SEA-based Humanoid Finger-functional Parallel Gripper with Two Actuators: PG2 Gripper

Yonggan Yan, Shuxiang Guo, Fellow, IEEE, Chuqiao Lyu, Duohao Zhao, Zhijun Lin

Abstract—The flexible grasping, force sensing, and in-hand manipulating abilities of the gripper are theoretically significant and practically valuable to solve. However, it is still difficult for most existing grippers to realize these three functions simultaneously. This paper proposed a novel humanoid finger-functional parallel gripper with two actuators based on overlapping parallelogram mechanisms and the series elastic actuator (SEA). Based on the in-hand manipulation principle for the ordinary contour object, an in-hand manipulation algorithm for grasping force and position decoupling was designed. Then, to adjust the posture and position of objects within parallel fingers, the rolling and sliding conditions of objects based on the molecular-mechanical friction theory were analyzed. Combined with the proposed in-hand manipulating conditions and algorithm, the PG2 gripper can control the grasping force and manipulate the ordinary contour object in-hand controllably. Evaluation experimental results showed that the force-position control of the PG2 gripper was decoupled stably and the gripping had high accuracy in controlling force and position. Finally, the physical features perception experiments and the in-hand manipulating experiment were carried out to demonstrate the utility of the proposed manipulating methods and algorithm, and in-hand manipulating and grasping force sensing abilities of the gripper. The possible applications of this gripper include tasks that need accurate force-position control or manipulating and sensing in-hand remotely.

Index Terms—Force sensing, in-hand manipulation, robot hand, parallel gripper, underactuated gripper, PG2.

I. INTRODUCTION

GRIPPERS, the end effectors of robotic arms, are required to grasp and manipulate various types of objects in various scenarios instead of human hands, such as in narrow workspaces, high radiation workspaces, and so on. Therefore, more and more grippers are designed to suit different needs, such as parallel grippers, suction grippers, and multifingered grippers. And robotics manipulations are also being intensively studied [1]. To date, parallel grippers are the most widely used type of robotic hands due to their simple finger motion [2], and in-hand manipulation, in which the position and posture of an object are controlled within the hand, is an important skill [3]. To perform in-hand manipulation, three component tasks must be performed simultaneously: grasping the object, suitable grasping force, and giving the object translational and/or rotational motion. One of the goals of the gripper design is to perform the three tasks simultaneously with fewer degrees of freedom (DoFs). Therefore, several grippers for in-hand manipulation have been studied.

Fig. 1(a) shows the widely used commercial gripper Robotiq, which is a reconfigurable 5-bar chain mechanism. It is a parallel gripper consisting of two parallelogram mechanisms when its reconfigurable links are secured by dowel pins [4]. In order to singulate and pick objects, Tong et al. added a rack-and-pinion mechanism to the Robotiq’s unilateral finger to adjust the length of the finger, as shown in Fig. 1(b), with the help of the extendable palm device, it can adjust the grasping position within fingers [5]. As shown in Fig. 1(c), the gripper can grasp and manipulate objects in-hand, which is driven by four motors. However, it can only manipulate cylindrical objects because of rigid grasping [6]. Similarly, Chen et al. proposed a gripper imitating the twisting function of the human fingers, which is driven by six motors, but the object will have a large lateral displacement during the twisting manipulation, as shown in Fig. 1(d) [7]. Further, Kakogawa et al. replaced the sliding platform in Fig. 1(c, d) with conveyor belts with infinite stroke as shown in Fig. 1(e). Combined with the grasping function of the parallelograms and the coordinated adjustment of the three conveyor belts installed on the fingers, in-hand manipulation of objects with various contours were realized [8]. Hattori et al. designed an underactuated parallel gripper, which is driven by three actuators, as shown in Fig. 1(f). It realized the reliably grasping through the screw drive and the three-face grasp, but rigid grasping caused it cannot rotate the non-cylindrical objects [2]. TABLE I shows more characteristics of parallel grippers for in-hand manipulation. Although substantial achievements have been witnessed in robotic grasping during the past few decades [9], flexible grasping, dexterous in-hand manipulating, and force sensing abilities remain difficult [10]. Nevertheless, it is theoretically significant and practically valuable to solve the above three problems [11], [12]. On the one hand, it is important to control the grasping force between the gripper and the object [13], [14], because excessive force may cause damage to the object, especially for fragile or soft ones. However, an insufficient grasping force can cause objects to slip and lead to task failure. Therefore, flexible grasping with controllable grasping force can greatly improve the grasping performance [11]. On the other hand, if the gripper installed on the robotic arm only has a grasping function, when adjusting the pose of a small object, multiple joints of the robotic arm are controlled to achieve it. Even if the robot arm can solve...
The major objective of this paper is to develop a humanoid finger-functional gripper with simultaneous flexible grasping, force sensing, and in-hand manipulating abilities. For this purpose, we design a two-finger gripper based on the series elastic actuator (SEA) and parallelogram mechanism, investigate its intrinsic force sensing method and manipulating conditions, and finally realize real-time force sensing and dexterous in-hand manipulating for ordinary contour objects (OCO). Different from the existing parallel grippers based on the symmetrically installed parallelogram mechanism, the two parallelogram mechanisms of the designed gripper are installed overlappingly. In this case, the highly overlapping workspace of two fingers enables rich motion forms with the help of SEA-based redundant DOF. The SEA can not only measure the grasping force but also reduce the number of actuators. Only two actuators are used to realize various functions such as reaching, grasping, retracting, in-hand manipulating, and grasping force control. Then experiments are performed to evaluate the performance of the PG2 gripper. Finally, two experiments are also carried out on perceiving the physical feature of five objects and in-hand manipulating an ellipsoid tablet to further prove the feasibility of the designed structure and algorithm.

The remainder of this paper is organized as follows. First, Section II presents the design of the SEA-based parallel gripper, manipulating algorithm, and in-hand manipulating conditions. Then, experimental validations and analyses are carried out in Section III. Finally, discussions are made in Sections IV. Section V concludes this article.

