DESIGN OF A 3D-PRINTED THREE-CLAW ROBOTIC GRIPPER END-EFFECTOR

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Abstract

The development of a novel 3D-printed three-claw robotic gripper shall be described in this paper with the goal of incorporating various design considerations. Such considerations include the grip reliability and stability, grip force maximization, wide object grasping capability. Modularization of its components is another consideration that allows its parts to be easily machined and reusable. The design was realized by 3D printing using a combination of tough polylactic acid (PLA) material and thermoplastic polyurethane (TPU) material. In practice, additional tolerances were also considered for 3D printing of materials to compensate for possible expansion or shrinkage of the materials used to achieve the required functionality. The aim of the study is to explore the design and eventually deploy the three-claw robotic gripper to an actual robotic arm once its metal work fabrication is finished.

Introduction

The robot arm, generally known as robot manipulators, has been frequently used to perform specific tasks while interacting with humans, inanimate objects, machines, and its working environment [1]. These devices are extensively used in automating the manufacturing industry by executing different actions such as pick and place [2], painting [3], welding [4], riveting [5], and drilling [6], among others [7]. Some examples of these robot manipulators are readily available in the market such as Fanuc [8], Kuka [9], and Universal Robots Systems [10].

Manipulators are usually identified according to the type of end effector utilized. An example of such end effector what people commonly used are robotic grippers. These tools are used to move and grasp objects from one predetermined location to another. Furthermore, the utilization of such mechanisms encompasses several applications such as medicine [11] [12], military [13] [14], agriculture [15] [16], education [17] [18], etc. Thus, these promising fields of research appeal to the interest of numerous researchers to design and manufacture such devices.

Typically, robotic gripper mechanisms implement the concept of underactuation to provide simple control in initiating gripping action [19]. An example of such configuration is the three-finger gripper model developed by Telegenov et. al. was presented and manufactured using minimal number of 3D-printed components and commercially-available servo actuators [20]. Another example is the iRobot-Harvard-Yale (iHY) hand developed by Odhner, et. al. that is capable of performing wide range of grasping and in-hand repositioning

tasks [21]. In addition to, Backus, et. al. featured an underactuated design of a three-fingered robotic hand that utilizes radially symmetric, prismatically actuated fingers controlled by a single actuator [22]. Ultimately, the proponents will develop a novel design of three-claw gripper that will involve improved gripping stability, gripping force maximization, and ability to grasp wide objects.

Recent disruptive strategies have been developed to improve the existing methods in manufacturing robot end effectors [23]. Additive manufacturing or three-dimensional (3D) printing allows to provide such innovation available to all individuals ranging from hobbyists to researchers [24]. It makes the process of prototyping easier, faster, and more cost effective [25]. In addition to, the introduction of new materials in the intended robot gripper design will allow for greater flexibility and strength in the design [26]. It becomes practical to make mistakes and perform revisions in the design during the 3D printing stage [27]. Thus, 3D printing provides an avenue to reproduce end effector designs that cannot be done by conventional means.

This paper aims to develop a 3D-printed three-claw gripper design. The structure of this paper will adhere the following organization: Section 2 discusses the theoretical considerations of the novel three-claw robotic gripper design, Section 3 previews the practical considerations of the novel three-claw robotic gripper design and finally, Section 4 draws the conclusions of the study.

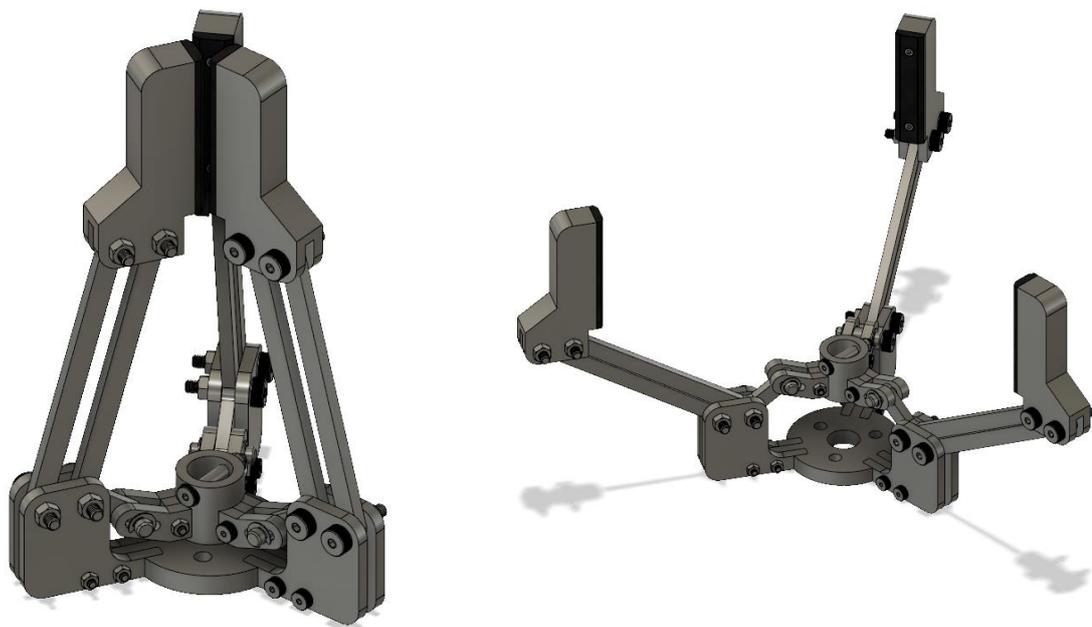## Theoretical Considerations for the Three-Claw Gripper Design

