MECHENG 736 - Biomechatronics Project Report

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I. Introduction

The versatility of the human hand is indispensable for a myriad of daily functions, ranging from simple to complex activities. The significance of this is underlined by the growing number of upper limb amputees, emphasizing the need for advanced prosthetic solutions [1].

The robotics domain has witnessed substantial growth, especially concerning grippers mimicking the functions of the human hand. These robotic hands find applications in diverse fields, from industrial manufacturing to space exploration [2]. Conventional rigid grippers, while efficient in certain scenarios, face difficulties when interacting with non-standard or fragile items [3]. Emerging trends in soft robotics present potential answers to these challenges, focusing on producing grippers that merge adaptability with flexibility [4]. Even though some state-of-the-art robotic hands showcase remarkable agility, their intricate design often results in high production costs [5].

In light of these considerations, our research aims to conceptualise a five-fingered robotic gripper. The objective revolves around integrating optimal materials, design attributes, and functional capabilities to proficiently manipulate a wide array of objects while maintaining a balanced perspective on efficiency and weight

II. Related Work

A. Design and Mechanisms

Robotic grippers, vital in numerous robotics applications, have seen advancements driven by design details that influence their adaptability and efficiency. Flexible joints, pivotal in modern gripper designs, enable the distribution of contact forces, ensuring a more stable grasp on objects with varying geometries. The choice of materials and the design intricacies of the joint largely contribute to the success of this flexibility [6].

Locking mechanisms, imperative for ensuring a secure grip, particularly on heavy or slippery objects, have evolved from intricate ratchet systems to more straightforward electromagnetic locks. Their intrinsic capability to maintain grip without constant energy input holds implications for both energy efficiency and safety [7].

The versatility of grippers can be augmented through adjustable finger positions, which can be achieved through mechanisms such as rotary joints, sliding rails, or modular designs. These systems, by permitting flexibility in finger positioning, empower grippers to manipulate objects of diverse sizes and shapes [8].

B. Material and Functional Enhancements

The emulation of human anatomy in gripper design has led to features such as nails or specialised surfaces to enhance grip. These innovations focus forces at specific points, proving indispensable for tasks requiring precision, like pinching or handling thin materials [9].

In gripper design, material selection profoundly influences factors like durability, weight, flexibility, and cost. Common choices encompass metals, polymers, and composites. Soft materials like elastomers are often favoured in designs intended for human-robot interaction or delicate object manipulation [10].

Underactuation, characterised by grippers having fewer actuators than degrees of freedom, is a strategy that allows for economical designs while ensuring passive adaptability to object shapes for a firm grip [11].

C. Prosthetics and Material Innovations

A myriad of commercially available prosthetic hands cater to various price points and dexterity levels. Notably, Ottobock emphasises an anthropomorphic design, albeit with limited articulation. For those seeking high dexterity, brands like I-Limb, TASKA Prosthetics, and Ottobock offer solutions. These prosthetics, functioning through electrical signal transmissions, enable predefined hand motions, from robust grasps to intricate grips [12].

Efforts to democratise prosthetic access include innovations like 3D-printed components. Yale University, for instance, explored ABS for its cost-effectiveness and assembly advantages. A focus on material innovation has also emerged, with a shift from commonly used polylactic acid (PLA) to thermoplastic polyurethane

(TPU) due to its superior elasticity and suitability for 3D printing [13].

Furthermore, techniques like Hybrid Deposition Manufacturing (HDM) have been introduced, integrating 3D printing to incorporate moulds directly into the final design, allowing the creation of intricate internal structures, and ensuring robust connections with a polished exterior [14].

III. Designs

Gripper design, particularly for underactuated mechanisms, requires a careful balance of material selection, spatial organisation, and functional versatility. Through iterative development, this project explored various design concepts, leading to a final prototype that combines the advantages of each iteration.

A. Gripper Fingers

Our first attempt employed TPU 95A material for the finger, capitalising on its flexibility. The goal was to print a finger as a single unit, streamlining assembly and reducing the overall weight of each finger by removing the necessity for additional hardware like nuts and bolts. Figure 1 shows the initial TPU finger design we ended up with, with wide finger pads in an attempt to improve the friction between the finger and objects. The channel along the back of the finger is designed to allow for adjustable positioning of rubber bands for passive extension; however, the natural flexibility of the TPU meant the finger already had integrated passive extension, further reducing the need for additional components.

