A Universal Gripper Base on Pivoted Pin Array with Chasing Tip

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Abstract. In order to challenge universal grasp capability beyond human hands, a pin array gripper is presented. It consists of a matrix of passively slidable pins which conform themselves to the contour of various objects. The swing motion of pins enable multiple lateral contacts with objects to provide grasp force via force-closure. Possible configurations of pin unit and dimensions of the CAD embodiment are analyzed, showing critical parameters for improving grasp performance. The feasibility of the gripper design is verified by analytical model.

Keywords: Gripper · Universal grasp · Pin array · Shape adaption

1 Introduction

Since the first introduction of robot last few decades, the development of robotic gripper is progressing fast. In the context of Industrial 4.0, production lines are becoming more flexible, in order to meet the consumers' demand of a wider variety of product choices. Conventional grippers which is designed for repetitive tasks are not satisfying. More versatile grippers are needed for handling different parts and processes continuously, without the effort of exchanging grippers for different grasping tasks. Universal grasp capability is favorable, which is the capability of grasping a wide range of objects of different shape, size and pose effectively. There are generally two categories of these grippers: articulated robot hands and universal grippers.

Similar to human hand, articulated robot hand has 3 or more articulated fingers. By replicating the six grasp mode of human hands, articulated robot hands are potential to perform 80% of our daily grasp [1]. Dexterous hands are first introduced in late 1970s [2, 3]. They are usually full-actuated, where number of degrees of freedom (DOF) equals the number of actuators. By integrating sensory systems, implementing proper control schemes, they can perform many tasks like human hands. However, the high DOF make it a redundant robot system, for example, Shadow Hand with 20 actuated degrees of freedom. It requires great effort for grasping planning [4], which is still not yet well understood nowadays. A compromise on the dexterity is underactuation. By implementing passive elements, underactuated robot hand has less actuators than its DOF. A finger is usually actuated by only one actuator, which can adapt to different shape of objects mechanically [5]. This mechanical intelligence not only

reduces the control complexity, but also allows for more compact structure and agile manipulation due to the weight reduction of actuators. It is clear that the drawback of underactuation is loss of dexterity. Sometimes ejection of object occurs, which is reported in [6].

Not constrained by the structure of human hand, universal grippers are designed to achieve universal grasp capability beyond our hands. They are usually unarticulated, able to conform its shape to objects effectively. The conformation can be achieved by soft material or pin array. A sphere gripper based on the jamming of granular material was proposed by University of Chicago [7]. Due to its high universal grasp capability, it is later commercialized [8]. Based on this gripper, a further attempt on magnetorheological (MR) fluid is presented in [9]. The granular material is replaced with MR fluid, which solidifies when exposing to magnetic field. Rather than solidification, FESTO company has developed the Flex-Shape-Gripper [10] by manipulating fluid within a silicon cap, which is inspired by the tongue of chameleon. Soft finger is an alternative to the articulated rigid one. The PneuNet gripper [11] can wrap itself on target objects without damaging them. A commercially available soft robotic gripper [12] composes of several pneumatic fingers, which is capable of shape adaption during high acceleration. By taking the advantage of gecko-inspired adhesive, the S^2DM gripper [13] can grasp various objects by its curve surface using shear forces. The intrinsic limitation of soft material is the reliability of the material. Because of frequent deflection, soft materials are often not suitable for long-term operation. A rigid gripper is favorable for its robustness. Pin art is an executive toy with array of pins that can create 3D relief, which shows high adaptability to various objects. In a similar way, pin array gripper is developed with passively slidable pin array. Presented in 1985, Omnigripper [14] is the first pin array hand, to the best of the authors' knowledge. After shape adaption, two ranks of pins move towards each other as a two jaw gripper, so that objects adapted by the pin array can be grasped. Rather than translating pin, CTSA hand [15] bundle up a group of pins using 3 tendons. Pins pivot on one end, swinging towards gripper center to build lateral contacts with objects. Pin array hand [16] developed by Mo et al. is special for its lateral contact mechanism. Pins with elliptical contour contact with objects by rotating itself, therefore transfer is rotation to translation in a manner of cam mechanism. Lateral fixed pins are also possible. 3D Bernoulli gripper [17] use pin array to secure deformable surface after shape adaption, then apply Bernoulli principle on irregular objects for grasping. Microspine units [18, 19] can be integrated into gripper or palm, withstanding great shear forces on rough surface. These multiple-pin design shows high potential for universal grasping, whereas existing research is still sparse.

In this paper, to challenge the universal grasp capability, a novel gripper base on swinging pin array with chasing tip in presented. In Sect. 2, the basic concept and working principle of pin array gripper is demonstrated. In Sect. 3, the pin array embodiment is introduced. In Sect. 4, the actuation mechanism with control scheme is analyzed. In Sect. 5, the grasp analysis is carried out to verified the feasibility of the design. In Sect. 6, conclusion and future works are covered.

