University of Southern Queensland

School of Engineering

Boston Dynamics Spot gripper attachment development

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Thomas Eustace

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School of Engineering

ENP4111 Dissertation Project

(This is a 2-unit research project in Bachelor of Engineering Honours Program)

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ABSTRACT

The Boston Dynamics Spot and its robot arm are a revolutionary development however, it is still not being utilized to its full potential. The problem that was identified, and that this project seeks to solve, is that Spot and its robot arm are limited by its end effecter being a gripper. The goal of this project is to try to increase the Spot robot arms ability to interact with the world. The way this is achieved is through the design and development of an attachment system used by the robot arms gripper. This system was prototyped and refined by testing with a 3D printed replica of the gripper. The use of a 3D printer allowed rapid production of test prints and the attachments themselves. The final design consisted of a base attachment which was then modified to create both an LED and a saw attachment. These attachments were able to successfully prove that this system is a viable option which requires little adjustment to the existing gripper. It is also shown that the attachments can n receive electrical signals and are also easily modified. Due to the time and monetary constraints, the scope of this project is focusing on the development of the attachment. Further development of the system is needed before it would be ready for production, including additional FEA analysis, investigations into real world attachments to determine connector suitability and QR code integration for attachment identification.

ACKNOWLEDGEMENTS

I would like to acknowledge my project supervisor Dr Tobias Low who was always there to provide help when needed.

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CHAPTER 1 INTRODUCTION

Figure 1 Robot dog AKA Spot (Boston Dynamics 2023)

The quadrupedal autonomous robot from Boston Dynamics, aka Spot, is an important step for robotics everywhere. Not only is it an important step in researching robotic capabilities but it is also a step towards increasing the quality and safety of human lives. However, Spot still has a few areas that need to be addressed before it can reach its full potential. The area that this research project is focusing on is the limitation of Spots ability to interact with the real world. Currently Spots only way to interact with the real world is through its robotic arm which has a gripper end effector. While this end effector can be very useful for many actions it is still limited to grabbing, pushing and pulling. This research project aims to answer the question: can an attachment system be developed for Spots robotic arm so that it can use different attachments?

The methodology for this research topic will be relatively simple and require some trial and error. The basic method will be to create a prototype, test it and make design adjustments as required. Each stage of the design will be tested to ensure it works well before it is added into the prototype. Demonstration of attachment with the actual Spot will not be done as it would require modification of spots current gripper and there would be difficulties faced with coding the operation into spots software. To aid in the testing and development of the attachment, a replica of the gripper claw will be created with adjustments to allow for operation with a servo. All 3D modelling and simulating was completed with Autodesk Fusion, slicing for 3D printing was completed with Ultimaker Cura and coding done with Arduino IDE.

CHAPTER 2 BACKGROUND AND LITERATURE REVIEW

The Boston Dynamics Spot

2.1 CURRENT CAPABILITIES

Boston Dynamics didn't just release Spot and stop there, they continued to develop different options to increase Spots capabilities. Boston Dynamics accomplished this by releasing an array of different attachments as detailed below. The attachments available appear primarily to focus on enabling Spot to be used for surveying. The below details are from the Boston Dynamics Spot website (Boston Dynamics 2023).

2.1.1 Robotic Arm

The Robotic arm available for Spot has a full range of motion due to its six-degrees of freedom, a gripper, and can reach up to 1m away. The gripper comes with an integrated 4K RGB camera and sensors for time of flight and inertia. With the gripper, Spot can lift items weighing up to 11 kg and drag weights of up to 25kg. The gripper also has a clamping for of 130N at the end of the jaw.

2.1.2 Spot CAM+ and Spot CAM+IR

Both the CAM+ and CAM+IR come with a spherical, pan tilt zoom camera with 360X170° view and 30X optical zoom. They also have 4 pairs of LEDs to illuminate dark environments and can be configured for rear or front mount. Spot CAM+IR also comes with an integrated radiometric thermal camera and two speakers and microphones for two-way communications.

2.1.3 Spot GXP

The GXP module allows users to add external devices to Spot by providing 5, 12 and 24V power output options and RJ45 connection points.

2.1.4 Spot CORE I/O

The CORE I/O features a compact GPU and CPU with 5, 12 and 24V power output options and RJ45 connection points.

2.1.5 Spot EAP 2

The EAP 2 allows for the option to add lidar to enhance Spots navigation autonomy with sensing up to 100m as well as 5, 12 and 24V power output options and RJ45 connection points.

The CORE I/O and EAP 2 can be packaged together

2.1.6 Rajant Kinetic Mesh Radio Kit

The Mesh Radio Kit provides an option for when Wi-Fi is not available on site for teleoperation of Spot. It features a range of up to 200,00 square feet with roughly a 250ft radius per radio. It also allows 2.4 and 5.8GHz and is easily mounted on top of Spot, Spot EAP or Spot CORE I/O.

2.1.7 Persistent Systems MPU5 Radio Kit

The MPU5 Radio kit allows for point-to-point communications between Spot and the operator without requiring a secure network, however it only supports 2.4GHz.

2.2 CURRENT SPOT RESEARCH

In the search for current research into options for the Spot gripper attachments a gap in research was found as there were no research articles discovered. Considering the arm was only released in Feb 2021 (Ackerman, 2021), this is understandable and there could potentially be research in progress now that has not been completed or published. There has been some research published that is relevant to developing an automatic attachment changer and these are shown below.

2.2.1 Go Fetch! - Dynamic Grasps using Boston Dynamics Spot with External Robotic Arm

The article Go Fetch prepared by Zimmermann, Poranne and Coros (2021, pp. 4488-4494) investigates using Spot and its restricted control access with hardware not developed by Boston Dynamics. The importance of this article is that they showed the benefits and increased usefulness of Spot when combining public and proprietary hardware. In this article they explained that they combined Spot with an externally operated Kinova robotic arm as seen in figure 2. They used the Spot and arm to perform a “Snatch” experiment where they would snatch a ball off the ground. In the conclusion of this article, they discuss that they were able to successfully snatch the ball from the ground, however the accuracy of the arm needs improvement. This highlights the need for Boston Dynamics to allow the integration of other hardware with Spot to optimize its adaptability.

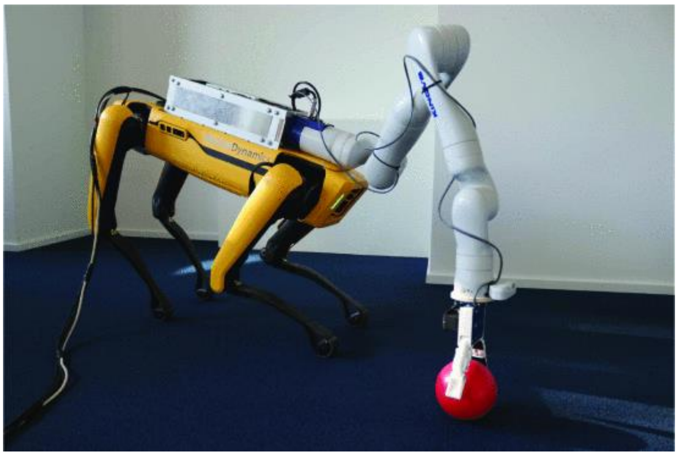

Figure 2 Spot with the Kinova arm attached (Zimmermann, Poranne and Coros, 2021, pp. 4488-4494)

2.2.2 ASC: Adaptive Skill Coordination for Robotic Mobile Manipulation

In this article Yokoyama et al (2024, pp. 779-786) propose the Adaptive Skill Coordination (ASC) protocol in order to increase Spots ability to perform tasks autonomously. The ASC consists of three components: Skill library, Skill selection policy and a Corrective policy. In this experiment they used Spot with the robotic arm to perform a pick and place task of tidying up a certain area, shown in figure 3. In this experiment the skill library consisted of three simple tasks, navigate, pick and place. The ASC protocol used the skill selection policy to identify which of these skills were to be actioned. Lastly, the corrective aspect of ASC would allow for the ASC protocol to handle dynamic environments where changes are occurring, such as the object to be picked up is laying down or rotated instead of being in a pre-programmed orientation. This research is very important as it will allow Spot to become more autonomous and not require pre-programmed paths/actions. This research is also relevant to the proposed research topic as it allows a potential option for the attachment programming where attachments could come with skill libraries that could be easily loaded.

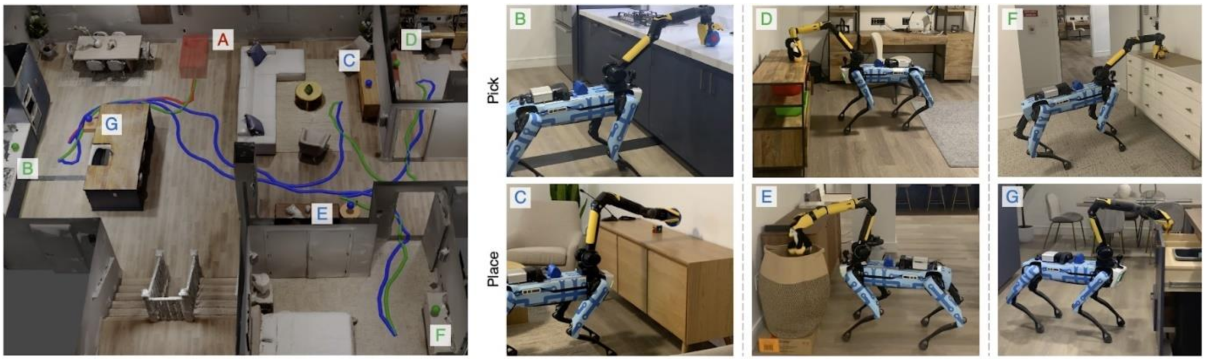

Figure 3 Spot performing pick and place to tidy up an area (Yokoyama et al, 2024, pp. 779-786)

2.3 EXISTING TOOL CHANGING SYSTEMS

With there being no existing research found on an attachment system for the Spot robotic arm, the scope of research was expanded to include other forms of autonomous robotic arm tool changers. These options can provide some indications of options that have worked and what direction the design can go in. However, these options don't suit the design aspects for the most part as they usually rely on the tool, tool rack and robot arm to be in a static location where the operation to replace the tool has a preprogrammed path. The below research articles are the most useful that were found, providing different ideas that can help shape the final design.

2.3.1 The Dynamic Simulation of Robotic Tool Changer Based on ADAMS and ANSYS

In this article the Li et al. (2016, pp. 13-17) proposed a potential design for a Robotic tool changer to swap out the end effector of a robotic arm. This design, shown in figure 4, uses a male connector on the robotic arm which uses a pneumatic piston connected to a locking cam. When pressure is applied to the piston, the locking cam moves outwards, forcing several ball bearings to protrude out of the sleeve. While this male connector is inserted into the female connector, these ball bearings are forced against a locking ring, ensuring the two connectors are secured together. When the connectors are released, air is pushed into the opposite side of the piston, allowing the ball bearings to move inside the sleeve. This system has electrical pins on both the master plate and the tool plate as well as air connection ports to allow the system to control the attachment electronically and provide air pressure for any pneumatic attachments. This article is important to the research topic as it outlines a potential method for the attachments to be swapped out. The ability to also pass through pneumatic and electrical controlling of the attachment would be of great benefit to the design. One downside is that the use of pneumatics on Spot is not feasible so the method of using air pressure to lock the attachment in place is not going to work.

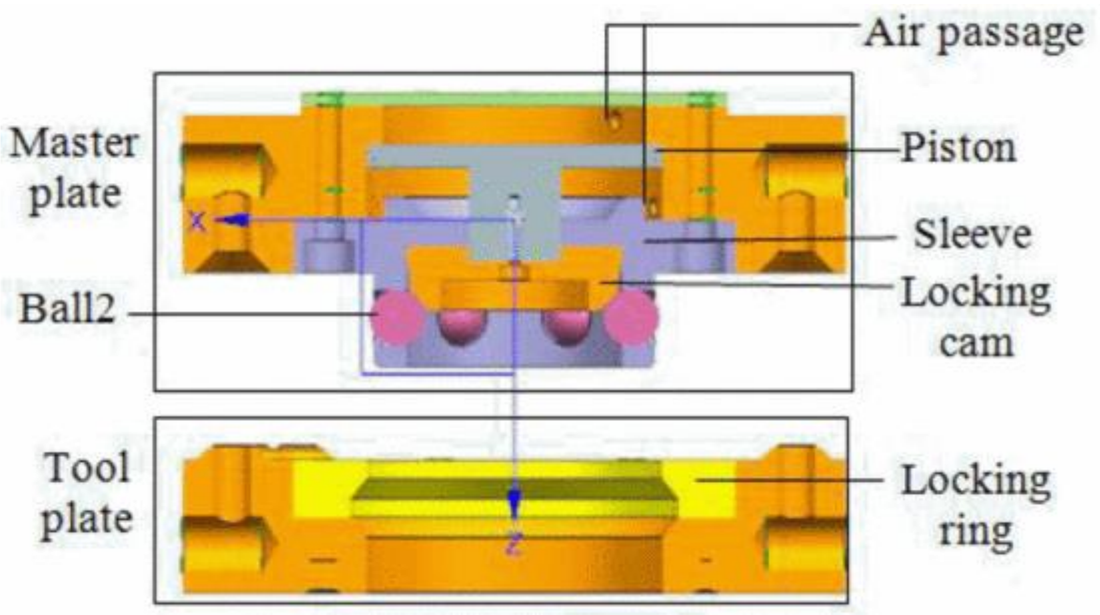

Figure 4 Master and tool plate for tool changing system (Li et al, 2016, pp. 13-17)

2.3.2 Integration of Robotic Vision and Automatic Tool Changer Based on Sequential Motion Primitive for Performing Assembly Tasks

In this article Deng et al, (2023 pp 5320-5325) identified that currently industrial robotic arms are not utilized to their full potential due to being assigned to one specific task. The researchers then explained the development of their system that uses robotic vision to scan an object and determine what operation needs to be performed and hence which tool needs to be used. The robotic arm will then move to swap out the tool and perform the required operation. The tool changing system, shown in figure 5, consists of a mechanism that uses a pneumatically actuated device to lock the robotic arm male connector to the attachment female connector, similar to the system mentioned above. One downside of this system is that it relies on the required tool being in a specified location and it also uses a pneumatic connection, which as mentioned above, would not be ideal for Spot. This research is important to the proposed topic as it details a method for using machine vision to scan an object and autonomously determine the attachment required and then control the robotic arm to connect to that attachment. This verifies that the ability for Spot to use the integrated cameras to determine what attachment is required for certain tasks and then proceed to select that attachment is a viable option.

