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A Compressible Gripper for Articulated Robotic Arms

Kyler C. Bingham, Matthew Hessler, Safal Lama and Taher Deemyad *

Department of Mechanical Engineering, College of Science and Engineering, Idaho State University, Pocatello, ID 83209, USA; bingkyle@isu.edu (K.C.B.); matthewahessler@gmail.com (M.H.); lamasafa@isu.edu (S.L.)
* Correspondence: taherdeemyad@isu.edu; Tel.: +1-(208)-282-5655

Abstract: This research presents a comprehensive study on the design and implementation of a flexible robotic gripper. Conventional grippers utilized in articulated robotic arms are often limited in their capabilities, being restricted to specific tasks or fixed object sizes. While soft grippers are a viable option, they have limitations in terms of grasping objects across a wide range and providing complete coverage. In this study, a novel compressible gripper is developed to enable safe and secure grasping of objects with varying sizes and shapes within a wide range. The gripper features a grasping area measuring 14 cm $\times$ 6 cm, allowing complete coverage of objects within this surface area. The current prototype with 7 cm of compressibility demonstrates the ability to grasp objects with a width difference of 7 cm with a maximum thickness of 15 cm, enabling manipulation of objects with varying widths, as defined by user-programmable parameters. The functionality of the gripper is based on the compressibility of the 3D-printed thermoplastic polyurethane (TPU) material. The flexible part of the gripper can be easily interchanged, offering versatility by accommodating different thicknesses without the need to replace the entire gripper mechanism. The gripper system operates using an open-loop control system, enhancing user-friendliness. Experimental evaluation of the gripper involved the creation and analysis of a CAD model followed by the fabrication of a prototype. The prototype exhibited exceptional performance in grasping objects of diverse sizes, shapes, and textures, demonstrating the effectiveness of the developed soft gripper system. The scalability of the soft gripper enables seamless integration with various types of articulated robotic arms, while the maximum weight limit for objects will be defined based on the robotic arms' limitations. The research findings highlight the promising capabilities of the compressible gripper in enhancing the versatility and efficiency of robotic grasping systems, offering a significant contribution to the field of robotics.

Keywords: soft gripper; compressible gripper; grasping mechanism; minimum actuation; grasping various sizes & shapes; flexible robotic gripper

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1. Introduction

In many industrial systems, the final task of a robot is to grasp and reposition an object. Recent research and development efforts in the field of robotics have focused on designing grippers with high torque and accuracy for grabbing various objects and replacing humans with robotic systems in dangerous or difficult jobs [1]. Common types of robotic grippers in industries are vacuum grippers, pneumatic grippers, hydraulic grippers, and servo-electric grippers. Currently, the state of the art in compliant mechanisms, as seen in [2,3], requires sophisticated control structures, as well as having a low torque motor that is able to only lift small and light objects. The major problem with using these grippers is related to their rigidity and limitation in grasping a variety of objects, specifically when we are dealing with objects with fragile or soft surfaces. One potential approach involves using pressure sensors to replicate a human-like sense of touch. However, due to cost-effectiveness and concerns regarding the reliability of the gripper's tip strength, alternative options need to be explored and taken into consideration [1,4]. An alternative emerging technology that has significant potential is flexible and inexpensive materials that can be 3D-printed and used in designing robotic grippers [5]. One of these materials, thermoplastic polyurethane (TPU), is starting to become more available in the market, however, it is not being used in many gripper tasks effectively, as most grippers only use it as a finger cushion [6,7]. TPU, because of its high resistance, is used in many grippers on the end-effectors to help in picking up objects [6]. This flexible material is also used on tactile sensors that can be implemented into robotic grippers or be designed in a way to create a compressible mechanic for the end of a gripper mechanism [7,8].

With recent advancements in the technologies of electronic components like electrical motors and additive manufacturing, industrial grippers are continuously going to be better and cheaper [1]. Moreover, the increasing influence of automation and robots in various aspects of human life highlights the necessity of grippers with the capability to perform multiple tasks in a single setting. Many grippers already come equipped with a tactile end effector to increase friction and grip strength, however, to grab a wide variety of objects, the gripper needs compressible material on the surface of it [6,7,9].

Compressible material on the end-effector reduces the damage to the object being grasped while increasing the friction between the object and the surface of the robotic hand, allowing a variety of objects to be grabbed [9]. A compressible gripper can work in any condition or environment that is considered hostile to humans, as well as being able to grab any object [1]. One such example of a common commercial application would be the inspection of and work in radiation zones [10,11]. Another example of a potential application is manufacturing production lines. Most of the current robotics grippers have been made for certain applications and are designed based on exact synthesis. Therefore, they can grasp only similar objects with minimal changes in the application, and even for that, they need readjusting (physical/program adjustment). This is not ideal for applications and industries that want to use robotic arms for grasping a variety of objects with different sizes, shapes, weights, etc., during a process without changing robotic grippers [12].

On the other hand, the total weight that a robot can lift is partially dependent on the gripper (end-effector) it is carrying. This is one of the main concerns of designers, which can be solved by minimizing the number of actuators, applying the optimization algorithms, and making the parts hollow [1,4,13,14]. These parameters become even more important in designing a gripper for robotic arms with limitations in maximum load (most small industrial robots) as well as mobile robotic arms, like an autonomous robot with a robotic arm in a radiation zone [12].

Existing robotic grippers are relatively heavy, often featuring many actuators to provide dexterity, and some of these mechanisms even have counterweights or interchangeable ends. Although these features provide stability in the design and allow for different objects to grab, they result in increasing the weight of the robotic gripper, which is not ideal [12,15]. While additional weight may not be a concern for large-scale industrial robotic arms, it is important for small-scale robots in daily applications. Lower weight and, as a result, minimal energy consumption is another advantage of using compressible material in designing the robotic end-effectors. The arm must support its weight as well as the weight of the gripper, plus the weight of whatever objects it grasps. Thus, a heavy multipurpose gripper for robotic arms can be a major drawback [16].

On the other hand, the current grippers are often designed for one application, and they must be completely changed when objects are changed [12]. This drawback makes some companies see grippers as useless in their applications. Efforts are currently underway to make grippers easily interchangeable with robotic arms, thus enabling more companies to recognize their potential. However, this technology can still be further improved [12,17]. This paper studies a compressible robotic gripper with the ability to deform and grab objects, grasping objects with different sizes, weights, and shapes. This mechanism is made of flexible and dexterous plastic (TPU) which acts as a combination of form closure and force closure mechanism to be able to grasp objects in a range of sizes and weights [18].

