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RESEARCH ARTICLE

Design and manufacturing of a novel four-fingered reconfigurable robotic gripper with enhanced grasping capabilities

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Abstract
The effectiveness of robotic grippers is critical for the secure and damage-free manipulation of objects with diverse geometries and material properties. This paper presents the design, analysis, and experimental evaluation of a novel reconfigurable four-finger robotic gripper. The proposed design incorporates two stationary fingers fixed to a circular base and two movable fingers repositioned and reoriented via a face gear mechanism, enabling multiple finger configurations to enhance adaptability. A single geared motor drives the opening and closing motions of all four fingers, simplifying the actuation mechanism. The robotic gripper was fabricated using 3D printing technology, ensuring cost-effective and precise manufacturing. Experimental tests were conducted to evaluate the robotic gripper's reconfigurability and grasping performance across a range of objects, demonstrating its effectiveness in various configurations. Additionally, a closed-loop force control system was implemented to assess the grasping performance of a soft reconfigurable variant. Grasping force measurements were performed on three distinct objects, yielding a grasping curve that confirmed successful adaptation and secure handling. While the results validate the robotic gripper's performance, further refinement of the control algorithm is recommended to optimize its capabilities. Compared to conventional three-finger designs, the proposed robotic gripper offers superior reconfigurability and adaptability, making it suitable for a broader range of industrial and research applications. The innovative face gear mechanism and modular design expand the robotic gripper's functionality, positioning it as a versatile tool for advanced robotic manipulation tasks.

1. Introduction
Robotic grippers are becoming increasingly relevant and advantageous, gaining traction in industrial sectors and attracting interest from a diverse range of professionals, including researchers, engineers, and clinicians [1]. While the term "robotic grippers" can have multiple interpretations, they are generally understood as devices that employ mechanical manipulation. This involves exerting force on an object, causing movement or deformation [2–4]. One key function of robotic manipulators is gripping. Thus, in a scientific context, grasping is defined as the act of securing and maintaining hold of an object. The task of gripping can be delegated to robotic grippers, which are typically attached to the terminal end of the manipulator, also known as the end-effector [5, 6]. Industrial robotic grippers come in various sizes and payload capacities to accommodate a wide range of tasks. Some grippers are specifically

designed for particular applications, such as welding, painting, and cutting [7]. Robotic grippers can be classified based on the number of fingers. They generally fall into four categories: 2-finger, 3-finger, 4-finger robotic grippers, and anthropomorphic hands [8]. Different types of robotic grippers and their underlying technologies will be discussed in the following section.

One of the key elements of a robotic gripper system is the actuation technology used to provide force or torque to the robotic gripper. The classification of robotic grippers based on actuation technology, sensing capabilities, and mechanism type was discussed in ref. [9–12]. A tendon-driven robotic gripper, made using shape deposition manufacturing, is an advancement over conventional robotic grippers with stiff joints and links. This design has joints made of elastomers and incorporates actuators and sensors into solid polymer structures [13]. Different criteria have been used to group research robotic grippers into categories such as hydraulic, electric, and pneumatic systems. Two interesting types of pneumatic soft robotic grippers use a pneumatic system to create a vacuum and grasp objects by suction, such as the robotic gripper reported by Wang et al. [14, 15]. Soft pneumatic robotic grippers have also been proposed to achieve successful grasps of flat and flexible objects. They combine the advantages of electro-adhesive and soft pneumatic robotic grippers.

On the other hand, hydraulic actuation in robotic grippers is employed in commercial systems such as Schilling Robotics, LLC, or Hydro-Lek, Ltd. [16]. Despite the strong grasping force of hydraulic robotic grippers, their heavy bulk makes them unsuitable for everyday use [17–19]. Electric actuation is used to drive different types of robotic gripper mechanisms [20–22]. Additionally, the robotic gripper's mechanism is crucial for successful grasping. For instance, the underactuation and structural compliance of the proposed adaptive mechanism allow for gentle handling and grasping of delicate objects [22–24]. Furthermore, a review paper presents research trends in actuation technology, focusing on soft robotic grippers, micro- and nano-robotic grippers, multi-fingered robotic grippers, and underactuated robotic grippers [25–27]. Various combined technologies are used to provide force to the robotic gripper, such as cable-and-motor systems, which are used in developing variable-stiffness robotic gripper systems [28].

The concept of a reconfigurable design has not yet been fully realized in robotic gripper systems. However, preliminary efforts by researchers [29–33] have explored the potential for developing reconfigurable robotic grippers. In related work, [34] proposed a configuration and planning methodology to reduce the complexity of determining finger contacts from a six-degree-of-freedom problem to a single-degree-of-freedom problem. This approach involves a specific arrangement of fingers, wherein one jaw is equipped with two fixed cylindrical fingers, while the third finger is positioned along the perpendicular bisector of the central axis defined by the other two fingers. The reconfigurable design offers significant advantages, including enhanced grasping versatility and simplified solutions for industrial applications.

On the other hand, recent advancements in single-actuator robotic grippers have focused on enhancing the simplicity and efficiency of various grasping tasks. For instance, a three-finger rigid robotic gripper was developed for grasping medium-sized spherical fruits using a single gear motor as the actuator, which provided movement to all three fingers. The prototype was tested using a UR5 robot arm, and its performance in pick-and-place tasks demonstrated that the robotic gripper met all necessary requirements effectively [35]. Another example is a low-cost, three-fingered robotic gripper that was 3D-printed for educational purposes. It featured an underactuated design, with each finger having two degrees of freedom, and was actuated by a single servo motor connected to a worm gear system. The system allowed the fingers to grip objects effectively with minimal mechanical complexity, demonstrating its potential in educational settings [36]. Additionally, a soft-rigid robotic gripper actuated by a single pneumatic actuator was developed for applications requiring delicate handling. The robotic gripper, consisting of three fingers, was actuated via a soft pneumatic actuator connected to polyethylene air tubes. Performance tests, both static and dynamic, showed that the robotic gripper was effective at handling delicate objects, such as strawberries, with minimal damage, showcasing its efficiency in specific applications [37]. These examples demonstrate that single-actuator robotic grippers offer a range of benefits, such as simplicity, low cost, and ease of implementation, depending on the application. However, these designs often face limitations in terms of the number of fingers, which may restrict the robotic gripper's grasping ability. For instance, the examples demonstrated three-finger robotic grippers that are suitable for grasping mostly spherical objects, such as tomatoes and apples. In comparison, the proposed robotic gripper can expand its grasping ability by handling objects with different geometries, as will be shown later. Additionally, the proposed robotic gripper stands out due to its simple configurability and the ability to adjust the number of fingers, which enhances the robotic gripper's overall grasping capability.

A review of the literature indicates a notable gap in research addressing the configurable nature of four-fingered robotic grippers, particularly in terms of cost-effective solutions utilizing off-the-shelf components and 3D printing technologies. The reconfigurable robotic gripper proposed in this study aims to address the gap in reconfigurability observed in existing robotic gripper systems. By focusing on configurability, this work seeks to enhance grasping versatility beyond the capabilities of conventional robotic grippers. The primary contributions of this study are as follows: (1) the introduction of a novel underactuated reconfigurable mechanism for a four-fingered robotic gripper; (2) the development of a new reconfigurability concept based on a face gear mechanism, enabling the gripper to adapt to objects of varying shapes and sizes across diverse scenarios; and (3) the implementation of a straightforward closed-loop control algorithm to regulate the grasping force of the reconfigurable robotic gripper. In this study, the term "robotic gripper" may be used frequently instead of "reconfigurable robotic gripper" for simplicity, conciseness, and readers' convenience.

The paper is organized as follows: Section 2 describes the materials, methods, and design of the reconfigurable robotic gripper. Section 3 explains the working principle of the four-fingered reconfigurable robotic gripper. Section 4 discusses underactuation and the absence of a differential system. Section 5 covers the fabrication process. Section 6 presents the results and testing. Section 7 details the modification of the robotic gripper by attaching soft materials to the fingers. Section 8 addresses grasping force measurements. Section 9 explores grasping force control. Section 10 examines scalability considerations. Section 11 compares grasping performance with soft and rigid fingers. Section 12 outlines the limitations of the current study. Section 13 provides a discussion. Finally, Section 14 concludes the study.