Figure 1. Three-finger gripper model (closed) Figure 2. Three-finger gripper model (open)

Reliability and stability of the grip, the maximum grip force allowable, and the ability of the gripper to grasp wide objects are the main factors being considered in the design of the novel three-claw gripper. The expected design of the said gripper is illustrated in Figure 1 rendered by Autodesk Fusion 360, a 3D CAD software. To achieve reliable and stable grip, a three-claw configuration was choses. The use of four-bar linkage design allows the linear actuator to effectively translate the forward-retraction motion to sideways gripping action. The maximum wide opening for grasping wide objects by at least 30 cm is ensured by specifying in design the required linkages length, illustrated in Figure 2.

The assembly of the novel gripper design is divided into different modular components such that the proposed design can be applicable for two-finger configurations or multi-finger configurations. This makes the proposed novel gripper design reusable. Also, breaking down the gripper design into different modular components provides the opportunity to machine parts easier. As presented in Figure 3, the modular components are described as follows: finger plate rubber, finger plate, straight bar, bent bar, actuator prongs, actuator plate, base prongs, and base plate. If one wishes to modify the design from the initial proposition to a desired configuration, only the actuator plate and base plate of the gripper end-effector design can be modified and machined differently; the rest of the modular components can be manufactured with similar dimensions or can be reused.

The actuation mechanism is described as follows: (1) The linear actuator attached to the actuator plate is bind to it by means of a M6 bolt. The motion of the linear actuator pushes the actuator plate upwards or downwards relative to the base plate. (2) The motion of the linear actuator plate pushes the actuator pin is pushed by the actuator prong and in turn (3) cause the bent bar to rotate around its pivot point. (4) Finally, by means of four-bar linkage mechanism, the outer bar ensures that the finger plate stays vertically upright as the bent bar rotates which indeed translates the rotary motion into translation. Thus, the push or pull motion of the linear actuator is effectively translated into sideways gripping motion.
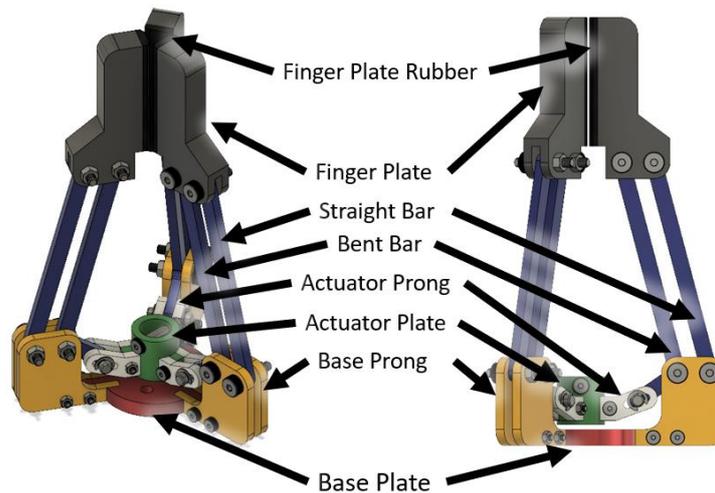