Figure 5 Robotic arm attachment system (Deng et al, 2023 pp 5320-5325)

2.3.3 An Open-Access Passive Modular Tool Changing System for Mobile Manipulation Robots

In this article Berenstein et al, (2018, pp. 592-598) investigated a potential tool changing system for use with passive tools. The system consisted of three parts as shown in figure 6 where there is the tool, the robot arm attachment module and the housing. In this system the tool sits in the housing, the robot arm with the attachment module moves over the top and then lowers onto the tool. The tool has two locking pins on the side and when the robot arm moves the tool out of the housing, a built-in ramp in the housing pushes the locking pins into place, locking the tool via two locking blades which are released when the tool exits the housing. The decoupling of the tool is achieved by reversing this procedure. In conclusion, this design works in theory but during the experiments it was found that the housing didn't provide enough support for the system. Another issue found was that the robotic arm was manually controlled during this experiment, resulting in some misalignments. This experiment was important to the research project as it also provides a potential attachment system to consider that is different from those above. However, this connection type may not be suitable as it would require the tool to always be in the housing and correctly oriented. There also is not an option for electrical connections to power the attachments which is a desired trait.

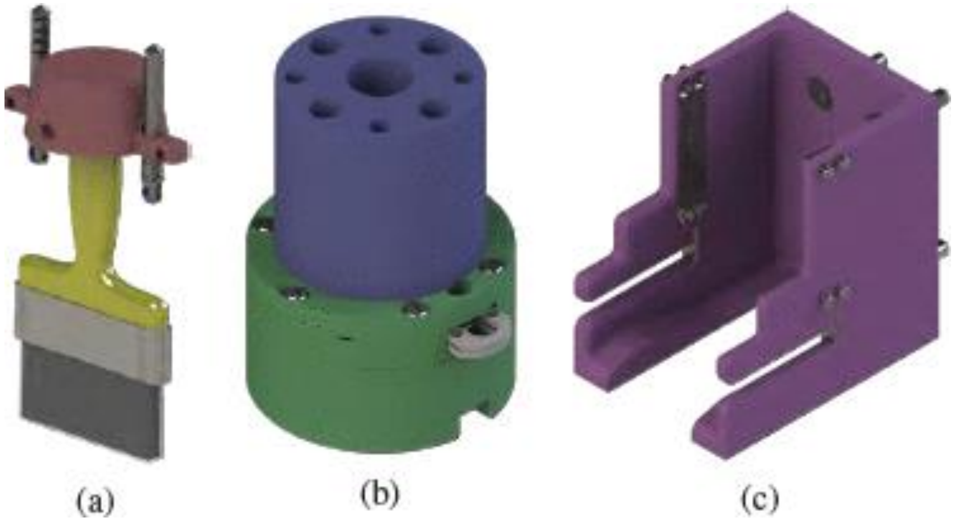

Figure 6 a) Tool and connector, b) Robot arm module, c) Tool housing (Berenstein et al, 2018, pp. 592-598)

2.3.4 Modular End-Effector System for Autonomous Robotic Maintenance & Repair

In this report Li et al. (2022 pp. 4510-4516) experimented with using a Modular End Effector System which uses a tool holder/ changer, Robot Side Mating Socket (RSMS), End Effector Mating Socket (EEMS) and a modular camera system. The RSMS is a socket that has rails and a latch which allow the EEMS to slide into it and lock in. To attach the EEMS to the RSMS the robot arm will line up the RSMS with the EEMS and move forward, sliding over the EEMS. The latch then secures the EEMS into place and then the robot arm moves the whole system upwards along the rail to release them from the tool holder. To store the EEMS the robot arm will move the end effector into place above the tool holder, move the system down onto the rails until it reaches the end stop. Then a solenoid is energized, releasing the latch, allowing the RSMS to be moved back off the tool changer. This experiment is important for the research project as it proposes a robust tool changing system with pneumatic and electrical through connections. The system also had the tool holder on a robotic platform, allowing the attachments to move around with the arm. This also means that this system also does not require the tool to be in a predetermined position, allowing the robotic arm more freedom. Along with these considerations is also the fact that this system doesn't require pneumatics for the connection to be made.

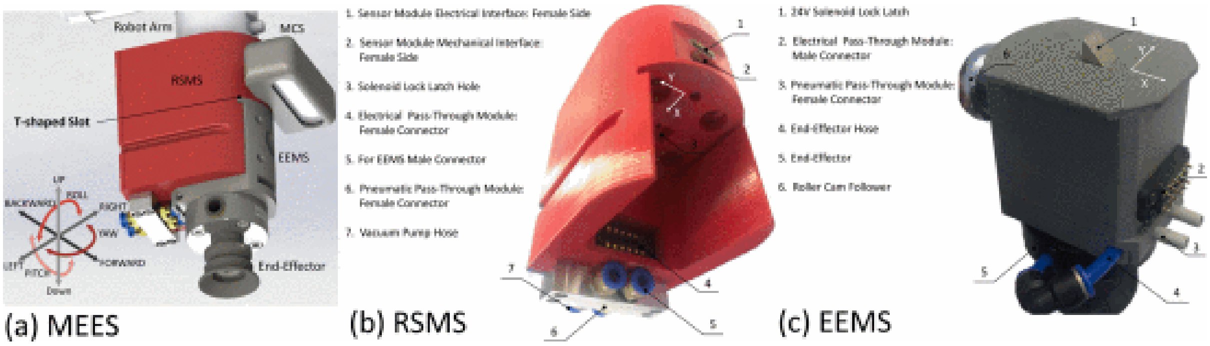

Figure 7 Modular end-effector system (MEES): (a) Assembled and individual (b) Robot (RSMS) and (c) End-effector (EEMS) side socket modules (Li et al. 2022 pp. 4510-4516)

2.3.5 Experimental evaluation of a novel automatic service robot tool changer

In this article Gyimothy & Toth (2011 pp. 1046-1051) identified that there was a gap in tool changers where most used a taper and ball bearing style lock where the unit used pneumatics to lock the attachment in place as detailed in some systems above. This led the researchers to propose their design of a tool coupler, shown in figure 8, that uses a rotating system to lock in. For this system there is a tool base plate, a master side and a servo drive. To couple the tool, the master side and servo drive lower down onto the tool base plate where a tapered pin ensures correct alignment. The servo drive then rotates a disk in the master side which allows the wedges to be extended out from spring pressure. These wedges extend out into cutouts in the tool base plate, locking it into position. To decouple the tool, the servo drive rotates the disk in the master side the opposite way, which pulls the wedges back in, allowing the tool plate to separate. A key part of this research paper that applies to the proposed project is the way that this system has 2 ways of aligning. The main unit is tapered allowing for “rough alignment” and then there is a tapered pin ensuring “fine alignment”. There is also the consideration that the master side and tool plate have electrical connections allowing through connection of electrical connections. This system also uses purely electrical connection, no pneumatics required, which is better suited for Spot.

Figure 8 1) Tool base plate, 2) Master side, 3) Servo drive (Gyimothy & Toth 2011 pp. 1046-1051)

CHAPTER 3 METHODOLOGY

The proposed method below outlines the steps the project is to take to be completed.

Step 1: Basic sketch of idea

At this stage a few basic sketches of the attachment will be produced of different designs before a selected design moves to the next stage.

Step 2: 3D models

The design chosen in the previous step will be used to create the 3D models of the attachment as well as a 3D model of the claw.

Step 3: 3D printing

The claw and attachment will be 3D printed and assembled. The attachment will be tested to ensure it can sit into the claw properly, if not, adjustments are to be made to the 3D model until it does.

Step 4: Electrical circuit design

Draw a simple circuit for the spring-loaded connector and end tool. Circuit should perform something simple such as motor spinning/ LED flashing.

Step 5: Build circuit

Build circuit on prototype board and ensure functionality. If unsuitable, adjust circuit and reflect changes in circuit drawing.

Step 6: Coding

Write up code which, at the push of button will open/close the Spot gripper onto attachment. Once connected (could potentially be determined using pressure feedback or possibly a small circuit inside attachment where if expected result isn't returned, error is flagged) attachment motor will spin, LEDs will flash signifying operation of attachment.

Step 7: Assembly

Build and assemble attachment and gripper claw. If any design elements need to be adjusted, such as cutouts for electrical components, ensure these are changed in drawings.

Step 8: Testing

Testing will be conducted throughout all stages and revisions will be done to the design where needed. Final testing of the attachment will determine if the design is successful or not. This final test will be conducted by holding the attachment up to the replica gripper claw and activating the claw to close. Once closed, the claw should send through the signal to activate the test circuit and operate the LED or motor. This final test will be successful if the gripping of the attachment is solid and correct operation of the test circuit. If unsuccessful, adjust the design and retest.

CHAPTER 4 DESIGN REQUIREMENTS AND CONSTRAINTS

4.1 DESIGN REQUIREMENTS

The design requirements that have been identified for the Spot gripper attachment are listed below. These requirements are the main points for the attachment to be assessed against to determine if the design is successful.

- Require minimal changes to spot
- Attachment held securely in gripper
- Attachment has electrical connection points
- Attachment is easily aligned in gripper jaw
- Attachment is easily customizable

4.2 CONSTRAINTS

The main constraints of this design are the materials/parts used and the deadline of the project. The deadline for the project is the presentation on the 18th of September where the attachment needs to be completed and tested so that it can be demonstrated at the presentation. The material constraints of the design are that it needs to be constructed from PLA and printed on an Ender 3 V2 3D printer as this is the printer available. This means that the design needs to be adjusted for the tolerances of this printer. The parts constraints are that an Arduino is to be used and there is a limited budget of $400, $300 of which is provided by USQ and an additional $100 is provided for additional parts required. This constraint will limit the electrical components used, thus limiting the demonstration attachments. These attachments also need to be powered by the 5V provided by the Arduino.

Additional constraints are that free software to be utilised, such as Autodesk Fusion, and utilisation of existing tools such as drills, files and screwdrivers.

CHAPTER 5 BASE ATTACHMENT AND ELECTRICAL CIRCUIT DESIGN

5.1 ATTACHMENT DESIGN

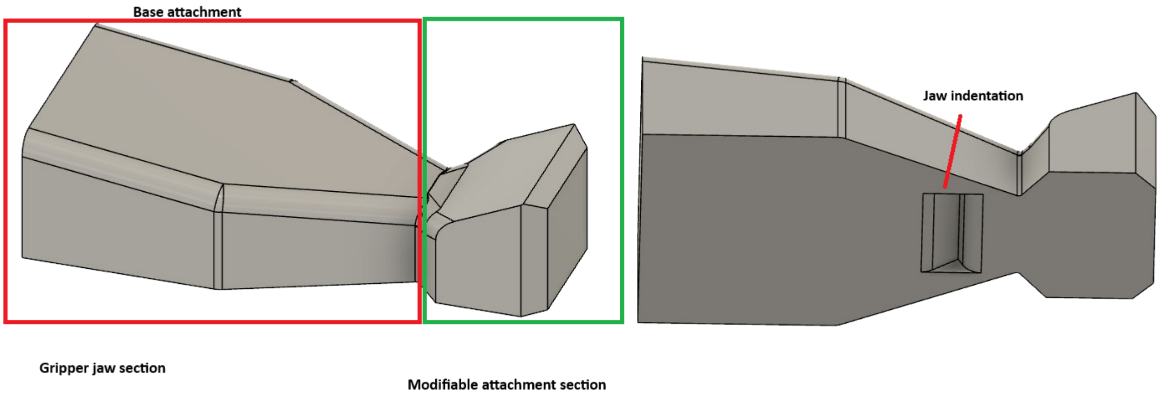

Figure 9 Base attachment

The design of the attachment was split into 2 steps, the design of the base version of the attachment and the alteration of this base design into the different attachments. The design of the base version of the attachment was developed from the shape of the Spot gripper jaw. This was decided to take the shape of the inside of the jaw while it was mostly closed, while still open enough to allow enough material at the pinch point to ensure that it won't snap. The final design was developed by printing several iterations of an initial design and evaluating their suitability. These prototypes were then adjusted and refined until the final design above was settled on. The suitability of this was determined by testing the ability of the spot gripper to hold it securely and the ease of the attachment to align itself withing the jaw. This design was also tested with a basic FEA analysis which is shown in figure 10 below.