2. Materials and methods

Numerous grasping techniques observed in nature [38–41] illustrate the diverse methods employed by animals and birds to manipulate objects. For example, fish utilize their mouths, while birds employ their beaks for prehension tasks [42]. The male diving beetle is equipped with suction cups on its forelegs, and lizards leverage adhesion lamellae on their toes to traverse smooth surfaces such as glass plates by exploiting surface roughness. This work is inspired by natural systems, particularly the grasping mechanism of the osprey. The osprey demonstrates exceptional grasping capabilities, facilitated by its long, sharp claws on its talons (Figure 1), which enable it to securely capture prey with surfaces characterized by extremely low friction coefficients.

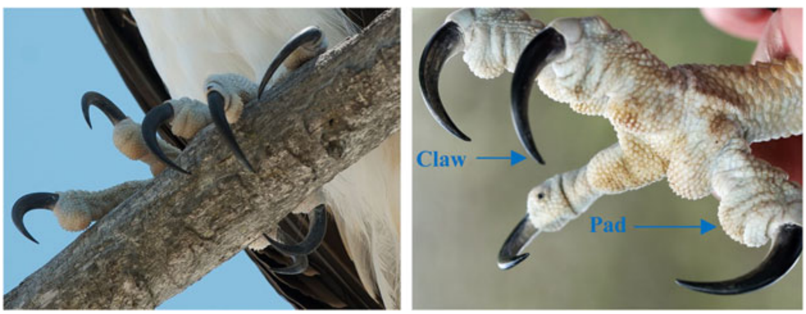


Figure 1. *Mechanism of the osprey's grasping fingers.*

The design of the reconfigurable robotic gripper was developed through the iterative construction and evaluation of multiple computer-aided design (CAD) models to ensure its reconfigurability and adaptability. The robotic gripper comprises four fingers, each actuated by an electric motor. Underactuated fingers, which possess fewer actuators than degrees of freedom, are widely utilized in robotic hands for industrial and service applications due to their simplified design compared to fully actuated dexterous fingers. The orientation of two of the four fingers can be dynamically adjusted using two servomotors. As illustrated in Figure 2, the robotic gripper can be reconfigured to support various finger arrangements (two, three, or four fingers) depending on the geometry and shape of the target object. This adjustability is enabled by the two servomotors, which facilitate the reconfiguration process.

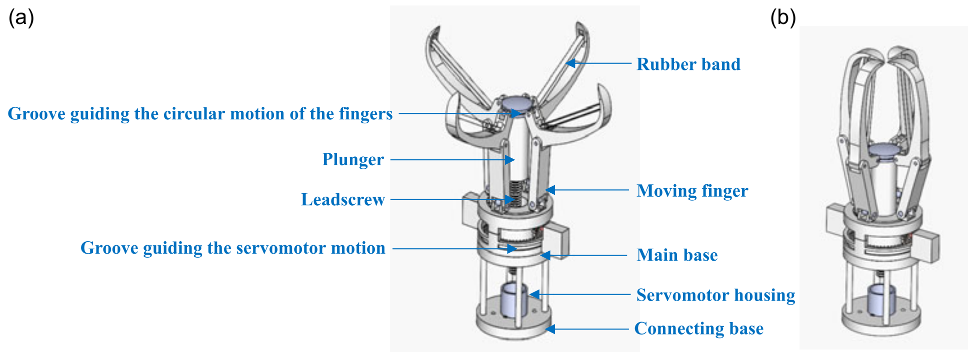


Figure 2. *CAD drawing of the proposed reconfigurable robotic gripper: (a) assembly of the robotic gripper in the opening state, (b) closing state.*

2.1. Design of the reconfigurable robotic gripper

The design of the proposed robotic gripper is based on a design criterion that is adopted by ref. [43], which is using the Grasping Index (GI). The prior criterion can be used to characterize the grasping mechanism based on the grasping action. The GI can be seen in Eq. (1).

$$\text{G.I.} = \frac{2\,F\cos\varphi}{P} \tag{1}$$

where

F: The force exerted by the robotic gripper fingers on the object (the applied gripping force).

φ : The configuration angle of the mechanism at the point of grasp, typically representing the angle of the robotic gripper fingers or links.

P: The force exerted by the actuator that drives the grasping action.

The robotic gripper is equipped with four fingers, each actuated by a lead screw and nut assembly. Each finger is composed of two primary segments, interconnected by revolute joints. As depicted in Figure 3, each finger incorporates three such joints. This joint configuration is consistent across all four fingers. The actuation sequence commences with the angular displacement of the first link, which subsequently triggers the movement of the second link.

Referring to the design parameters shown in Figure 3 (b) and (c), the robotic gripper structure has the following kinematic relationship as shown in Eqs. (2) and (3).

$$l_1 \sin\theta_1 = l_2 \sin\theta_2 \tag{2}$$

$$\cos\theta_1 = \frac{X_b^2 + l_1^2 - l_2^2}{2X_b\, l_1} \tag{3}$$

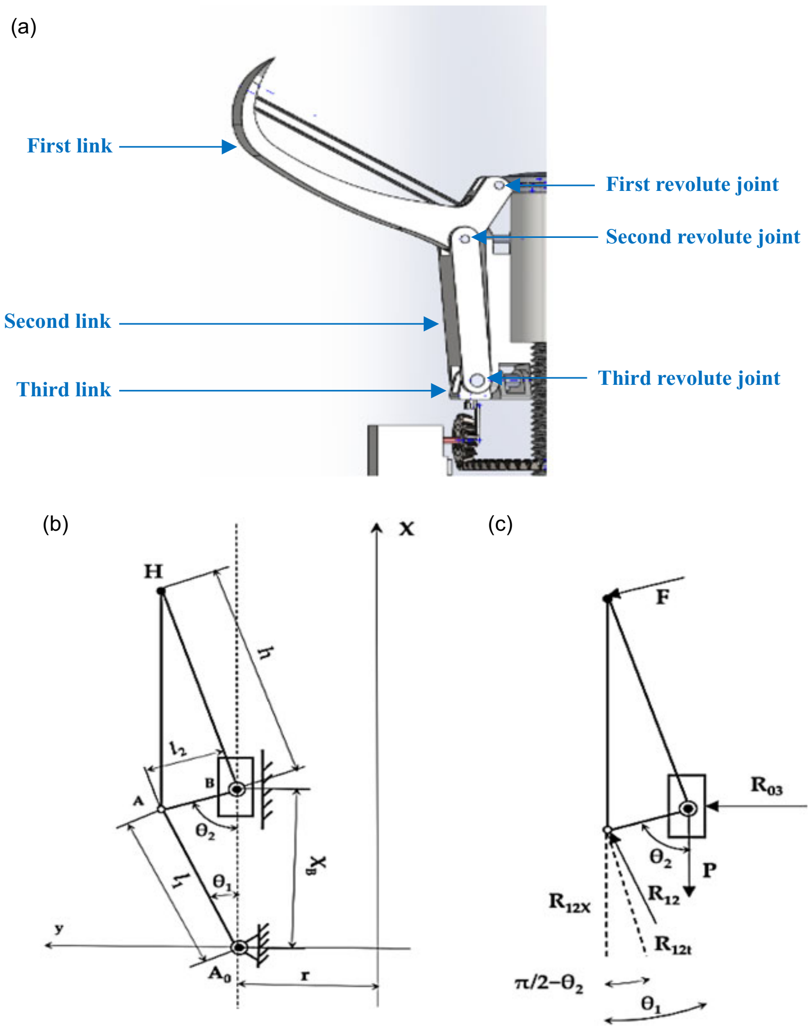


Figure 3. *Finger configuration of the robotic gripper: (a) links and joints, (b) kinematic diagram, (c) free-body diagram.*

where

l_1 and l_2 : The lengths of the two links in the mechanism.

θ_1 and θ_2 : The angles between l_1 and l_2 and the X-axis direction, respectively.

X_b : The coordinate position parameters of the slider.

When the grasping of the target object is in equilibrium, grasping performance can be evaluated by the relationship between the grasping force and driving force. The moment balance at point B in Figure 3(b) can be written as follows in Eqs. (4) and (5).

$$F\,h - R_{12t}\,l_2 = 0 \tag{4}$$

$$R_{12x} - P = 0 \tag{5}$$

where

h: The height of the finger.

R_{12x} and R_{12t}: The components of constraint reaction R_{12}, respectively, along the X-axis and the axis normal to link 2 (AB).