II. METHODOLOGY

A. Basic Design

To realize the grasping and manipulating for multi-size and multi-shaped objects, especially for thin objects, the GP2 gripper is designed based on two overlapped parallelogram mechanisms, as shown in Fig. 2. The gripper mainly consists of a reference finger, a redundancy finger, and a spring-based SEA. SEA is widely used in human-machine interaction equipment due to its flexibility and impact resistance [23], [24]. SEA can indirectly calculate the force by measuring the deformation of elastic elements through position sensors, which have higher stability and signal-to-noise ratio than force sensors. In addition, during force-based operation, the large deformation of the elastic element can be controlled by the position-based closed loop, which can filter out high-frequency force noise caused by dynamic operation and avoid large force fluctuations [25]. In this paper, the deformation direction of the SEA is set to the horizontal direction to avoid coupling gravity. The reference finger and the redundancy finger are respectively obtained by extending the connecting links of two congruent parallelogram mechanisms in the same direction. To facilitate the calculation, the contact planes of the reference finger and the redundancy finger are set to be coplanar with the rotating joints A1, B1, and A2, B2, respectively. The motion space of the two fingers are completely coincident when the SEA

### Table I

<table>
<thead>
<tr>
<th>Studies</th>
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<th>Grasping force control</th>
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The master-slave system can separate the operator from the object being operated and is widely used in tasks that are not suitable for direct human manipulation [17], [18]. At present, the visual information of the master-slave system can be collected by cameras, and a powerful and practical target recognition function is realized based on image processing, deep learning, and other technologies [19]. However, the current master-slave systems are insufficient in perceiving object features other than contour features, which are important for understanding and controlling objects. For example, traditional vascular interventional surgery (VIS) requires surgeons to insert thin catheters (1.3-2.3 mm diameter) and guidewires (0.2-0.8 mm diameter) into the bloodstream in the operating room with radiation. It required the dexterous operation for the surgeons’ fingers, especially the control of the operating force. Rigid grasping is easy to damage the interventional instruments and lacks the maximum inserting force limit based on the grasping force control, which affects the safety of surgery [20]–[22]. Besides, in the exploration of unknown environments, collecting samples and perceiving their physical features are important for operators to understand and explore remotely, such as hardness, elastoplasticity, and so on.
Fig. 2. Gripper manipulation schematic. (a) Initial state. (b) Opening. (c) Grasping. (d) Retracting. (e) Manipulating. Where A1, A2, B1, B2, C1, C2, D1, and D2 represent the center of each joint axis, respectively.

is not loaded, and the overlapping motion space decreases with the compression of the SEA. By adjusting the position relationship of the two fingers with highly coincident motion space, a multiple manipulation functions for the objects can be realized, with the help of the SEA that provides redundant DOF perpendicular to the contact plane.

As shown in Fig. 2(a-e), the initial state, opening, grasping, retracting, and manipulating of the finger-down gripper, respectively. Fig. 2(a) shows the initial state of the PG2. The two parallelogram mechanisms are completely coincident, and the SEA is not loaded. As shown in Fig. 2(b), the gripper reaches the object. It should be noted that, in the no load case, the SEA will align the two parallelogram mechanisms crank joints, that is, C1, C2 and D1, D2. Therefore, the opening of the two fingers requires the cranks to move to different angles, and then the asymmetrical fingers will be caused. However, it is beneficial for dig-grasping objects from clutter. It can reduce the opening amount of the gripper for singulating, and avoid the collision between the short finger and the object during digging to improve the success rate of singulating from clutter [5]. As shown in Fig. 2(c), the critical state of grasping, the two-finger work surfaces are in contact with the object, and the SEA is still uncompressed, that is, the grasping force is 0. Fig. 2(d) shows the normal grasping state. Compared with Fig. 2(c), the grasping position of the object relative to the fingers does not change, while the SEA is compressed. Therefore, force control can be performed by decoupling the grasping force. Fig. 2(e) shows a quasistatic interaction state of the gripper in-hand manipulating. By controlling the two fingers motion relationship, with the assistance of redundant DOF based on SEA, the twisting of the object under a controlled grasping force can be realized. Besides, the force measured by the SEA is equal to the grasping force of the object, because the reference finger, the object, the redundancy finger and the SEA form a closed kinematic chain.

B. Manipulating Principle Analysis

Objects whose outline has no special conditions are defined as ordinary contour objects (OCO). When the OCO is manipulated by the designed gripper, adjusting the grasping force is coupled to twisting the object, which is difficult to deal with it only by kinematics. For the PG2, adjusting the state of the object, including the pose and grasping force, is converted into adjusting the crossing amount of two fingers and the compression amount of SEA, as shown in Fig. 3.

As shown in Fig. 3(a), an OCO is twisted. With the help of SEA, the interval of the two fingers can be adjusted passively according to the contour of the object, and there is a passive grasping force. The twisting can be equivalent to adjusting the crossing amount of the two fingers along the x-axis under suitable grasping force. And the crossing amount of two fingers is twice times the arc length of OCO rolling on one finger contact surface.

The grasping force adjustment, that is, only adjusting the grasping force of the object without changing the posture relative to the fingers, is shown in Fig. 3(b). Without considering the deformation of fingers, the output links and the object can be equivalent to a trapezoidal rigid body, as shown in the red area in Fig. 3(b). The adjustment of the grasping force can be equivalent to the reverse driving of the parallelogram mechanism to adjust the compression amount of SEA, as shown by the red dotted lines in Fig. 3(b). It should be noted that the premise of reverse driving is to ensure that the joints C1 and C2, D1 and D2 are kept on the same horizontal line respectively because the SEA works in the horizontal direction.
C. Manipulating Algorithm Design

Based on the manipulating principle, an automatic manipulating algorithm for the OCO is designed, and the control block diagram is shown in Fig. 4.