Figure 3: Gripper modular components

To analyze the movement of the proposed novel three-claw gripper design, two kinematic relationships must be established namely the movement of the finger plate relative to the actuating pin and the movement of the actuator pin relative to the linear actuator movement. Figure 4 shows the dimensions for a single claw module. The horizontal displacement R and the vertical displacement H of the finger plate is determined by the displacement of the actuator pin. The horizontal displacement r and vertical displacement h of the actuator plate is determined by the linear actuator stroke movement. Equations (1) and (2) shows the relationship among the parameters just described:

$$R = 40 + 135[0.342(60 - r) - 0.940(45 - h)]/30 \qquad (1)$$

$$H = 135 + 135[0.940(60 - r) + 0.342(45 - h)]/30. \qquad (2)$$

where $\theta_b = 110°$ is the bent angle of the bent bar. In approximation, we truncate $\cos\theta_b \approx -0.342$ and $\sin\theta_b \approx 0.940$. The use of 110 degrees allows the maximum gripper opening of at least 30 cm diameter wide. A linear relation is observed for the respective variables R and H as evidenced by Equations (1) and (2).

Next, we shall derive the relationship of the actuator pin movement and the linear actuator stroke. The relevant insight needed to derive the equations is illustrated in Figure 5 showing how the actuator plate motion produces a rotary motion for the actuator pin. Due to this rotary motion, two parameters r and h are needed to describe its position and are named horizontal and vertical displacement of the actuator pin respectively. The linear actuator stroke is designated as a from the top of the base plate up to the bottom of the actuator plate.

$$r = 60 - \sqrt{30^2 - (45 - h)^2} \tag{3}$$

$$h = 20 + a + (r - 22)\tan(\pi/9) \tag{4}$$

Using Figure 5 as a reference enables us to derive the relationship of r, h and a. Solving the system of Equation (3) and (4) gives us,

$$r = 63.590 - 0.321a - \sqrt{697.449 + 17.418a - 0.780a^2} \tag{5}$$

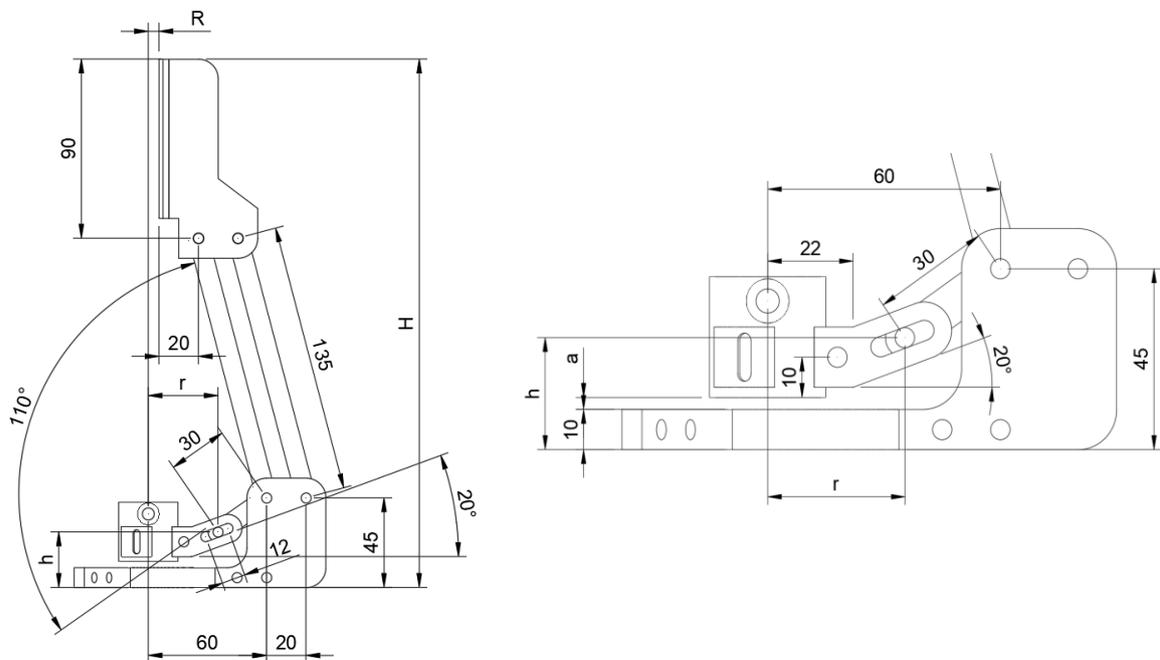$$h = 35.137 + 0.883a - \sqrt{92.394 + 2.307a - 0.103a^2} \tag{6}$$

Figure 4: Relevant component dimensions Figure 5: Close-up view of actuator pin mechanism

Equations (5) and (6) completely describes the motion of the actuator pin with respect to the base plate by a single parameter a, the linear actuator stroke. The coefficients were calculated using the Symbolic Math toolbox from the MATLAB software. Approximation is sufficient enough to meet the accuracy requirements of the three-claw gripper mechanism. By the relation just established in Equations (1) and (2), it is now possible to completely determine the position of the finger plates with respect to the base plate by a single parameter a. Thus, by controlling the amount of linear actuator stroke, we can predict within the accuracy permissible the gripper opening diameter as well as the amount of the fingerplate tip recession.