The current scientific challenges in robotics gripper technology revolve around developing a grasping system capable of safely and securely gripping objects of different sizes and shapes across a wide range. Given the significance of these considerations, the primary focus of this research is to design a compressible gripper with the capability to grasp diverse objects with varying sizes, shapes, and textures.

2. Materials and Methods

The mechanism of this gripper is made of ten different parts, as shown in Table 1 and Figure 1, excluding the electrical components. The gripper operates by a high-torque stepper motor (1) and a 22.5W (max) power bank. The output rotational motion of this motor will be changed to the linear motion of the gripper by using a rack–pinion system (2). The rack is merged into a handle (3) at the end and slides inside the rail in the main body (4) of the gripper. The handles will be covered by the grasping segment, which includes a hard shell (5) and a flexible element (6). A custom lock mechanism (7) is implemented to keep the flexible element securely inside the hard shell, while a stop (8) is added to maintain the handle's position on the main body. Also, for the controlling system of the gripper and other electrical components, a specific box (9) is designed which will be attached to the back of the main body. The box is secured to the body through a connection piece (10) that is also able to attach directly to the robotic arm.

Table 1. Gripper Components.

Component	Item #	Material
Stepper Motor	1	N/A
Rack and Pinion	2	NYLON Carbon 12
Handle	3	NYLON Carbon 12
Main Body	4	NYLON Carbon 12
Hard Shell	5	NYLON Carbon 12
Flexible Element	6	TPU
Lock	7	NYLON Carbon 12
Rubber Stop	8	TPU
Controller Case	9	ABS-ESD
Connector	10	NYLON Carbon 12

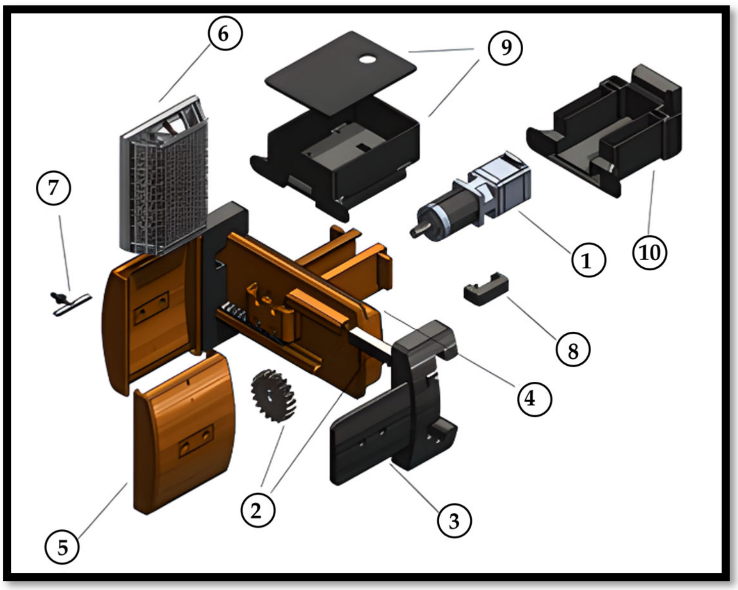


Figure 1. Exploded view of the mechanical components of the gripper with balloon numbering as part numbers from Table 1.

Most parts of this gripper are made of NYLON 12 carbon fiber because of its low weight and high tensile strain [19]. The flexible element is made of TPU with superior flexibility and longevity compared with non-polyurethane or thermoplastic elastomeric materials (TPE) [18]. The controller box is made of ABS-ESD, which is acrylonitrile butadiene styrene with electrostatic discharge properties. This material is resistant to electrostatic discharge with rigidity and is ideal for keeping all electrical components of this gripper. Further, most of the background knowledge and information about the materials is obtained from [20].

3. Results

3.1. Grasping System

In this project, the grasping mechanism includes three main components: (1) hard shell, (2) handle, and (3) soft/flexible part. The hard shell is designed in a way that various flexible shapes for different purposes can easily slide into it. The gripper also includes an actuation mechanism and is programmed to be able to open/close the gripper between the minimum and maximum positions. Users can control the close (grasp object) or open (release object) position of the gripper, while an automatic stop switch helps the gripper not go over the maximum open position.

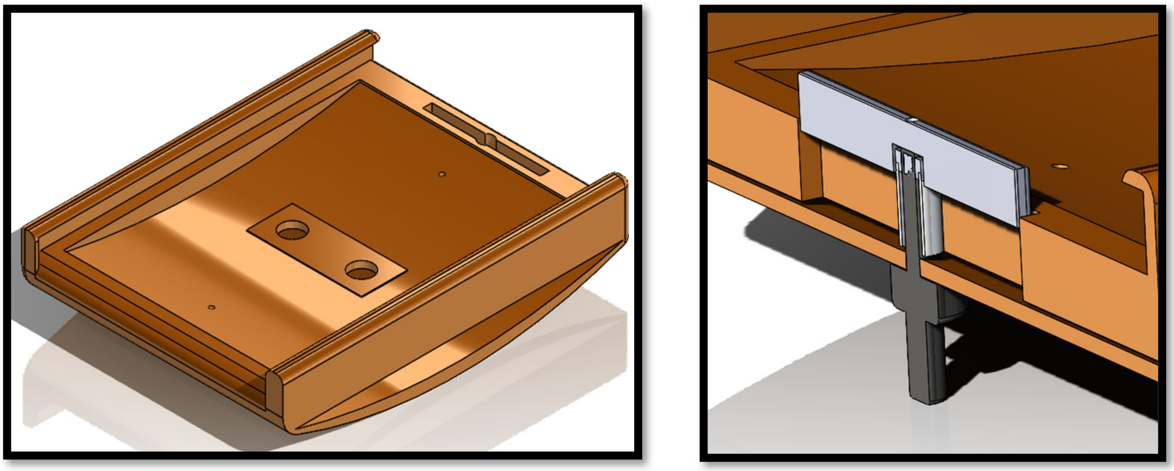
The CAD model of this gripper mechanism was designed around the constraints of the articulated robotic arm, as well as the actuation method. An industrial ABB robotic arm with a maximum payload constraint of 3 kg was selected for this project. To ensure safety, the designed metrics should accommodate objects with a width of no more than 15 cm, and the total weight of the gripper system, along with the objects being grasped, should not exceed 3 kg. This would allow for a variety of objects to still be grasped while allowing for significant factors of safety for any potential scalability of the gripper. Minimum actuation is also desired for this project to reduce user inputs and potential repair if damaged, as well as minimize the overall weight.