The connecting rod has no other external force and can be regarded as a tensile bar according to the material mechanics. The direction of the internal force is a pair of interactions in the link direction. Moreover, the relationship between them is given by the Eqs. (6) and (7).

$$R_{12t} = R_{12}\sin[\pi - (\theta_1 + \theta_2)] \tag{6}$$

$$R_{12x} = R_{12}\cos\theta_1 \tag{7}$$

The expression for the driving force P can be obtained as follows in Eq. (8).

$$P = \frac{F\,h\cos\theta_1}{l_2\cos[\theta_1 + \theta_2 - \frac{\pi}{2}]} \tag{8}$$

Then, substituting Eqs. (2) and (8) into Eq. (1), the GI for the proposed robotic gripper can be expressed as follows in Eq. (9).

$$\text{G.I.} = (l_1/\,h)\tan\theta_1\cos[\theta_1 + \theta_2 - \pi/2] \tag{9}$$

On one hand, the index of the robotic gripper is influenced by the height h of the manipulator. However, since the minimum height of the manipulator must be greater than half the diameter of the target, it is clearly impractical and unreasonable to increase the index by reducing h. On the other hand, another parameter l_1 can be optimized to enhance the index value.

There are two specific parameters for the optimization evaluation index. One of these parameters is the mean index, which represents the average of the GI. The optimization goal is to maximize the GI, thereby enhancing the grasping ability during the process. The formula can be expressed as follows in Eq. (10).

$$\max\ index_{mean}\ subject\ to\ l_{i,\min} < l_i < l_{i,\max},\ for\ i = 1,2 \tag{10}$$

Another parameter is to minimize the average deviation of the GI, which represents the value of index changes during the grasping process. It can be expressed as follows in Eq. (11).

$$\min(index_{\max} - index_{\min})/index_{mean}\ subject\ to\ l_{i,\min} < l_i < l_{i,\max},\ for\ i = 1,2 \tag{11}$$

The dimensions of each geometric parameter of the robotic gripper are constrained within a defined minimum and maximum range, based on the object size requirements for grasping. Therefore, the boundary conditions for the size parameters of each component of the mechanical claw are initially defined. In addition, smaller links complicate the manufacturing and assembly of the hinges, while larger links result in a robotic gripper that is oversized for the task. Each geometric parameter of the robotic gripper is restricted within a specified minimum and maximum range, which corresponds to the product range provided, as detailed in Table I.

Table I. *Ranges of the designed parameters for the robotic gripper.*

Parameter	Min (cm)	Max (cm)
l_1	3	6
l_2	1.5	2
r	3	3

Two design criteria are identified: the $\text{index}_{\text{mean}}$ and the deviation of the GI. The results, based on these criteria, are shown in Table II. The calculation of the $\text{index}_{\text{mean}}$ and deviation for values of l_1 and l_2 starting from 3 to 6 cm and 1.5 to 2 cm, respectively. The best trade-off would be to select values close to the ones with the highest mean while considering the lowest deviation. A reasonable compromise could be $l_1 = 4.0$ cm and $l_2 = 1.5$ cm, which offers mean = 0.295522 (high mean value) and deviation = 0.089854 (relatively low deviation). The result of the minimum deviation can be considered the appropriate choice at this stage.

Table II. *Results of robotic gripper dimensions.*

l_1 (cm)	l_2 (cm)	$\text{Index}_{\text{mean}}$	Deviation
3	1.5	0.277236	0.095319
3	1.6	0.293345	0.101113
3	1.7	0.309454	0.106907
3	1.8	0.325564	0.112701
3	1.9	0.341673	0.118495
3	2.0	0.357782	0.124289
4	1.5	0.307226	0.089854
4	1.6	0.323337	0.095291
4	1.7	0.339447	0.100728
4	1.8	0.355558	0.106165
4	1.9	0.371669	0.111602
4	2.0	0.387780	0.117039
5	1.5	0.351258	0.084389
5	1.6	0.367370	0.089404
5	1.7	0.383481	0.094419
5	1.8	0.399592	0.099434
5	1.9	0.415703	0.104449
5	2.0	0.431814	0.109464
6	1.5	0.395289	0.079924
6	1.6	0.411400	0.084517
6	1.7	0.427511	0.089110
6	1.8	0.443622	0.093703
6	1.9	0.459733	0.098295
6	2	0.475844	0.102888

Based on prior analysis, the dimensions of the robotic gripper have been designed to accommodate a wide variety of objects. The maximum and minimum extensions of the robotic gripper fingers are 225 mm and 4 mm, respectively. Another key dimension is the maximum and minimum angles between the moving fingers, which provide the robotic gripper with its reconfigurable feature. These angles are 131 degrees and 49 degrees, respectively. These dimensions allow the robotic gripper to grasp a variety of everyday objects, as demonstrated later in the paper. Figures 4 and 5 illustrate the robotic gripper's dimensions in terms of its finger extension range and angle adjustments.

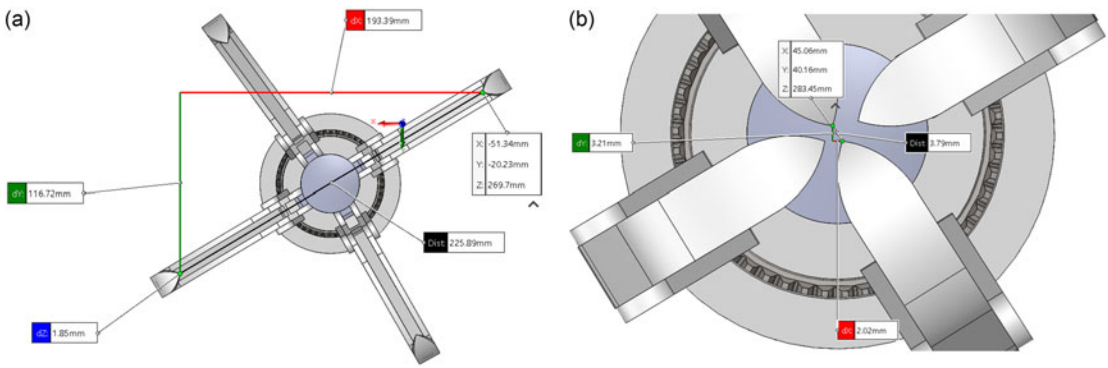


Figure 4. *The maximum and minimum extensions of the robotic gripper fingers: (a) opening state, (b) closing state.*

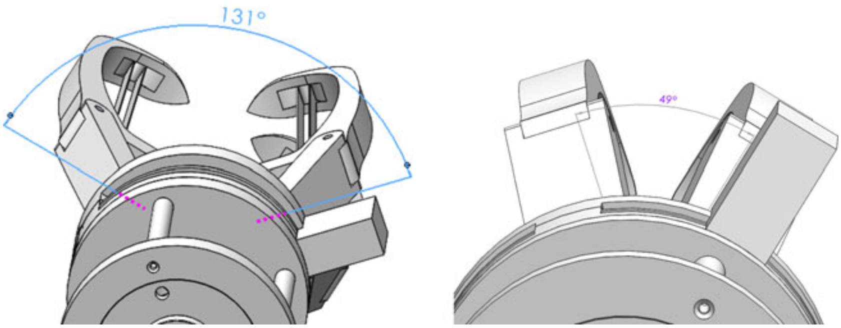


Figure 5. *The range of angles of the moving fingers of the robotic gripper.*

3. Working principle of the four-fingered reconfigurable robotic gripper

This section describes the movement mechanism of the four-fingered robotic gripper and the gear system responsible for adjusting the orientation of two fingers to accommodate objects of varying shapes and sizes. The movement mechanism is driven by electrical actuation, offering several advantages, including lightweight construction, high efficiency, and reduced complexity in connections, making it well-suited for driving the device. The robotic gripper is actuated by a single geared motor mounted on the main base. This motor drives a lead screw mechanism that controls the motion of the four fingers. The direction of rotation determines whether the fingers open or close. Two of the fingers are designed to move along a curved path on the base, enabled by a face gear mechanism. Each of these fingers is connected to a circular gear, which interfaces with another fixed circular gear on a lower base, ensuring synchronized motion.