The manipulating algorithm is mainly divided into outer and inner closed-loop. The former is a twisting position loop based on the joint encoders, and the latter is a grasping force loop based on SEA. The input parameters of the algorithm are the manipulating arc length \( \Delta x_m(t) \) and the grasping force \( F_m(t) \), and the output is the rolling arc length \( \Delta x(t) \) and the grasping force \( F(t) \) of the object. The control process is as follows:

- First, the current two-finger joint angles \( \theta_1(t) \) and \( \theta_2(t) \) are collected by encoders, and the rolling arc length \( \Delta x(t-1) \) of the object is calculated through forward kinematics.

- Then input the difference between the current arc length and the target arc length into the arc-length-based inverse kinematics and calculate the adjusted angles \( \theta_1'(t) \) and \( \theta_2'(t) \) relative to the pose at the last moment.

- The difference between the current grasping force \( F(t-1) \), obtained by SEA, and the target grasping force \( F_m(t) \), is input into the force-based inverse kinematics. The force-based kinematics model, considering the current gripper pose, adjusts the grasping force based on \( \theta_1'(t) \) and \( \theta_2'(t) \) to obtain the adjusted joint angles \( \theta_1''(t) \) and \( \theta_2''(t) \).

- Then the angles are input into the PI controller, converted into electrical signals, and then input to the robot model to manipulate the OCO.

1) Arc length-based inverse kinematics: The sum of the arc lengths that the object rolls on the two fingers is the crossing variation along the \( x \)-axis of the fingers. Since the arc length-based position loop is the outer loop, the grasping force can be ignored temporarily, which will be adjusted in the inner loop based on the current gripper state. To reduce the influence on adjusting grasping force, the crossing amount of two fingers is evenly distributed, that is, the same components move toward or away from each other along the \( x \)-axis. The adjusted angles of two fingers can be calculated as:

\[
\begin{align*}
\theta_1'(t) &= \arccos\left(\frac{e_{Arc}(t)}{l} + \cos \theta_1(t-1)\right) \\
\theta_2'(t) &= \arccos\left(\frac{e_{Arc}(t)}{l} + \cos \theta_2(t-1)\right)
\end{align*}
\]

(1)

where \( e_{Arc}(t) \) represents the difference between the current arc length and the target arc length, \( l \) represents the crank length of the parallelogram mechanism.

2) Force-based inverse kinematics: The force-based inverse kinematics model can adjust the SEA compression amount to the desired value under the relatively fixed work surfaces of two fingers. Based on the adjusting principle of grasping force, the model requires the following conditions to be met:

\[
\begin{align*}
\frac{F_m(t)}{K_s} &= d + l \sin \theta_2(t) - l \sin \theta_1(t) \\
\left[f\left(\cos \theta_1(t) - \cos \theta_2(t-1)\right)\right] &= l \left(\cos \theta_2(t) - \cos \theta_2(t-1)\right)
\end{align*}
\]

where \( F_m(t) \) represents the grasping force of the master side at time \( t \), \( K_s \) represents the elastic coefficient of the SEA spring, \( d \) represents the interval between the contact surfaces of the two fingers. The model detects the error between the current force and the desired force and corrects it. And the joint angles of the two fingers when the desired grasping force is \( F_m(t) \) can be calculated as:

\[
\begin{align*}
\theta_1''(t) &= f_1(\theta_1(t-1), \theta_2(t-1), F_m(t)) + \theta_1'(t) \\
\theta_2''(t) &= f_2(\theta_1(t-1), \theta_2(t-1), F_m(t)) + \theta_2'(t)
\end{align*}
\]

(3)

where \( f(\cdot) \) represents a function that contains the variables.

D. In-hand Manipulating Condition Analysis

The no-sliding manipulation is a premise for precise twisting, while the one-sided sliding manipulation can adjust the grasping position of objects. To perform the one-sided sliding manipulation, it is assumed that the friction coefficients of the work surfaces of the two fingers are \( \mu_1 \) and \( \mu_2 \) respectively, and \( \mu_1 < \mu_2 \). The force analysis of an ellipsoid tablet, which is a typical OCO, is performed during manipulating, as shown in Fig. 5. The gravity-based manipulating conditions are complex and unstable, especially for light objects, as shown in the appendix. For such objects, assuming that the gravity effect is not considered, and the manipulation is slow. In the quasistatic situation, the static friction of the object can be written as:

\[
f_1 = \frac{F_{N1} \cdot x_1}{d}
\]

(4)

The condition of the one-sided sliding can be expressed as:

\[
x_1 > \mu_1 \cdot d
\]

(5)

The Coulomb friction theory holds that the sliding friction force is proportional to the surface friction coefficient and the normal pressure, and is slightly smaller than the maximum static friction force. Based on this theory, the one-sided sliding...
condition is only related to the object's posture within two fingers rather than the grasping force. In fact, the gripper and the object are not rigid, but elastic. The contact area will change with the normal pressure, and then the equivalent friction coefficient will also change.

The molecular-mechanical friction theory applies to the analysis of dry friction and boundary friction of elastic materials such as silicone rubber [26]. The theory holds that friction is the sum of resistance generated by molecular and mechanical actions on the contact area. The contact friction can be expressed as:

\[ F = \alpha A_r + \beta P \]  \hspace{1cm} (6)

where \( F \) represents the contact friction, \( \alpha \) is a parameter related to the molecular properties of the surface, \( \beta \) is a parameter related to the mechanical properties of the surface, \( A_r \) represents the contact area, \( A_r = A_{mol} + A_{mech} \), and \( P \) represents the external load. \( A_{mol} \) represents the contact area of molecular action, and \( A_{mech} \) represents the contact area of mechanical action. For elastic contact, \( A_r \) is related to the size of the contact force, the geometric contour of the object, and so on. The surface material of the gripper is silicone, which is isotropic and less rigid than the ellipsoid tablet. According to the Hertz contact theory [27], the contact area of two objects with ordinary contour in elastic contact gradually becomes an ellipse with the increase of load, and its area can be expressed as:

\[ A_r = \frac{9\pi k \varepsilon^2}{E^{*2}} \left( \frac{PR}{3} \right)^{2/3} \]  \hspace{1cm} (7)

where \( k \), \( \varepsilon \) and \( R \) are parameters related to the contact shape, \( E^{*} \) represents the equivalent elastic modulus. Then the contact friction coefficient can be expressed as:

\[ \mu = \frac{F}{P} = \beta + \alpha \left( \frac{9\pi k \varepsilon^2}{E^{*2}} \right)^{1/3} \left( R^{2/3} \cdot P^{-1/3} \right) \]  \hspace{1cm} (8)

It can be seen that for elastic contact, the friction coefficient decreases gradually with the increase of load. In addition, the interval \( d \) of fingers also decreases with the increase of the grasping force due to elastic deformation of the contact surfaces. The trend line of \( \mu \cdot d \) with the grasping force \( F_N \) is shown in Fig. 6.

