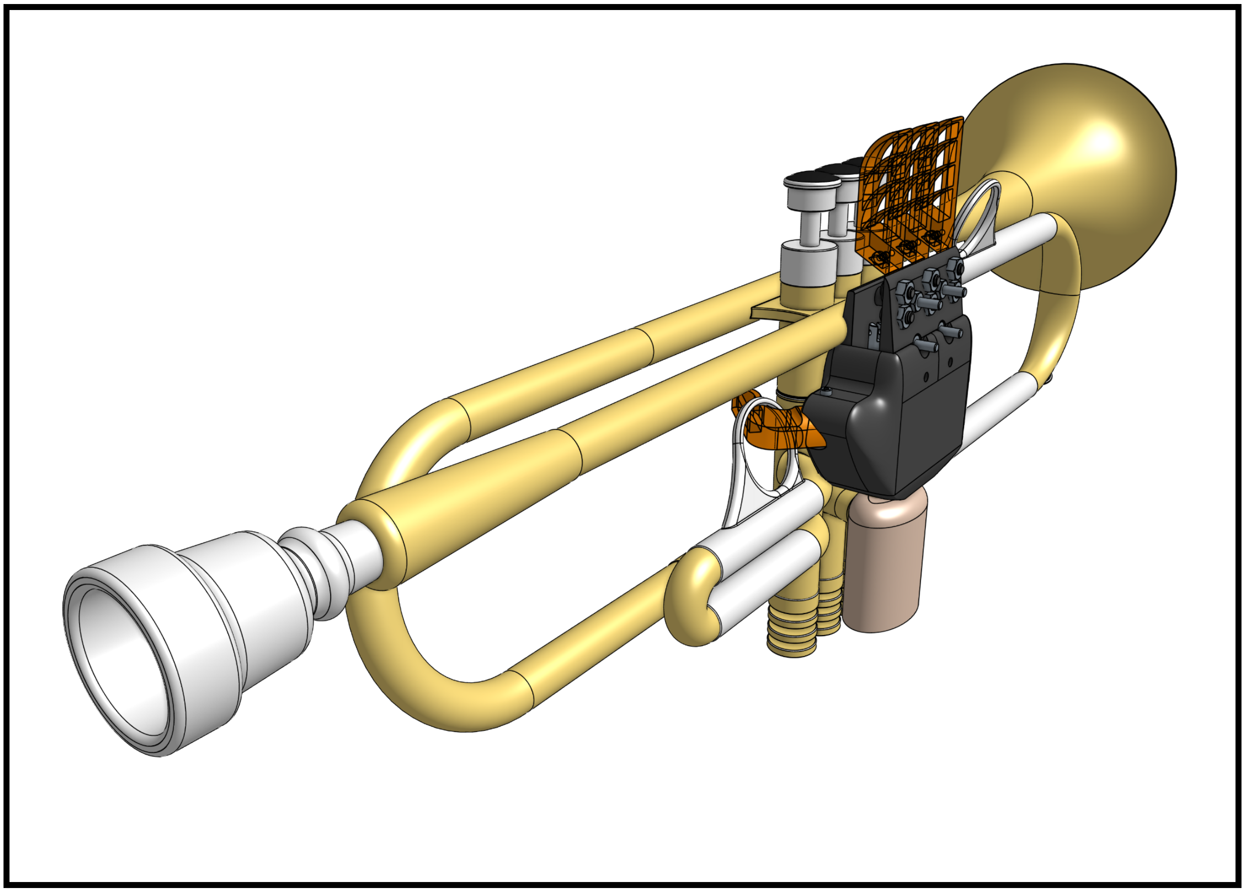

BEN 363: Prosthetics Closing Report

By Anna Johnson, Emily Hanscom, Zoe Vittum

Executive Summary

As technology advances, accessibility solutions are becoming increasingly vital. Allowing people who have lost a limb to regain mobility, independence, as well as improve mental health through exploration of hobbies, is necessary. Thus, a 3D printed prosthetic that is comfortable, cost-efficient, and capable of performing the motions necessary to play a trumpet has been prototyped. To help aid in the mental health of amputees, the device should also allow for the user to participate in a musical hobby, like playing the trumpet.

A right-handed, four-digit device (three fingers to press valves, one to support the instrument) has been modeled in Onshape, a computer-aided design program, manufactured on a Prusa MK3S+ printer, and tested on its corresponding capabilities as a trumpet playing instrument. Solenoids and a user interface to read musical instrument digital interface (MIDI) files allow the device to automatically press down different valves in tempo, "reading" the music. The hand was 3D printed in thermoplastic polyurethane (TPU) and polylactic acid (PLA) filaments to minimize weight and cost. The modular attachment point, including an in-vivo rod attachment, enables comfortability and accessibility for amputees, while giving them a functioning hand for musical adaptation.

The rapid prototype was successfully printed using TPU and PLA on a 3D printer. Solenoids and relays were implemented into the device to allow movement in the individual digits, creating an overall circuit powered by a 12V DC power source. Testing of the solenoid linkage showed that a maximum of 1 A at 6 V could safely be applied to the device to avoid overload. The spacing between the prosthetic fingers, as well as their design, aligned with the trumpet valves and prevented damage to the horn. The anchor of the prosthetic thumb successfully held the trumpet and helped support the weight of the prosthetic.

To control the prosthetic a MIDI file converter was integrated within a graphical user interface (GIU) to allow for a user-friendly, accessible platform for personalization and individual song downloading. This connects to a RaspberryPi, allowing for remote access through the cloud for additional access. The MIDI converter and GUI proved to be a useful addition to the device. The potential for a right-handed, four-digit, trumpet-playing prosthetic was proven to be physically possible, with a few modifications to the current prototype.