Finite Element Analysis and Strength Evaluation

The finite element analysis of the gripper was performed using Autodesk Fusion 360 Simulation, on which the design was tested in loading conditions that occurs on the actual use of the gripper. To speed up calculations only one finger was tested in the simulation and two load cases with different opening positions were tested. The material tested for the gripper metal parts was Stainless Steel 304 and for the fasteners and pins A-2 stainless was used. The gripper weighs 1.012 kg.
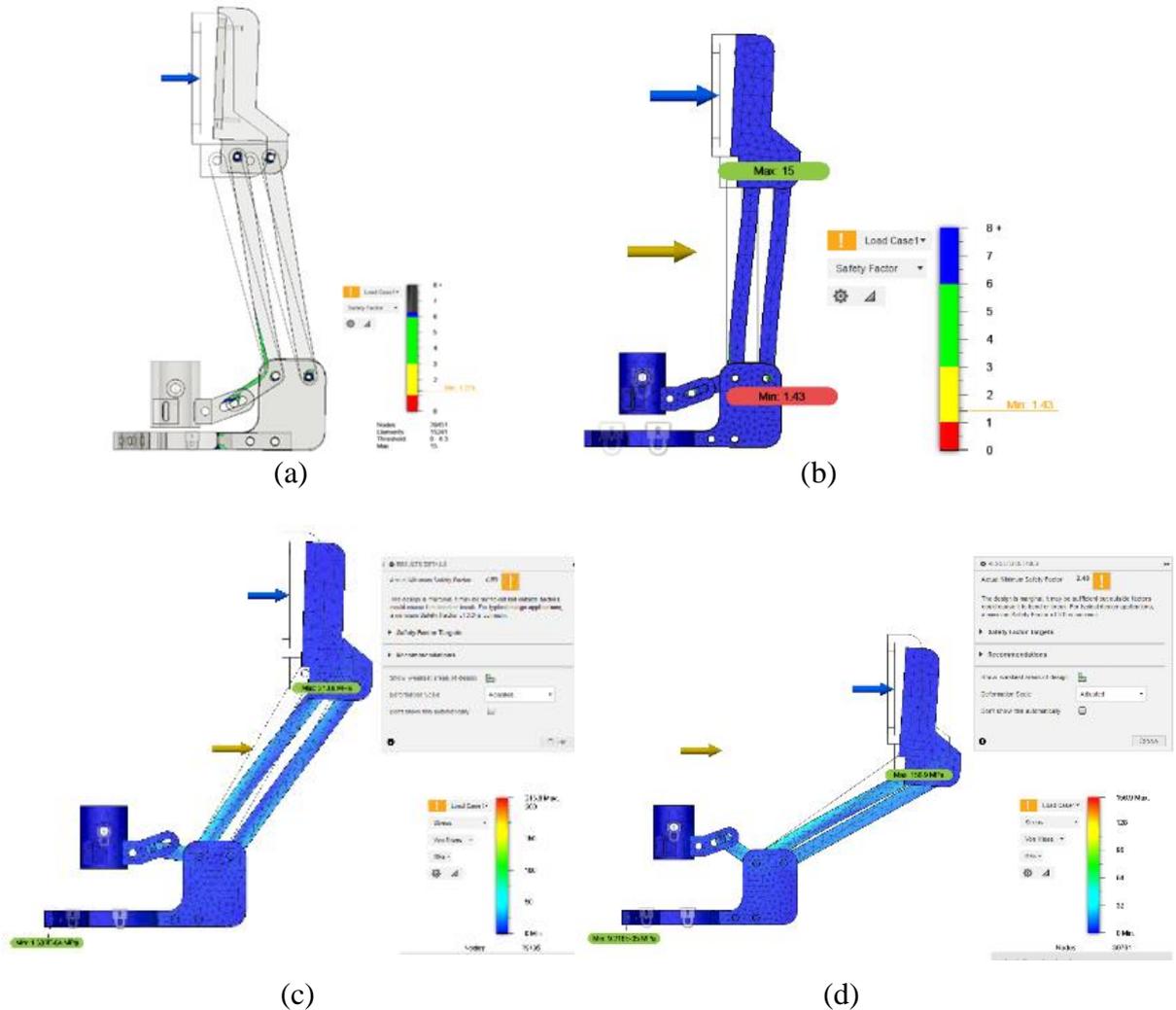