2   Concept of Pin Array Gripper

As indicated by its name, pin array gripper can grip objects though a set of pins. It composed of 2 major parts: pin array and actuation system, as shown in Fig. 1. Pins are array arranged, parallel to each other, attached to the actuation system above. Each pin is passively slidable along its axis when pushed against objects. In this way, shape adaption is realized in vertical direction. The actuation system is to drive pins simultaneously toward target items in radial direction for grasping. It is the key difference to pin art and the core of the gripper.
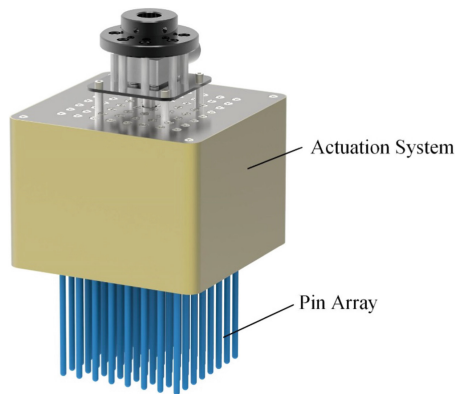

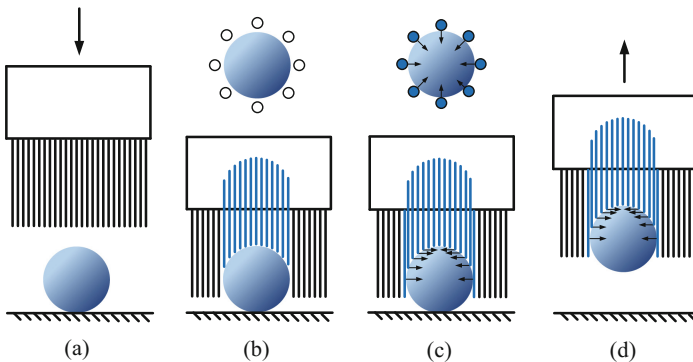**Fig. 1.** Structure of pin array gripper.

Fig. 2. Grasp process of pin array gripper. (a) Approaching; (b) Adaption; (c) Grasping; (d) Lift.

The grasp process of pin array gripper is illustrated in Fig. 2. A demonstrated spherical object is grasped in 4 steps:

- Approaching: The gripper approaches a target object along the pin axial direction. The object is placed on a surface.
- Adaption: When the gripper is forced over the object, group of pins in contact with the object will be pushed inwards the housing thereby conforming the pins to the object's contour.
- Grasping: Driving by the actuation system, pins around the object move towards it. Rigid contacts between lateral surface of pins and the object are built, which provide normal forces on the object.
- Lift: When the gripper lifts for further manipulation. The normal forces applied on the object lead to friction to overcome object's gravity, so that the object is securely grasped. The release process of the object is reverse.

Slidable pins can be easily realized in many ways, such as whip antennas and bicycle pumps. The difficulty is on the actuation system. Ideally, pins should be able to move towards the object, without know the exact shape, position or orientation of it. In the following sections, the pin design together with the actuation system is introduced.

3   Pin Array

The proposed pin array can be divided into 3 layers. The bottom layer is pivoted pin. Setting up in a defined way, several pivoted pins constitute a pin unit. Array arranged pin units form the desired pin array.

Table 1. Nomenclature

O	Pivot point between guide pin and pin base
A	Pin actuation force applied point
P	Lateral contact point between pin and object
α_i	Swing angle of pin (rad)
β_i	Lateral contact angle (rad)
γ	Pressure angle between linkage and sliding frame (rad)
γ_0	Initial pressure angle between linkage and sliding frame (rad)
k	Spring constant (N/mm)
μ	Friction coefficient between pin and object
l_{OA}	Distance between O and A (mm)
l_{OPi}	Distance between O and P of the (mm), for i = 1~n
L	Length of linkage (mm)
s_0	Half-length of sliding frame (mm)
Δs	Displacement of sliding frame (mm)
Δm	Displacement of nut (mm)
Δxj	Displacement of sliding pin (mm)
F_{vj}	Vertical force applied on the jth pin (N), for j = 1~m
F_{pi}	Pin actuation force applied on the ith pin (N), for i = 1~n

(*continued*)

Table 1. (*continued*)

O	Pivot point between guide pin and pin base
F_{ci}	Contact force applied on the ith pin (N), for i = 1 ~ n
F_{Ni}	Normal force applied on the object by the ith pin (N), for i = 1 ~ n
F_{gi}	Grasp force applied on the object by the ith pin (N), for i = 1 ~ n
F_t	Traction force applied on the sliding frame (N)
F_M	Motor output force on the nut (N)
n	Number of pins laterally in contact with object
m	Number of pins vertically in contact with object

3.1 Pivoted Pin

The design of a single pin is shown in Fig. 3(a). The guide pin is a slender pin that pivot on the base. The sliding pin is a thin tube slides freely on the guide pin, constrained by a spring. This pin has 2 DOFs, which are translation along its axis and rotation on the pivot point O. The translation motion is passive while the rotation actuated.