To further improve the current prototype, more powerful solenoids capable of producing 12N of force as well as a larger battery (12V, outputting 12 Amps) should be implemented in order to ensure efficient and rapid finger movement of the device. New, more powerful solenoid actuators will be explored. The finger geometry will also be modified to generate a greater lever arm and downward component of the applied force to compress the valve. Future experiments should explore the accuracy and speed of the device itself, enabling a larger range of musical talent.

Introduction

Accessibility and assistance with mental health struggles are the forerunning focuses in prosthetics-related medical studies. The loss of an upper extremity can lead to psychological disorders, with 84% of amputees experiencing these struggles (Sahu, 2016). Patients who know how to play an instrument and believe they can no longer do so, experience a severe lack of morality, leading to anxiety and depression (Burt, 2022). Enabling the ability to regain or develop a new music-related hobby acts as a form of music therapy has been shown to be very effective in combating mental health problems (Pressman, 2009 & Aalbers, 2017).

Today, there are a limited number of musical adaptation solutions for amputees. Remodeled instruments, supports, stands, and hang-up lines do exist, but prove to be difficult and inaccessible to some audiences (Burt, 2022). Only a few types of instruments have been explored in literature, brass instruments being excluded (Charles, 1988; Burt, 2022). To aid in the mental wellbeing of brass-playing amputees, a prosthetic solution for playing the trumpet has been prototyped as a right-handed, 4 digit prosthetic, as seen in Figure 1. The prosthetic design was named “Hand-et” as a play on the hand’s ability to play the trumpet.

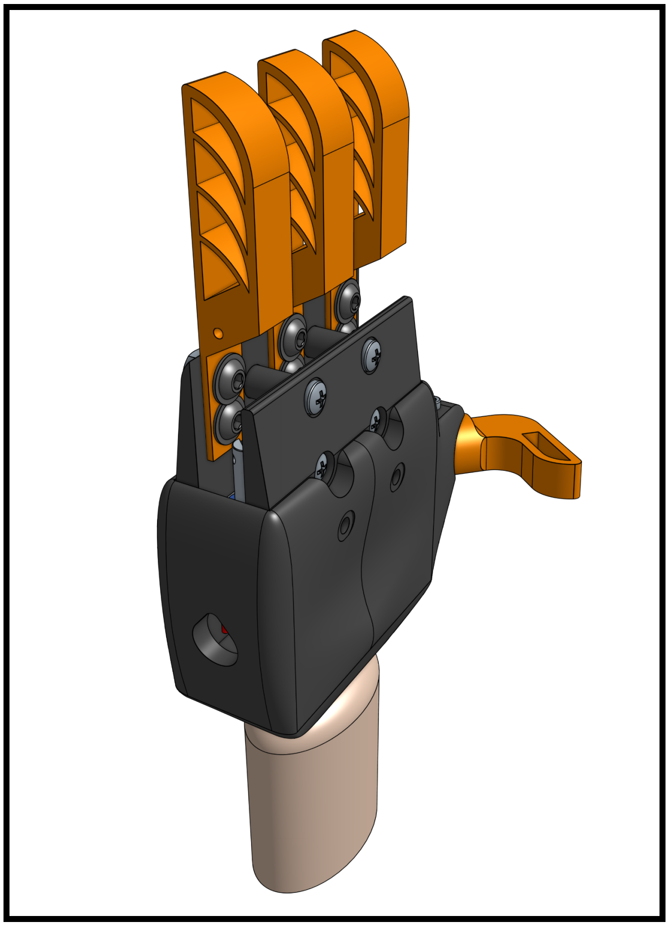

Figure 1: Lowered isometric view of “Hand-et” prosthetic hand attached to modeled partial forearm as represented by the pale pink fileted cylinder.

In the 3D printed prototype, polylactic acid (PLA) and thermoplastic polyurethane (TPU) were used to help lower the cost and mass of the device. Material selection is important in prosthetics, as even if the device is of equal mass to the preexisting limb, it is perceived as heavier (Buckingham, 2018). Therefore, PLA and TPU constructed all major components of the prosthetic, as both are low-weight materials that have strong stress and strength characteristics even under load (Liacouras, 2017; Afrose, 2016). The majority of the device’s mass was placed towards the attachment point, lessening the effective force on the user (Afrose, 2016).

To replicate how a trumpet is played by a right-handed individual, three actuated digits on the prosthetic move the trumpet's three valves.. The flat shape of the fingers allows for correct positioning and physical playing of the trumpet. A soft-robotics-inspired "spring joint" was also designed to replace the metacarpophalangeal joint to be used as the bend point for the digit actuation. By eliminating the distal and proximal interphalangeal joints from the finger, it forces the valve to be pushed directly downward, preventing potential harm (through rubbing or friction) to the trumpet and reducing potential breakpoints in the prosthetic (Burt, 2022).

The pinky, as seen on the hand, has not been produced on the prosthetic, as it is a hindrance to efficiently playing the trumpet, often getting in the ways of the musician (Burt, 2022). Devices with three fingers have already been developed and have proven to function equivalently to their full-digital counterparts (Castellini, 2008; Leal-Naranjo, 2013). By only having three moving digits, the cost and weight of the device are diminished, and the functionality for the specific task of trumpet playing is increased. The last digit, the thumb, helps support the weight of the trumpet. The thumb was designed to push into the trumpet, allowing for more stabilization in the prosthetic and correct alignment for comfortability while playing. It also acts as an anchor point, increasing the ease of use by automatically allowing for correct finger alignment.

Finally, a graphical user interface (GUI) was created, increasing the accessibility to different users. Here, a musical instrument digital interface (MIDI) file reader is implemented to allow any song to be inputted by the user and correspondingly played by the prosthetic. The GUI connects to the device through the cloud and actuates the solenoid-driven fingers, creating enough force to depress the valves on the instrument without external input from the user.