The four-fingered robotic gripper is actuated by a single motor, which controls the opening and closing motions of the fingers. The motor is positioned beneath the base of the robotic gripper. A lead screw is directly connected to the motor, and a nut attached to the lead screw converts the rotational motion into linear movement, driving the plunger upward and downward. The four fingers are arranged circularly around the top surface of the plunger. As the plunger moves linearly, the fingers open or close accordingly. To enable adjustable orientation for two of the fingers, a gear mechanism is incorporated into the robotic gripper design. The detailed arrangement and operation of this gear mechanism will be discussed in the following section. The overall driving mechanism of the robotic gripper is illustrated from multiple perspectives in Figure 6.

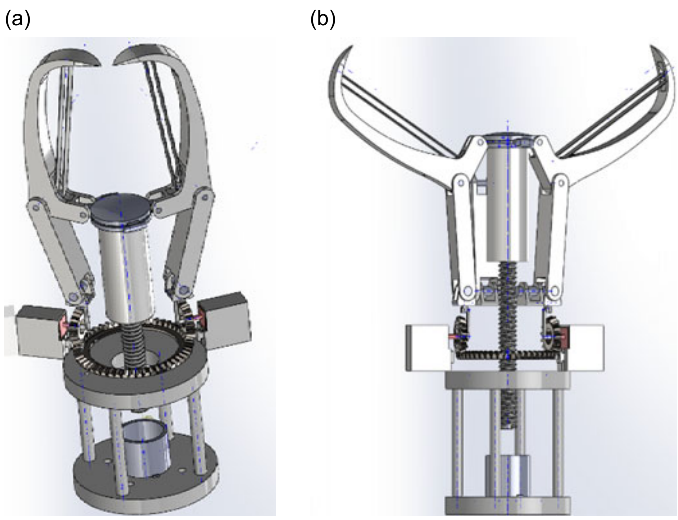


Figure 6. *Driving mechanism of the two fingers of the robotic gripper: (a) 3D view, (b) alternate 3D view.*

The movement of the two adjustable fingers is facilitated by a face gear system (Figure 7). A face gear is a type of gear system in which a spur or helical gear, acting as a pinion, meshes with a disk-shaped gear featuring teeth cut on its end face. Face gear transmission offers a novel approach to power transfer, where a face gear engages with a spur gear. Among the primary advantages of this gear system is its ability to distribute torque effectively and reduce overall weight. Face gears are categorized into three types: standard, helical, and offset. These gears offer several benefits, such as simplified assembly, with only the axial position of the face gears needing adjustment. The pinion, which is a standard spur gear (Figure 7 (a)), eliminates axial load with its straight spur teeth, while the slanted contact lines and high contact ratio ensure smoother meshing. Additionally, this design enables backlash-free transmission with minimal complexity. The CAD assembly drawing of the face gear and the partial meshing of the gear systems are illustrated in Figure 7 (b). The face gear system, integrated into the robotic gripper to drive the two movable fingers, is assembled with the other components of the robotic gripper. Various views of the face gear system are provided in Figure 8.

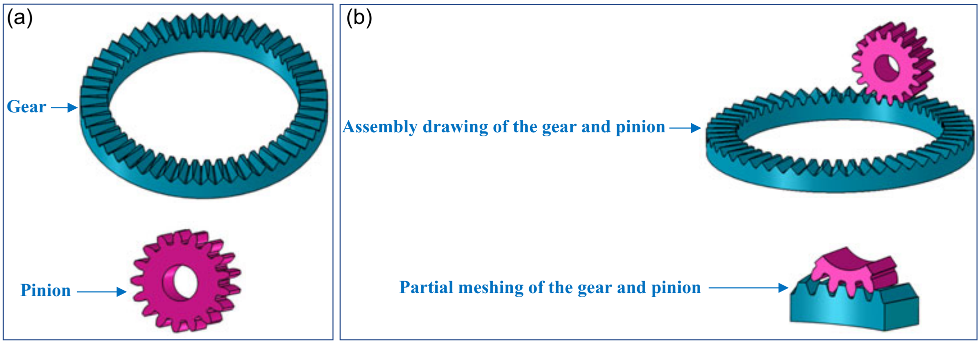


Figure 7. *Face gear system for driving the robotic gripper fingers: (a) CAD model of the gear and pinion, (b) assembly drawing and partial meshing of the pinion and gear.*

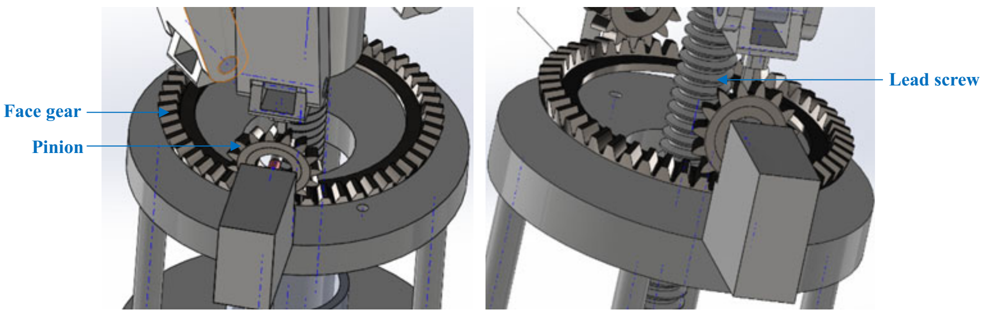


Figure 8. *Different views of the face gear system that is used to drive the two fingers of the robotic gripper.*

The robotic gripper is designed as an underactuated system, utilizing a single motor to actuate the motion of all four fingers. This design choice simplifies the mechanical architecture and reduces overall costs; however, it introduces a limitation: the two movable fingers are actuated simultaneously during grasping and cannot operate independently due to the absence of a differential system. To overcome this limitation, the robotic gripper incorporates a two-step operational process. In the first step, the two movable fingers are independently repositioned and reoriented using a face gear mechanism, thereby enabling the robotic gripper to adapt to the geometry and dimensions of the target object. In the second step, once the movable fingers are appropriately configured, the single motor engages the underactuation mechanism to drive all four fingers comprising both the two movable and two stationary fingers ensuring a secure grasp. This two-step process significantly enhances the robotic gripper's versatility, enabling it to accommodate a wider range of object shapes and sizes despite the absence of a differential system.

4. Underactuation and the absence of a differential system in the reconfigurable robotic gripper

The proposed robotic gripper is designed with an underactuated mechanism, utilizing a single servomotor to control all four fingers. This design choice reduces the number of actuators, simplifying the system while maintaining functional adaptability. The robotic gripper consists of two stationary fingers, which are fixed to the circular base, and two movable fingers, which can be repositioned using a face gear mechanism before grasping an object. Once the fingers are properly positioned, the servomotor drives a lead screw-based transmission system, simultaneously actuating all four fingers in synchronized motion.

Since the system is underactuated, it inherently lacks a differential mechanism, meaning the fingers do not move independently but rather in a coupled manner. In a fully actuated system, a differential mechanism would allow for force redistribution between the fingers, ensuring adaptive grasping based on contact conditions. However, in the proposed design, the absence of such a system results in equal torque and force distribution between the two movable fingers, as expressed in Eqs. (12) and (13), respectively.

$$\tau_1 = \tau_2 \tag{12}$$

$$F_1 = F_2 \tag{13}$$

where

τ_1 and τ_2: The torques applied to the two movable fingers.

F_1 and F_2: The contact forces.

The total grasping force (F_g) is determined by the actuation mechanism and can be approximated by q. (14).

$$F_g = \frac{\eta \tau_m}{r} \tag{14}$$

where

η : The mechanical efficiency of the transmission system.

τ_m: The motor torque.

r : The effective force transmission radius.

To partially compensate for the lack of independent finger motion, the robotic gripper leverages its reconfigurability. The two movable fingers can be repositioned before the grasping process using the face gear mechanism. This enables a two-step grasping strategy:

1. Finger reconfiguration phase: The two movable fingers are repositioned to accommodate objects of varying shapes and sizes.
2. Grasping phase: The leadscrew mechanism drives all four fingers simultaneously, ensuring a firm and stable grip.

This pre-grasp reconfiguration enhances adaptability, allowing the robotic gripper to handle a wider range of objects despite the absence of a differential system. The ability to reposition the movable fingers prior to actuation enables improved contact distribution, mitigating the limitations imposed by underactuation.