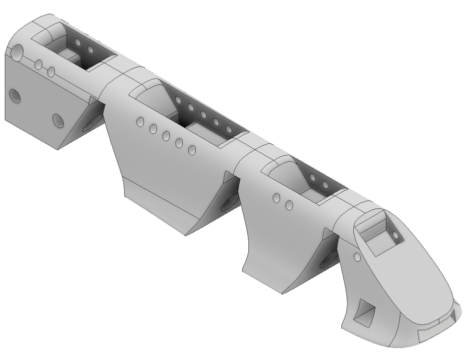

Fig. 1. CAD model of the initial TPU finger design, modelled in Inventor 2024.

During this phase, we explored various wall line counts to adjust joint properties. It was determined that a 6-line wall count combined with a 20% infill struck the right balance between joint stiffness and efficient print time. Figure 2 highlights the configuration of the walls and infill within the print. The walls provided the needed rigidity to help the finger avoid torsion and abduction, as well as enough stiffness to have a low infill percentage. A 0.2-mm layer height provided sufficient strength while also reducing print time.

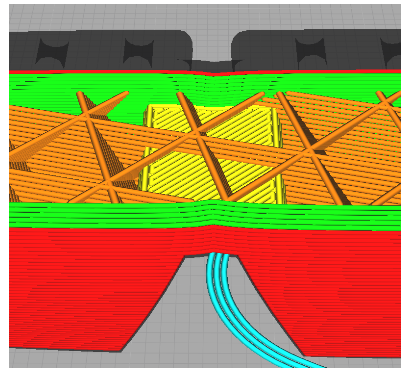

Fig. 2. Snippet of the Slicer .gcode generated by the Cura Slicer for the Ender V3 S1, showing the 6 line wall count and 20% infill.

This finger, although promising, had several downfalls, including:

1) **Excessive Abduction:** Although the six walls were enough to provide good strength, the shape of the joints, being thinner at the top than the underside, led to the fingers abducting too much during initial tests.
2) **Hyperextension:** Due to the flexibility of the TPU, the fingers could hyperextend, meaning when the fingers wrapped around a large-diameter object like a water bottle, the joint between the mount and the distal phalanx hyperextended backwards, reducing the contact between the finger and the object. This diminished its ability to pick up objects.
3) **Grip:** TPU, while a suitable material for joints and the finger body, did not have enough friction on the pads, even with an integrated tread. This meant that smooth objects slipped out of the grasp of the hand.

In parallel, we experimented with a PLA finger featuring simple hinge joints. In order for the fingers to have any substantial grip, small removable HDM pads were designed; these used DragonSkin 20 silicone rubber in order to provide the necessary grip. These worked extremely well, with far greater friction than TPU. Rubber bands were used for passive extension over springs due to their weight and wide variety of options in terms of width, thickness, and length, allowing for lots of adjustability. However, the design of the PLA finger joints resulted in a binary motion for the fingers: either fully extended or completely retracted, with no middle ground. This led to poor performance in tasks like picking up a washer or card where the fingers needed to meet in the middle at the same time.

Building upon our learnings, we settled on an anthropomorphic final design resembling a human hand, featuring five digits. This configuration, with three digits on one side and two on the other, enhanced the gripper's adaptability. Specifically, two fingers on the three-digit side faced the two on the opposing side, facilitating the pickup of flat or slim objects, such as cards or washers. Figure 3 shows this configuration.

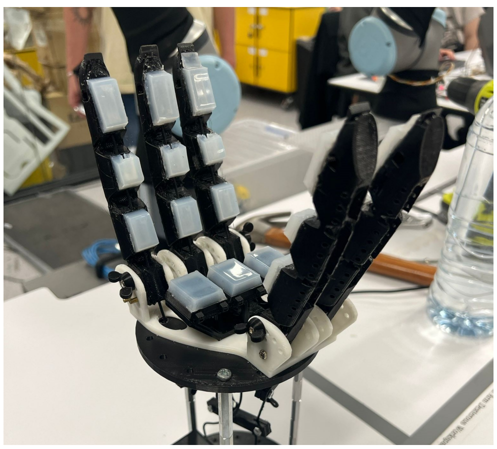

Fig. 3. Final TPU 95A Fingers for the hand, with DragonSkin silicone rubber pads and PLA finger nails.