Design, Details, and Analysis:

A four-digit prosthetic device capable of autonomously playing the trumpet was rapidly prototyped. As one of the biggest motivating factors for developing a trumpet playing prosthetic was mental health, developing a prosthetic that the end-user will be confident wearing and using was of the highest importance. When developing the mechanical design, the engineering team took four major design constraints into consideration: modularity, robustness, weight, and realism. These design constraints were chosen to ensure the development of the most functional, efficient, and appealing prosthetic to inspire confidence in the user.

The prosthetic hand controls the trumpet valves with 3 individually actuated digits. To articulate each digit, a DC-powered solenoid was used. The solenoids were connected to the fingers just past the simulated metacarpophalangeal joint with braided string, as seen in Figure 2. The prosthetic digits utilized “soft-robotics” techniques to minimize joints and failure points while maximizing functionality and realism. Soft-robotics involves components of high elasticity and low durometer that are implemented into rigid-body actuated systems strategically to act as shock absorbance, spring joints, and energy storage (A. Albu-Schaffer, 2004). As explained previously, the metacarpophalangeal joint is the only joint actuated on the prosthetic. Rather than implementing a standard pin or ball and socket joint, a soft-robotics-inspired “spring joint” is used for the actuation of the simulated metacarpophalangeal joint, as seen in Figures 1 and 2.

Solenoids were chosen over servo motors or linear actuators due to their rapid response time and low weight. Solenoids that are sized properly for this application can have response times of around 30 milliseconds–if supplied with full amperage while utilizing rotary motion can take much longer and risk damaging linkage components (Venkataraman, 2013). The solenoids used naturally exist in the open or extended position, allowing the attached digits to remain parallel to the palm of the hand. When the solenoids are powered, they retract, causing the digits to bend at the metacarpophalangeal joint and depress the trumpet valves. The solenoids then spring return to the open position once power is lost. To increase the maximum beats per minute and give the end-user the advanced playing capability, speed is incredibly important to the functionality of the prosthetic.

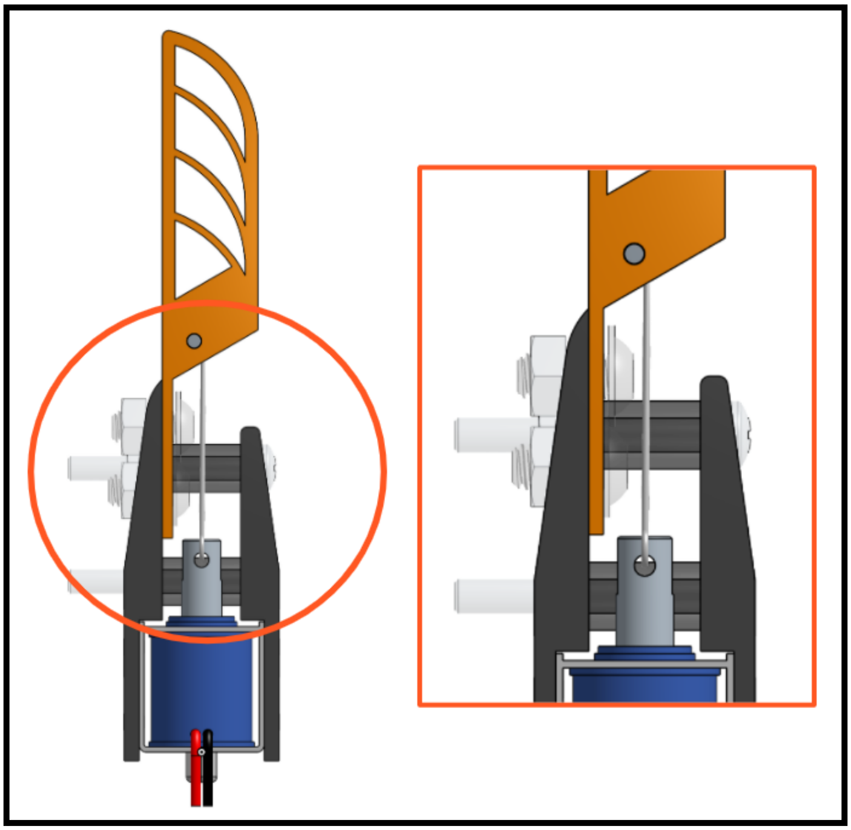

Figure 2: A full side view of the motion system is seen on the left and a zoomed-in image of the solenoid-finger actuation interface is shown on the right. The string attaching the solenoid and finger can be observed.

The device was designed to be modular to lower maintenance time and demand– while making the prosthetic easily adaptable for different patients and trumpets. To accomplish this, all motion-related components were made into one easily removable subsystem as seen in Figure 3. This subsystem consisted of the motion system and included components, such as the solenoids (which power the actuation of the fingers), the string system for force translation, and the fingers themselves. This subassembly nests within a large pocket on the outer hand case and is held in place by two pins as seen in Figure 1. The simple pin removal makes accessing the motion subsystem easy while protecting crucial components from drops or external forces. This also reduces potential failure by decreasing the likelihood of jamming or breaking the motion components by actions other than acute force. This aspect of modularity also increases the prosthetics robustness. The protection of these components also protects the user from catching hands, hair, or other items within the finger actuation components which improves user experience and safety. Within the motion subsystem, the fingers are attached by two easily accessible mounting screws. This allows for a quick and easy swap of fingers to best fit the patient's size or trumpet while also allowing the fingers to be interchanged rapidly in the event of break or maintenance.

