woody's facial expressions which could be done mechanically or with a screen display. This would be especially beneficial for the purpose of generating positive emotions, as tilted eyebrows generally indicate either sadness or anger depending on the direction of tilt.

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