The work performed by the soft gripper involves the compressible material used in a linear fashion for the end-effector. The CAD model was built around the rack and pinion system, considering the constraints and metrics. The body was designed to incorporate the rack and pinion system, with linear moving arms attached to the actuation rack. Mechanical stops were added to prevent the rack from dislodging or exerting excessive pressure on objects. Next, the hard shell was designed and attached to the rack arms (handle) to allow easy interchangeability of the compressible material for the end-effector. The flexible element was also designed with adjustable shape and size, showcasing two models for proof of concept. The controller housing was integrated with all electrical components in CAD software.

3.1.1. Hard Shell

To enable multiple soft grasping patterns, a hard and hollow shell was created for this gripper, allowing easy interchangeability of the flexible sector by sliding in and out of the shell. The hard shell is secured to the handles emanating from the base of the gripper and underwent topology analysis to reduce weight while maintaining structural integrity. To improve the quality of grasping various objects, two different flexible components with different shapes are designed that can be fixed inside the hard shell of the gripper. In the future, more patterns and shapes can be designed based on better adaptation to task requirements.

For safety, the hard shell incorporates a locking mechanism to prevent the separation of the flexible section from the hard shell during rapid 360 degrees rotations or swift movements of the robotic arm, especially when dealing with heavy objects. The hard shell and lock mechanism are shown in Figure 2.

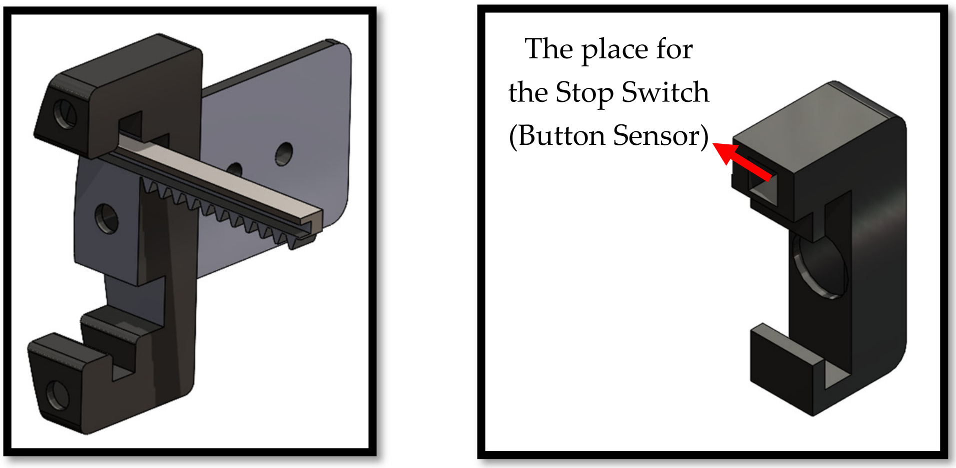


(a) (b)

Figure 2. (**a**) Hard shell for holding flexible element and (**b**) locking mechanism to hold the flexible element tightly during rotation and fast movement of the manipulator.

3.1.2. Handle

The gripper is equipped with handles that serve the dual purpose of supporting both the hard shell and the flexible component. Each handle incorporates a properly sized rack and is designed to smoothly slide along the integrated rail within the main body. This sliding motion is facilitated by the interaction between the racks and the pinion system, causing the handles to move in opposite directions. For secure fastening of the hard shell, each handle is equipped with two holes where bolts can be inserted and tightened. To prevent accidental displacement of the handles from the main body, flexible stops, including a stop switch, were developed and affixed to the ends of the main body. Figure 3a visually illustrates the handle design, while Figure 3b depicts the rubber stop mechanism.



(a) (b)

Figure 3. (**a**) Handle which holds the hard shell and actuates the gripping mechanism through the rack on it and (**b**) rubber stop, which is a mechanical stop printed out of TPU that prevents the handle and rack from moving off the body of the gripper.

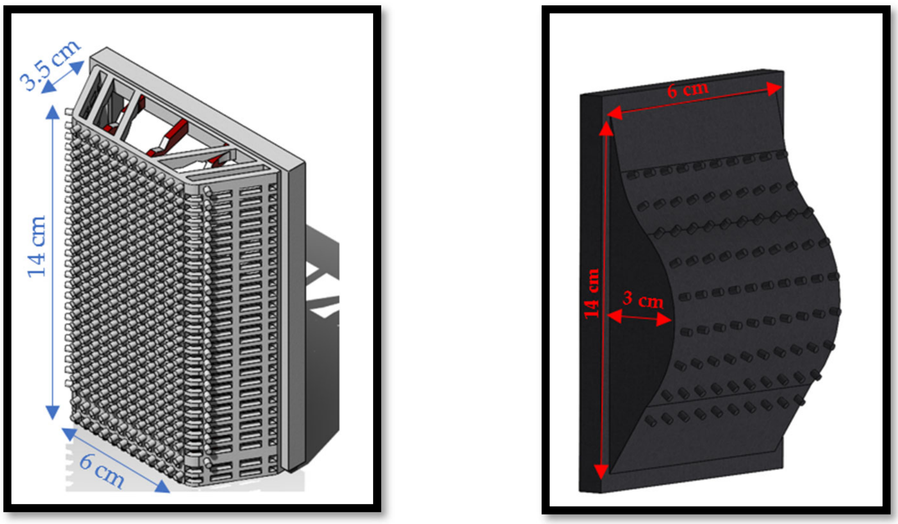
3.1.3. Flexible Element

In designing the robot gripper, an ideal system would feature a minimum number of actuators and the ability to grasp different objects of varying geometries. To achieve this, the design incorporates a flexible sector capable of deforming to match the shape of various objects, encompassing them completely. This allows the gripper to maximize the surface in contact with the object, thereby increasing the frictional force applied. Furthermore, since the gripping capability of the gripper relies solely on the formability of the flexible element around objects, it results in a form-closure grasp. Consequently, an open-loop control system proves sufficient, eliminating the need for feedback. The chosen material's softness and robustness enable the gripper to effectively grasp a diverse range of objects with different textures and weights. Thus, objects can be grasped by the minimum required force and avoid any potential damage. Additionally, the flexible nature of the gripper allows it to readily grip objects with unusual geometries, as more surfaces of the object can come into contact with the gripper.