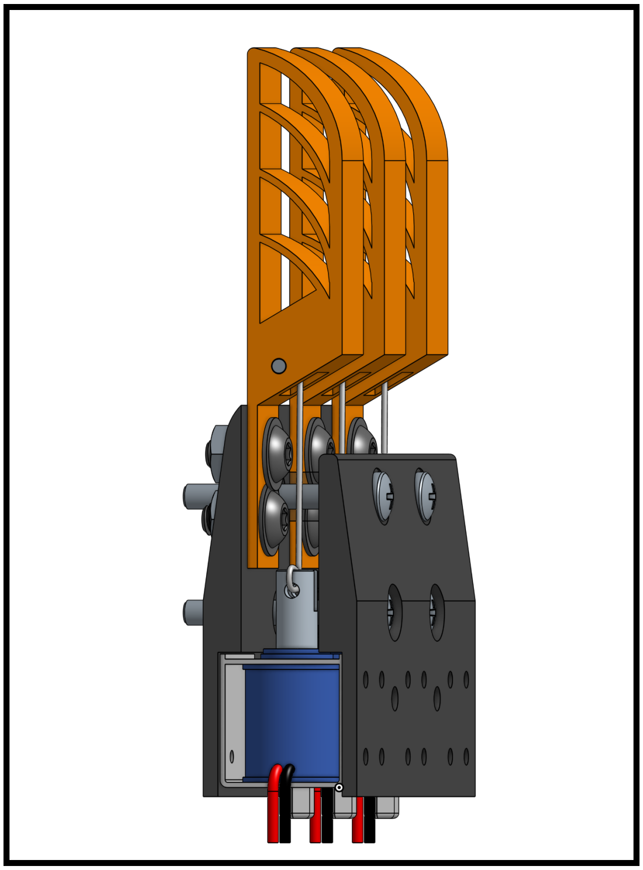

Figure 3: Motion subsystem is depicted from the side to allow the solenoids and string system to be visualized. Individual part numbers and names can be identified in Figure A-1.

Another modular aspect of the design is the arm attachment component which can be identified as Item 4 (BEN-A2Z-004) in the Bill of Materials (Figure A-1) and seen within Figure 4. The arm attachment component was designed separately from the outer hand case. Each patient with an in-vivo rod has a rod custom to their bone structure, physical build, amputation site while other patients may only have a stump (Thesleff, 2018). Therefore, it is necessary that this component is easily adaptable to increase the accessibility of the overall prosthetic device. When needed, this component could be customized for each patient, as it is only attached by 4 screws and is a low-cost part to individualize. Manufacturing these components separately also increases the print quality of both the outer hand case and the arm attachment component as they both require far less support material when printed as stand-alone parts. This increases the appearance, structure, and realism of the device.

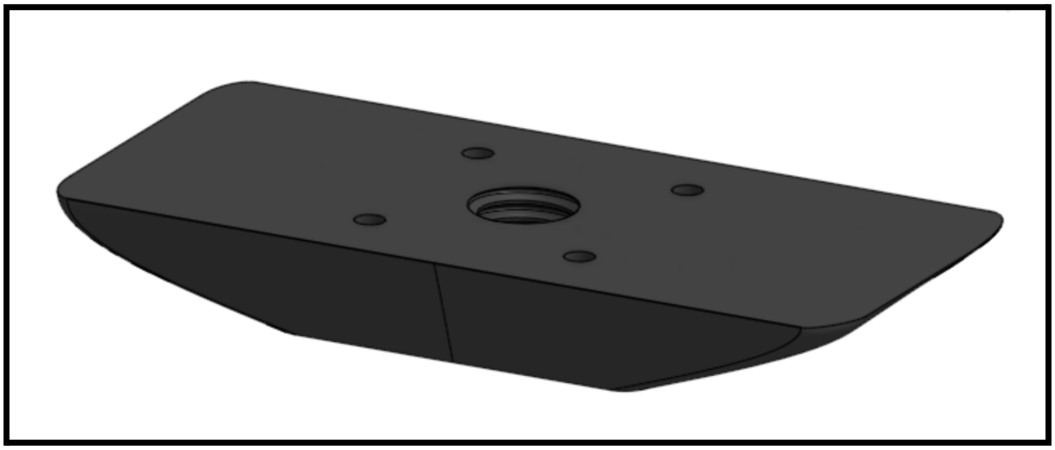

Figure 4: The in-vivo rod arm attachment component is depicted in a front-top isometric view. Threading can be seen through the center hole.

Robustness was one of the main design constraints for the prosthetic device. Within the prosthetic hand, the three digits and thumb were identified as both high-wear and high-movement components. Therefore, it was extremely important to make these components, as seen in Figures 5 and 6, robust. To do so, the fingers and thumb were printed in TPU and utilized “soft-robotics” concepts as discussed previously. 3D printing the “soft” joint and entire finger in TPU, which is low durometer and flexible filament makes the joint robust. TPU is extremely durable and abrasion-resistant, possesses a high shear strength, and has high elasticity (Xu, Tao, 2020). Utilizing a thin sheet of TPU as the “soft” joint allows the joint to be bent while not degrading the structural integrity at the bend point. TPU also has high enough elasticity to quickly return to the resting position once force has been removed, simplifying the design by only requiring pull force for the actuation of each digit.

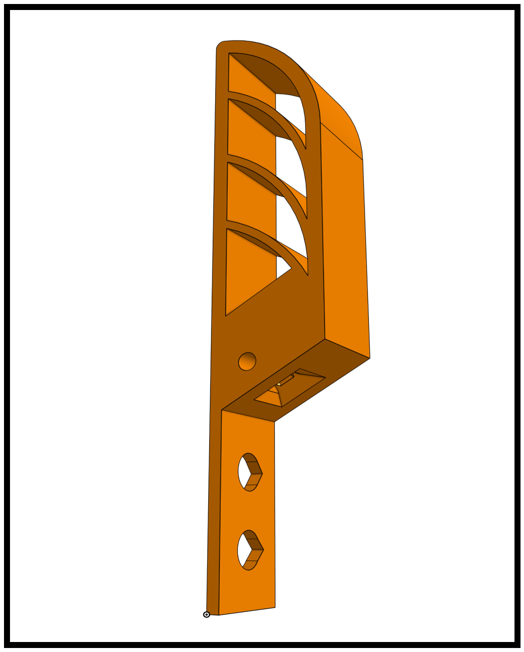

Figure 5: 3D bottom isometric view of the TPU finger.