(a)

(b)

(c)

(d)

Figure 6: Applying different a 10 kg loads at different gripper opening sizes: (a) 0° opening, (b) 15° opening, (c) 30° opening and (d) 55° opening

The first condition considers 10 kg load on one finger with the flat of the gripper parallel to the ground, the positions with reference angles 0 (closed position), 15, 30 and 55 (fully opened) degrees were tested. Different test conditions and results are shown in Figure 6. For the 0° opening, the attained factor of safety is 1.28, while for the 15° opening case the factor of safety was 1.43. A factor of safety of 2.43 was attained in the loading case of the 30° opening and a 2.49 for the 55° opening.

The second condition tests the gripping and lifting forces for a 10 kg load using a static coefficient of friction $\mu_s = 0.2$ between the object and the fingers. The gripper is oriented upside-down to simulate the case where the gripper is used to lift an object. Again, the positions with reference angles 0, 15, 30 and 55 degrees were tested to show different object sizes.
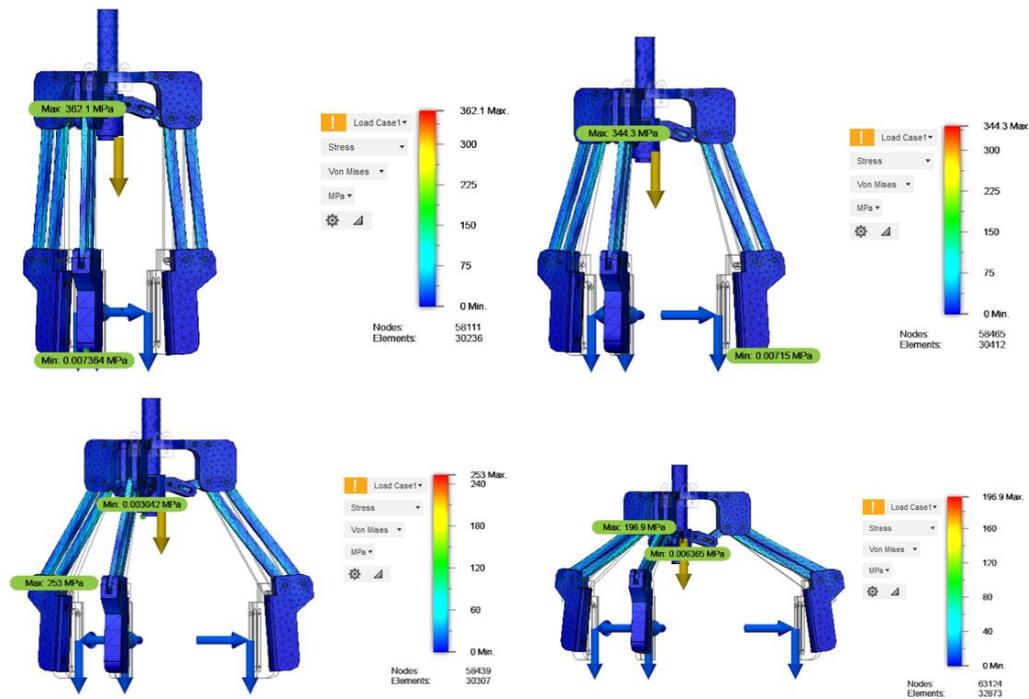
Figure 7: Applying a 10kg lift load for varying refence angles. From left-to-right and top-to-bottom: 0 degrees, 15 degrees, 30 degrees and 55 degrees.

Figure 7 shows the results for the second load case. For the 0° opening, the minimum factor of safety is 1.23, while for the 15° opening case the factor of safety was 1.30. A factor of safety of 1.09 was attained in the loading case of the 30° opening and a 2.27 for the 55° opening. As the gripper is opened, the maximum stresses developed decreased. The maximum stress condition of 362.1 MPa, as expected, occurs at the hinge points of the bent bar as this element carries much of the load to be transmitted between the linear actuator and the finger gripper.