To improve the quality of grasping various objects, two different flexible components with different shapes are designed to be fixed inside the hard shell of the gripper. In the future, more patterns and shapes can be developed to better adapt to specific task requirements.

The first design features a mesh pattern and a rectangular shape. There are several reasons for utilizing mesh in this design. Firstly, using mesh makes the surface softer and more flexible, making it ideal for grasping fragile or soft objects. Secondly, incorporating a mesh pattern allows for approximately 50 percent of the TPU material used in the detachable gripper head to be saved, thereby affecting the final product price. Thirdly, using less material reduces the overall weight of the gripper, enabling it to handle heavier objects when grasped by the robotic arm. Lastly, the motor requires less force to compress the soft section, allowing for the use of a lower torque motor (smaller motor) in the gripper, which affects the size, weight, and price.

In this design, the surface was extended downward and past the edge of the gripper, allowing it to potentially grasp small and thin objects like coins. Bumps were incorporated to increase the friction between the object and the end effector. This design is capable of easily grasping objects of any size and shape within a range of 7 cm width difference, with an upper limit of 15 cm (for instance 1–8 cm, 5–12 cm, etc.). The rectangular flexible element with a mesh design is shown in Figure 4a.



(a) (b)

Figure 4. Flexible elements printed out of TPU material and will flex around various objects (**a**) rectangular shape (**b**) curved shape.

Although using a mesh pattern has many advantages, as mentioned before, the design becomes too soft, resulting in variable and uncertain deformation of the soft component when grasping objects. To counteract this and add some strength to the gripper, angle bars were added to each end of the design. To make sure these bars will bend inside of the mechanism in the compressed position, notches were cut out of the bars so that they can bend in the correct direction. These bars and the notches can also be seen in Figure 4a. The thickness of the gripper design plays a critical role in determining its flexibility. By maintaining the shape and pattern of the design while adjusting the overall thickness, varying degrees of flexibility or stiffness can be achieved. Decreasing the thickness enhances flexibility, while increasing it results in greater stiffness.

To demonstrate the changeability of the soft elements in this gripper, a secondary design was created specifically for grasping cylindrical objects. This design showcases the ability to interchange soft elements and highlights the versatility of the gripper in accommodating different object shapes. While this design is not ideal for grasping flat objects, it excels in applying more force to cylindrical objects and grasping them securely. The curved shape and numerous small bumps of this design help to increase friction between the surface of the gripper and round objects. The gripper can be programmed to easily grasp any cylindrical shape within a range of 6 cm diameter difference, with an upper limit of 15 cm (for instance 2–9 cm, 7–14 cm, etc.). Based on the structural limitations of the current prototype, the size and distance can be adjusted by increasing the size of the hard shell in the future. This secondary design is shown in Figure 4b.

3.2. Actuation System

3.2.1. Actuation Mechanism

To achieve the desired linear motion of the gripper handles for the purpose of grasping and releasing objects, several actuation mechanisms were evaluated, including four-bar linkages, pneumatic actuators, and linear actuators. However, the adoption of linkage mechanisms was deemed impractical due to their requirement of significant space and complex design to generate the required motion. Similarly, utilizing two linear actuators simultaneously was found to be problematic because of their need for extra space for the linear actuators' housing. Although pneumatic actuators are commonly used in robotic grippers, they were unsuitable for this gripper's application. This is due to their inherent high operating speeds, which are not conducive to the delicate and soft objects that necessitate a slower grasping process. Additionally, pneumatic systems have other problems, such as air leaking and the heavy weight of the vacuum compressor.

During the design process, worm gears and spur gears were evaluated for the rack and pinion mechanism. Ultimately, spur teeth were selected as the optimal choice for the rack and pinion mechanism due to their simplicity and efficiency. As for actuation, a stepper motor was selected based on its precision and ease of control. To enhance the motor's torque, a planetary gearbox was incorporated. This mechanism facilitates the conversion of rotational motion from the motor into the linear movement of the gripper arms. By utilizing an open-loop control system, this gripper is capable of reliably grasping and releasing various objects. The performance of the gripper system relies solely on the pressure exerted by the flexible component on the objects. If the motor is sufficiently strong to compress the flexible element, the mesh design will be able to surround and grasp any object within the specified range. Several factors, including the size, shape, and orientation of the object, influence the required grasping force, which needs to be provided by the motor. However, the most crucial factor for grasping force is directly related to the thickness of the flexible element. To reduce the motor's workload, the wall thickness of the flexible component was determined through experimental and analytical methods as the controlling factor. A thinner wall allows for increased flexibility of the gripper end-effector and requires less power from the motor for grasping the object. The wall thickness of each component within the flexible element can be adjusted to suit the desired application.

Figure 5 depicts the pinion gear utilized in the design. Additionally, a keyhole was incorporated into the gear design to allow for the insertion of the key between the gear and the motor shaft.

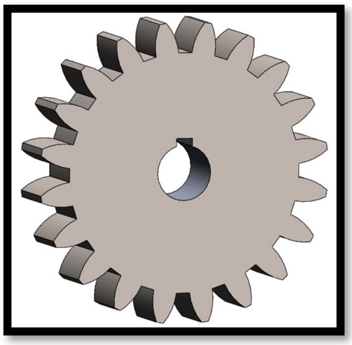


Figure 5. Pinion gear that directly fits the motor and gearbox to actuate the rack and gripper handles and translates rotational movement to linear.

3.2.2. Designing Rack and Pinion

In the process of gear design, the maximum traveling length for each handle (the rack) and available space for the rack and pinion are important parameters. These parameters serve as input information for calculating the number of teeth and gear ratio. To ensure a precise fit between the pinion and rack teeth, the pinion was designed first, and then the rack was developed accordingly. The calculations and design of the rack and pinion for the gripper were performed based on parameters like module, pitch, tooth profile, backlash, clearance, etc. [21]. NYLON Carbon 12 was chosen as the material for the prototype due to its favorable characteristics, such as lightweight, high strength, and rapid reproducibility of parts.