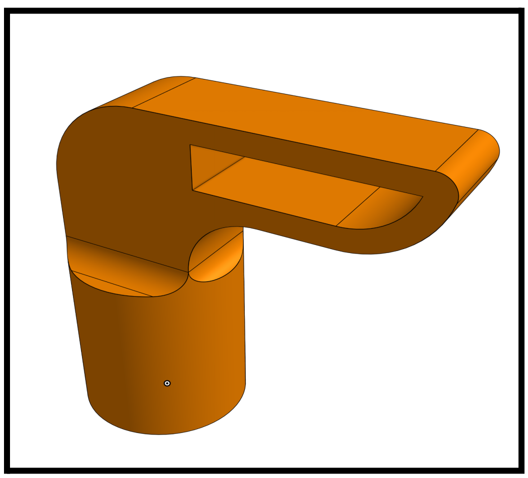

Figure 6: 3D top isometric view of the TPU thumb.

The final design constraints considered were weight and realism. Another reason TPU and PLA were used was to minimize weight. Both PLA and TPU are low-weight materials that are reliable and consistent in strength and stress-tests (Liacouras, 2017; Afrose, 2016). Being low weight in nature, but strong enough that parts do not have to be printed solid allowed the component to be printed at an infill gradient where the densest areas of the prosthetic are closest to the wrist or other crucial areas. This puts more of the prosthetic's weight closer to the pivot point of the arm, decreasing the lever arm created by the device. This helps the user bear the weight and maintain better control. The overall design weighed 455 grams.

The thumb digit will also be printed out of TPU to allow the user to push the digit into the trumpet. Many parts were modified to both look more realistic and be lighter. For example, a "palm" contour was made in the outer hand case as seen in Figure 1. This removes unnecessary material and makes the design more closely resemble a true hand. The fingers and thumbs are mostly hollow or an outline of the shape of the digit as seen in Figures 5 and 6. This is to allow the digits to compress as finger pads do. This also benefits the interface between the trumpet valve and finger, as there is a greater contact area due to the compression of the TPU finger– generating a more realistic interface. Removing this material in the thumb helped stabilize the weight of the prosthetic and trumpet, as well as align the prosthetic with the valves– allowing for successful alignment and comfortable use when compressed into the thumb hook.

To control the mechanics of the prosthetic a RaspberryPi 4 was used as the main microcontroller for the prosthetic hand. The general-purpose input/output (GPIO) pins on the Pi were used as variable voltage sources that can turn the solenoids on or off. One GPIO pin was designated for each solenoid, allowing each finger to be actuated independently. As the solenoids require 6 V at 1 A in order to function properly, a separate voltage source was required as the Pi can only output 3.3 V. Relays, which are current-driven switches that operate within an electronically separated circuit, were the most apparent solution. Dual output relays typically require at least 50 mA of current at the coil in order to produce a strong electric field that will reverse the polarity of the switch. The Pi could only output a maximum of 34 mA, so an intermediate single output relay was required to trigger the dual output relay. The final schematic of a single solenoid circuit is shown in Figure 7. Three of these designs are required; one for each finger. The circuits driven by 3.3V and 9V DC power sources are electronically isolated from the other solenoid circuits. The circuit driven by the 12V DC power source, represented in Figure 8, is an electronically static system containing all three solenoids**.** The switches, which are part of the dual output relays, allow for constant current throughout the system, regardless of the status of each solenoid.

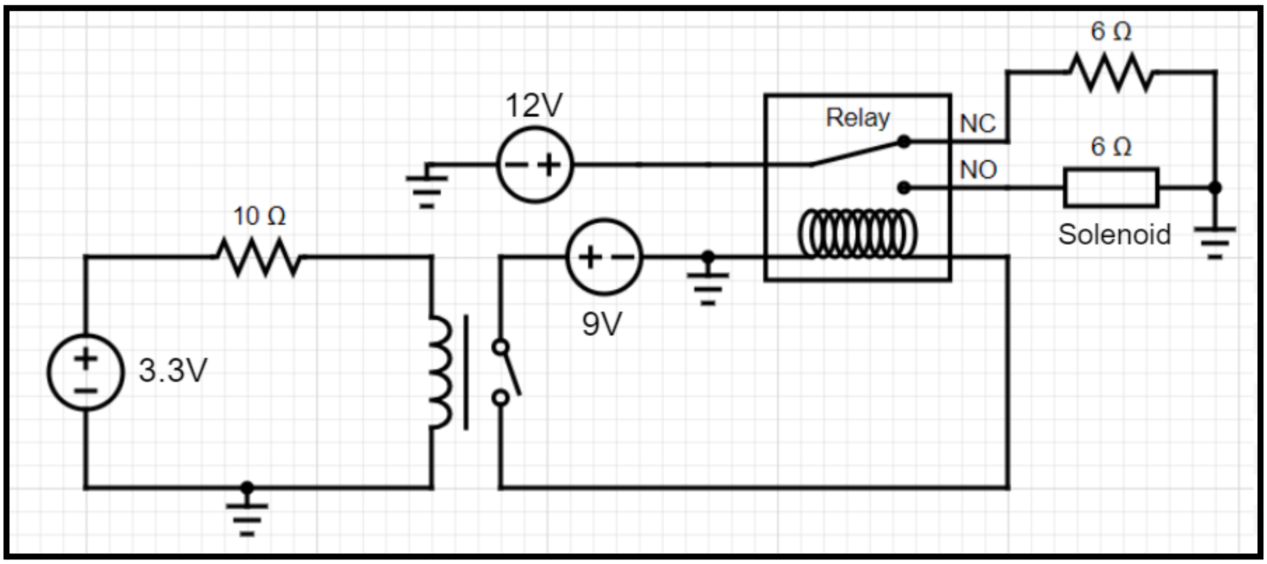

Figure 7: Final design of a single solenoid circuit including a variable voltage source from a GPIO pin on the Raspberry Pi, an intermediate 9V driven single output relay circuit, and a portion of the 12 V joint solenoid circuit.