5. Fabrication of the proposed reconfigurable robotic gripper

The proposed reconfigurable robotic gripper was fabricated using additive manufacturing, specifically 3D printing with acrylonitrile butadiene styrene (ABS) (Figure 9), to ensure modularity, adaptability, and structural integrity. Iterative prototyping was conducted to refine the design and meet the reconfigurability requirements outlined in this study. The final 3D-printed prototype, depicted in Figure 9 (a) alongside its CAD model, integrates three primary subsystems: (i) a grasping mechanism comprising four articulated fingers, (ii) a linear plunger for actuation, and (iii) a structural base housing the components. A key feature of the robotic gripper is the face gear system, which facilitates the synchronized motion of the two movable fingers. This system, also fabricated using 3D printing with ABS, was meticulously assembled to ensure precise functionality. A detailed view of the face gear system is provided in Figure 9 (b), illustrating its structural and functional configuration. The overall features of the reconfigurable robotic gripper are summarized in Table III.

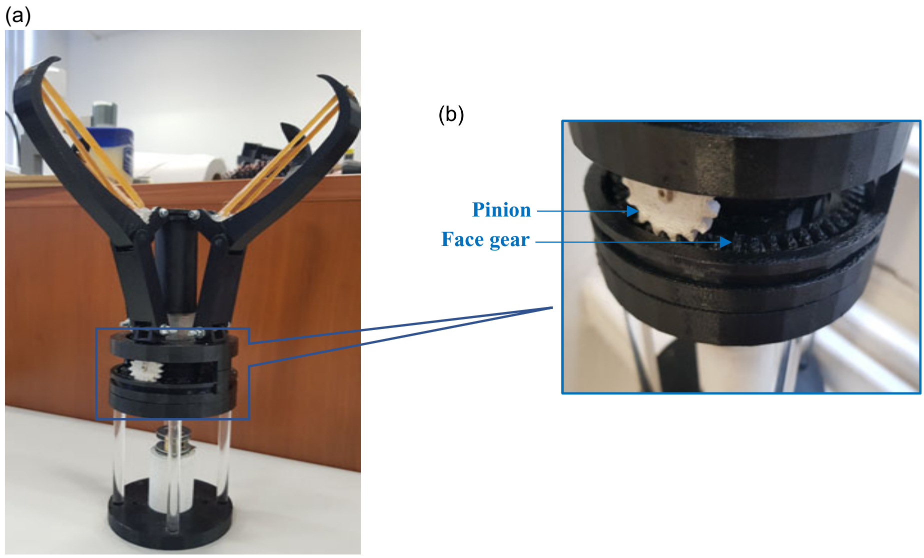


Figure 9. *The proposed reconfigurable robotic gripper: (a) 3D-printed robotic gripper, (b) face gear mechanism for moving the two fingers.*

Table III. *Overall features of the reconfigurable robotic gripper.*

Feature	Definition/value
Weight	584 gm
Plunger stroke	50 mm
Maximum closing distance	86 mm
Maximum opening distance	145 mm
Mechanism of movement	Underactuation mechanism
Drive source	Servo motor
Number of fingers	Four fingers
Mode of operation	Open loop/closed loop

6. Results

6.1. Testing of the reconfigurable robotic gripper

The testing of the reconfigurable robotic gripper is detailed in the following sections, divided into two primary components: (i) evaluation of the robotic gripper's reconfigurability and (ii) assessment of its grasping capabilities. Additionally, the modification of the robotic gripper through the integration of soft materials is discussed. Experimental tests are performed to measure the grasping force, followed by the implementation of a closed-loop control system to regulate the applied force. The proposed reconfigurable robotic gripper features a simple yet effective design, with reconfigurability achieved by adjusting the finger arrangements. This adaptability is facilitated by a face gear system, allowing the two fingers to traverse a semi-circular path on the base, thereby supporting multiple configurations. This section describes the various possible configurations of the robotic gripper, which can be adjusted to accommodate the geometry of the object being grasped. As summarized in Table IV, The arrangements of the fingers are driven by a mechanism mounted on the circular base, enabling alternative configurations in both the opening and closing states. A top view of the robotic gripper's different configurations in the opening state is shown in Figure 10.

Table IV. *Different states of the reconfigurable robotic gripper in both opening and closing positions.*

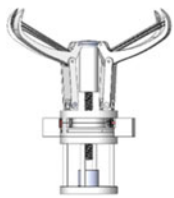
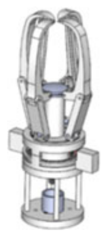
Robotic gripper state	**Reconfigurable robotic gripper configuration (state number)** (1)	(2)	(3)	(4)
Opening				
Closing				
Top view-opening sate				
Top view-closing sate				

Figure 10. *Top view of the robotic gripper in different configurations, shown in the opening state.*

6.2. Experimental tests of real objects

The reconfigurable robotic gripper was tested in both opening and closing states by connecting its terminals to a power supply. The fingers responded effectively to actuation from the electric motor, confirming the robotic gripper's operational functionality. This preliminary experiment focused on assessing the basic opening and closing mechanisms. Future experiments will integrate a force sensor to enable closed-loop control. The arrangement of the fingers used in this test is illustrated in Figure 11, showcasing both the opening and closing states.

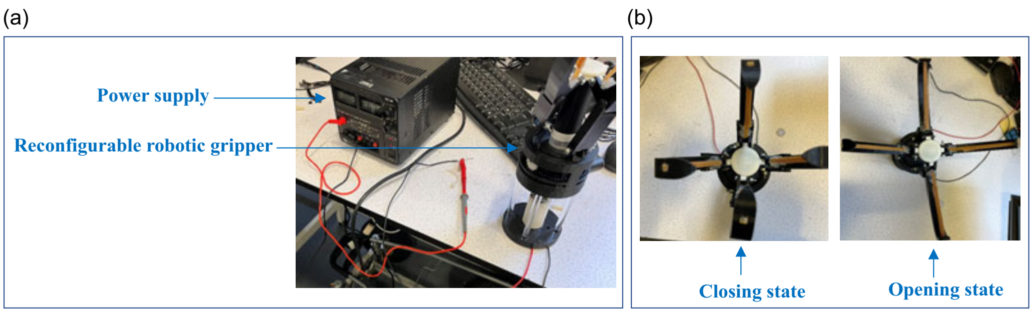


Figure 11. *Testing the robotic gripper for opening and closing states: (a) connection of the robotic gripper to the power supply, (b) opening and closing states of the robotic gripper.*

To assess the grasping capabilities of the robotic gripper, a set of objects with varied sizes, shapes, and weights was selected, as illustrated in Figure 12. The names and weights of these objects are summarized

Figure 12. *Set of objects that are tested by the reconfigurable robotic gripper.*

in Table V. The robotic gripper's performance was evaluated by adjusting the orientation of its two movable fingers to grasp the selected objects. This experiment aims to determine the range of objects the robotic gripper can successfully manipulate and those it cannot, providing critical insights for future modifications to the finger design and improvements in grasping force control.

Table V. *Names of the tested objects and weights.*

Object	Weight (g)
Headphone case	381
Screwdriver box	48.5
Gloves box	63
Brush	199
Square piece of wood	202.5
Plastic tape	147.5

The arrangement of the robotic gripper's four fingers was manually adjusted to achieve an optimal grasp based on the geometry of the target object. A top-down view of the finger arrangement and the object is depicted in Figure 13. During the test, the robotic gripper was positioned with its base facing upward, and the fingers fully extended, while the headphone case was placed on a flat surface. The fingers were then actuated to transition into the closing state, grasping the case as shown in Figure 14. Although the robotic gripper successfully secured the object, a gap was observed between one finger and the case, resulting from the adjustment of the movable finger on the circular base.

