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A universal robot gripper based on concentric arrays of rotating pins

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Dear editor,

Recent advancements in robotics and flexible production lines have increased the demand for versatility in grippers. The autonomous grasping of a variety of objects has been a challenge for decades [1], and different scales of robot hands/grippers [2] have been developed to achieve universal grasping capability.

By mimicking the human grasping motion [3], articulated robotic hands offer great potential for dexterous manipulation. However, a dexterous robot hand with independently actuated joints [4] is a highly redundant system that requires complex grasping algorithms. One possible tradeoff is an underactuated hand [5], in which a single actuator drives multiple joints with the aid of passive elements. However, such a gripper might eject the target objects under certain circumstances.

To bypass the limitations of articulated finger designs, universal grippers achieve universal grasping with minimum control effort. Inspired by pin art toys that can create a 3D relief of the surface of an object with a group of sliding pins, pin-array grippers can accomplish universal grasping. The grasping force is provided by the lateral contacts between the pins and target object via friction, and the contacts can be established with a swinging [6], translating [7], meshing [8] or even fixed [9] pin array. All of these gripper designs leave room for improvement [5–9]. To further improve grasping performance, this study proposes a novel concentric rotating pin array (CRPA) mechanism.

Mechanism. The CRPA gripper comprises two parts: a sliding pin array at the bottom and a driving mechanism above that drives lateral rotational motion of the pins. When grasping an object, the gripper first approaches the target object in the axial direction of the pins. The pins that contact the target object will passively slide inwards, thereby adapting to the shape of the object as the gripper is lowered onto the object. Then, the pins move along the radial direction towards the object. Each pin around the object acts like a small jaw. With the assistance of the increased friction generated by this pin lateral contact, the object can be lifted for further manipulation.

The conceptual design of the CRPA gripper is explained through a structural drawing in Figure 1(a). Each pin passively slides in the axial direction, and the pins are mounted around a ring. Sets of rings are arranged concentrically. Adjacent rings rotate in opposite directions. A belt drive is advantageously used to transmit rotational motion to the rings. Opposite rotational directions of rings are achieved by connecting adjacent rings with open and crossed belts. Slipping connections between the belts and the pulley-rings assembly allow for shape adaption. When one ring is blocked, the other rings can continue rotating until their pins make solid contact with the target object.

A base frame on the top supports the rings and the motor (Maxon RE25 with planetary gearhead

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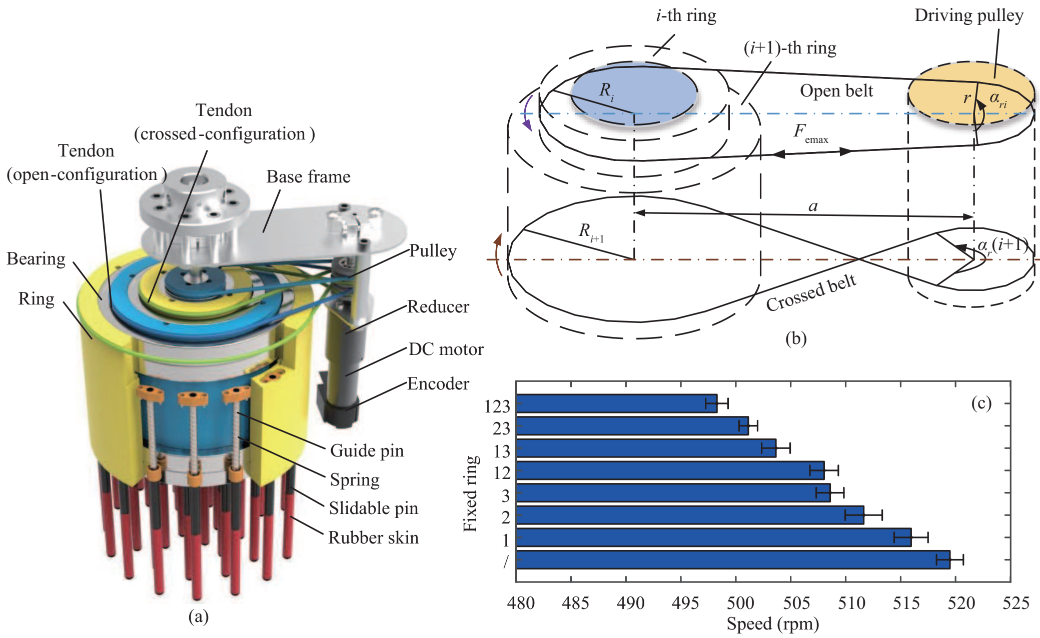

Figure 1 (Color online) (a) Structure of CRPA gripper; (b) force transmission to two adjacent rings from the driving pulley; (c) motor speed when a set of rings are fixed with their belts sliding.

GP 32A). A rotary encoder (HEDL 5540) is used to determine the contact situation and facilitate closed-loop control. The rings and pulleys are 3D printed from PLA material.