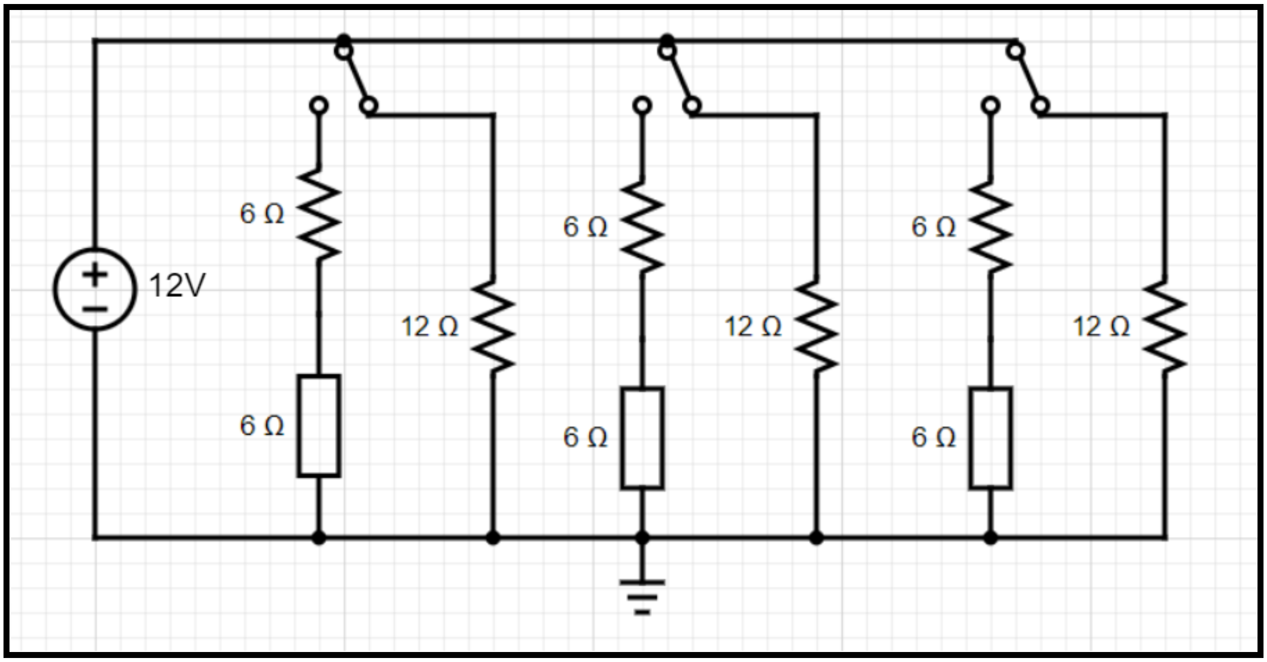

Figure 8: Final design of the multi solenoid schematic utilizing dual output relay switches to maintain cohesive current across each branch of the circuit.

A test program and circuit were constructed to accept the final circuit design. In lieu of solenoids, three light-emitting diodes (LEDs) were used to visually indicate the success of the program. This program successfully read a text file that contained the notes and timings to a song, converted the notes into the proper valve combinations, and lit up the corresponding LEDs. This allowed for the verification of the circuit design, as well as the hardware integration program, as it was successfully able to "play" a song at 120 beats per minute containing sixteenth notes - the fastest duration note that was implemented within the design.

A MIDI file converter was designed to increase the accessibility of the final product. MIDI files are universally used throughout the music community and are quick and easy to generate. A converter allows "Hand-et" to interpret any MIDI file and play it instantly. These converted files are preprocessed, allowing for the hand to allocate its computational power to translation before attempting to play the song. This allowed for smooth playing without restraints from lagging processors.

The GUI was designed to allow the user to upload any song, store songs within memory, and customize settings, statistics, and preferences. The layout of the interface is shown in Figure 9. This allows the user to play any song whenever they would like while needing no prior technical knowledge to operate the prosthetic.