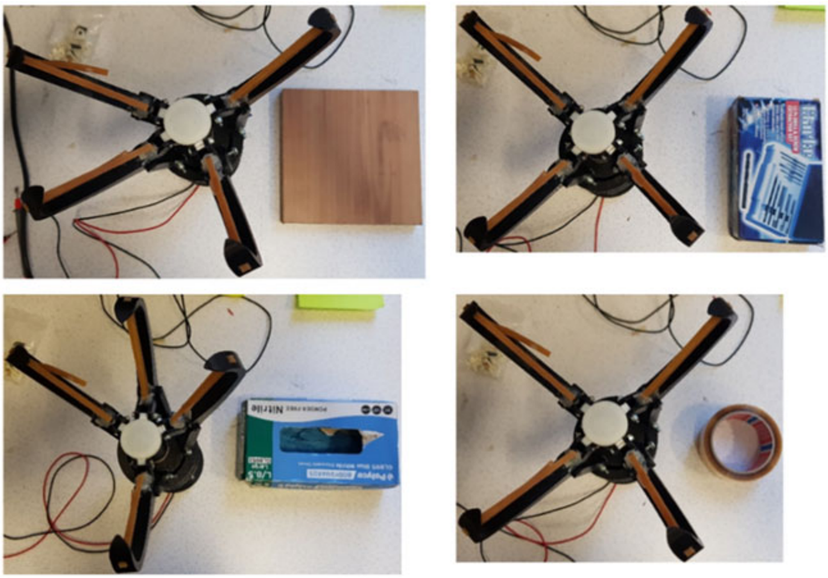


Figure 13. *Top view showing the orientation of the robotic gripper fingers and the objects to be grasped.*

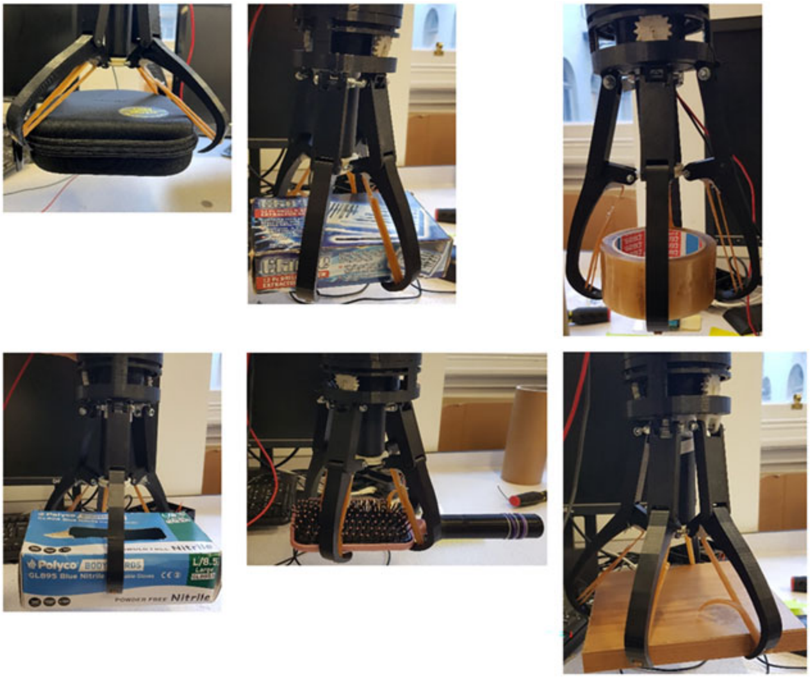


Figure 14. *Robotic gripper prototype grasping various objects.*

7. Modification of the reconfigurable robotic gripper by attaching soft material to the fingers

The reconfigurable robotic gripper was developed, and its grasping performance was evaluated using a variety of objects. To improve the robotic gripper's ability to handle objects effectively, the original design was modified by incorporating a softer material into the fingers. Sponge material was attached to each finger, replacing the rubber band used in the initial design. This modification aimed to reduce potential slippage during the grasping process. The updated design, which incorporates the sponge attachment to the fingers, is illustrated in Figure 15.

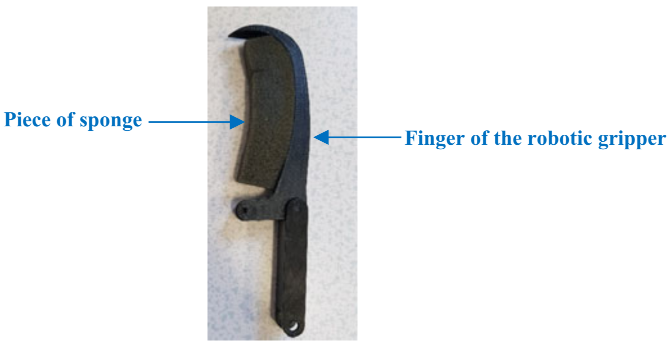
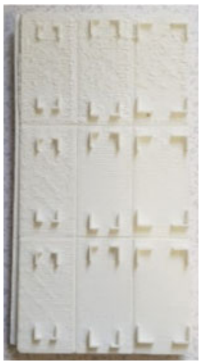


Figure 15. *Finger of the robotic gripper with a piece of sponge attached to its inner surface.*

7.1. Testing the modified soft reconfigurable robotic gripper with real objects

Table VI summarizes the performance of the soft reconfigurable robotic gripper during grasping tasks with objects made from wood, paper, and plastic. These materials were chosen to assess the robotic gripper's capability in handling diverse and challenging grasping scenarios. Two distinct grasping positions were recorded to evaluate the robotic gripper's adaptability and effectiveness. Additionally, grasping

Table VI. *Grasping positions of the soft reconfigurable robotic gripper while grasping three different objects.*

Grasping position 1	**Grasping position 2**	**Object shape**	**Object size**
			Length × Width × Height 180 × 106 × 42 mm
			Length × Width × Height 175 × 175 × 20 mm
			Length × Width × Height 175 × 93 × 10 mm
			Diameter × Height 100 × 50 mm

times were measured to assess the robotic gripper's response speed. The average grasping times for the three objects are provided in Table VII.

Table VII. *Average grasping times for three different objects.*

Object	Grasping time (s)
Square piece of wood	13
Screwdriver box	8
Rectangular piece of plastic	10
Plastic tape	11

8. Measurements of the grasping forces

The grasping force of the proposed robotic gripper was measured using a load cell (STALC3 model) while grasping selected objects. Initially, the load cell was positioned on one of the four fingers; however, it became apparent that additional sensors would be necessary on the remaining fingers to obtain a complete force measurement. In the updated design, a sufficient number of sensors will be integrated to measure the total grasping force. Three objects – plastic tape, a hard plastic plate, and a glove box – were selected for force measurement, as shown in Figure 16. The grasping force was recorded and plotted in Figure 17, demonstrating an initial increase followed by stabilization. During the final phase, the mechanical fingers were gradually released to determine the sliding grip force. The resulting grasping force values are also presented in Figure 17.

Figure 16. *Grasping states of three different objects: (a) hard plastic plate, (b) gloves box, and (c) plastic tape.*

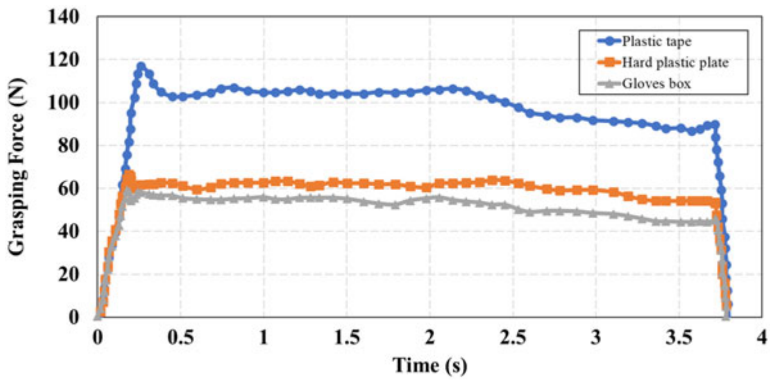


Figure 17. *Grasping forces measured for three different objects: plastic tape, hard plastic plate, and gloves box.*

9. Grasping force control of the soft reconfigurable robotic gripper

A closed-loop force control system was developed to regulate the grasping force and evaluate the soft reconfigurable robotic gripper's ability to securely hold an object. A block diagram of the closed-loop force control system is presented in Figure 18. The system operates by inputting a reference force signal into the controller, which generates the corresponding actuator torque. A conventional PI controller was employed, with the proportional term addressing the difference between the measured and desired forces, while the integral term compensates for steady-state errors. In the experiment, the soft reconfigurable robotic gripper was tasked with grasping a plastic tape, as illustrated in Figure 19. The grasping force was measured using an STALC3 load cell with a range of 0–1 kN, positioned between one finger and the tape. It was assumed that the force applied by a single finger represented one-quarter of the total force exerted by all four fingers. To implement the closed-loop force control for the soft reconfigurable robotic gripper while holding the plastic tape, the experimental setup was configured as shown in Figure 20. The setup consists of the following components: (1) power supply, (2) soft reconfigurable robotic gripper, (3) load cell, (4) plastic tape, (5) laptop, (6) Arduino microcontroller, and (7) load cell module.