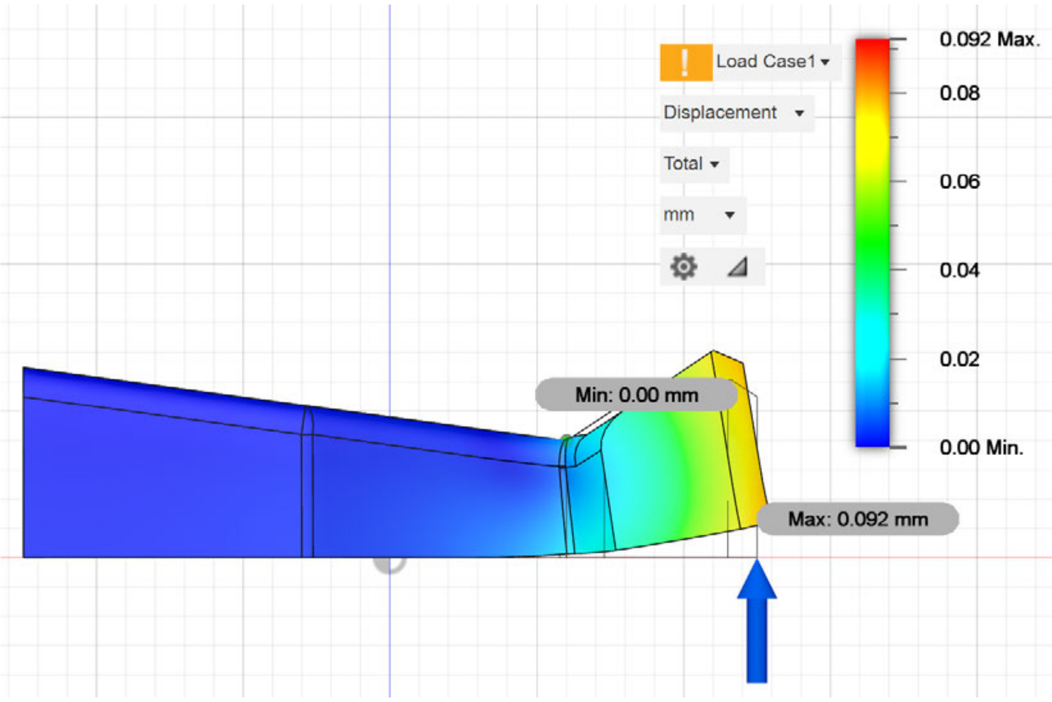

Figure 10 FEA analysis of base attachment

5.2 CIRCUIT DESIGN

The design of the electrical circuit was split into 3 stages, design of the Arduino circuit, design of a motor circuit, and the design of a LED circuit. The motor and LED circuit were design so that these circuits can be switched without modification to the Arduino circuit. A motor and LED circuit were both chosen for their simplicity. The LED circuit was chosen to show the attachments ability to transmit signals while the motor circuit was chosen to show the attachments ability to house circuits that require higher levels of power.

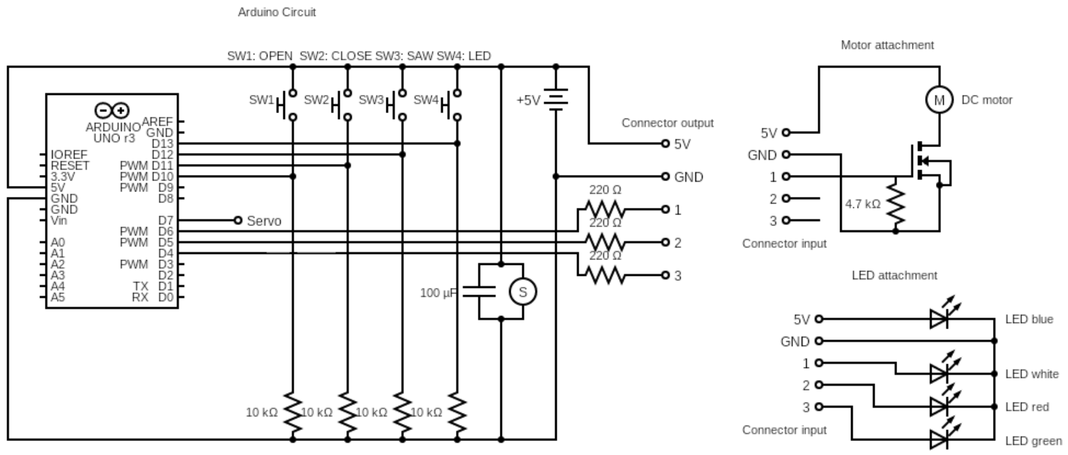

Figure 11 Circuit diagrams for Arduino circuit (left), Motor attachment (top right), LED attachment (bottom right)

5.2.1 Arduino circuit

The Arduino circuit (figure 11 left) consists of the Arduino, the servo, a capacitor, four switches with resistors and three outputs with resistors. The servo is powered by the 5V and a signal from the Arduino. There is also a capacitor included to help with the initial draw of the servo. There are four switches with 10KΩ pull up resistors and inputs to the Arduino used to trigger the different functions of the program. There is also three output lines to go to the attachments with current limiting resistors.

5.2.2 Motor circuit

The motor circuit (figure 11 top right) consists of a DC motor, a MOSFET and a resistor. The DC motor required connection to the 5V output of the Arduino due to the signal's pins output being too weak to power it. To solve this issue the MOSFET was included in the circuit. This will ensure the motor is receiving enough power while retaining the ability to switch the motor on and off instead of it being on as soon as the attachment connector contacts the jaw connector. With the MOSFET in place a resistor was required over the ground and signal pin to pull it down, otherwise the motor would not turn off.

5.2.3 LED circuit

The LED circuit (figure 11 bottom right) is four LEDs connected in parallel. Three of these LEDs are activated by signals output by the Arduino with one connected directly to power. This was done to assist with testing, with one LED used to confirm power to the attachment and the other three used to confirm signal transmission.

CHAPTER 6 ATTACHMENT DESIGN, ARDUINO CODE AND MATERIAL SELECTION

With the completion of circuit design and development of the base version of the attachment finalised, the project can proceed to the next stage of attachment design. The development of the LED and the saw attachment 3D models.

6.1 LED ATTACHMENT

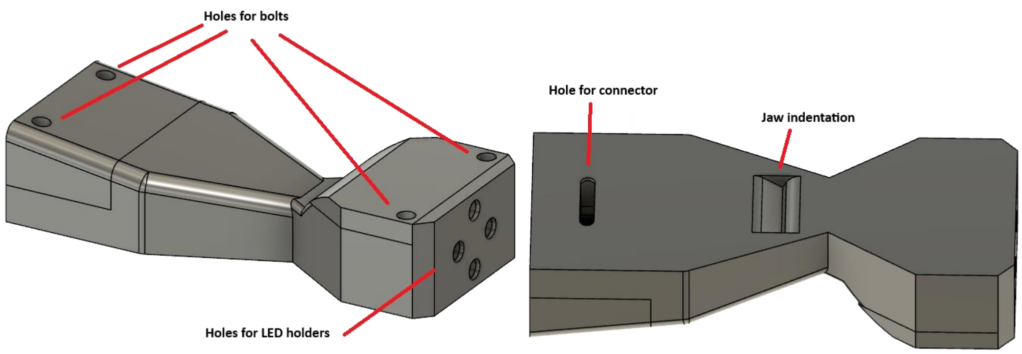

Figure 12 LED attachment

The LED attachment design was made to fit four LEDs equally spaced. This design required the front section of the base attachment to be widened and lengthened to fit the four LEDs.

6.2 SAW ATTACHMENT

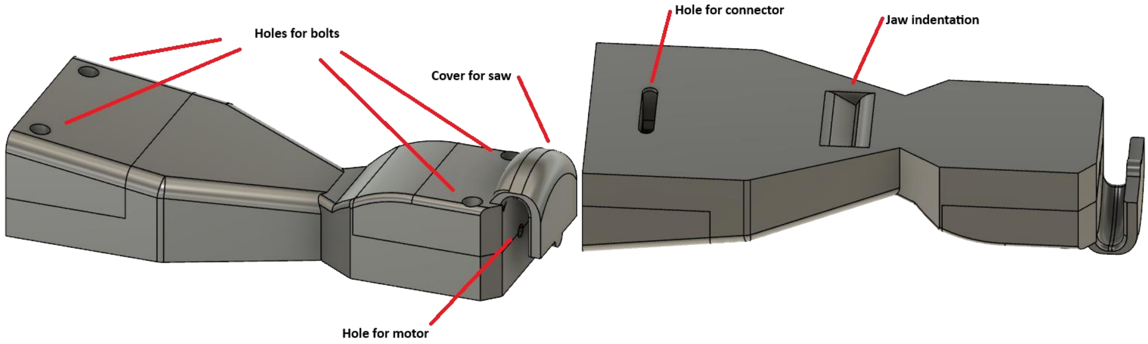

Figure 13 Saw attachment

The saw attachment was initially designed to just fit a small DC motor but with the need to be able to control it with a MOSFET, the design was modified to fit the MOSFET. This design required the front section to be elongated. The front was also modified to include a piece to support to blade as well as to provide some safety protection. For this design a saw blade was also designed.

6.3 ARDUINO CODE

The Arduino code starts by setting up the input and output pins, the servo and the initial values. The body of the Arduino code started with four individual sections, Jaw open/close functions, LED function, saw function and the main body. The main body of the code consists of four “if” statements that are checking for the switches to be pressed. These “if” statements will call either the close, open, LED or saw functions. Both the open and close functions are for statements that are used to step the servo motor which is attached to the upper jaw of the gripper. These functions slow the opening and closing of the jaw. The saw function is used to control the saw. Currently, it is just turning the saw on the whole time. It could be adjusted in the future to control the motor with PWM. The LED function is set to flash the LEDs in a rotating pattern. The Arduino code and the initial code flow chart can be found in appendix B.

6.4 MATERIAL SELECTION

With the design and code completed the material selection needed to be completed.

6.4.1 3D printing materials

The body of the attachment and the gripper jaw are to be 3D printed in Polymaker Polylite PLA due to it being a familiar material which provide good clean prints, reducing the need for any materials to be reprinted. The strength of PLA is sufficient to use for this purpose, with the bonus of easy workability.

6.4.2 Electrical components

The main electrical components needed are an Arduino, servo, dc motor and attachment connector.

The Arduino starter kit was chosen as it includes the Arduino Uno R3, a breadboard and several electrical components used for initial circuit design and testing such as LEDs, push buttons and resistors. The starter kit also came with the MOSFET and capacitor that was used in the circuit.

The Servo selected was the Tower Pro SG-5010 which is a 4.8V 5.5kg.cm servo and was selected as it can be powered by the Arduino while still providing good holding capacity.

The DC motor selected for the saw attachment was a small 3-6V hobby DC motor. This motor was chosen for its suitability to be used with an Arduino and its low cost.

The connector chosen for the attachments was a spring loaded, magnetic connector. These connectors were chosen due to the magnets which will help with secure attachment and proper alignment. They were also chosen for the spring connectors, which help to ensure a good electrical connection. Their small profile also contributes to the requirement for minimal adjustment to the face of the lower jaw.

There were two different push buttons selected, a red and black version of each. This was chosen to easily differentiate the open/close buttons and the LED/saw buttons.

Additional electrical components required were the electrical wiring, battery pack, batteries and LED holders. A 5 x AA battery pack was chosen as it had the capacity to supply the Arduino enough power to operate the servo and the DC motor. LED holders were utilised so that, if necessary, the LEDs can be swapped out while still being held securely.

6.4.3 Additional materials

A wooden base was used to mount the gripper claw and circuit, this provides additional weight to stop it from toppling over. Heat shrink was used on the wires after soldering to the connectors to provide electrical isolation, ensuring that they won't short out. M3 cap head bolts and nuts were used to bolt the parts together. Plastic screws were considered but as it was likely that the parts would need to be opened repeatedly, it was decided they would not be suitable and instead bolts should be used. The jaw and attachments were also painted using spray paint to ensure an even coat.

6.4.4 Total cost

Below is a table of the cost of the items used for the project. This does not truly reflect the cost of the project as spares of some items were ordered in case of part failure, this does not include the cost of shipping and some items like wiring were ordered but only part of it was used. Additionally, some items like the resistors, capacitor and the MOSFET were included in the starter kit so costs of some items may change depending on where they are purchased from. The other factor that this table does not consider is the electricity used during printing.

Table 1 Parts cost

Part	QTY	Unit	cost/unit	Cost
Arduino	1	ea	43.86	43.86
MOSFET	1	ea	1.5	1.5
Capacitor	1	ea	0.49	0.49
Resistor	7	ea	0.1	0.7
PLA	2	kg	36.95	73.9
motor	1	ea	3.57	3.57
LED's	4	ea	0.34	1.36
heat shrink	2	ea	1.136	2.272
Push buttons	4	ea	2.37	9.48
wire	5	m	0.488333	2.441667
servo	1	ea	$29.95	29.95
connectors	2	ea	12.73	25.46
LED holder	4	ea	0.2375	0.95
battery holder	1	ea	8.02	8.02
batteries	5	ea	0.9	4.5
			Total	208.4537

CHAPTER 7 MODELING AND CONSTRUCTION OF ATTACHMENT

The construction stage of the attachment can be separated into 4 stages, Gripper, LED, saw and additional pieces. Fortunately, a copy of the Spot gripper was able to be sourced from Boston Dynamics. This allowed the gripper to be accurately replicated and modified. For most parts there were test pieces made to check fits and tolerances first. Sometimes these test pieces were constructed by creating a new test part file and other times they were made by cutting away all irrelevant sections of the part.

7.1 GRIPPER CONSTRUCTION

Construction of the gripper jaw was the first stage to be completed as the gripper was needed for the testing and evaluation of the attachment prototypes. In preparation for the printing of the gripper it needed to first be separated in Autodesk fusion to be able to seat the servo motor. Then various test pieces needed to be printed to check tolerances and finally the pieces can be printed.