Prior to manufacturing a prototype of the rack and pinion system, a CAD model was created to visualize and analyze the components. A simple support beam analysis was conducted to assess the performance of this gear system. In the design, a spur gear was chosen with a diametral pitch of 25.4 cm (10 in) and a pressure angle of 20 degrees. Similarly, the rack was designed with the same diametral pitch and pressure angle. The motion analysis was performed within the CAD software, and the results were validated with printed parts with a 3D printer. The final design of the rack and pinion system can be observed in Figure 6.

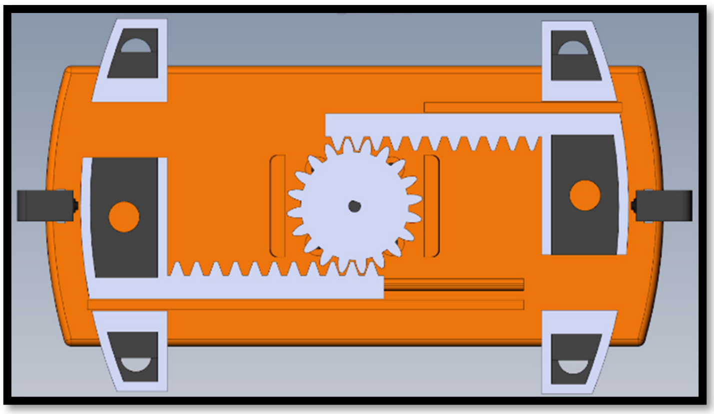


Figure 6. Front cross-section view of rack and pinion system and the rubber stops.

3.3. Controlling System

3.3.1. Electrical Circuit

The electrical components are listed in Table 2, and Figure 7 illustrates their connections. This gripper can be controlled either manually through remote control (#1) or programmed using the robotic arm. The gripper can perform motion between a closed position for grasping objects and an open position for releasing them. The gripper's motion is facilitated by a stepper motor (#2), which controls the steps involved in transitioning between the two positions. To ensure accurate positioning and prevent step losses in the motor, a switch button (#3) is integrated into the gripper. This button serves to reset the gripper's position after each release and calibrate it for the next grasping task. In this design, a single button is sufficient due to the synchronized movement of the gripper arms, operated by the pinion–rack mechanism.

Table 2. Electronic Components from Figure 7.

Component	Item #	Quantity
IR Remote	1	1
Stepper Motor	2	1
Push Button	3	1
IR Sensor–Receiver Module	4	1
Resistor—10 kΩ	5	1
L298N Motor Driver	6	1
Arduino Uno	7	1

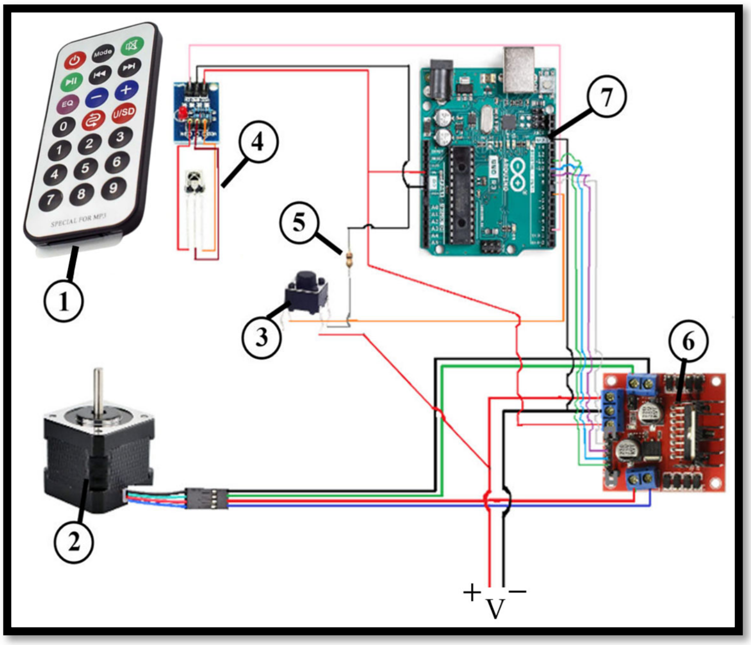


Figure 7. Wiring diagram of the gripper with balloon numbering as part numbers from Table 2.

To enable remote control functionality, an infrared remote and sensor (#4) are employed. The reset switch is connected to a microcontroller through a ten-kilo-ohm resistor (#5).

The gripper employs a NEMA17 Stepper motor with a torque rating of 59 N cm. To enhance the gripping force for effectively grasping objects, a planetary gearbox with a torque transmission ratio of 40:1 is attached to the motor shaft.

To operate the motor, an L298N Motor Drive Controller (#6) is utilized. This controller acts as an intermediary between the microcontroller, battery, and motor. To optimize space, an Arduino Uno (#7) microcontroller board is employed for controlling the gripper's open and closed positions and receiving infrared signals. Both the stepper motor and Arduino are powered by a compact 22.5 W (maximum) power bank. The power bank provides a 5 V output for the Arduino Uno and a 12 V output for the stepper motor.

The gripper is controlled through user commands using an IR Remote and its sensor. The remote features a specific button for opening and closing the gripper. Pressing it once closes the gripper until the flexible surfaces touch each other or, in the presence of an object, grasp it. Pressing the button again fully opens the gripper to release the object.

The range for opening is fixed, but the user can adjust the closing range based on the size range of the target objects in the program. To enhance safety and system accuracy, a stop switch button is integrated into the rubber stops. When the gripper reaches the fully open position, it activates the stop button switch, immediately halting the motor and resetting the code. This position becomes the starting position, preparing the gripper for the next grasp. Alternatively, instead of employing a remote-control system, the gripper can be directly connected to the robotic arm controller for control.