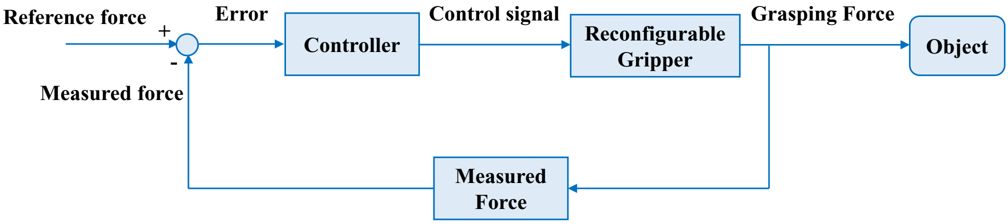


Figure 18. *Block diagram of the closed-loop control system for the reconfigurable robotic gripper.*

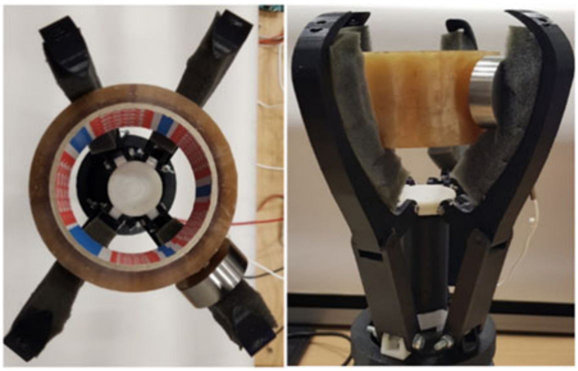


Figure 19. *Location of the load cell for testing the grasping force of the selected object (plastic tape).*

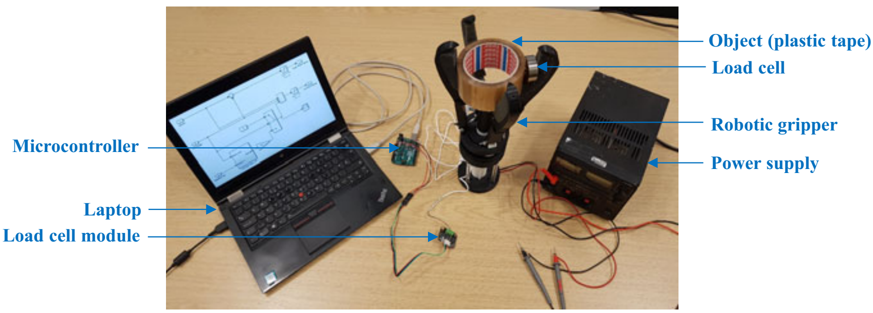


Figure 20. *The experimental platform of the reconfigurable robotic gripper showing the closed-loop system.*

A reference input force was provided to the controller, and the grasping force exerted by the finger during the closed-loop force control experiment, in response to a step input, is shown in Figure 21. As observed in Figure 21, several key parameters can be identified and are summarized in Table VIII.

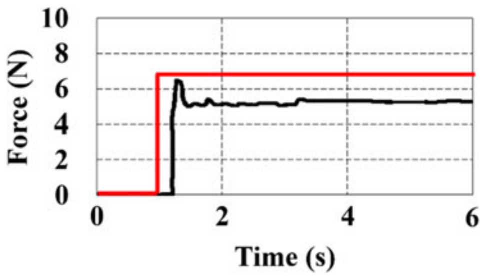


Figure 21. *The response of the grasping force due to step input.*

Table VIII. *Parameters of the grasping force response corresponding to a specific force reference input.*

Parameter	**Value**
Delay time	1.2 s
Peak time	1.25 s
Settling time	3 s
Steady-state error	2 N

Adjusting the controller parameters is a critical process aimed at improving the system's grasping force performance. As observed in Figure 21, a noticeable discrepancy exists between the reference force and the actual force response. This gap highlights the need for fine-tuning the controller parameters. To address this, adjustments were made to the controller's parameters, and the resulting impact on the grasping force is depicted in Figure 22. These modifications were implemented to achieve better alignment between the desired reference force and the actual force response, thereby optimizing the system for enhanced performance and accuracy in grasping force control. The updated parameters of the force response, as shown in Figure 22, are summarized in Table IX.

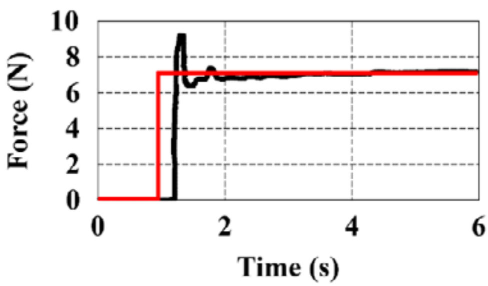


Figure 22. *The response of the grasping force due to step input after tuning the controller parameters.*

Table IX. *Parameters of the grasping force response corresponding to a specific force reference input.*

Parameter	Value
Delay time	1.2 s
Peak time	1.25 s
Settling time	2 s
Steady-state error	0 N at time of 4 s
Maximum overshoot	2 N

10. Scalability considerations of the reconfigurable robotic gripper

This section examines the impact of scaling the robotic gripper on its performance, focusing on reach, contact area, and required grasping force. Understanding the scalability of the robotic gripper is essential for ensuring its adaptability when handling objects of varying sizes. The analysis explores how these factors change when the robotic gripper is scaled by different factors (N).

10.1. Scaling equations and relationships

The scaling factor N affects various robotic gripper dimensions. The main parameters that change with scaling are the maximum and minimum finger extension as well as the contact area. The scaling relationships of finger extension, contact area, and grasping force will be outlined in the following two points:

Point 1: Finger extension (L);

The maximum and minimum finger extensions scale linearly with N can be seen as in Eqs. (15) and (16).

$$L_{max,\,scaled} = N \cdot L_{max} \tag{15}$$

And

$$L_{min,\,scaled} = N \cdot L_{min} \tag{16}$$

where

$L_{max,scaled}$: The maximum finger extensions scale.

$L_{min,scaled}$: The minimum finger extensions scale.

L_{max} : The maximum finger extension.

L_{min} : The minimum finger extension.

Contact area (A):

The contact area scales quadratically with N. If the original contact area is $A_{original}$, the scaled contact area is shown in Eq. (17).

$$A_{scaled} = N^2 \cdot A_{original} \tag{17}$$

where

A_{scaled} : The scaled contact area.

$A_{original}$: The original contact area.

Point 2: Gripping force (F);

The grasping force depends on both the contact area and the force applied by the robotic gripper mechanism. The grasping force generally scales with the cross-sectional area of the fingers and the actuation force. Assuming that the force is proportional to the contact area, the grasping force increases quadratically with N, as shown in Eq. (18).

$$F_{scaled} = N^2 \cdot F_{original} \tag{18}$$

where
F_{scaled}: The scaled grasping force.
$F_{original}$: The original grasping force.

10.2. Numerical example of scaling

Consider the robotic gripper with the following initial dimensions and force values, maximum finger Extension (L_{max}) = 225 mm, minimum finger extension (L_{min}) = 4 mm, contact area ($A_{original}$) = 100 cm^2, and grasping force ($F_{original}$) = 10 N.

For $N = 2$, the scaling equations provide the following four results:

1. Scaled maximum finger extension:

$$L_{max,\,scaled} = 2 \cdot 225 = 450\,\text{mm}$$

2. Scaled minimum finger extension:

$$L_{min,\,scaled} = 2 \cdot 4 = 8\,\text{mm}$$

3. Scaled contact area:

$$A_{scaled} = 22 \cdot 100 = 400\,\text{cm}^2$$

4. Scaled grasping force:

$$F_{scaled} = 22 \cdot 10 = 40\,\text{N}$$

Thus, when the robotic gripper is scaled by $N = 2$, its reach doubles, the minimum extension doubles, the contact area increases four times, and the grasping force increases by a factor of four as well. Table X summarizes how key dimensions and the grasping force change with different scaling factors N.

Table X. *Dimensions of the robotic gripper and grasping force with different scaling factor N.*

Scaling factor (*N*)	**Maximum finger extension (mm)**	**Minimum finger extension (mm)**	**Contact area multiplier**	**Grasping force multiplier**
$N = 1$	225	4	1	1
$N = 2$	450	8	4	4
$N = 3$	675	12	9	9
$N = 4$	900	16	16	16
$N = 5$	1125	20	25	25

Scaling the robotic gripper by different factors increases its ability to handle larger objects and provides more surface area for a secure grip. Table XI below summarizes how the scaling factor N affects the robotic gripper's ability to handle objects and apply grasping force.