7.1.1 Modifying the jaw model

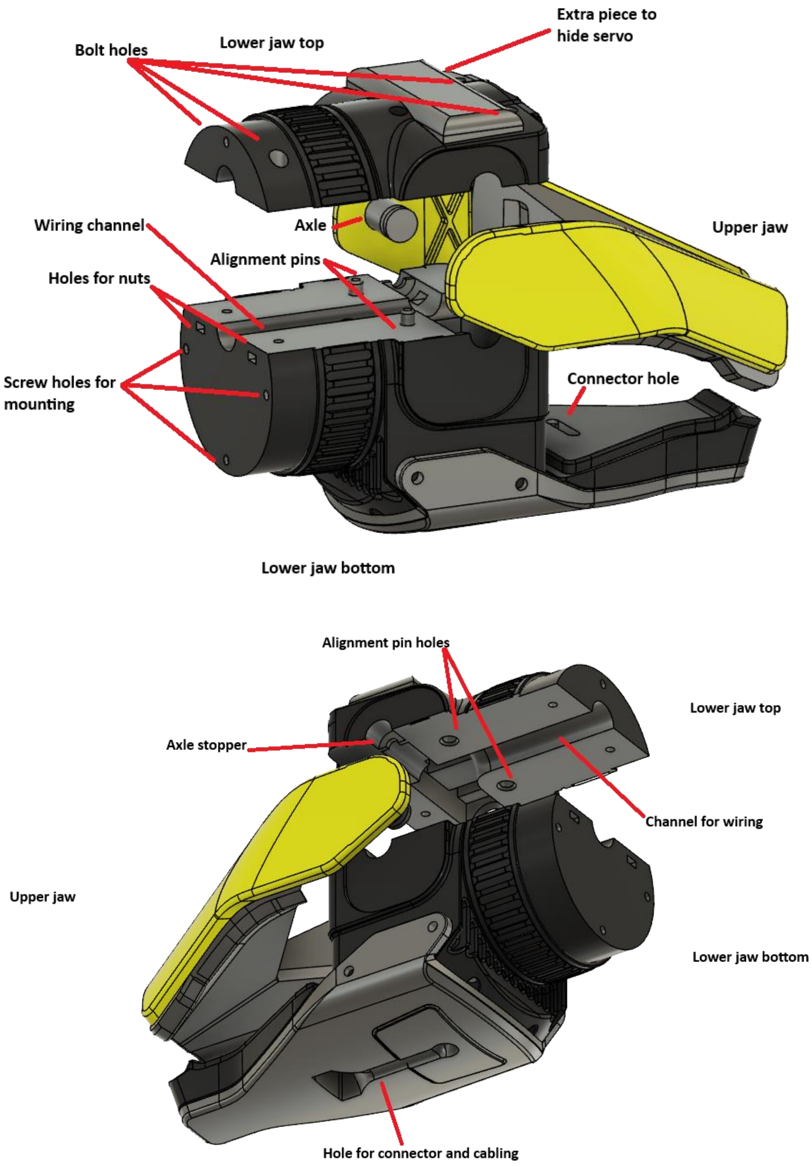

Figure 14 Gripper jaw

The first step in 3D printing the jaw was to separate the main body of the jaw that will house the servo, which is the lower jaw. This was done by extruding a rectangular sketch, where the line of the sketch intercepts the centre of the pivot point of the upper jaw. The placement for this was determined by measuring the central pivot point of the jaw in the file obtained from Boston dynamics. This point was chosen due to the ease of centring the servo motor and assembly of the jaw. There was also a cutout done in the bottom part of the jaw where the connector will sit. Along with this a channel was created for the connector and servo wiring. Lastly, to fit the servo wiring, a small amount of material had to be added to the top of the lower jaw so that the space didn't cut all the way through.

7.1.2 Test pieces

Figure 15 Jaw axle test (left), Servo top cavity test (middle), Jaw pivot tests (right)

The next step before printing the jaw was to print test pieces to ensure that all pieces will fit and align correctly. There were two sections that needed to be tested, the hole for the servo and the pivot for the other side of the jaw. The servo hole (figure 15 middle) was the first to be created and tested. Due to the shape of the jaw the servo needed to sit upright. The servo has a tab on the top and bottom for screwing in which needed to be allowed for as well as the main body. There is also a bevel leading up to the gear of the servo which was allowed for. The lower test piece of the servo hole was the first printed and then adjusted to ensure correct positioning for the gear within the hole. To ensure a tight fit, the rubber pads for the servo were used.

The next test piece printed was the top of the servo hole (figure 15 middle) which had to account for the same issues as the bottom test piece plus some allowance for the wiring.

The other side of the jaw required several different test pieces due to there being multiple methods for pivoting that were tested. The first method (figure 15 right) required a piece that screwed through the upper jaw, into the lower jaw. The second method (figure 15 right) was to have a piece of dowel with cap that was inserted through the lower jaw. The third and final method (figure 15 left) was to edit the upper jaw to have an axle extrude from it, into the lower jaw. The third method was chosen for simplicity and fewer parts.

7.1.3 3D printing

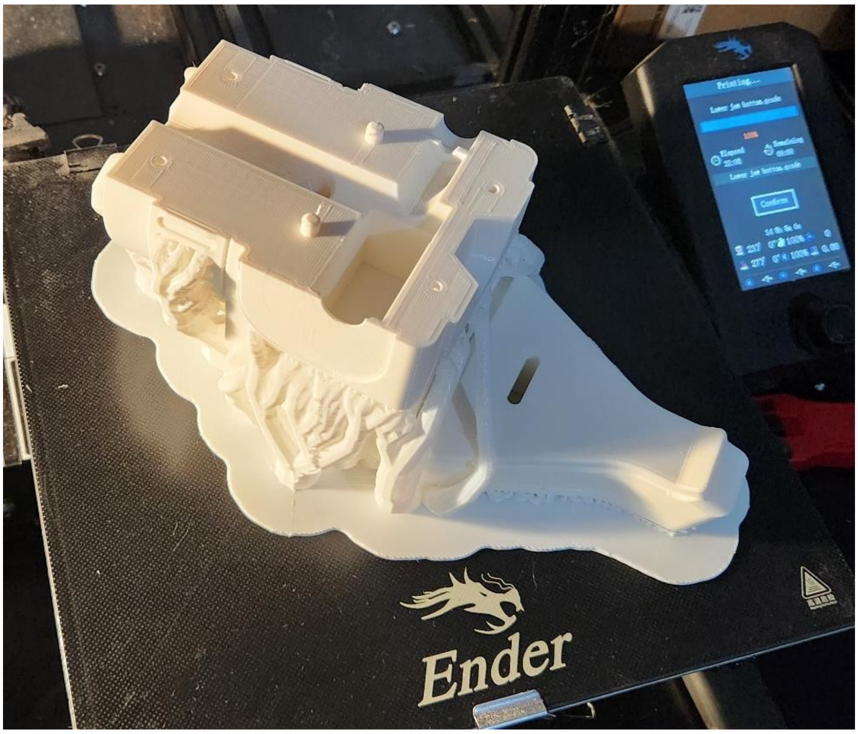

Figure 16 Finished 3D print of Lower jaw bottom

With all the test pieces completed, the tolerances checked and the fit of all items confirmed, the next step was to edit the jaw to get it ready for printing. This required the creation of holes and slots for the nuts and bolts and pins and holes for alignment as well as holes for cabling. Once this was completed the parts needed to be loaded into a 3D printing slicer. A 3D slicer takes a 3D object and slices it into layers according to your settings. The slicer used was Ultimaker cura and the main settings used are in the table below. There are many settings available so only the most important or the settings that have been changed are listed, all other settings that were not listed were left as default.

Table 2 Slicer settings

Slicer setting	Value
Quality/layer height	0.2mm
Wall line count	3
Infill	40%
Printing temperature	210℃
Build plate temperature	60℃
Speed	50mm/s
Support	On, tree support
Build plate adhesion	Raft where needed

7.1.4 Assembly of the jaw

Figure 17 Test assembly of gripper parts

With the parts now printed, the jaw components could be assembled. The connector was first to be put in place and was able to be seated very securely and didn't require any glueing. The servo horn was glued into place with superglue and allowed to dry. The axle on the other side of the upper jaw needed some sanding to fit in place and rotate freely. Once this was completed the jaw was assembled with the servo and connector in place. The operation of the jaw was then tested and confirmed. The jaw was then painted to match the appearance of the actual Spot gripper.

7.2 SAW ATTACHMENT

The next piece to be constructed was the saw attachment. As was the case with the gripper jaw, some preparation needed to be done to the 3D model before printing.

7.2.1 Modifications to the attachment

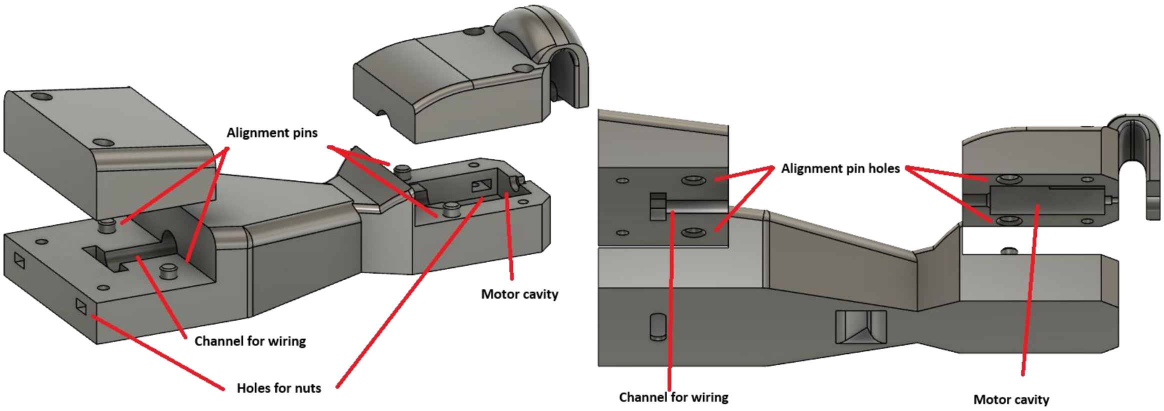

Figure 18 Saw attachment split

The modifications to the attachment consisted of the hole for the connector, a channel for the wiring, the cavity for the motor and splitting the attachment to allow access to insert components. The decision was made to split the attachment into three parts instead of in half to retain the strength of the attachment at the point the gripper clamps down. The front of the attachment was split at the centre of the hole for the DC motor to allow correct alignment of the motor. The back of the attachment was also split to allow access to insert the connector.

7.2.2 Test pieces

Figure 19 Saw attachment test pieces

With the modifications done some test pieces can be printed to test the fit and alignment. The connector dimensions were tested and confirmed in previous test pieces. This still left the motor cavity and the top section that was separated from the front of the attachment. These test prints were checked for fit with the DC motor and a miniature saw blade which was printed.

7.2.3 3D printing

With the above steps completed, the three pieces of the saw attachment were printed. Starting with the base of the attachment and the back section, both of which were printed flat on the print bed. The front section had to be printed with a raft and supports due to the shape.

7.2.4 Assembly of the saw attachment

Figure 20 Saw attachment

The assembling of the Saw attachment was completed in two stages. In the first stage the connector and wires were put in place, fitting tightly without needing any glue. In the next stage the motor, MOSFET and resistor were soldered to the wires and seated in place. After this, the mini saw was glued to the motor and aligned to fit with the front top section. All parts were then assembled, sanded where needed and then painted. The main body was painted black, and the removable sections were painted yellow to match the colour scheme of the Spot gripper. Additional pictures in appendix C.

7.3 LED ATTACHMENT

The LED attachment was the last attachment to be completed and followed the same process as the previous two sections.

7.3.1 Modifications to the attachment

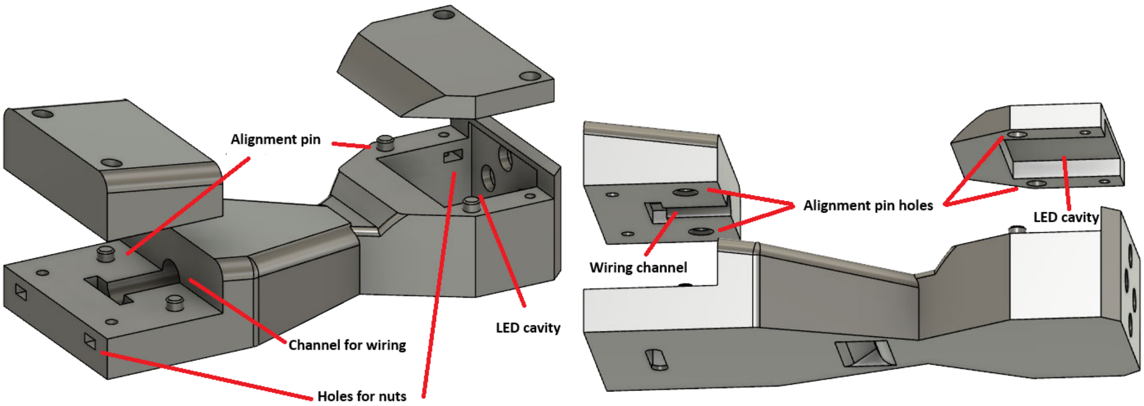

Figure 21 LED attachment split

The modifications to the attachment for the LEDs were to widen and lengthen the front of the attachment and adding the holes for the LEDs. The attachment was split at the same point as the saw attachment at the rear with the front of the LED attachment split at the very top due to the LED hole placement.

7.3.2 Test pieces

Figure 22 LED attachment test pieces

As the LED attachment is only different at the front from the attachment, the back part didn't need to be tested. The only test part necessary was the front part where the 4 LEDs and LED holders were to be inserted.

7.3.3 3D printing

With the test pieces done and the model modified where needed, the attachment can be printed. As with the saw attachment, the rear and base of the attachment were printed flat with the front top part printed on a raft to ensure the top was printed with a nice finish.

7.3.4 Assembly of the LED attachment

Figure 23 LED attachment

With all pieces printed, the attachment was then assembled. The connector was inserted, and the wiring put through to the front. The LEDs were arranged, and their cathodes were soldered together. The wires were then soldered to the corresponding LEDs with shrink wrap over the soldered sections. The LED holders were then glued in place and once dried, the LEDs were inserted into them, with the excess wiring curled into the bottom of the cavity. All sections were then assembled and bolted together, sanded where necessary and then the attachment was painted. As with the other attachment, the base was painted black, and the removable sections were painted yellow. Additional pictures in appendix C.

7.4 ADDITIONAL PIECES

Figure 24 Switch holder/circuit cover and Jaw holder

Along with the gripper and the attachments, a holder for the gripper was printed as well as a cover for the circuit, which also holds the switches.

7.4.1 Jaw holder

The Jaw holder was designed and printed so that it can hold the gripper upright. This was mostly used to enable the testing of the attachment fit but it was also useful for the presentation.

7.4.2 Switch holder and circuit cover

The circuit cover that was designed and printed also doubled as a holder for the switches. This was printed to protect the circuit and ensure nothing would damage the circuit and as a safety precaution.