The final finger design retained the TPU 95A material due to its superior flexibility, with each finger measuring 130 mm in length. This length allows for a versatile grip, be it around large bottles or more slender objects like tool handles.

Further enhancing the design, we incorporated PLA-made nails. These were designed to mimic the hard nature of human nails. Sharpened at a 45-degree angle, the nails' orientation varied between pairs to aid in gripping objects of differing sizes. For instance, one pair's slope pointed inward for items like washers, while another pair's pointed outward, optimal for card-like objects.

In order to provide enough grip, small DragonSkin pads were glued to the fingers, providing sufficient friction over the TPU, while avoiding the addition of more necessary hardware like bolts for attaching the pads.

Addressing the challenges posed by the soft TPU, we employed a 2mm nylon cord as a tendons. This decision ensured that the cord did not easily slice through the

Fig. 4. Nail configuration on the figures, with the close finger nail orientation suitable for picking up washers, and the back finger nail orientation suitable for picking up objects like cards.

filament, a problem encountered with thinner cords like Dyneema.

B. Differential

For our five-fingered gripper, the main objectives were to distribute force evenly and allow fingers to adjust based on the object being grasped.

Our design required a differential mechanism to ensure that while some fingers were stationary due to an object's shape, others could still move. Initially, we chose a circular differential for its small size and minimal motion. However, its design limited the individual movement of adjacent fingers.

We then opted for a whiffle tree differential, as shown in Figure 5. This design gave each finger the ability to move independently, enhancing the gripper's adaptability.

The whiffle tree, however, had their own challenge: aligning tendons and keeping the whiffle bars horizontal without tension. To fix this, we introduced a clamping lock on the whiffle bars. This allowed us to easily adjust and secure the tendons, improving the motion range for each finger.

Although we faced hurdles with the initial designs, our modifications resulted in a versatile and customisable base, well-suited for grasping a variety of objects. Its adjustable and modular features further enhanced its efficiency and functionality.

1) Differential Casing and Motor: In order to house the differential and mount the fingers and palm to the robot arm, a casing was needed. This casing also

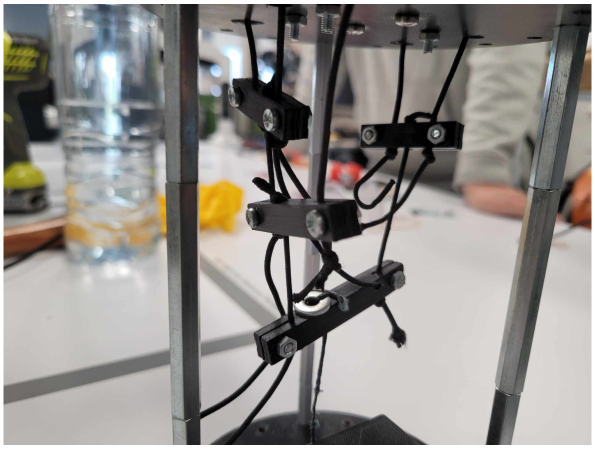

Fig. 5. Whiffle tree differential

needed to include the motor mount and female dovetail mount.

Our initial design was a single lightweight 3D-printed casing. It was designed for the disc differential explored in Section III-B which meant we did not allow for much spacing between the motor and the top of the casing. Once we realised we could not use a disc differential, this casing did not have enough space for the whiffle tree differential. As well as this, the motor mount walls were too thin, meaning during initial testing they snapped.