Based on the one-sided sliding condition (5), for a rigid object, the value range of \( x_1 \) is shown in the red area in Fig. 6, and the maximum value is \( x_{1 \text{ max}} \). For an elastic and plastic object, \( x_1 \) is related to the grasping force, and has a non-fixed maximum value \( x_{1 \text{ max}} \). When the grasping force is below the critical point, that is, \( x_{1 \text{ max}} < \mu \cdot d \). The manipulation is a pure rolling motion. Conversely, when the grasping force is greater than the critical point, that is, \( x_{1 \text{ max}} > \mu \cdot d \), which is divided into two cases. When the object moves to \( x_1 < \mu \cdot d \), that is, the red area below the blue line in Fig. 6, the pure rolling condition is satisfied. When the object moves to \( x_1 > \mu \cdot d \), that is, the red area above the blue line in Fig. 6, it will slide on the contact surface with a smaller friction coefficient. One-sided sliding the object can adjust the position relative to the reference finger and rolling can adjust its pose and position relative to the redundancy finger. Therefore, combining the two manipulations can adjust the object to any pose and grasping position in-hand. Actually, the critical point is difficult to calculate because the contour of the object is unknown and diverse. However, after mastering the rules, the operator can observe and judge whether there is sliding, and adjust the manipulation through the master-slave system to realize the controllable in-hand sliding and rolling the object.

E. In-hand Manipulating Method

Based on the in-hand manipulating conditions, using the work surfaces with different friction coefficients and controlling the appropriate grasping force, the gripper can slide and roll the object if it can satisfy the manipulating conditions, as shown in Fig. 7.

In the initial state, the ellipsoid tablet is at the edge of the reference finger, and the interval of the fingers is approximately equal to the long axis of the ellipsoid, as shown in Fig. 7(a). Fig. 7(b) shows the one-sided sliding of the object relative to the reference finger. First, the grasping force is increased, and the tablet is rolled to a suitable pose gradually until reaching the one-sided sliding condition, that is, \( x_1 > \mu \cdot d \). The tablet will slide on the reference finger side and be fixed with the redundancy finger. The tablet is slid to the reference finger pulp by adjusting the crossing amount of the two fingers. Then it can be rolled to adjust its position relative to the redundancy finger, as shown in Fig. 7(c). To this aim, the grasping force should be reduced to satisfy the rolling condition. Certain states that have been adjusted are shown as solid ellipses in Fig. 7(c), and their poses can be further adjusted. Therefore, by adjusting the grasping force,
the object can be manipulated at any position in-hand if it can satisfy the manipulating conditions.

**F. Detailed Structure Design**

The designed PG2 gripper is mainly divided into two components: the reference finger component and the redundancy finger component, as shown in Fig. 8. The thick red dotted box in Fig. 8(a) shows the designed reference finger component, and its mechanism schematic diagram is indicated by the thick red solid line, which is a parallelogram mechanism. The input joint of the reference finger component is rotatably connected to the frame and is driven by the Maxon motor-1 (EC-max 16, Maxon, Switzerland) through a bevel gear pair. A 15-bit absolute micro-encoder (1305, RoboBrain, China) is fixedly attached to the frame and its shaft is installed with a bevel gear meshing with the crank to measure the joint angle.

There are three reasons for measuring the joint angle by encoders, which possess 485 communication interface. Firstly, the encoders built in motors are incremental encoders and cannot record the initial position, which is related to the gripper initialization and the accuracy of the manipulation. Secondly, using the microcontroller unit (MCU) to read the motor encoder pulse consumes a lot of computing power and causes program jamming. RS485, which communicates in response mode, reduces the burden of the MCU to ensure real-time. The last key reason is that there is backlash and deformation in the resin gear pair between the input joint and the motor, which tends to increase with the load. It makes the transmission inaccurate and exists a return error. However, the encoder shaft is almost load-free to measure the joint angle more accurately.

The detailed design of each rotating joint is shown in Fig. 8(c), and its diameter is 18.5mm. A flange bearing is used to connect two rotating links. The outer ring is axially fixed by an end cap, and the inner ring is fixed with another link by a reamer bolt. The use of bearings can improve the joint bearing capacity, reduce the joint clearance, and improve the structural rigidity. 2mm thick silicone pads (Shore hardness: 20A) are pasted on the work surface of the replaceable parts.

The blue dotted line in Fig. 8(b) shows the designed redundancy finger component, and its mechanism schematic diagram is indicated by the thick blue solid line. Similar to the reference finger component, the Maxon motor-2 (EC-max 16, Maxon, Switzerland) drives the redundancy finger component via a bevel gear pair and the Encoder-2 (1305, RoboBrain, China) measures the joint angle. Unlike the reference component, the redundancy finger component is connected to the frame by the SEA, that is, the redundancy finger component and the frame are slidably connected by a linear guide, and a compression spring is installed along the sliding direction. The compression amount of the spring is measured by a 15-bit Encoder-3 (1505, RoboBrain, China) through a rack and pinion mechanism. The PG2 is placed horizontally, which makes the SEA not affected by the gravity of each part, so the force of the SEA is equal to the grasping force.