7.5 PRINT TIMES

Printing times were one of the biggest limiting factors during the development of the attachment. When printing a test piece of certain part, this would mean that no more alterations could be done to that part until the test pieces were completed. Either a different part would need to be worked on, or the work would be halted until the test pieces were completed. Some test pieces were relatively quick, taking less than 10 minutes, other took much longer. The initial base attachment prints, for example, would take approximately 5 ½ -hours to print even when printed with less infill (weaker but faster print). While this is still much faster than other prototyping methods, it was a major factor that needed to be considered. Below in table 3 are the listed print times of the different parts that were printed.

Table 3 3D printing times

Part	Sub part	Print time	Filament use (g)
Gripper	Upper jaw	14hrs 5mins	113
	Lower jaw top	10hrs 17mins	86
	Lower jaw bottom	36hrs 24mins	359
LED attachment	Attachment body	9hrs 46mins	87
	Attachment front	1hr 35mins	10
	Attachment back	2hrs 48mins	25
Saw attachment	Attachment body	7hrs 49mins	74
	Attachment front	4hrs 6mins	27
	Attachment back	2hrs 48mins	25
Gripper holder		28hrs 19mins	252
Switch holder		14hrs 37mins	117
	Total	132hrs 34mins	1175

CHAPTER 8 ANALYSIS AND PERFORMANCE.

The attachments were tested all throughout the design process and adjustments were made where necessary. The performance of the attachments was compared against the following design requirements:

- Attachment held securely in the gripper
- Attachment is easily aligned
- Attachment makes a secure electrical connection

To test the attachment could be held securely, during the design phase, it was placed in the gripper jaw with the servo providing clamping force. Removal of the attachment without opening the jaws was then attempted. When testing, if the attachment could be removed without the need for a lot of force, the attachment was then adjusted and retested.

To test the attachments alignment, it was placed in the jaw at various angles approx. ± 15° from centre. Angles outside of this range were not tested as it was determined that it would be easier to move the gripper if the attachment was beyond this range. The jaw was then closed, and the attachment checked for alignment visually and using the LED from the attachment. If the LED didn't light up, then the attachment wasn't connected.

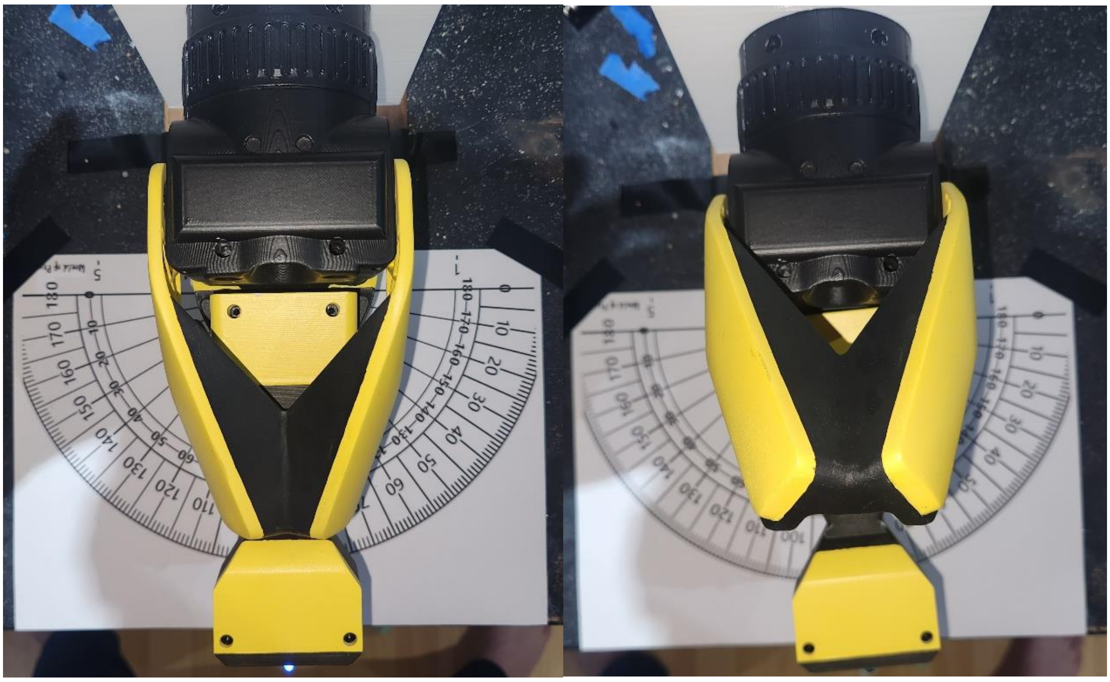

Figure 25 Attachment at 0 (left), Attachment at 10(right)

The electrical connection was tested by disconnection and reconnecting the attachment and measuring the continuity, an example of this test is shown below (figure 26). The attachment was considered to pass this test if the total resistance of the wiring and connector were less than 1Ω. Each wire was tested three times, and the results are listed in chapter 9.

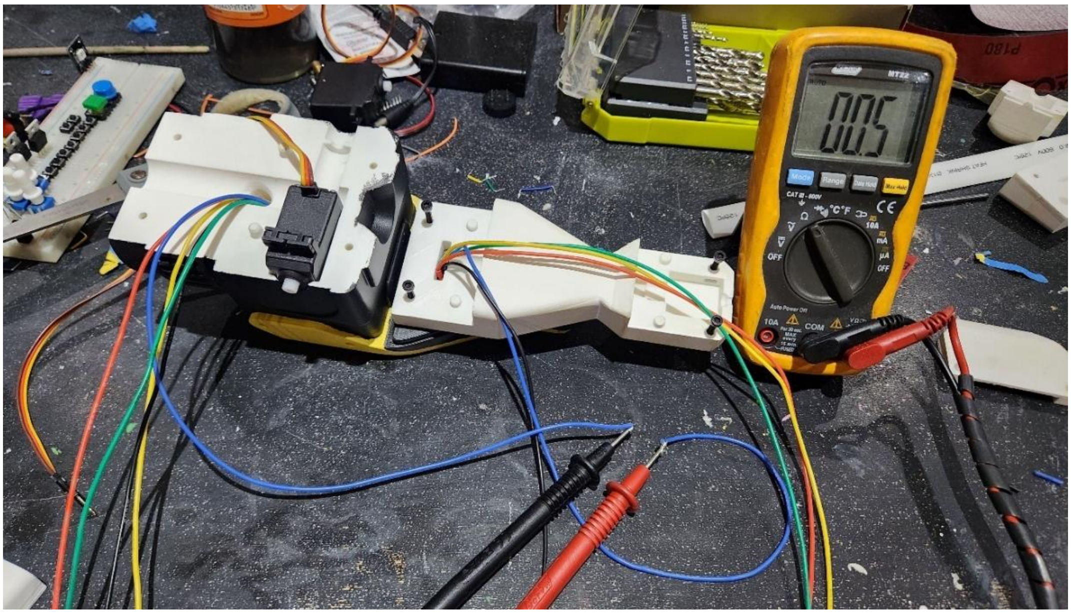

Figure 26 Electrical connection test

CHAPTER 9 RESULTS AND DISCUSSIONS

9.1 RESULTS

From the testing performed it was determined that the attachment base design and the attachment prototypes that were constructed were successfully able to meet the design requirements listed in the report.

The electrical test was successfully completed with all wires testing under 1Ω. At the time of testing the wires only passed if the resistance measured was less than 1Ω. The actual resistance values were not recorded but were typically between 0.5 and 0.3Ω.

Table 4 Electrical test

	Wires (Y = pass, N = fail)				
Test	Red	Black	Green	Yellow	Blues
1	Y	Y	Y	Y	Y
2	Y	Y	Y	Y	Y
3	Y	Y	Y	Y	Y

It was determined during b testing that the attachments were securely held by the gripper. By attempting to move the gripper it was found that the weakest grip is when the attachment was pulled away from the gripper. The most secure grip was when force was applied downward on the gripper. When the attachment was moved around side to side or twisted it was held securely. This test was found to be very subjective and perhaps not a good evaluation for two reasons. The first is that it didn’t use any repeatable, measurable method to test. The second reason is that the gripping force of the test gripper is significantly lower than that of the real gripper. Despite these two issues the test and results are sufficient to evaluate that the attachment isn’t poorly held nor will it come loose easily.

During testing it was found that the attachment can successfully align in the gripper when tested within ± 5° of centre, however any angles greater than this failed to align, as seen in table 5. The underside of the attachment has an indentation to conform with the lower gripper jaw, as shown below. During testing it was found that if the indentation was not near the corresponding part of the lower jaw, when the gripper closes, it will clamp the attachment in place (figure 27). During the testing it was also found that the magnetic connector was the main factor in the alignment. Due to the strength of the magnets, if the connectors get near each other, they would be attracted and force the attachment to align.

Table 5 Alignment test results

Test	Angle (approximate angles tested) (Y = pass, N = fail)						
	-15	-10	-5	0	5	10	15
1	N	N	Y	Y	Y	N	N
2	N	N	Y	Y	Y	N	N
3	N	N	Y	Y	Y	N	N

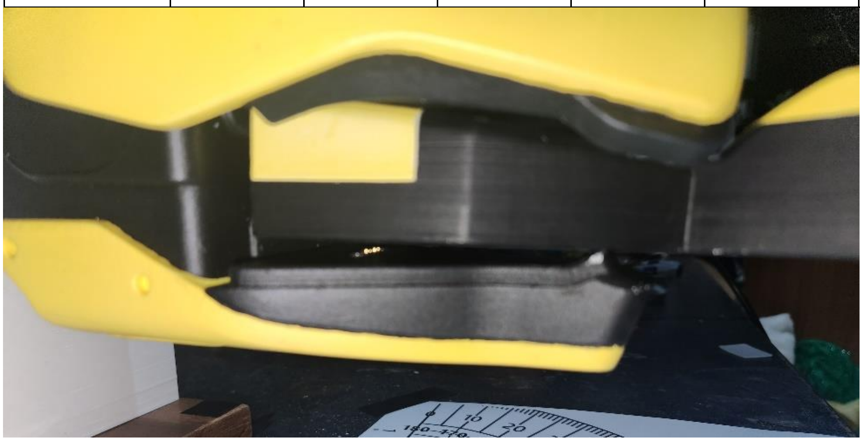

Figure 27 Failed alignment test

9.2 DISCUSSION

The test results above were sufficient to determine this "proof of concept" design is successful when evaluated against the requirements set out in chapter 4.

Some of the testing was relatively straight forward such as the continuity testing, however the test to determine if the attachment was secure needs to be refined. The tests also showed that the aligning of the attachment needs work to expand the range of angles that will work. This likely requires the adjustment of the underside indentation of the attachment as this, along with the connector, are the main points of alignment.

This attachment required minimal adjustment to the gripper jaw, only the addition of the connector in the lower gripper jaw. This is required for the attachment to have an electrical connection to Spot. Without this the attachment could be made that either uses batteries or isn't powered at all but this would reduce the options of the attachments. The connector could be retrofitted to existing grippers by cutting the small amount out of the gripper jaw, otherwise it would need to be incorporated into the production.

It was also shown that the attachment could be easily modified as a base attachment was first created and then this was then modified to create two different attachments.

The general basis of the attachment was designed and evaluated in this project. Most of the project was spent on designing and printing prototypes, checking fit and size etc with the testing conducted on the final design. Future work to be completed to enhance the attachment is material selection, development of real-world attachments and the integration of QR code recognition.

The initial concept of this project involved not just the attachment but also the use of a QR code to use for 3D orientation data and attachment identification. This would build on the work done by Yokoyama et al (2024, pp. 779-786) where the QR code would be scanned and then load the attachments skill library for use by Spot. The development of this system was determined to be outside of the scope of this project.

The material selection would require in depth FEA analysis on not just on the existing attachment files but also on revised versions of the attachment. There is the very strong likelihood that other attachments would require more space inside, and this would require stronger materials. If the attachment was to be made from steel for example, the attachment could be hollowed out with thin walls and allowing a lot more space for more circuitry.

While this attachment has a lot of potential and it has been shown that it can work, further exploration into real world use cases needs to be completed in order to further develop the attachment. This could potentially require the revision of the connector requirements if the attachments need additional signal lines or voltages above what the magnetic connector can handle.

CHAPTER 10 CONCLUSIONS

In conclusion this project has successfully shown that an attachment for the Spot gripper can be produced which meets the following criteria:

- Require minimal changes to spot
- Attachment held securely in gripper
- Attachment has electrical connection points
- Attachment is easily aligned in gripper jaw
- Attachment is easily customizable

While the attachment was successfully designed and tested there is more work to be done before it could potentially be moved into production. Work to further develop the attachment include additional FEA analysis on different hollowed out versions of the attachment and testing different materials. There also needs to be more research into potential uses to further develop the attachment and connector used. Lastly the investigation and development of better tests is recommended. This could be either the development of test rigs and the use of additional measuring devices, or new more comprehensive tests used. The use of either the actual Spot arm or just the gripper would also be recommended for further testing.