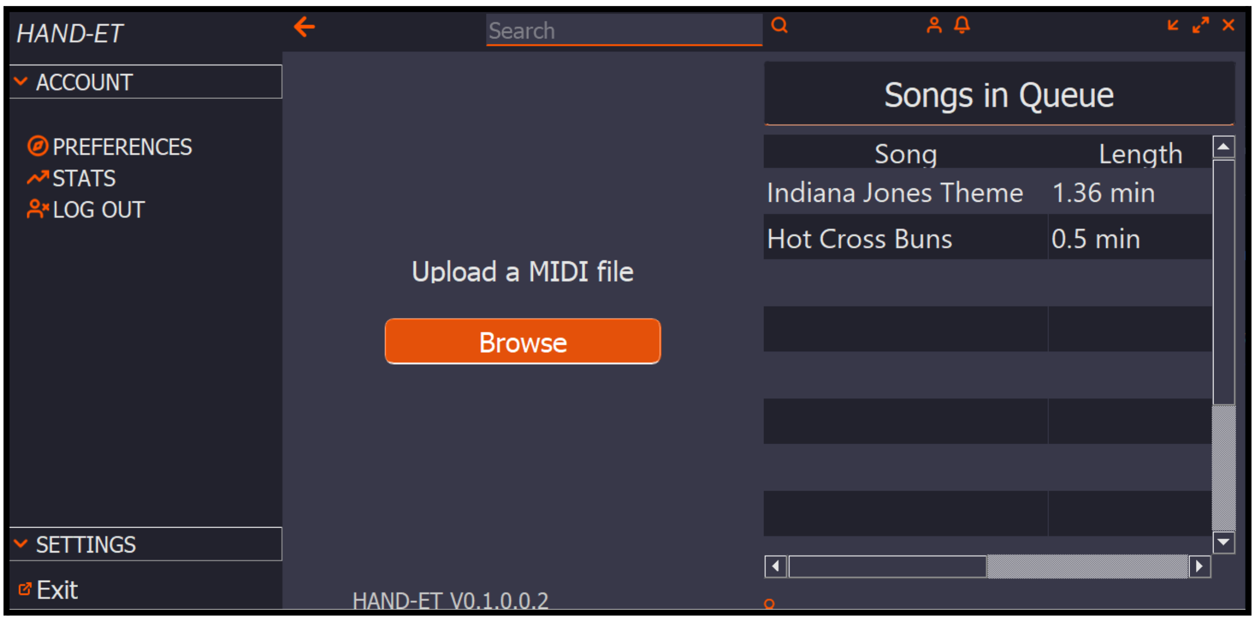

Figure 9: Final layout of the graphical user interface with embedded MIDI file converted and preloaded songs in the "Queue".

This interface was implemented on the RaspberryPi, but can be accessed through the cloud on a remote host, reducing the need for a tether to be attached from the hand to the user's computer. Thus, resulting in a more portable and accessible hand.

When testing the final assembled prosthetic, it was found that the solenoids could not generate enough pull force to depress the trumpet valve. Upon discovery, two tests were performed. First, the force required to depress the finger and trumpet valve was found. To determine the force required, a water bottle was hung from the string attachment point on a single finger, continuously adding water to the bottle until the finger fully depressed the trumpet valve. The mass of the water bottle was then determined. Multiplying the mass of the water bottle in kilograms by the acceleration of gravity (9.8 m/s^2) allowed for the calculation of the total force required from the solenoid to depress the finger. It was found that the water bottle weighed 490 grams which equates to 4.8 Newtons. This test confirmed that the solenoids were not outputting the force they were specified to, as the solenoids purchased were 6 N pull force solenoids. This also provided a true force value required for the solenoids, as the solenoids were originally chosen based on theoretical calculations and preliminary testing.

The second test included determining the actual pull force of the solenoids. The water bottle containing the 490 grams of water, from the previous test, was tied to the bottom of the solenoid and the solenoid was powered. Each time the solenoid failed to fire, water was removed incrementally until the solenoid fired. The solenoid successfully fired when the water bottle weighed 270 grams. This equates to the solenoid being capable of pulling 2.64 N, which was only 44% of the maximum output force specified by the manufacturer.

An additional discrepancy was found between the solenoids specifications and true output. The specifications for the solenoids on their product sheets calls for 6V and 1A with a 6Ω resistance across the solenoid, while "2A" is written on the physical product. This, however, is an impossible requirement to satisfy while maintaining 6V at 6Ω according to Ohm's Law [1].

Where:

$$V = IR \qquad [1]$$

$$6V \neq 2A * 6\Omega$$

V = Voltage
I = Current
R = Resistance

Combined, the two tests and the Ohm's Law proof showed that the solenoids purchased were theoretically capable of actuating the hand but, experimentally were not capable of providing the force they were marketed to provide. Due to this issue, the prototyped prosthetic was not fully functional. However, this failure was a result of faulty components rather than a design failure.

The total cost of the prosthetic hand device was $119.61, as seen in Table A-1. $35.41 of the total cost was mechanical components including the solenoids, filament, and fasteners, and $84.20 was spent on electrical components. Individual breakdowns of the PLA and TPU consumption can be found in Table A-2 and a full fasteners parts list can be found in Table A-3. While the total cost was ultimately extremely low compared to marketed prosthetic hands, the cost of the prosthetic can be reduced by utilizing appropriately sized fasteners. Reducing the length and size of the fasteners used in the design would not only be cost efficient but also reduce the weight of the total hand.

We can also customize the electronics within the hand. A RaspberryPi 4 was used for the purposes of rapid prototyping but is overpowered in terms of control capabilities. A smaller microcontroller that only contains 4 GPIO pins should be utilized, rather than the full 24 that the RaspberryPi 4 offers. A complete operating system (OS), like RaspbianOS, found on the Raspberry Pi, is also unnecessary for this application, adding not only to the price per unit, but also the overall weight and power consumption. A simpler, custom microcontroller board should be designed to reduce cost. A redesign of the final circuit could also be done to eliminate the need for the intermediate relay circuit, the 9V battery, and the relays altogether. Transistors, coupled with diodes to protect from overloading, are an inexpensive replacement for relays. Integrated circuits, such as an LM741 operational amplifier (OpAmp) and logic gates, could be used to reduce the total power consumption and size of the components. Additionally, a custom printed circuit board (PCB) could be developed to reduce size and cost as well as increase the ease of maintenance.

Conclusion and Recommendations:

A successful “proof of concept” design was rapidly prototyped as seen in Figure 10. The final mechanical design met the four crucial design constraints: modularity, robustness, weight, and realism. The modularity of the design allowed for easy maintenance, adaptability, and accessibility to a wide range of users. The materials used and design approach produced a robust product while maintaining minimal weight. Finally, the final design was also visually appealing in terms of form and aesthetics.

Figure 10: Fully assembled prosthetic hand propped against trumpet. Horizontal alignment and scale are correct but vertical positioning is incorrect as the device is unsupported.

From a software perspective, the final interface implementation proved to be robust and expandable. Error checks were implemented to reduce the probability of unforeseen bugs within the program as well as incompatibilities with a variety of user processing systems. The method of execution allowed for cohesive and well-organized development, as well as making future updates and additions simple to integrate.