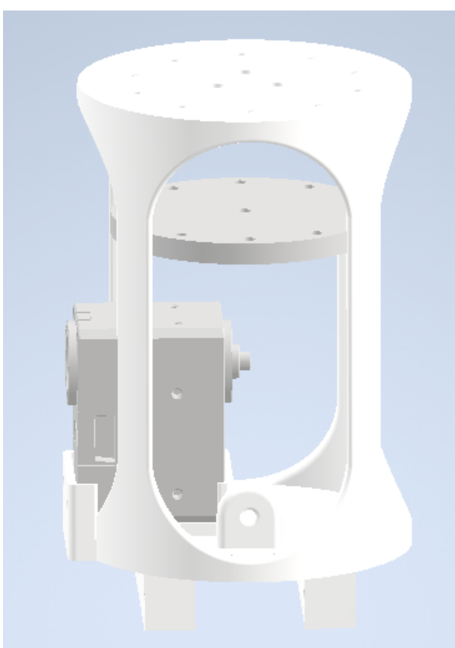

Fig. 6. CAD model of the initial casing with the XM-430 motor and disc differential

Our final design was a modular casing that used M3 and M4 stand-offs to allow for adjustability in the total length of the casing. As seen in Figure 7, 3 support standoffs were used to minimise weight while maintaining good stability during finger contraction. There is ample room for the different to move up and down depending both on the motor position and the finger position (see Section III-D for finger position adjustment). This final design was suitable for testing, adjustment, and assembly.

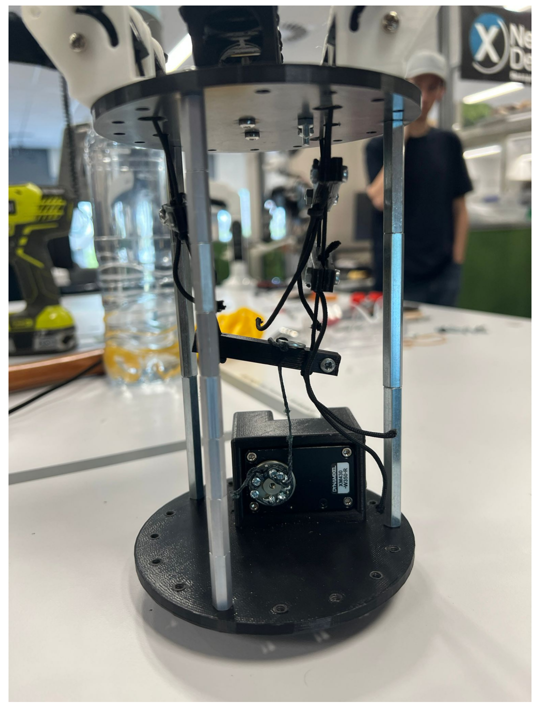

Fig. 7. Final motor mount and differential casing, using M3 and M4 standoffs

C. Gripper Palm Pad

The palm pad's main goal was to achieve a good grip. We first used a TPU and PLA combination, aiming for a one-piece design with TPU for the surface of the palm. However, this had bonding issues between the TPU and PLA layers and did not provide enough friction.

We then tried VytaFlex 40 silicone rubber to increase friction. However, its rigidity limited its flexibility, causing issues with objects like water bottles. Figure 8 shows the palm's steep angle, chosen because we expected VytaFlex 40 to deform at the corners for better contact. This did not happen, leading to weak contact between the palm and the bottle. Moreover, this palm weighed over 100 g, which contributed over 1/6th of the allowable weight, making it unsuitable for the final design.

Our final design used Dragon Skin 20 (refer to Figure 9). It offered both good compliance and friction. Its

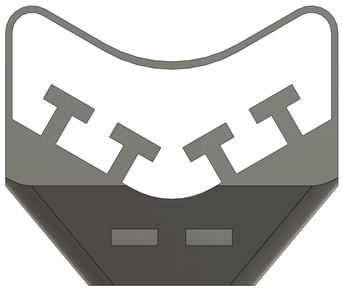

Fig. 8. VytaFlex 40 Palm Mould

softer material and flatter shape adapt well to different objects. Plus, with a slimmer pad and open frame, it weighed only 36 g.