Four reasons for using SEA are as follows: First, the elastic element with high deformable potential is the key to flexible grasping, which can passively adapt to the change of the interval of fingers caused by the OCO contour. The flexible grasping prevents the object from slipping or damaging due to improper interval. Second, SEA, with the spring inherent properties, can cushion the impact during manipulation, and protect the object and the gripper. The third is that the absolute encoder has a higher signal-to-noise ratio than the force sensor, and the obtained signal is more stable. The last is that the cost of the encoder is generally less than 1/2 of the force sensor, and more durable. The initial grasping force can be adjusted manually by the adjustable gear, which can be fixed by the gear holder, and the initial grasping force in this paper is 0.

The horizontal kinematic chain of the gripper determines the opening, closing and grasping force of the fingers. It is a closed kinematic chain composed of the frame, the reference finger, the object, the redundancy finger, and the SEA, as shown in Fig. 8(d). The components of the reference finger and redundancy finger in the horizontal direction are adjusted collaboratively to adjust the spring compression of the SEA, thereby controlling the grasping force of the object.

**G. Control System Design**

The control system of the PG2 gripper is shown in Fig. 9. The upper program is developed based on PyQt5, which mainly includes system initialization, operation mode selection, and data collection. The bottom program is written based
on Arduino mega 2560, which is mainly used to realize motion control based on the designed manipulating algorithm.

Firstly, the manipulating parameters of the operator are collected by the master side, which are used to calculate the desired moving arc length and grasping force of the object, and then they are sent to the Arduino through the serial port. After receiving the command, Arduino processes it based on the designed manipulating algorithm and PI controller to obtain the target angle of each joint, which is the input parameter of the motor driver. The motor driving program contains an ESCON driver-based inner velocity loop and an encoder-based outer position loop to control the two active joints precisely. The detecting of grasping force error is shown by the orange line in Fig. 9. The current grasping force is detected by SEA and made the difference with the force of master side, which is used as the input of the designed manipulating algorithm. During manipulating, the Arduino collects the position of the three encoders of the gripper in real time through RS485, calculates the fingers pose and grasping force through forward kinematics, and continuously corrects the two fingers to the desired position. It should be noted that the gripper is used to control the weak force, which can be adjusted by springs with different spring elastic coefficients, so an integrator is added after the master-slave grasping force error to improve force control accuracy. Besides, operator observes the motion state of the object in the whole process, and adjusts the grasping force and moving arc length through the master side in real time.

III. EVALUATION AND EXPERIMENTS

A. SEA Calibration Experiment

The designed SEA was calibrated using a pressure sensor (SBT674-19.6N, SIMBATOUCH, China) with an accuracy of 0.01%. The pressure sensor was placed between the two fingers to measure the grasping force. The spring compression measured by Encoder-3 is:

$$L_s = \theta_3 \cdot r_s$$ (9)

where $L_s$ represents the compression amount of spring, $\theta_3$ represents the angle measured by Encoder-3, $r_s$ represents the indexing circle radius of the gear in the rack and pinion mechanism. The relationship between the actual grasping force and the SEA spring compression was plotted as shown in Fig. 10. The result showed that the deformation of the SEA spring changes linearly with the grasping force, and they presented a proportional function relationship. The relationship obtained by linear regression is:

$$F_r = 1.122L_s$$ (10)

where $F_r$ represents the real grasping force. Therefore, the calibrated spring coefficient $K_s$ of the SEA is 1.122 N/mm.

B. System Performance Evaluation

The experimental setup for the performance evaluation of the GP2 gripper is shown in Fig. 11(a-c). It was mainly composed of master and slave sides, as shown in the red dotted box and the blue dotted box in Fig. 11(a), respectively. The designed GP2 gripper is shown in Fig. 11(b). It was mounted on the DoBot Magician robotic arm, which can move the PG2 simply. The designed master side was a semi-open operator, including an Encoder-M (1505, RoboBrain, China) for collecting the moving arc length and a pressure sensor (SBT674-19.6N, SIMBATOUCH, China) for collecting the grasping force, as shown in Fig. 11 (c).

In the experiments, in order to collect the moving arc length expediently, the catheter for VIS was selected as the object, which was a cylindrical hollow tube with a diameter of 1.54 mm. Evaluation experiments for the master-slave grasping force tracking performance, moving arc length tracking performance, and force-position manipulating performance were performed. The evaluation experimental results are shown in Fig. 12.
Fig. 11. Performance evaluation experimental setup for the GP2 gripper. (a) Master-slave manipulating system. (b) PG2 gripper. (c) Master side. (d) Five objects for feature perception experiment.

Fig. 12. Performance evaluation experimental results of the GP2 gripper. (a) Master-slave grasping force tracking curves. (b) Master-slave arc length tracking curve under different grasping forces. (c) Comprehensive performance evaluation for manipulating grasping force and moving arc length. The black solid line represents the moving arc length of the master side, the red solid line represents the moving arc length of the object, the yellow solid line represents the relative moving length of the two fingers of the slave side, the blue solid line represents the grasping force of the master side, the green solid line represents the grasping force of the slave side, the black dotted line represents the master-slave grasping force tracking error, the purple dotted line represents the moving arc length error between the master side and the object, and the brown dotted line represents the moving arc length error between master and slave sides.

1) Evaluation experiment for the master-slave grasping force tracking performance: In the experiment, the operator’s grasping force was collected by the pressure sensor on the master side, and the slave side’s was collected by the SEA. The operator randomly applied the grasping force on the master side. The grasping force data of the master and slave sides were collected in real time, as shown in Fig. 12(a). After taking the absolute value of error at all times, the mean absolute tracking error of the master-slave grasping force was 0.0894N, and the mean relative error was 3.74%. The results showed that the slave grasping force tracked accurately. As shown by the green arrows in Fig. 12(a), the tracking errors fluctuated greatly. The reasons should be the existence of the master-slave system response delay, and the relatively high manipulating speed of the force. However, these errors were adjusted to a smaller range within about 0.28s.