Electronically, the design of the circuit within Figure 7 was accepted by means of a test program. Hardware control was also successfully integrated into the software design and proven by means of a speed test, allowing the user to play 16th notes. Apart from the faulty solenoids, the electronic and software aspects of “Hand-et” were successfully designed, built, tested, and passed previously discussed test criteria.

As discussed above, the solenoids purchased and implemented were not capable of outputting the amount of force they were specified for; therefore, finger actuation in the fully assembled device was not achieved. These findings were proved by the results of the two force tests discussed above.

Without the use of more complex circuit components, such as transistors, a maximum of 1 A at 6 V could be applied to the solenoids. Alternatively, different solenoids may be used to reduce the complexity of the overall circuit, reducing the size of the final product, and increasing the maximum output force that they can drive. Adapting the design for more powerful solenoids will also allow the device to be more finely tuned. Utilizing an overpowered solenoid allows for a wide tuning range where the balance between preventing the device from slamming the valves and pushing the valves down in a quick controlled motion can be found. However, increasing the power of the solenoid should not compromise the weight of the device. Therefore, it is recommended that the solenoids purchased are as close to the same dimensions and weight as the old solenoids while increasing the force if possible.

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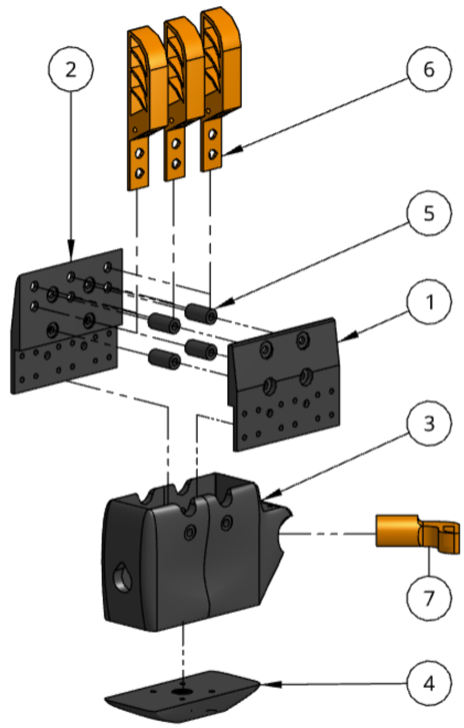
Appendix

1. **Overall Equipment and Materials Cost List**

Table A-1 : Equipment and Materials List (Amazon, 1995)

Mechanical			
Name	**Quantity**	**Cost Per Unit**	**Cost**
Solenoid Actuator	3	$7.50	$22.5
Duramic PLA+	175.16 grams	$0.02	$4.20
SainSmart TPU	21.44 grams	$0.04	$0.86
Fasteners	See Table A-3		$7.85
Electrical			
Tactile Button	1	$1.00	$1.00
Raspberry Pi 4	1	$35.00	$35.00
Resistors	10	$0.05	$0.50
LEDs	1	$0.25	$0.25
12V, 6A Battery	1	$20.00	$20.00
9V Battery	1	$2.45	$2.45
Jumper Wires	<50	~$0.08	$4.00
Single Output Relays	3	$5.83	$17.49
Dual Output Relays	3	$1.17	$3.51
Total Materials Cost			**$119.61**

2. Bill of 3D Printed Materials



Item	Quantity	Name	Part number
1	1	Front Solenoid Plate	BEN-A2Z-001
2	1	Back Solenoid Plate	BEN-A2Z-002
3	1	Outer Hand Case	BEN-A2Z-003
4	1	Arm Attachment Component	BEN-A2Z-004
5	4	Standoff	BEN-A2Z-005
6	3	Digit	BEN-A2Z-006
7	1	Thumb	BEN-A2Z-007

Figure A-1: 3D printed components exploded view and bill of materials. Part numbers correspond to part numbers within Table A-2 : 3D Printed Parts List.

3. **Filament Itemized Weight List**

Table A-2 : 3D Printed Parts List

Part Number	**Part Name**	**Quantity**	**Filament Type**	**Part Weight (grams)**	**Support Weight (grams)**	**Total Weight**
BEN-A2Z-006	Digit	3	SainSmart TPU	11.89	0	11.89
BEN-A2Z-007	Thumb	1	SainSmart TPU	9.55	0	9.55
Total Grams of SainSmart TPU						**21.44**
BEN-A2Z-001	Front Solenoid Plate	1	Duramic PLA+	20.14	3.68	23.82
BEN-A2Z-002	Back Solenoid Plate	1	Duramic PLA+	22.31	3.67	25.98
BEN-A2Z-003	Outer Hand Case	1	Duramic PLA+	100.01	4.58	104.59
BEN-A2Z-004	Arm Attachment Component	1	Duramic PLA+	19.57	0	19.57
BEN-A2Z-005	Standoffs	4	Duramic PLA+	1.2	0	1.2
Total Grams of Duramic PLA+						**175.16**

4.

Table A-2 : 3D Fasteners Parts List (McMaster-Carr, 2002)

Fastener Type	**Quantity**	**Price Per Unit**	**Total Cost**
10-32 x 1.5” Pan Head Machine Screw	4	$0.13	$0.52
10-32 Hex Nut	4	$0.02	$0.08
¼” - 20 x 0.5” Flanged Button Head Screw	6	$0.42	$2.52
¼” - 20 Hex Nut	6	$0.06	$0.36
M2 x 12mm Socket Head Cap Screw	3	$0.15	$0.45
M2 Thin Hex Nut	3	$0.82	$2.47
M3 x 25mm Flat Head Screw	4	$0.19	$0.76
M3 x 8 mm Socket Head Cap Screw	1	$0.09	$0.09
M3 x 5 mm Flat Head Screw	6	$0.10	$0.60
Total Fasteners Cost			**$7.85**