Table XI. *Scaling factor N affects different the robotic gripper parameters.*

Scaling factor (N)	**Maximum object length (mm)**	**Minimum object height (mm)**	**Scaled contact area (cm^2)**	**Scaled grasping force (N)**
$N = 1$	225	4	100	10
$N = 2$	450	8	400	40
$N = 3$	675	12	900	90
$N = 4$	900	16	1600	160
$N = 5$	1125	20	2500	250

It can be concluded that scaling the robotic gripper by different factors N enables it to handle a wider range of object sizes while also increasing the grasping force. The increase in contact area and force ensures secure grasping for objects of varying sizes and weights. Tables X and XI illustrate how key robotic gripper dimensions and the grasping force change with scaling. By adjusting the scaling factor, the robotic gripper can be tailored to perform various tasks that require handling different object sizes, applying varying grasping forces, and adapting to diverse handling capabilities.

11. Grasping performance with soft and rigid fingers

The performance of the robotic gripper varies depending on the type of finger used in the current study, with rigid fingers and soft sponge fingers exhibiting different capabilities in handling objects. The rigid finger, lacking the adaptability of a soft material, can struggle to securely grasp objects with smooth surfaces or irregular shapes. In contrast, the addition of a soft sponge to the robotic gripper fingers enhances the robotic gripper's ability to conform to objects, providing a more reliable and secure grip on delicate, irregular, or smooth-textured objects. Table XII summarizes the tests of the grasping performance for the two objects named plastic tape and square piece of wood and their grasping performance with both the rigid finger and the soft sponge finger.

Table XII. *Grasping performance of the rigid finger versus the soft sponge finger in grasping two objects: plastic tape and a square piece of wood.*

Object	Dimensions	Robotic gripper finger type	Grasping success	Challenges/improved performance
Plastic tape	Diameter: 100 mm, Height: 50 mm	Rigid finger (no sponge)	Unsuccessful	Smooth surface caused slippage
		Soft sponge finger	Successful	Soft sponge enhanced grip, preventing slippage
Square piece of wood	Length: 175 mm, Width: 175 mm, Height: 20 mm	Rigid finger (no sponge)	Unsuccessful	Irregular shape made it difficult to maintain a secure grip
		Soft sponge finger	Successful	Soft sponge conformed to irregular surface for better grip

Table XIII summarizes the size and weight limitations based on the robotic gripper's testing. It provides details on the smallest and largest successfully grasped objects, as well as the maximum weight the robotic gripper can handle effectively. This information highlights the robotic gripper's performance boundaries and its capacity to grasp objects of varying sizes and weights.

Table XIII. *Minimum and maximum object sizes and weights for successful grasping.*

Category	Object	Weight (g)	Grasping performance
Minimum object size	Screwdriver box	48.5	Successfully grasped
Maximum object size	Headphone case	381	Successfully grasped
Maximum weight for successful grasping	Headphone case	381	The maximum weight the robotic gripper can handle effectively. Objects heavier than this may surpass the robotic gripper's force capabilities, especially with the soft sponge finger

12. Limitations of the current study

This study presents a reconfigurable robotic gripper designed to grasp objects of various shapes and geometries. The key innovation is the robotic gripper's reconfigurability, achieved by adjusting the orientation of two movable fingers to improve grasping performance. Currently, the fingers are manually driven, which limits the robotic gripper's functionality. Future work aims to incorporate two servo motors to automate finger movement. Although the robotic gripper demonstrated versatility in handling a wide range of objects, certain limitations must be considered. The rigid finger, without the soft sponge, faced difficulties in securely grasping objects with smooth or irregular surfaces, as its lack of adaptability restricted its effectiveness to regularly shaped and non-slippery objects. On the other hand, the soft sponge finger significantly improved the robotic gripper's ability to handle delicate and irregularly shaped objects. However, the flexibility of the soft sponge can limit the application of higher grasping forces, and it may still struggle with very large or heavy objects due to the reduced force it can exert. These limitations should be considered when evaluating the robotic gripper's practical applications. Additionally, future developments will focus on optimizing sensor placement to enhance the robotic gripper's sensing capabilities.

To summarize the overall performance of the robotic gripper, Table XIV compares the performance of the gripper fingers with and without the soft sponge when grasping various objects. It outlines the weight of each object, the success or failure of the grasp, and the challenges encountered with each robotic gripper type. Table XIV provides insights into how the soft sponge enhances the robotic gripper's ability to handle objects with irregular shapes or smooth surfaces, compared to the rigid finger.

Table XIV. *Comparison of the performance of robotic gripper fingers (with and without soft sponge).*

Object	Weight (g)	Robotic gripper finger type	Grasping success	Grasping challenges
Headphone case	381	Rigid (no sponge)	Successful	N/A
		Soft sponge	Successful	N/A
Screwdriver box	48.5	Rigid (no sponge)	Successful	N/A
		Soft sponge	Successful	N/A
Gloves box	63	Rigid (no sponge)	Successful	N/A
		Soft sponge	Successful	N/A
Brush	199	Rigid (no sponge)	Successful	N/A
		Soft sponge	Successful	N/A
Square piece of wood	202.5	Rigid (no sponge)	Unsuccessful (slippage)	Irregular surface and inability to conform to shape
		Soft sponge	Successful	N/A
Plastic tape	147.5	Rigid (no sponge)	Unsuccessful (slippage)	Smooth texture and cylindrical shape
		Soft sponge	Successful	N/A

13. Discussion

By addressing the contributions outlined above, this study presents a novel reconfigurable four-finger robotic gripper with potential applications in various domains, such as picking and placing fruits and vegetables in agricultural settings or similar industrial environments. In comparison to existing studies, the proposed robotic gripper introduces a unique perspective in terms of both the number of fingers and the reconfigurability mechanism. For instance, [37] proposed a three-fingered robotic gripper actuated by a pneumatic actuator, primarily intended for grasping soft fruits such as strawberries and other multiple objects such as candy pieces, powder packs, pyramids, and spheres. While those studies provided valuable insights into the design, mechanisms, and applications of robotic grippers, the current work distinguishes itself by introducing a four-finger reconfigurable robotic gripper with a novel mechanism. It is anticipated that this design will expand the range of objects that can be grasped, as demonstrated in this study, compared to existing solutions. Furthermore, the four-finger configuration offers enhanced redundancy and reliability. In the event of a failure or issue with one finger, the remaining fingers can maintain a secure grip, thereby improving the overall reliability of the robotic gripper. Overall, the proposed reconfigurable robotic gripper demonstrated acceptable performance in terms of reconfigurability and adaptability. However, limitations were observed in its grasping performance, particularly when handling specific objects or during the process of attaching and detaching the soft sponge. These limitations are discussed in detail in the previous section titled limitations of the current study.

14. Conclusion

In this paper, a novel reconfigurable robotic gripper is introduced, featuring an underactuation mechanism and a four-finger design, with two fingers driven by face gear mechanisms to enhance reconfigurability and grasp adaptability. The robotic gripper was developed using cost-effective off-the-shelf components and 3D printing technology, ensuring low production costs and ease of replication. Experimental evaluations showcased its ability to grasp objects of varying geometries, sizes, and materials, achieving a high success rate and a maximum grasping force suitable for diverse applications. A soft reconfigurable variant was also tested, with force measurements conducted on multiple objects to validate its performance. A force closed-loop control system was implemented, and step input tests yielded a stable response time after tuning, confirming effective system dynamics. However, further improvements could be achieved through advanced control techniques, such as adaptive or model predictive control. The robotic gripper was successfully demonstrated in tasks involving objects with diverse shapes and material properties, highlighting its potential for real-world applications. Future work will focus on integrating the robotic gripper into collaborative robotic systems, such as the UR10 model, for deployment in industrial and agricultural tasks, including fruit harvesting in unstructured environments.

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Author contributions. Amr M. El-Sayed conceived and designed the study, conducted the experiments, analyzed the data, and wrote the manuscript. Xiu-Tian Yan provided guidance and support during the early stages of this research.

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Competing interests. The author declares no conflicts of interest exist.

Ethical approval. Not applicable.

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