3.3.2. Controller Programming

The microcontroller is programmed using Python codes to establish the configuration of the IR remote and define the functionalities of the remote controller button for clockwise and counterclockwise turning. Furthermore, it incorporates a setup for the push button to enable the gripper to come to a stop at its maximum position. When the gripper is turned clockwise, the gripper arms move inward by a specific number of steps, while counterclockwise rotation causes the gripper arms to continuously extend until the gripper handle contacts the push button. Once the handle reaches the push button, the code ceases operation and resets the stepper motor's step count, ensuring a fresh count when the gripper moves inward again. Other parts of the code related to the motor's rotation and step-counting process are based on the input pins depicted in Figure 7. Despite the simplicity of the code, it offers user-friendly operation and can be adapted for any gripper utilizing a stepper motor and IR remote. It is important to acknowledge that while both the wiring and codes have been successfully tested, it is crucial to monitor and analyze the code and motor performance regularly, as not all stepper motors exhibit long-term reliability.

The programming of the gripper necessitates careful consideration of the grasping speed to accommodate objects with diverse textures. The speed can be adjusted by manipulating the programming parameters. However, it is important to strike a balance, as excessive speed can endanger delicate objects, like eggs, while excessively slow movements restrict the gripper's functionality and user-friendliness. Additionally, speed has an impact on the required torque for effective grasping, as there is an inverse relationship between speed and motor torque.

To boost the motor's torque output, a gearbox with a gear ratio of 40:1 is incorporated into the stepper motor, resulting in a substantial decrease in speed. This reduction is considered when determining the ideal speed and duration for grasping operations. The motor is programmed to operate at 60 RPM (1.5 RPM when accounting for the gearbox), enabling the gripper to complete full opening or closing motions in approximately 4–6 s. The motor speed can be adjusted within the specified limitations outlined in the motor and gearbox manual, permitting speeds of up to 400 RPM (10 RPM with the gearbox) to remain within the optimal torque range.

The gripper design utilizes an open-loop control system, which can lead to overshooting movements during both the opening and closing stages. To address this concern in the rack and pinion system, mechanical stops are integrated into the open direction. In this system, a button sensor is placed within one of the mechanical stops during the opening motion. This sensor functions to stop and reset the code and motor once the object release process is completed.

Insufficient programmed tightening force may result in objects slipping and falling if they are not fully grasped from all sides. The effective force applied by the gripper to the object depends solely on the thickness of the flexible element, which is determined through iterative experimentation. By identifying a range of acceptable thicknesses based on the handle's safety factor, the flexible element can flex and conform to the object's shape. Users have the option to adjust the perceived force on objects by modifying the thickness of the flexible component. The mesh design of the flexible material acts like a spring force, and the thicker it is, the greater the force it provides. The force exerted on the object remains constant throughout the grasping process, and this system effectively reduces the risk of object damage. Moreover, to prevent object slippage, the TPU material and small bumps are integrated to enhance the frictional force between the object and the grasping surface. The combination of high friction and formability of flexible elements around the object facilitated by the flexible materials contributes to preventing objects from being dropped or damaged when gripped by the gripper.

3.4. Analysis and Selection

After defining the general motion of the mechanism, explaining all mechanical and electrical components, and presenting the electrical circuit, the stress analysis of components and motor selection are the final steps to complete the design. Components directly involved in the grasping process must be capable of withstanding maximum stress, which is directly related to the thickness and design of the flexible element. The gripper consists of various components, but only the moving parts are essential for motion and stress analysis. This study focuses on two components: the flexible element, made of TPU, and the handle, made of NYLON Carbon 12. During the grasping process, both components experience a maximum damped force resulting from the actuation. Following the stress analysis, the motor will be selected based on the maximum force required to move the handle.

3.4.1. Stress Analysis

To ensure safe grasping of the objects, any components directly involved in the grasping process must be able to tolerate the maximum stress. This gripper is composed of various components, but only the moving parts are essential for motion and stress analysis. Two components are analyzed in this study: the flexible element, made of TPU, and the handle, made of NYLON Carbon 12, both of which experience the maximum force during the grasping process.

The flexible element is connected to the handle, and therefore, the entire grasping force will directly transfer to the handle. The most vulnerable part of the handle is the end of the connection part to the gripper hard shell, which experiences maximum torque. Through a SolidWorks stress analysis, and based on the current material (NYLON Carbon 12) and the thickness of the parts, it is found that the handle can withstand a maximum force of 220 N. This force is also equivalent to the maximum force that can be applied by the motor. The result is presented in Figure 8.

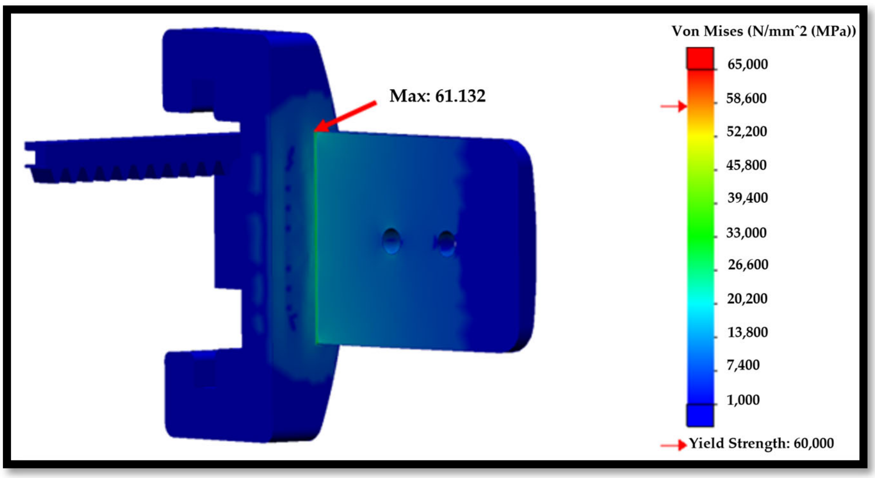
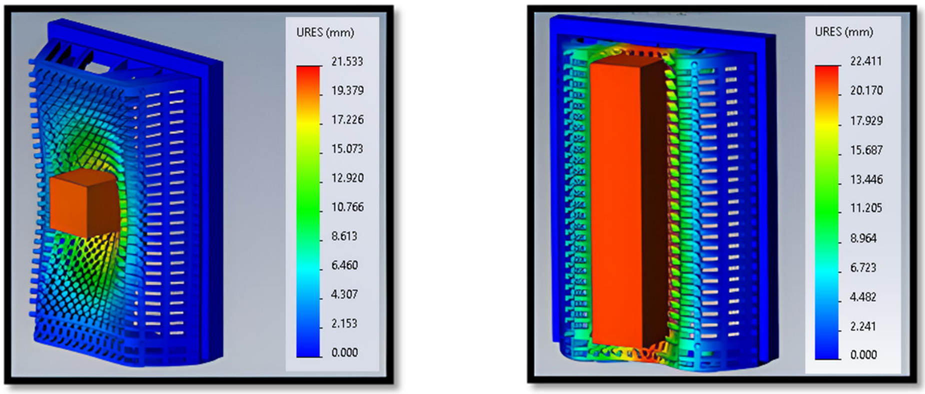


Figure 8. Stress analysis of the handle—the maximum stress at the connection corner.