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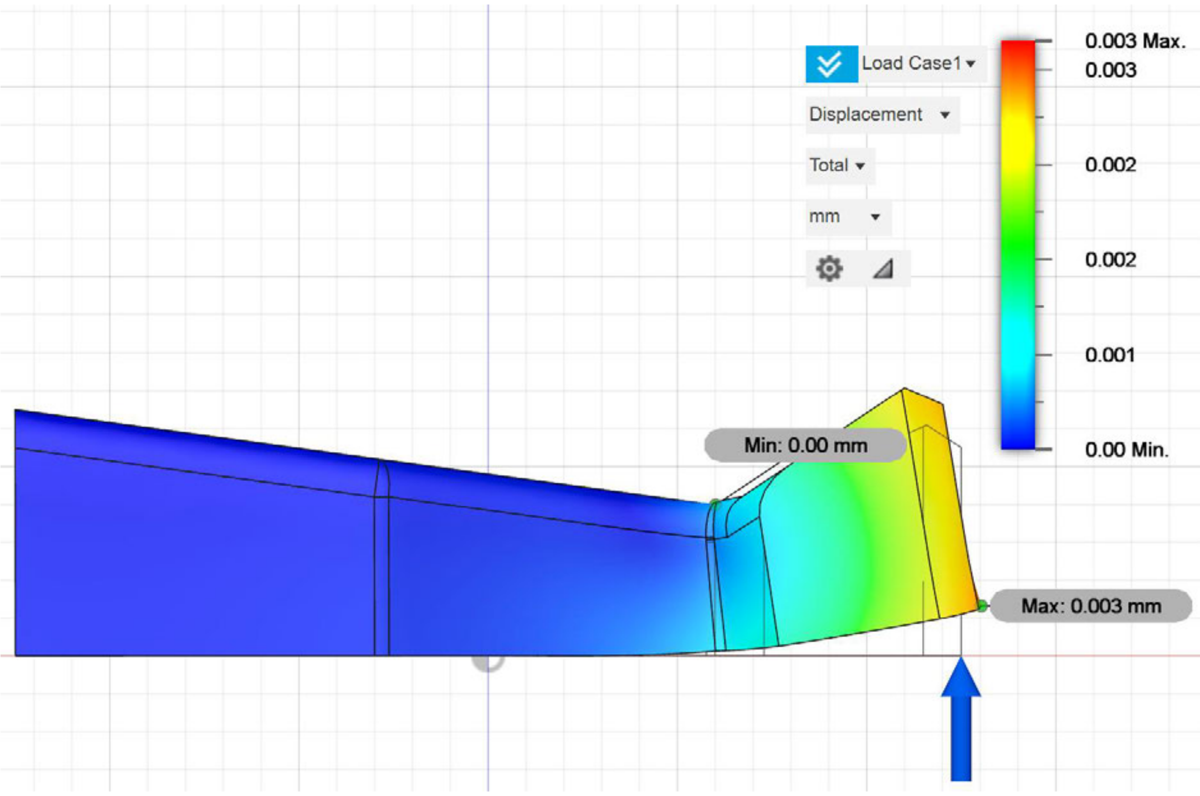
Advanced Intelligent Mechatronics (AIM), Budapest, Hungary, IEEE , pp. 1046-1051 viewed 18 March 2024, <https://ieeexplore-ieee-org.ezproxy.usq.edu.au/document/6027122>.

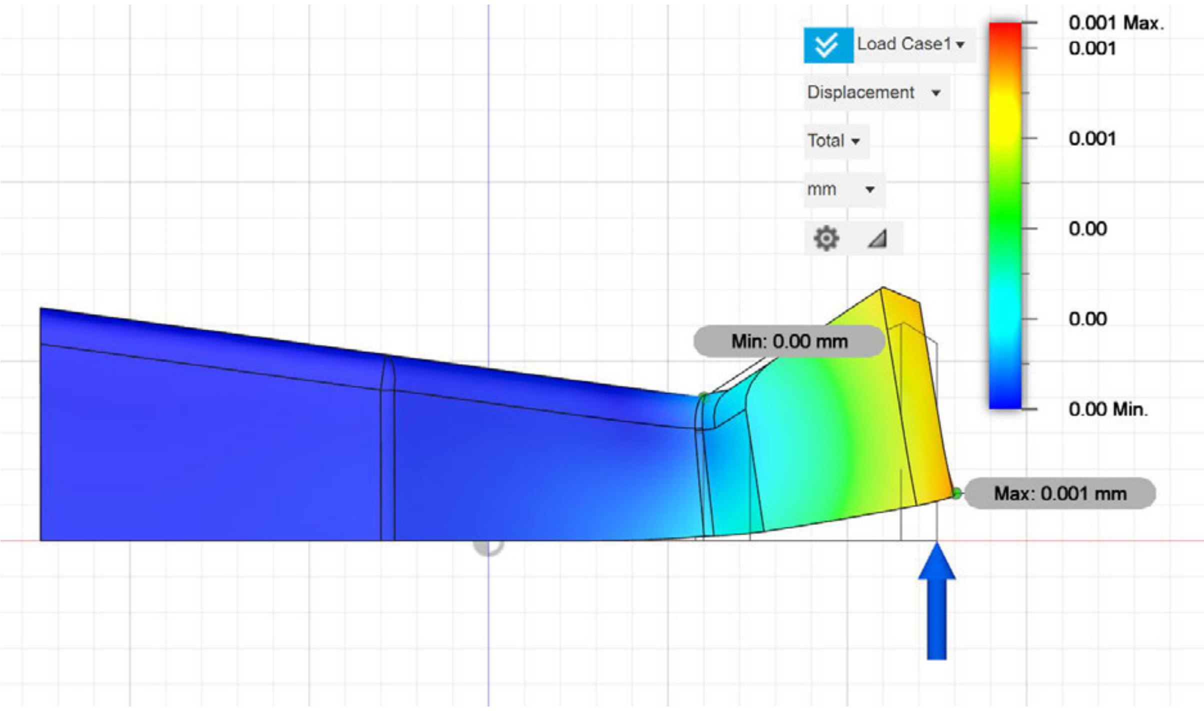
APPENDIX A

Additional FEA analysis of base attachment in aluminium, steel and plastic (PLA).

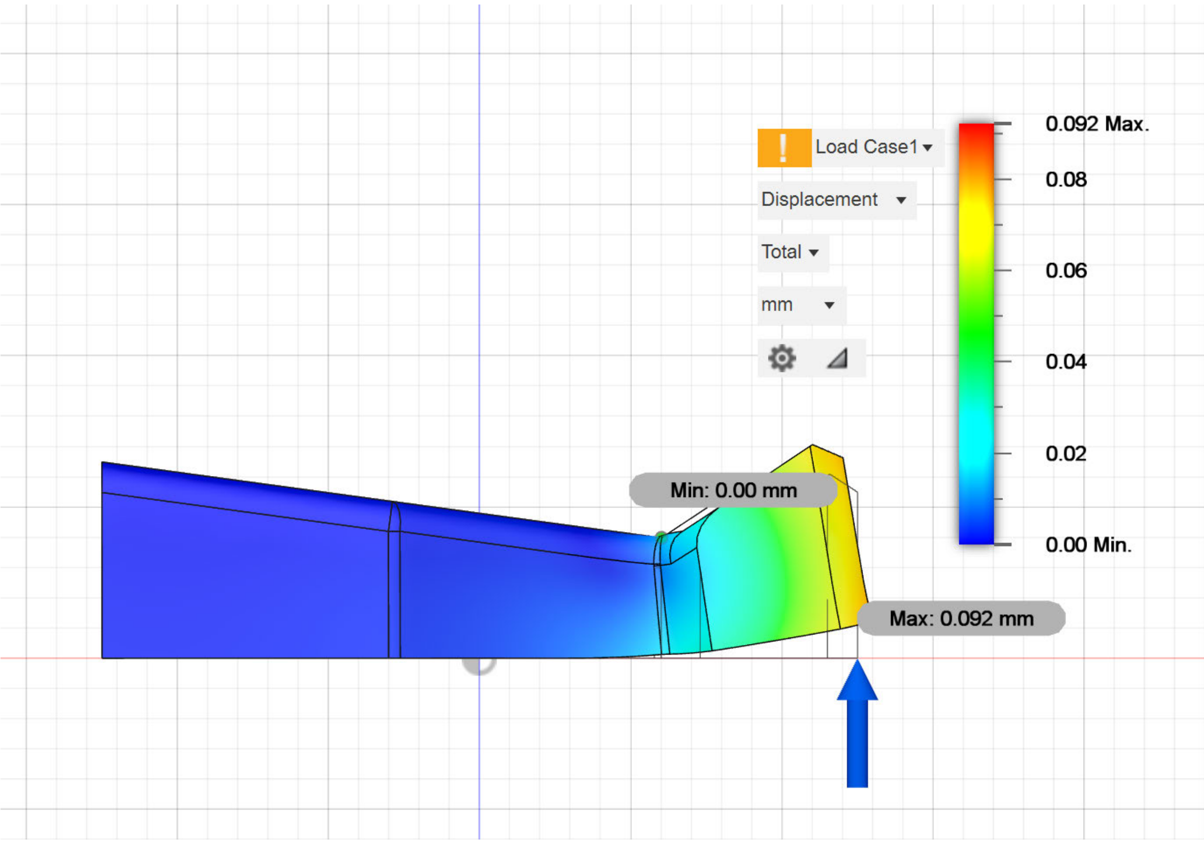
Aluminium



Steel

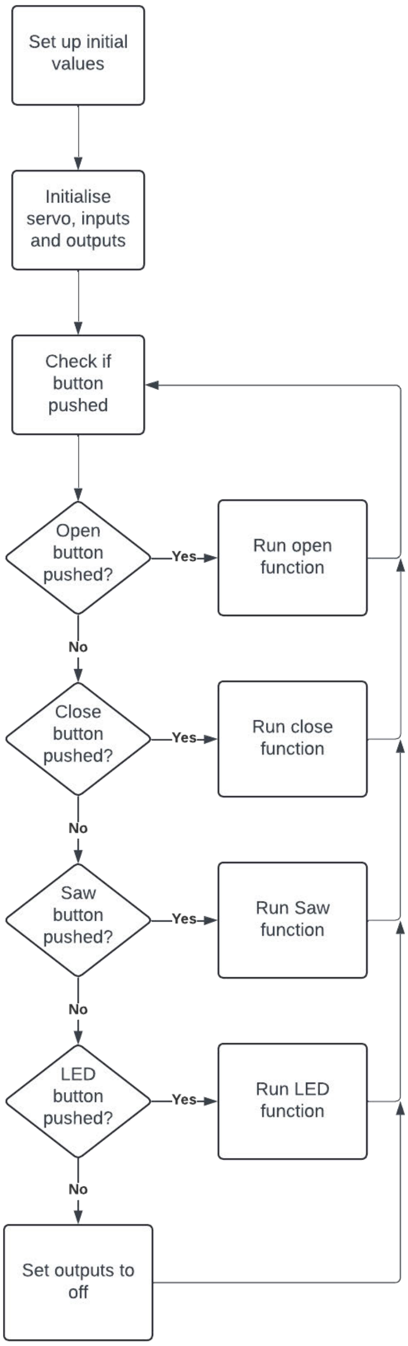


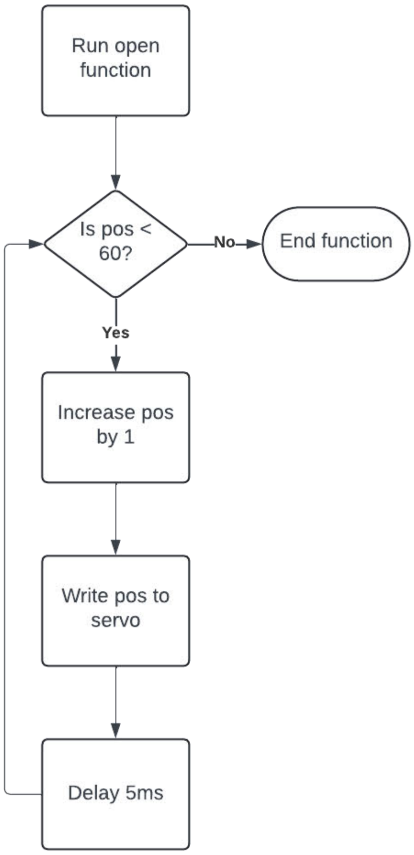
Plastic (PLA)

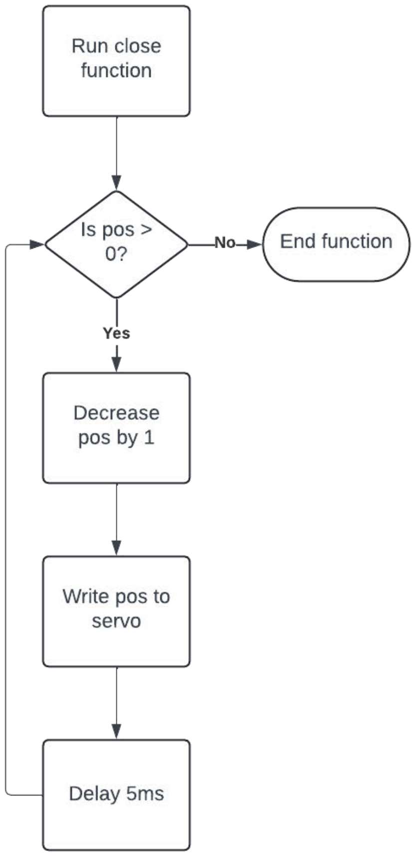


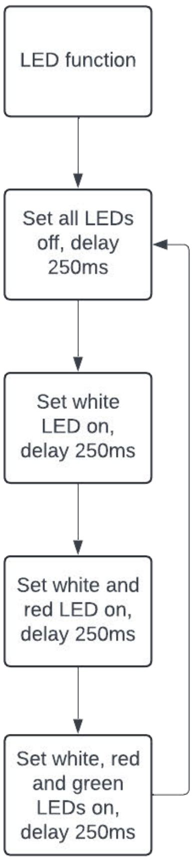
APPENDIX B

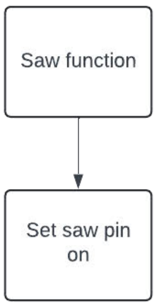
Coding flow chart and code.