In order to evaluate the influence of adjusting force, which requires two fingers to move collaboratively, on the moving arc length of the slave side, the arc length fluctuation of the slave side was measured. The brown dotted line represents the master-slave arc length tracking error, that is, the slave side arc length fluctuation, because the master side arc length was 0. After taking the absolute value of the arc length fluctuation, the average fluctuation was 0.091mm. The results showed that although coupled force-position control existed in the designed structure, the force decoupling was accurate based on the designed manipulating algorithm. The gripper can control the grasping force individually, accurately, and in real-time.

2) Evaluation experiment for the master-slave arc length tracking performance: In the experiment, the master moving arc length can be expressed as:

In order to evaluate the influence of adjusting force, which requires two fingers to move collaboratively, on the moving arc length of the slave side, the arc length fluctuation of the slave side was measured. The brown dotted line represents the master-slave arc length tracking error, that is, the slave side arc length fluctuation, because the master side arc length was 0. After taking the absolute value of the arc length fluctuation, the average fluctuation was 0.091mm. The results showed that although coupled force-position control existed in the designed structure, the force decoupling was accurate based on the designed manipulating algorithm. The gripper can control the grasping force individually, accurately, and in real-time.
where $\Delta x_m$ represents the moving arc length of the master side, $\theta_m$ represents the rotating angle of the catheter collected by the Encoder-M, $r_m$ represents the radius of the catheter. To calculate the moving arc length of the object expediently, the catheter with the same radius was twisted by the gripper and collected by an encoder.

In order to evaluate the tracking performance of master-slave moving arc length under different grasping forces, the forces were set to 0.2N, 0.5N, 1N, 1.5N, 2N, respectively, and the master-slave moving arc-length tracking curves under different grasping forces were shown in Fig. 12(b). After taking the absolute value of the tracking error at each time, the evaluation results were calculated as shown in Table II.

### TABLE II

<table>
<thead>
<tr>
<th>Grasping force (N)</th>
<th>Master-slave moving arc length tracking</th>
<th>Master-object moving arc length tracking</th>
<th>Master-slave grasping force tracking</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean absolute error(mm)</td>
<td>Mean absolute error(mm)</td>
<td>Mean absolute error(mm)</td>
</tr>
<tr>
<td>0.2</td>
<td>0.168</td>
<td>1.36%</td>
<td>0.334</td>
</tr>
<tr>
<td>0.5</td>
<td>0.209</td>
<td>3.56%</td>
<td>0.380</td>
</tr>
<tr>
<td>1.0</td>
<td>0.165</td>
<td>3.81%</td>
<td>0.321</td>
</tr>
<tr>
<td>1.5</td>
<td>0.149</td>
<td>3.72%</td>
<td>0.315</td>
</tr>
<tr>
<td>2.0</td>
<td>0.201</td>
<td>3.72%</td>
<td>0.417</td>
</tr>
<tr>
<td>Average</td>
<td>0.1784</td>
<td>3.04%</td>
<td>0.3534</td>
</tr>
</tbody>
</table>

As shown in Table II, the moving arc length tracking errors of the master-slave and master-object have no obvious relationship with the grasping force. The mean absolute tracking error of the former was 0.1784mm, and the mean relative tracking error was 3.04%. The mean absolute tracking error of the latter was 0.3534mm, and the relative tracking error was 6.02%. The results showed that the master-object moving arc length tracking error was nearly twice larger than that between the master and slave sides. It can be seen from Fig. 12(b) that the arc length curves of the master side, the slave side and the object were basically the same, but gradually lag. Therefore, the larger master-object moving arc length tracking error should be caused by the time delay due to the communication of multiple sensors. The actual tracking error should be close to the master-slave error, because the delay caused by the physical system can be ignored.

As shown by the green solid lines in Fig. 12(b), the grasping force of the slave side fluctuated slightly near the target force. It can be seen that the master-slave moving arc length tracking error was large in the position where the slave side grasping force fluctuated. Therefore, when the gripper corrected the moving arc length error, it slightly interfered with the grasping force due to the intrinsic force-position coupling of the designed structure. Table II showed that the master-slave grasping force mean tracking error increased gradually with the increasing grasping force, which was caused by structural reasons related to the force such as the deformation of the plastic gears of each joint, the backlash, and the joint assembly gap. The relative mean grasping force error reached 9.45% at the target force of 0.2N. Except for it, low relative errors were achieved at other forces. However, the mean absolute error was 19mN at the target force of 0.2N, which was acceptable in many applications [28], [29]. Therefore, the PG2 gripper can control the moving arc length precisely under the desired grasping force.

3) Evaluation experiment for the master-slave force-position manipulation performance: The experimental results of the master-slave force-position manipulation are shown in Fig. 12(c). The operator in master side controlled the moving arc length and grasping force of the gripper in master-slave mode. First, the operator increased the grasping force to 1.28N at about 1.0s with the moving arc length almost 0, and then released it after about 1.0s. The operator increased and retained the grasping force to 1.89N at 4.0s, and then moved the arc length. At about 14.0s, the operator released the grasping force to about 1.0N and moved the arc length reversely at the same time. At about 29.5s, the grasping force was released back to about 0.2N. At around 31.0s, the moving arc length of the object began to show an obvious tracking error. Further, around 32.0s, although the master and slave sides were still moving, the moving arc length of the object no longer changed. The reason was that the grasping force was so low that the object slipped, as shown in the red background area in Fig. 12(c). At around 35.0s, the object was manipulated again with the increasing of the grasping force. The operator stopped the manipulating at about 41.0s.

In the evaluation experiment, controllable grasping force, moving arc length, and object sliding were achieved. The master-slave arc length tracking mean absolute error was 0.091mm, and the relative mean error was 2.28%. The master-slave grasping force tracking mean error was 63.76mN, and the relative error was 3.37%. The results showed that the force-position control of the gripper was accurately decoupled when the object was a cylinder, and the grasping force and moving arc length can be controlled by the master side simultaneously. Several fluctuations of the master-slave grasping force tracking error appeared, as shown by the green arrows in Fig. 12(c). The reason included the high manipulating speed and the existing response delay of the master-slave system, but the fluctuations were adjusted to a low range after about 0.5s.