Parametric analysis. To understand how the components interact with each other, parametric analysis of the force transmission was conducted. Figure 1(b) shows two layers of opposing rings and the driving pulley with belts connecting them. We assume that the contact force between the pins and the target object is equal to the friction force applied to the ring, which corresponds to maximum belt tension when slipping. According to belt-drive theory, the maximum tension F_{emax_i} is

$$F_{\mathrm{emax}_i} = 2F_0 \frac{\mathrm{e}^{\mu_t \alpha_i} - 1}{\mathrm{e}^{\mu_t \alpha_i} + 1}. \tag{1}$$

Further, the total grasping force F_G provided by friction can be calculated as follows:

$$F_G - \sum_{i=j}^{m} F_{vj} = \sum_{i=1}^{n} \mu_t F_i = \sum_{i=1}^{n} \mu_p F_{\mathrm{emax}_i}, \tag{2}$$

where F_0 is the pre-tension in the belt, μ_t is the friction coefficient between the belt and pulley, μ_p is the friction coefficient between the pins and object, α is the wrap angle, F_{vj} is the vertical pushing force of pins, and F_i is the contact force at each ring.

Given constant friction coefficient μ_t, $\mu_p = 0.5$, pretension $F_0 = 5$ N, and radius of the first ring $R_1 = 20$ mm, the effects of the pulley radius r, center distance a, spacing between rings $(R_i - R_{i-1})$, and number of rings n were investigated using MATLAB. These simulation results provide guidelines for the CRPA gripper design. The radius of the pulley and spacing between rings have little effect on the grasping force output. With more rings, the total grasping force increases, and the gripper can adapt to a target shape more easily. Hence, the spacing between rings should be designed to be as small as possible so that the maximum number of rings can be installed. For a 4-ring configuration, the grasping force can reach 27 N, which is sufficient for many robot-manipulation applications.

Control. Although the computational effort required for this adaptive mechanical design is relatively low, information regarding the grasping force is useful for closed-loop control. A rotary encoder is included on the motor shaft for this purpose.

Because all the belt tensions are applied from the same driving pulley, the rotary encoder output can be used to determine each ring's contact force from the load on the driving pulley. As the diameters of rings are different, the resultant loading when each ring is blocked will differ. Those different loadings are translated to the motor shaft, which will affect the motor speed. The motor speed can be measured by the encoder. For example, when the speed decreases to the speed at which all rings were blocked, the sensor output indicates that all rings have made contact with the object.

Calibration was conducted with the prototype gripper to formulate the mapping between the ring contact situation and motor speed. The motor speed was measured while different sets of rings were manually arrested. The results are plotted in Figure 1(c). The motor speed varies considerably with the combination of blocked rings. Therefore, the motor can be effectively controlled by the feedback of the motor speed to ensure secure contact between the gripper and target object.

Experiments. A prototype CRPA gripper was built to validate the design and test its predicted performance. The size of this prototype is approximately 180 mm×250 mm×340 mm.

To understand how the number of contacts influences grasping performance, grasp-force testing was conducted. In each test, the tested object was connected to a push gauge (Elecall NK-500) via a thin cable. When the object was securely grasped, the number of lateral contacts and pins being pushed were recorded. Then, an external force was applied through the push gauge to pull the object away from the gripper in the axial direction of the pins (downward) until the object separates from the gripper. This downward force was recorded as the maximum grasping force, and it was measured for each possible contact situation. In 30 tests, the gripper applied maximum grasping force ranging from 5 to 15 N. Depending on the shape of the target objects, the gripper could be designed with more lateral contacts and fewer sliding pins to increase the grasping force.

The universal grasping capability of the prototype was validated through testing with a range of different objects. 50 different irregular objects were tested with lengths ranging from 20 to 300 mm. Approximately 80% of the objects was grasped successfully without requiring specific grasp positions or orientations. Note that the grasping failures mainly fall into the following two categories. First, the gripper could not grasp thin planar objects that pushed all pins in equally and made no lateral contact. Second, failure occurred when the object was smaller than the distance between the rings because the object could not block the ring motion. Nevertheless, the prototype was highly adaptable to gripping various objects. A video of this experiment is available at the website[1)], as well as in the appendix video.

Conclusion. This study has presented a novel CRPA gripper that can grasp a wide variety of objects. Thanks to its self-adaptive CRPA mechanism, various objects can be grasped without the need for complex algorithmic planning. The design was simulated, and a prototype was built and tested to verify the feasibility of the proposed design. Critical design parameters were investigated by modelling force transmission in MATLAB, revealing the most-effective design revisions that would improve grasping performance. The design implements a control scheme that needs only one encoder to provide feedback. The functional prototype was highly adaptable to gripping various objects. Further effort in this research program will focus on the testing of a prototype with higher pin density along with designing a tactile display for the pin array.

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Supporting information Video. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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