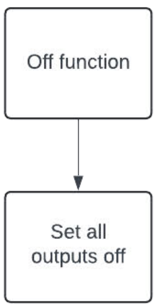



Run open function
Is pos < 60?
No
End function
Yes
Increase pos by 1
Write pos to servo
Delay 5ms


Run close function
Is pos > 0?
No
End function
Yes
Decrease pos by 1
Write pos to servo
Delay 5ms


LED function
Set all LEDs off, delay 250ms
Set white LED on, delay 250ms
Set white and red LED on, delay 250ms
Set white, red and green LEDs on, delay 250ms


Saw function
Set saw pin on


Off function
Set all outputs off

Arduino code

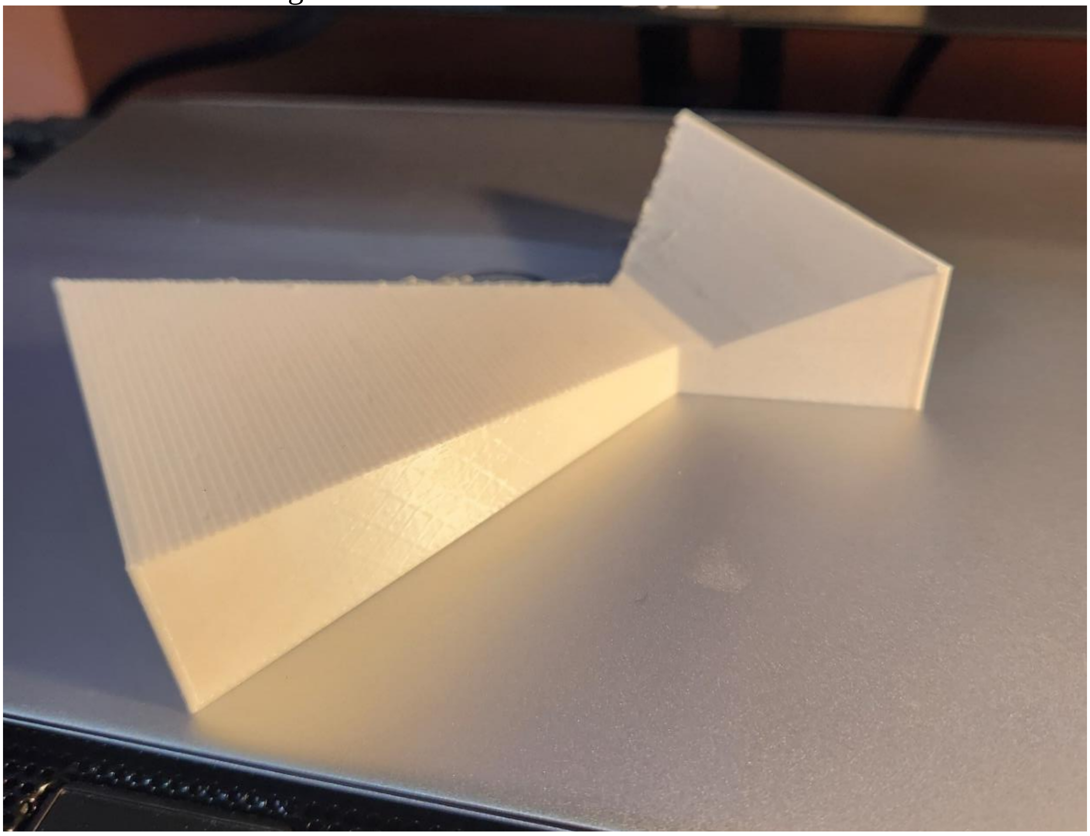
```
/*
  Jaw Program
 Created 28/08/2024
 by Thomas Eustace
 This code was created for my final thesis project "Spot gripper attachment".
 This code is designed to control the servo that opens and closes the gripper jaw
 as well as switching signals sent through to the attachment.

 last modified 12/10/2024
 by Thomas Eustace
*/

#include <Servo.h>

// create Servo object to control a servo
Servo myservo;
int pos = 0;

// Set the pin numbers for arduino
const int OpenbuttonPin = 13;
const int ClosebuttonPin = 12;
const int SawbuttonPin = 11;
const int LEDbuttonPin = 10;
const int ServoPin = 7;
const int Output1 = 5;
const int Output2 = 4;
const int Output3 = 3;

// Set up variables for buttons
int OpenState = 0;
int CloseState = 0;
int SawState = 0;
int LEDState = 0;
int OutputState = 0;

void setup() {
  // Initialize the Servo and set starting position 45 degrees
  myservo.attach(ServoPin);
  myservo.write(45);
  // Initialize output pins
  pinMode(Output1, OUTPUT);
  pinMode(Output2, OUTPUT);
  pinMode(Output3, OUTPUT);
  // Initialize the pushbutton pins as inputs
  pinMode(OpenbuttonPin, INPUT);
  pinMode(ClosebuttonPin, INPUT);
  pinMode(SawbuttonPin, INPUT);
  pinMode(LEDbuttonPin, INPUT);
}

void loop() {
  // Read the state of the pushbuttons and write to a State variable
  OpenState = digitalRead(OpenbuttonPin);
  CloseState = digitalRead(ClosebuttonPin);
  SawState = digitalRead(SawbuttonPin);
```

```
  LEDState = digitalRead(LEDbuttonPin);

  // Check if a Jaw pushbutton is pressed.
  //If it is, perform the included function
  if (OpenState == HIGH) {
    // Run open function
        Open();
    }
  else if (CloseState == HIGH) {
    // Run close function
      Close();
  }
  else{
  }
 // Check if an attachment pushbutton is pressed.
 //If it is, perform the included function, if not, stop all output
  if (SawState == HIGH) {
    // Run saw function
    SAW();
    }
  else if (LEDState == HIGH) {
    // Run LED function
    LED();
  }
  else{
    OFF();
  }
}

// Jaw close program
void Close(){
  // While servo position is greater than 0 decrease position by 1
  while (pos > 0) {
  // Decrease the position by 1 degree at a time with a 5ms delay
    pos--;
    // Tell servo to go to position in variable 'pos'
    myservo.write(pos);
    // Waits 5 ms for the servo to reach the position
    delay(5);
  }
}

// Jaw open program
void Open(){
  // While servo position is less than 60 increase position by 1
  while (pos < 60) {
    // Increase the position by 1 degree at a time with a 5ms delay
    pos++;
    // tell servo to go to position in variable 'pos'
    myservo.write(pos);
    // Waits 5 ms for the servo to reach the position
    delay(5);
  }
}

// Saw program
void SAW (){
  // Output high signal on pin to activate the DC motor
  digitalWrite(Output1, HIGH);
```

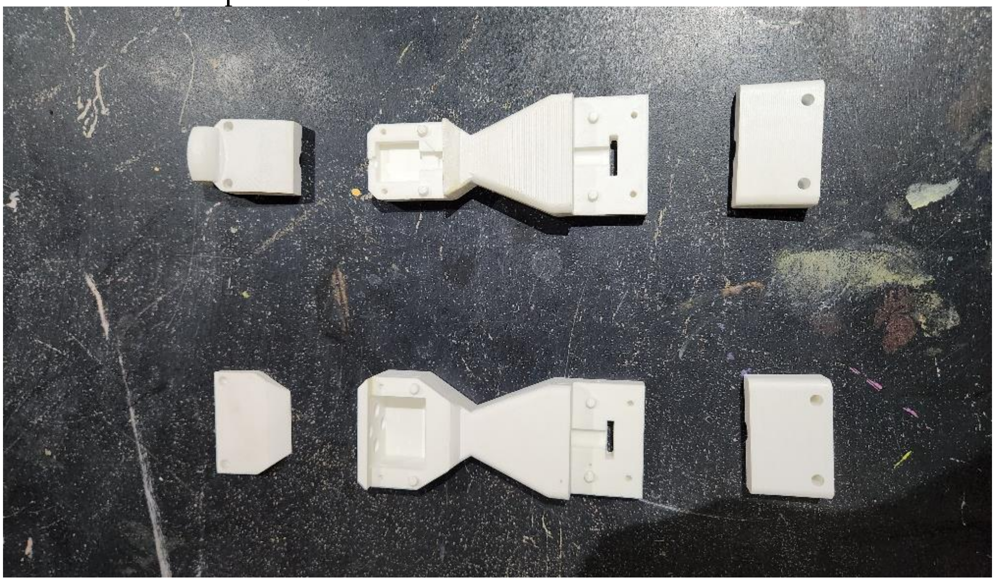
```
  digitalWrite(Output2, LOW);
  digitalWrite(Output3, LOW);
}

// LED program
void LED (){
  // Set white, red and green LEDs to off and delay for 0.25s
  // Blue stays on permanently
  digitalWrite(Output1, LOW);
  digitalWrite(Output2, LOW);
  digitalWrite(Output3, LOW);
  delay(250);
  // Set white LED on, red and green off
  digitalWrite(Output1, HIGH);
  digitalWrite(Output2, LOW);
  digitalWrite(Output3, LOW);
  delay(250);
  // Set white and red LED on, green off
  digitalWrite(Output1, HIGH);
  digitalWrite(Output2, HIGH);
  digitalWrite(Output3, LOW);
  delay(250);
  // Set all LEDs on
  digitalWrite(Output1, HIGH);
  digitalWrite(Output2, HIGH);
  digitalWrite(Output3, HIGH);
  delay(250);
}

// Off function
void OFF(){
  // Set all outputs to off
  digitalWrite(Output1, LOW);
  digitalWrite(Output2, LOW);
  digitalWrite(Output3, LOW);
}
```

APPENDIX C

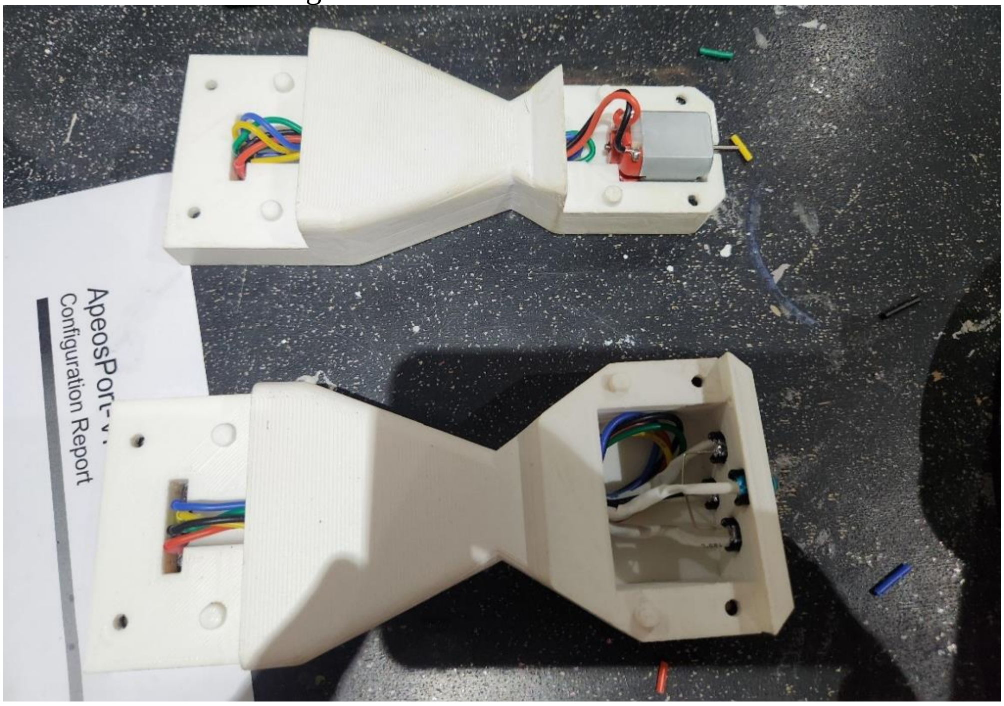
Additional pictures of test pieces, construction pieces and completed pieces.
Initial attachment design.



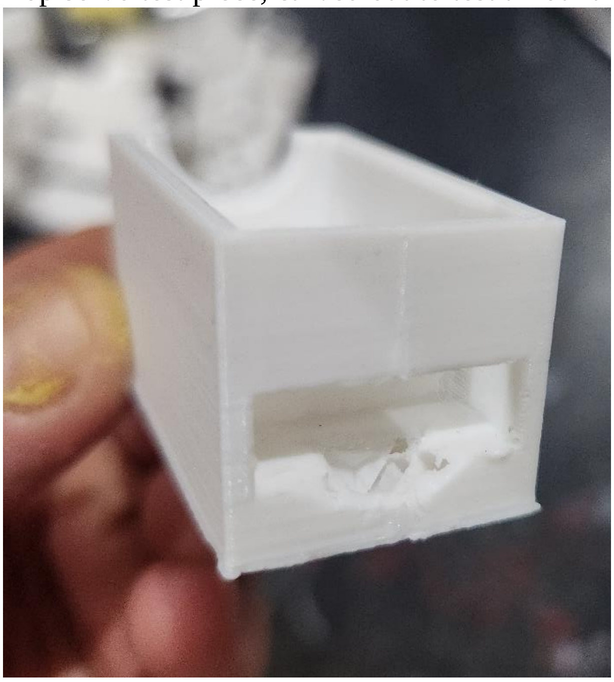
All 6 attachment pieces.