### C. Gripper Application: Objects Hardness and Elastoplastic Feature Perception

The pinching hardness of an object is defined as a relationship between the interval of parallel planes and the grasping force during the force of the in-hand object being increased and then decreased gradually. It is similar to the hardness perception by human fingers tentatively. The relationship curve can characterize the hardness and elastoplasticity of an object. Five kinds of objects were selected for the experiment, as shown in Fig. 11(d), including resin gear, foam roller, clay bag, sponge, and silicone cube. First, the replaceable parts of the gripper were replaced by ones with harder work surface (Shore hardness: 30A, Thickness: 1mm) to reduce the influence of the
The deformation of the operator increased and then decreased the grasping force to a lower level gradually in the master side. The pinching hardness curves of each object were obtained, as shown by the red and blue solid lines in Fig. 13. In order to describe the characteristics of these objects, linear regressions were taken for each curve, as shown by the red and blue dotted lines in Fig. 13. The linear regression coefficients of the five objects are shown in Table III.

**TABLE III**

<table>
<thead>
<tr>
<th>Objects</th>
<th>Linear regression coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Force increasing process</td>
</tr>
<tr>
<td>Resin gear</td>
<td>-0.1993</td>
</tr>
<tr>
<td>Foam roller</td>
<td>-1.0362</td>
</tr>
<tr>
<td>Clay bag</td>
<td>-1.2379</td>
</tr>
<tr>
<td>Sponge</td>
<td>-3.0758</td>
</tr>
<tr>
<td>Silicone cube</td>
<td>-0.3993</td>
</tr>
</tbody>
</table>

As shown in Fig. 13, the difference among the pinching hardness curves of five objects was obvious and comprehensible. As shown in Fig. 13(a), the deformation of the resin gear was not obvious under the grasping force of 2N. The deformation curves in the two processes were almost coincident. The linear regression coefficients were slightly less than 0 due to the slight deformation of the gripper contact surface and the existence of fit clearance in the replaceable parts, which were related to the grasping force. The pinching hardness curve of the foam roller is shown in Fig. 13(b). Under the grasping force of 2N, 2mm deformation was generated. After the force was removed, the fingers almost rebound to the interval before the force was applied, and the linear regression coefficients of the two processes were basically equal. The results showed that the foam roller had good elasticity and soft texture. The deformation-force curve of the clay bag is shown in Fig. 13(c). Obviously, after the force was removed, the fingers interval can’t revert back, and the linear regression coefficients were different. The results showed that the clay bag was plastic, but there was still a certain rebound in removing the force. The elasticity came from the outer wrapping of the nitrite butadiene rubber (NBR). The deformation-force curve of the sponge is shown in Fig. 13(d). At the initial stage of force applying, the deformation of the sponge increased rapidly. Then, with the increasing of the grasping force, the deformation gradually reached 6 mm, which indicated that the sponge texture was soft. The absolute value of linear regression coefficient in removing force process was smaller than that of the force applying, and it can’t revert to the previous fingers interval. The results showed that the sponge had plasticity or anelasticity. Another reason was that its resilience was too small to resist the friction of the linear guide of SEA. The pinching hardness curve of the silicone cube (Shore hardness: 20A) is shown in Fig. 13(e). There was some deformation in applying force, and the linear regression coefficients of the two processes were basically equal, which indicated that the silicone cube was elastic. The function, combined with the in-hand manipulation of the gripper, can detect the pinching hardness of the object in different directions like human fingers. It can be used to perceive the macroscopic features of unknown objects, such as hardness, elastic-plasticity, in some situations that are difficult for human hands to reach.

**D. Gripper Application: In-hand Manipulation**

The experimental object was an ellipsoid tablet with a major semi-axis of 4mm and a minor semi-axis of 1.8mm. The initializing, grasping and in-hand manipulating of the PG2 gripper are shown in Fig. 14(a), (b-c) and (d-r), respectively. The initial state of the tablet was at the tip of the reference finger. First, to slide the tablet to the pulp of the reference finger, the grasping force was kept low, and the tablet was rolled to a suitable angle, as shown in Fig. 14(d-e). In fact, the process was adjusting the \( x_1 \) to satisfy the sliding condition. Then, the operator tentatively increased the grasping force to slide the tablet, until the operator observed that the tablet slid, as shown in Fig. 14(e-f). Once the tablet was adjusted to the proper position, controllable in-hand manipulating, such as rolling and sliding, can be performed. As shown in Fig. 14(g-i), the gripper rolled the tablet clockwise, which needed to keep the low grasping force to satisfy the rolling condition. After rolling, the tablet approached the edge of the reference finger again, so the operator increased the grasping force again and slid the tablet, as shown in Fig. 14(i-j). After sliding to a suitable position, the operator rolled the tablet clockwise and counterclockwise twice successively, as shown in Fig. 14(j-l), Fig. 14(l-n), Fig. 14(n-p) and Fig. 14(p-r), respectively. In the manipulating, the master side operator kept a low grasping force to satisfy the rolling condition. The experimental results showed that the ellipsoid tablet can be adjusted to any position in-hand as long as the grasping force and the moving arc length were controlled collaboratively.
The master-slave grasping force and moving arc length tracking curves during manipulating are shown in Fig. 15, where the meaning of the curves is the same as that in Fig. 12. In the experiment of manipulating the tablet, the master-slave moving arc length mean tracking error was 0.164mm, and the relative mean tracking error was 2.5%. The master-slave grasping force mean tracking error was 119.29mN, and the relative tracking error was 9.18%. The experimental results showed that the PG2 gripper can manipulate the OCO in-hand dexterously and accurately, which also proved the feasibility of the proposed in-hand manipulating method.

IV. DISCUSSION

Previous sections present the structure design, algorithm design, and experimental validation of the PG2 gripper, where its abilities in terms of force sensing and in-hand manipulating are proved. Before the end of this article, we think that the following discussions are necessary to enhance comprehension.