The plot of ratio of gripper forces to applied linear actuator force is illustrated in Figure 8. As the opening diameter of the gripper mechanism is varied, the reaction forces are acquired for a gripper. An applied linear actuator force of 10 kilograms was used and the measured forces at the gripper is divided by the applied force to obtain the ratio. The maximum ratio is attained with a gripper opening of about 210 mm. The gripper was designed to handle object with size of up to 300 mm. Thus, the greatest force ratio occurs when the object has larger diameter and at the same time keeps a reasonably controlled force for objects with smaller sizes.
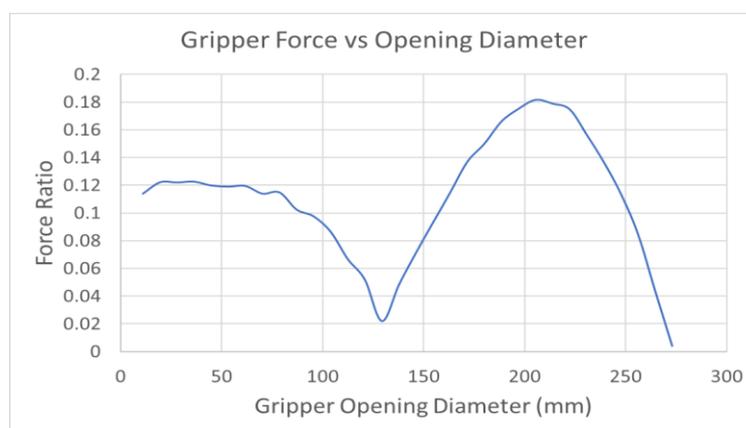

Figure 8: Force ratio response of the gripper as the opening diameter is varied.

Practical Considerations for the Three-Claw Gripper Design

The novel design of the three-claw gripper discussed earlier was realized by means of 3D printing. The modular components, as described in Section 2, were converted into STEP files separately. These STEP files are fed to the 3D printer's slicing software to generate different GCODE files. There were 8 different GCODE files generated representing the modular components described in Section 2 as well. The beauty of modularity allows the printing of similar components without modifying the GCODE files; all that was done was to duplicate some components such as the base prongs and the bars. If a certain component fails due to breaking, only that part is necessary to print which saves time in testing the prototype.

Metallic silver polylactic acid (PLA) material was used for the base plate, base prongs, actuator plate, actuator prongs, bent bar, straight bar, and finger plate components. Blue-colored thermoplastic polyurethane (TPU) was used for the finger plate rubber component. Figures 9a and 9b illustrates the actual 3D-printed three-claw gripper assembly. Several factors and limitations needs to be considered during the prototype realization process. Material expansion and shrinkage is inevitable during 3D printing process [29] primarily because of different cooling rates induced by variation temperatures throughout the duration. Another consideration is the inherent resolution that the 3D printer is capable to print and thus, details should be made as large as possible whilst keeping in mind the minimization of material usage. Functionality of the 3D printed prototype was required in a form of configuring the motion of the joints; in particular, the sizes of the joint holes needed for proper actuation needs to be determined correctly. The joints of the design are 8 mm holes in size but in order to ensure that the joints perform the intended motion, adjustment to the hole diameters has to be made. Printing the part with an 8 mm holes as is creates a measured 7.8 mm hole, the resulting in a reduction of 2 mm diameter. In this regard, hole sizes of 8.3, 8.4 and 8.5 mm were considered. Accordingly, using an 8.3 mm hole creates a press fit hole, 8.4 mm hole is good enough for slip fit and using 8.5 mm creates a loose fit already.

(a)   (b)

Figure 9: Actual 3D-printed three-claw gripper at (a) open position and (b) closed position

Conclusions

The study has proved to be able to realize the design and development of a novel 3D-printed three-claw gripper. The 3D printing process involved several iterations in order to determine the correct tolerances. Modifications to the 3D model where necessary in order to meet the required hole tolerances for proper functionality and motion of joints. Fortunately, the modularity in design has substantially helped in minimizing the time needed for modifications. Gripping reliability and stability are achieved by utilizing a three-claw gripper configuration with material utilization minimization in mind. The use of four-bar linkage allows maximum force transfer from linear actuator to the claws, converting the forward-retract motion into sideways gripping motion. The ability to grasp wide objects is realized by calculating the longest bar length whilst minimizing the material utilization. These design considerations where needed for the future directive of the research – final design shall be fabricated using stainless steel and aluminum materials to be utilized as an end-effector for a robotic arm required to lift heavy payloads.

Acknowledgements

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