The minimum force required for the complete deformation of the flexible element during object grasping is crucial for successful gripping. However, this force is influenced by factors such as the thickness, shape, size, and orientation of the object, making it difficult to directly measure. Therefore, a simulation study was conducted to estimate the maximum allowable thickness by subjecting square or rectangular objects of various sizes to the flexible element with different thicknesses. It was found that a thickness of 0.3 cm required a force of 186 N for full deformation, which falls within the safe maximum stress limit of the hard shell when considering a safety factor of 1.183. Simulation studies were also performed to analyze displacement forces, calculate von Mises stress, and determine the factor of safety for the flexible element. The deflections of the flexible element with a thickness of 0.3 cm during grasping of square- and rectangle-shaped objects are shown in Figures 9 and 10.



(**a**) (**b**)

Figure 9. (**a**) Displacement of the flexible element grasping a small square-shaped object and (**b**) displacement of the flexible element grasping a large rectangular-shaped object.

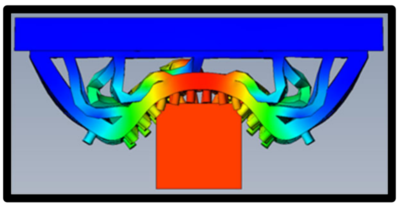


Figure 10. Flexible element displacement in the grasping process (top view). The diagonal bars are designed to be easily folded during maximum displacement.

3.4.2. Motor Selection

Based on the maximum force required for grasping, the rack/pinion equation, and the torque equation, the motor was selected. The force required to compress the flexible elements is approximately equivalent to the force applied to the rack. Based on this assumption, the minimum torque from the motor to grasp any object can be determined from Equation [1].

$$T_p = F_r \times r_p \tag{1}$$

$$T_p = Torque\ on\ Pinion\ (from\ the\ Motor)$$
$$F_r = Force\ on\ Rack(include\ the\ Factor\ of\ Safety)$$
$$r_p = Pinion\ Radius$$

By performing the following calculations, it is possible to determine the necessary motor torque for grasping objects.

$$F_r = Force\ on\ Rack = 186\ \mathrm{N} \times 1.183 = 220\ \mathrm{N}$$
$$r_p = Pinion\ Radius = 0.02222373\ \mathrm{m}$$

$$T_p = F_r \times r_p = 220\ \mathrm{N} \times 0.02222373\ \mathrm{m} = 4.89\ \mathrm{N{\cdot}m}$$

According to the result of the calculations provided, it is determined that a motor with a maximum torque of 5 N·m or greater is necessary. However, if the handle material is changed from NYLON Carbon 12 to Aluminum 6061 and the flexible element's thickness is increased in future iterations of the design, the required torque for the motor will also increase. Consequently, a motor with significantly higher torque was chosen to accommodate potential future applications or design modifications. This motor is equipped with a gearbox capable of withstanding a maximum holding torque of 25 N·m while still fitting the designed gripper body.

4. Discussion

An ideal gripper, in addition to having the ability to grasp various objects, must be lightweight, strong, and reliable. After finalizing the gripper design, various analyses were conducted to ensure its performance in grasping various objects. Topology and stress analyses were carried out in CAD software to minimize the total weight of the gripper without compromising its grasping capability or risking broken parts. The motor was carefully selected based on calculations to ensure it could exert the required force to push the handles and overcome the compression force from the flexible elements for a complete grasp. Once all the analyses were completed in the CAD environment, the gripper components were 3D printed, assembled, and tested with real objects for their grasping performance.

Figure 11 illustrates the final assembly of the gripper design in CAD software. The prototype of the gripper was developed using additive manufacturing technology, specifically NYLON Carbon 12 for the main body and TPU material for the flexible grasping element. After 3D printing, all components were assembled according to the CAD model and subjected to testing to assess their performance in grasping objects of different sizes and shapes. The lightweight structure of this design is achieved by utilizing a single actuator, which significantly reduces the device's weight. The overall weight of the prototype mainly depends on the motor, gearbox, and the density of the 3D-printed material used. To further reduce the gripper's weight, the infill can be minimized, and a less dense 3D printing material can be utilized. These measures were implemented in the completed gripper prototype. During experimental evaluation, the gripper demonstrated outstanding performance in grasping objects of different sizes, shapes, and textures, meeting all expectations. It effectively grasped objects with a size difference of up to 7 cm (with a maximum size of 15 cm), as demonstrated by the successful grasping of the six objects presented later in this document, each exhibiting diverse sizes and shapes.

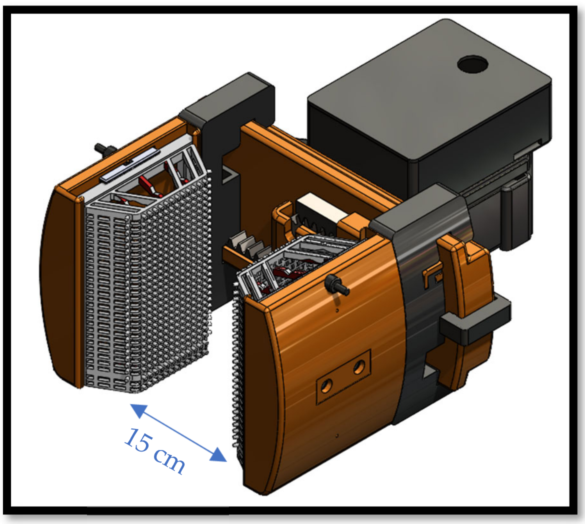


Figure 11. Final design and assembly of the gripper (CAD model).