Fig. 9. Final palm design with DraginSkin and lighter frame

D. Adjustable Finger Positioning

An adjustable finger positioning feature was integrated to allow for the grasping of the diverse sizes of objects the gripper might encounter. As seen in Figure 10 each finger can articulate around the lower bolt pivot and can be locked in place in 1 of 5 possible positions. By giving each finger a lower pivot as well as a bolt to lock the finger's position, each of the fingers' default positions could be manipulated. Such adjustability ensures the gripper's versatility, accommodating objects ranging from thin washers to larger-diameter items. For instance, having fingers on opposing sides set to the inmost position allowed the hand to easily pick up tiny objects like washers. Placing the fingers in the middle position allowed for a wide grip, improving the ability of the gripper to pick up wide objects.

IV. Experiments and Results

Object Grasping Test: The gripper was tasked with picking up the following items:

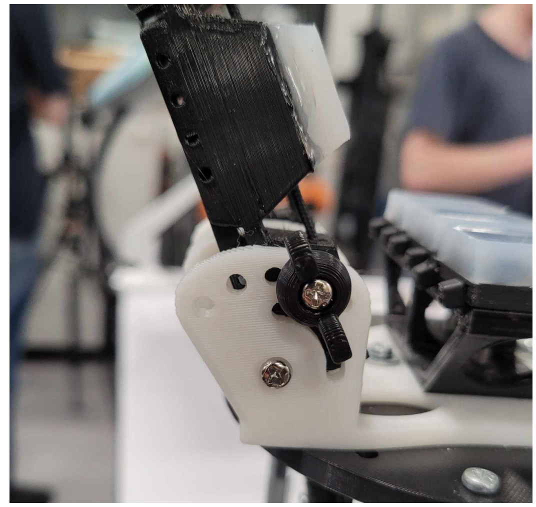

Fig. 10. Picture of the adjustable finger mechanism

1) washer
2) card
3) fork
4) articulated plastic chain
5) 1.5-litre water bottle
6) spanner
7) electric drill
8) hammer

It successfully picked up all objects, demonstrating good versatility in the gripper's ability to pick up a variety of objects.

Functional Grasping Test: To further demonstrate the gripper's ability, we made it operate a small electric screwdriver, specifically turning it on and off. It accomplished this task without issue, showcasing its ability to handle and operate a tool in a human-like manner.

Grip Force Measurement: The maximum force exerted by the gripper was measured using a force sensor. During this test, the gripper showcased a notable grip force of 63.2 N, highlighting its potential to securely hold heavier objects.

Video: `https://www.youtube.com/watch?v=d28OtIG1Ev0&ab_channel=ChristopherFong`

V. Conclusions and Future Directions

A. Conclusion

The underactuated gripper's design and validation process affirmed its capabilities in grasping and manipulating a broad array of objects. Through iterative design and insightful experimentation, the resultant gripper displayed commendable versatility and resilience. Despite its effective performance, certain design choices led the gripper to weigh 552 g. Although this was under the designated 600 g benchmark, it's undeniable that more weight optimisation could enhance the gripper's efficiency. While there were areas for improvement, the gripper's overall performance remains notable, setting the foundation for further refinements in future iterations.

B. Future Works

To further enhance the gripper's functionality and more closely mirror the capabilities of the human hand, several improvements and modifications have been identified:

1) **Closer Mimicry of the Human Hand:** Transitioning to a configuration of four fingers and one thumb will emulate the human hand structure more precisely. This adjustment can potentially improve grasping versatility and the range of objects the gripper can handle.
2) **Abduction of Fingers and Thumb:** Enabling sideways movement (abduction) will offer greater flexibility in object manipulation. This feature can be particularly useful in tasks requiring a more delicate or nuanced grip.
3) **Selective Whiffle Tree Link Locking:** By introducing a mechanism to lock specific whiffle tree links, the gripper could be modified to utilise only selected fingers for grasping. Such a feature would provide the ability to tailor grip configurations based on the object's size and shape. Moreover, allowing locks in both open and closed orientations can further diversify grip styles.
4) **Unified Differential Casing Print:** Replacing the current setup with a single print for the differential casing can simplify assembly and potentially enhance structural integrity. Eliminating the use of spacers might also lead to a more compact and streamlined design.
5) **Inclusion of a Pulley System:** Integrating a pulley would amplify the torque exerted by the lightweight motor, boosting the gripper's strength without a significant increase in weight or size.

Incorporating these advancements will drive the gripper's design towards greater adaptability and efficiency, reinforcing its utility in broader applications.

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