A. On the Continuously Fluctuating Grasping Force of the Slave Side in Fig. 15

As shown by the yellow and green solid lines in Fig. 15, the moving arc length and the grasping force of the slave side fluctuated to an extent during manipulating the tablet, and the fluctuations of the two curves were almost corresponding. There are two reasons for the fluctuations. On the one hand, the gripper structure determines the intrinsic force-position coupling, and the decoupling is completed by the designed manipulating algorithm. When the gripper manipulated an OCO, SEA can compensate for the variation in fingers interval caused by the rolling object, but the physical compensation resulted in fluctuations of the grasping force. With the help of the manipulating algorithm, they were adjusted to the desired value by the force and arc length closed loops of the gripper within about 0.5s. On the other hand, the moving arc length of the master side was discontinuous and stepped, which resulted in the continuously fluctuating grasping force of the slave side.

B. On the Sensing Rate

The sensing rate is vital for the real-time performance of the force-based perception method and also has an important influence on the data set collection [20]. The maximum stable measurement rate of the master-slave system was 20 Hz considering the constraints of the communication delay between the MCU, sensors, and motor drivers. At this system refresh rate, the motor response based on the PI controller was not tuned very fast. The reason is that an overly aggressive motor response will generate more instability factors when manipulating the OCO, such as grasping force and moving arc length fluctuations.

C. Object Shape

The designed PG2 gripper can only grasp objects with a maximum parallel envelope distance of about 10mm, which can be increased by increasing the limit angle of the redundancy finger and increasing the length of the two fingers cranks. Based on the manipulating principle of parallel planes, there is no special requirement for the object shape, that is, as long as the rolling and sliding conditions can be satisfied, it can be manipulated in-hand. Similar to human fingers functions, objects that cannot satisfy the sliding condition, such as cylinders and spheres with a width-to-thickness ratio close to 1, can only be twisted in-hand. When human manipulate such an object, the sliding of the object relative to the finger is often achieved with the help of a third finger or fingernails. In our future work, we expect to be able to develop a three-finger...
gripper with an auxiliary finger in some application scenarios to satisfy more complex in-hand manipulations.

D. On the Application Scenarios of the PG2

The parallel work surfaces are suitable for manipulating thin cylindrical objects, such as catheter (1.3-2.2mm diameter), guidewire (0.2-0.8mm diameter), and so on. And it can more realistically simulate the manipulation of the surgeon’s hands containing complex force sensing by controlling the grasping force. Besides, objects that cannot be directly perceived by the human hand, of which the hardness at different angles cannot be detected only by vision, can be perceived by the PG2. In our future work, the PG2 gripper will be attempted in VIs to simulate more advanced hand manipulations that are critical to surgery safety.

V. CONCLUSION

In this paper, a novel humanoid finger-functional PG2 gripper was developed with the purposes of flexible grasping, force sensing, and in-hand manipulating abilities. To this aim, a novel parallel gripper mechanism based on overlapping parallelogram mechanisms and SEA was proposed, and the in-hand manipulating principle based on parallel fingers was analyzed. Meanwhile, an in-hand manipulating algorithm for the OCO was proposed, which can realize double closed-loop control for the grasping force and moving arc length. Then to realize the controllable adjustment of the OCO, the parallel in-hand manipulating conditions and methods were proposed. Finally, the detailed mechanical structure and control system of the PG2 gripper were designed. Experiments were performed to validate the proposed design and methods. The grasping force control performance, the moving arc length control performance under desired force, and the combined force-position control performance were verified by experiments, respectively. Finally, the force-position control function of the PG2 gripper was used to perceive the physical features of the five objects, and dexterously manipulate the ellipsoid tablet in-hand. The experiments proved the feasibility of the proposed in-hand manipulating method and superior performance in force-position controlling and force sensing of the PG2 gripper.

APPENDIX

MANIPULATING CONDITIONS CONSIDERING GRAVITY BASED ON THE COULOMB FRICTION THEORY

The force analysis of an ellipsoid tablet is performed during manipulating, as shown in Fig. 5. Assuming that the contact surfaces of the gripper and the object are rigid and the manipulating is slow, the force balance state of the object can be written as:

\[
\begin{align*}
\sum f_1 &= f_1 - f_2 - mg = 0 \\
F_{N1} &= F_{N2} \\
F_{N1}x_1 - f_1d + mg(d - y_1) &= 0 \\
F_{N2}x_1 - f_2d - mgy_1 &= 0
\end{align*}
\]

(12)

where each force direction in Fig. 5(a) is a positive direction. Then the no-sliding conditions can be expressed as:

\[
\begin{align*}
|f_1| &= |\mu_1 F_{N1}| \\
|f_2| &= |\mu_2 F_{N2}|
\end{align*}
\]

(13)

Formula (12) is brought into formula (13) to calculate the grasping force conditions in no-sliding state can be expressed as formula (14).

\[
\begin{align*}
F_{N1} < \frac{mgd}{\mu_1} &< 0 & x_1 &\leq -\mu_2d \\
\frac{x_1 + d}{\mu_1} > F_{N1} &> 0 & -\mu_2d &< x_1 \leq -\mu_1d \\
\max (\frac{x_1 \pm d}{\mu_1} &> \frac{mgd}{\mu_1}) &< 0 & -\mu_1d &< x_1 \leq \mu_1d \\
F_{N1} &> \frac{mgd}{\mu_1 (1 + \mu_1)} &< 0 & x_1 &> \mu_1d
\end{align*}
\]

(14)

If the object does not satisfy the conditions shown in formula (14), sliding will occur. It can be seen that the manipulating conditions are related to the object contour, that is, the distance of each set of parallel envelopes of the object, the mass, the friction coefficient of the two contact surfaces, and the grasping force. Obviously, the manipulating conditions are established based on gravity of objects, which is unstable and difficult to apply, especially for light objects.

REFERENCES


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