To ensure the safety and protection of the electronic components, including the microcontroller, battery (power source), motor driver, and infrared sensor for the remote-control system, they were securely enclosed within a box to shield them from potential liquid exposure in the workspace. Figure 12 provides a visual representation of the physical prototype, which is attached to the articulated robotic arm and constructed based on the specified requirements. The figure demonstrates that the gripper effectively grasps and lifts objects with varying sizes, shapes, and textures.

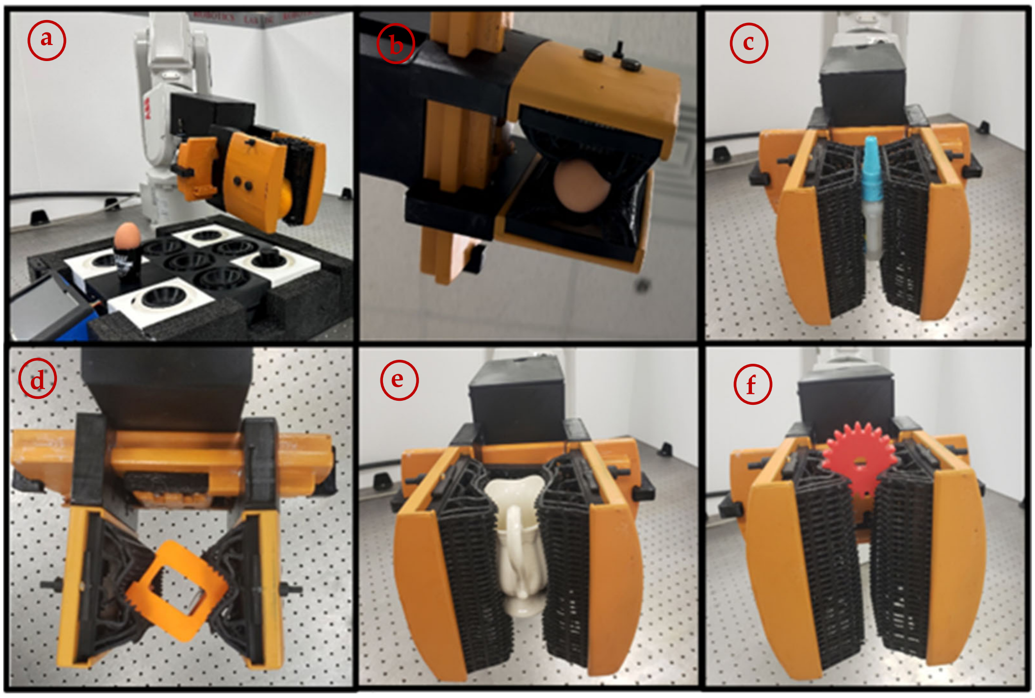


Figure 12. (**a**) Grasping an orange, (**b**) grasping an egg, (**c**) grasping a super glue bottle, (**d**) grasping a cube, (**e**) grasping a unique glass pitcher, and (**f**) grasping a gear.

During the experiments, the gripper had a few limitations for grasping objects. The maximum payload capacity of the robotic arm used in our tests was 3 kg, meaning that the combined weight of the gripper and the grasped object should not exceed this limit. The overall weight of the current gripper without the battery is 2.5 kg, indicating that the selected object should not weigh more than 500 g. It is important to note that in the final product, the battery will be eliminated, and the gripper will directly connect to the powered articulated robotic arm.

Another limitation relates to the dimensions of the objects that can be grasped by the gripper. The grasping area of the flexible element measures 14 cm $\times$ 6 cm, with a deformation capacity of 3.5 cm for each flexible element., This allows the gripper to accommodate objects with a width difference of 7 cm and a maximum width of 15 cm (which is the farthest the gripper handle can open). Various objects were used during the experiment to evaluate the gripper's performance. Figure 12 showcases six sample objects of different sizes, shapes, and textures, including a soft-textured orange, a fragile-surfaced egg, a small bottle of super glue, a randomly oriented square box, a distinct pitcher glass, and a gear.

While the current gripper prototype performs well, a few minor modifications could enhance its performance. In the industrial version, incorporating stronger and lighter materials like Aluminum Alloy 6061, along with conducting a thorough topology analysis, can significantly reduce the gripper's overall weight. Additionally, exploring alternative patterns for the flexible element can cater to different application requirements. Although successful tests have already been conducted using an Arduino microcontroller, power bank, and remote-control system, future generations of the gripper could establish a direct connection to the robotic arm controller to eliminate the need for most of the electronic components in the gripper. This would minimize the gripper's weight and size while increasing operational efficiency.

In comparison with other state-of-the-art compliant grippers, the proposed gripper offers several advantages. Existing compliant robotic graspers, as demonstrated in [2,3,22], often utilize three or more fingers to achieve a complete grasp of the object. In contrast, our gripper utilizes two fingers with a larger surface area, providing greater stability regardless of the object's orientation thanks to the form closure enabled by the compliant material. Additionally, during the grasping process, the trapezoidal shape of the flexible element ensures that regardless of the part of the surface used to grasp the object, the flexible element bends inward and pushes the object toward the center of the gripper, fully encompassing it. This results in more secure and safe grasping than similar multifingered soft/flexible grippers. Also, this gripper, using a passive grasping force, does not have the problem of soft grippers and pneumatic actuators regarding air leaking or heavy compressors for creating vacuum pressure [23–25].

5. Conclusions

This article discussed the design and implementation of a flexible gripper for robotic applications. The primary objective was to address the limitations of traditional grippers by developing a flexible gripper capable of grasping objects of various sizes and shapes. The gripper utilizes a combination of a hard shell and flexible structures, allowing for versatile grasping capabilities. It incorporated a high-torque stepper motor and a rack–pinion mechanism for precise control of linear motion. The controlling system operated on an open-loop control system, offering user-friendly operation while producing precise and secure grasping with a combination of form and force closure grasps. Extensive stress analysis ensured the gripper's components could withstand the required forces, ensuring reliability and safety. The successful testing of the gripper in grasping various objects demonstrated exceptional performance, with the ability to grasp objects effectively using different flexible patterns. This flexible gripper design represents a significant advancement in the field of robotics, particularly for industrial applications. Its versatility, reliability, and efficient grasping capabilities offer practical solutions for handling diverse objects.

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