Attachments with wiring

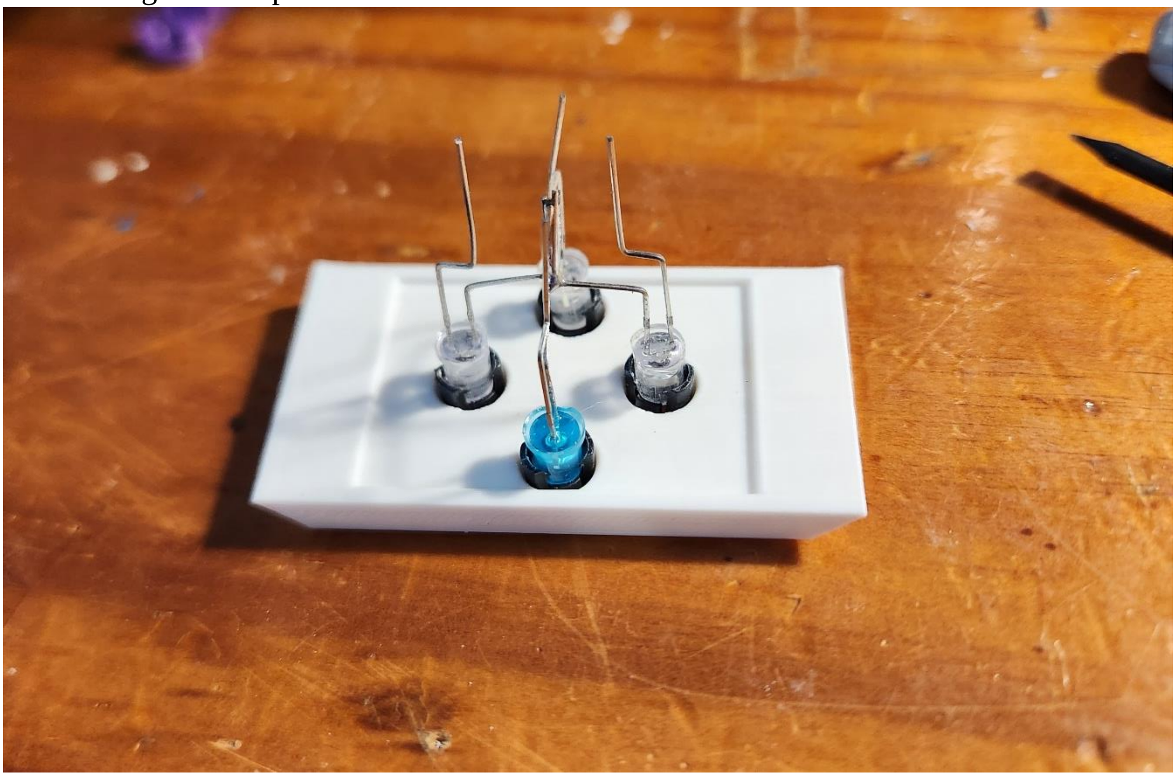


Top servo test piece, carved out to test amount of clearance needed



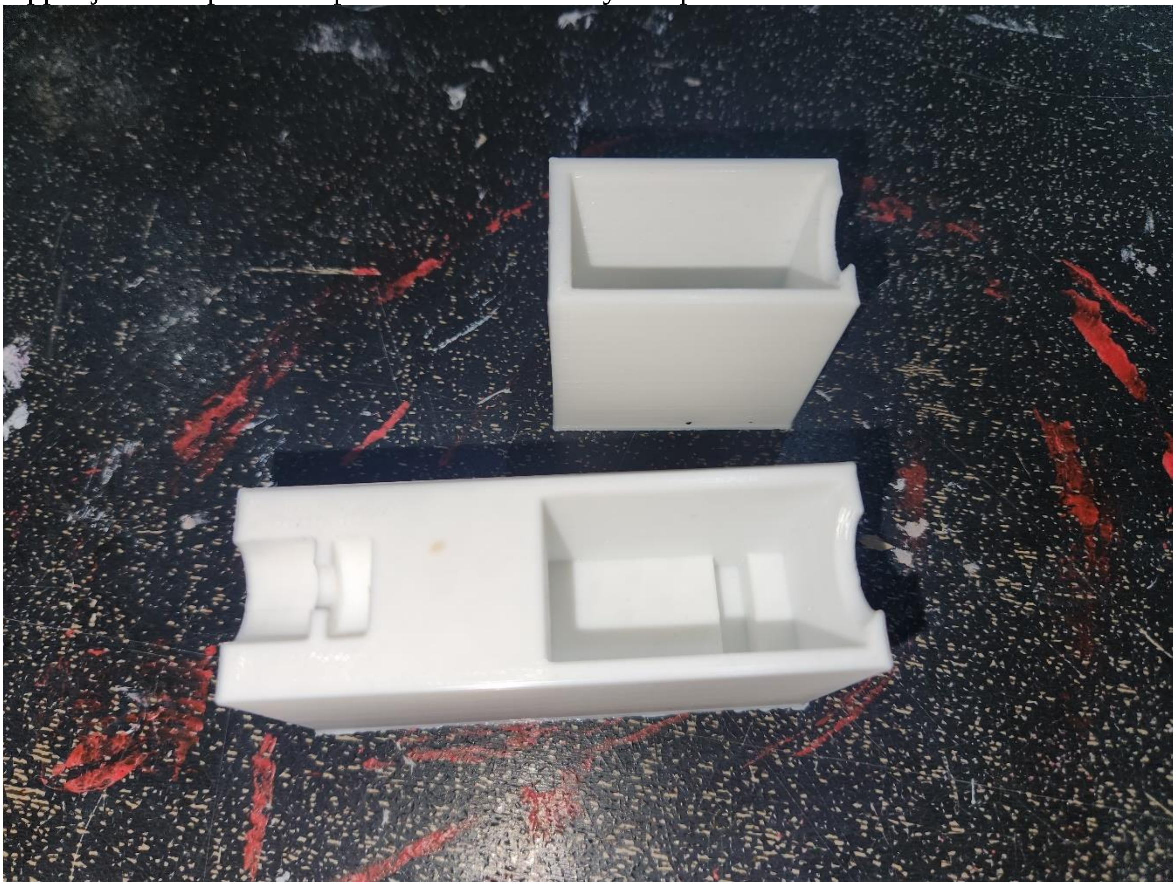
Connector test pieces. Ver minor changes made per test piece.

LED wiring and test piece



Upper jaw axle pivot test piece. Servo hole on the left, axle cavity on the right.

Upper jaw axle pivot test piece and servo cavity test piece.



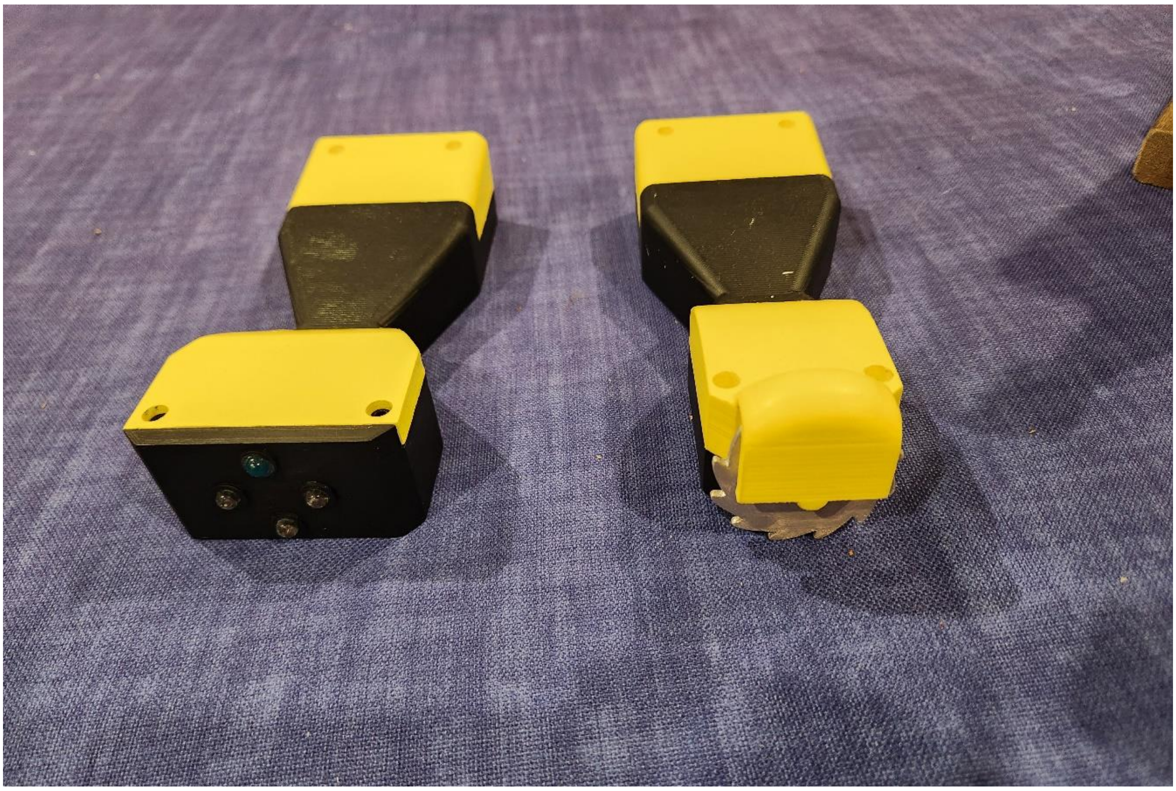
Lower gripper connector and wiring cavity test pieces underside view.

Lower gripper connector and wiring cavity test pieces topside view.

Attachment connector and gripper indentation alignment test piece.

Lower gripper jaw with connector at the bottom.

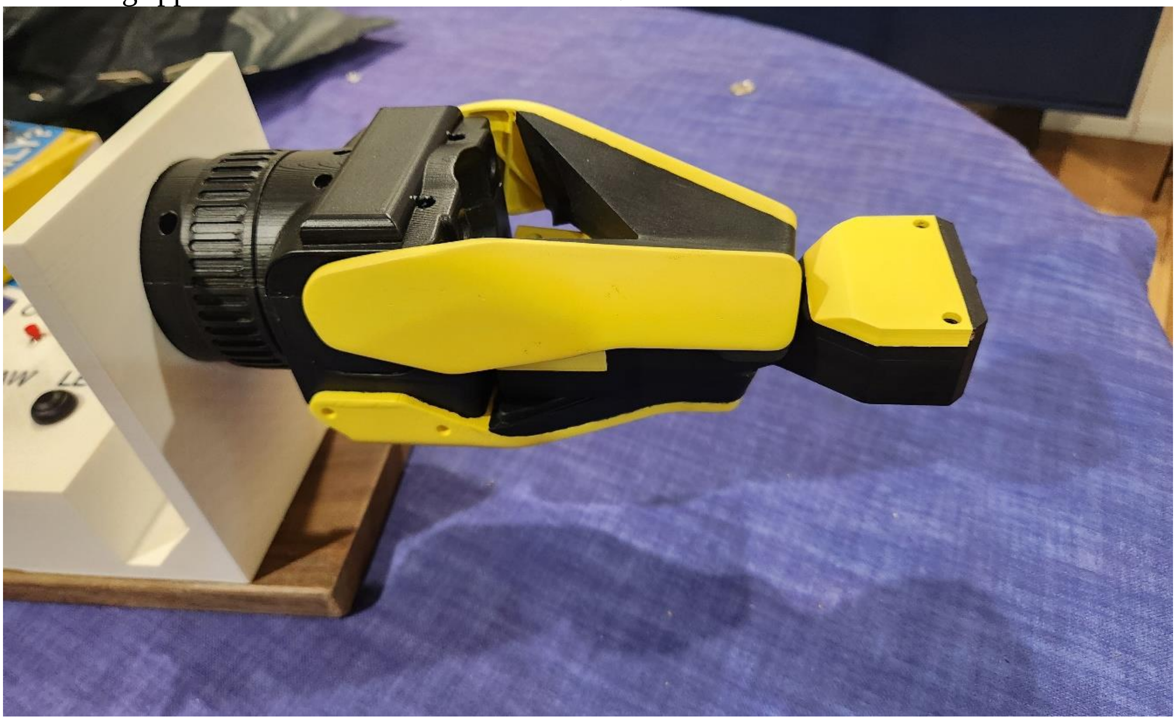
Finished attachment’s front view



Finished attachment’s side view

Finished attachment’s top view

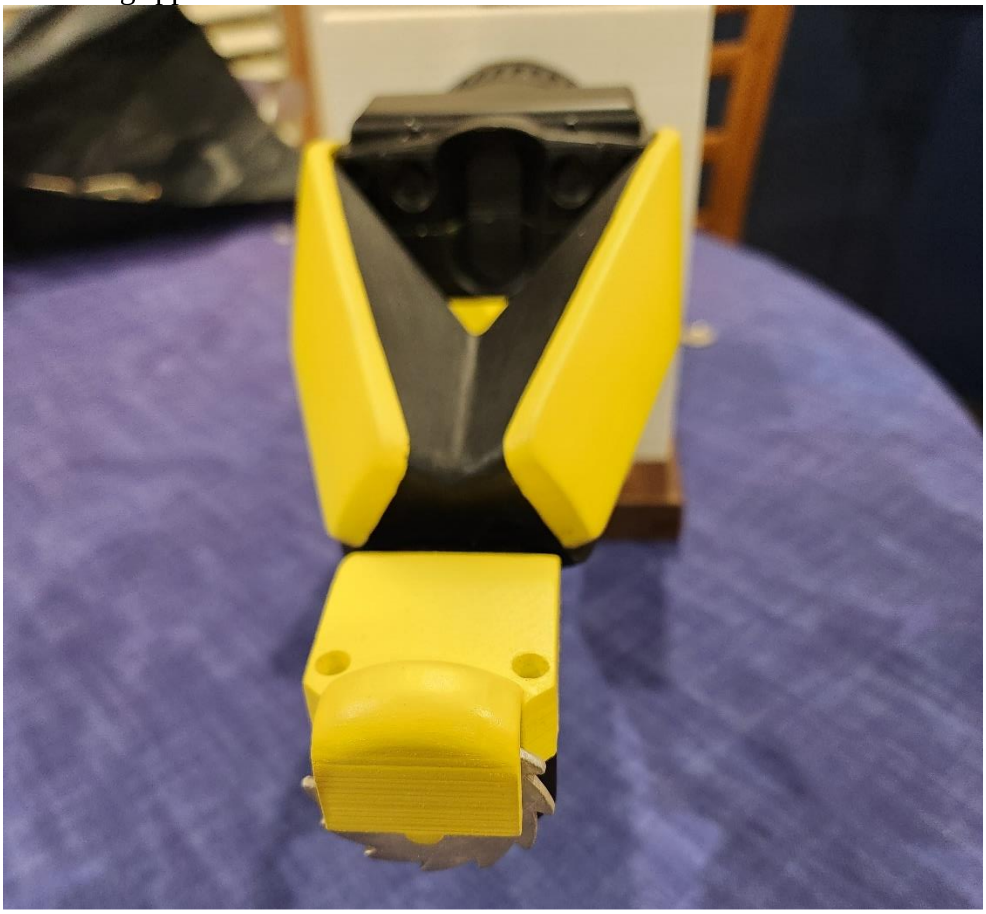
Finished gripper and LED attachment side view.



Finished gripper and LED attachment front view.

Finished LED attachment rear view with QR code.

Finished gripper and saw attachment front view.



Finished gripper and saw attachment side view.

Finished saw attachment rear view with QR code.