Contact point with target items might occurs at 2 locations. First is at the bottom of pin during the adaption step, as shown in Fig. 3(b). The gripper is forced over the object, which in return pushes the sliding pin upwards. The displacement of sliding pin Δxj results in a contraction of the spring, where the vertical force applied on this pin can be obtained by Hooke's law
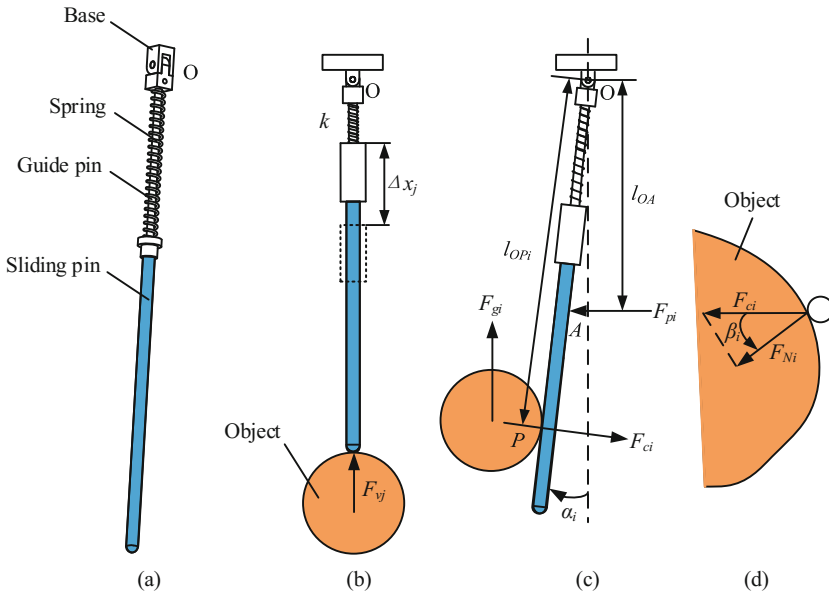

Fig. 3. Single pin in contact with an object.

$$F_{vj} = k\Delta x_j \tag{1}$$

The other possible contact point is on the lateral surface at point P with a resultant contact force F_{ci}, as shown in Fig. 3(c). It is realized by the swing motion of the pin, which is enable through the pin actuation force F_{pi} applied at point A in the pin body by the actuation system. Considering moment balance at point O and lateral contact angle β_i (See Fig. 3(d)), the normal force applied on the object F_{Ni} can be calculated with

$$F_{ci}l_{OPi} = F_{pi}l_{OA} \tag{2}$$

$$F_{Ni} = F_{ci}\cos\beta_i \tag{3}$$

If the friction coefficient between pin surface and objects is μ, swing angle of pin is α_i, a single pin can provide grasp force

$$F_{gi} = F_{Ni}\sin\alpha_i + \mu F_{Ni}\cos\alpha_i \tag{4}$$

3.2   Pin Unit with Chasing Tip

The swing motion of pin establishes lateral contact with object, whereas a single contact does not make sense. Multiple contacts are needed around a target object, which means the pins should be able to swing at different directions to build the necessary number of contacts. Note that the pins should not interfere with each other. It requires appropriate pin array setup, including pin position and swing orientation, so that objects in different shape or position can be grasped.

To tackle with these issues, pin unit with chasing tip is proposed to group pins together. It enables pins swing at several different directions, traveling across each other without interference. See from axial direction, possible pin unit configurations are shown in Fig. 4. Each pin is constrained in a respective slot, placing around the middle of the pin. The slots are radial patterned where the angular difference of slot axes is the same. The motion of pin sections in the slots are coincident. For example, in Fig. 4(a), 3 pins move towards one other, like chasing. Although the sections as shown can only move within the slots, the tip of a pin can actually swing to the original position of the other pin in front of it. Other configurations with more pins are also possible, with pins chasing each other or not, as shown in Fig. 4(b)–(f).

The (b) configuration is preferable for several reasons. It can achieve high pin density which is important for shape adaption. 4 pins allow for 4 contact directions with tolerable actuation effort. Whenever an object pushes any pin of a pin unit, lateral contact will be established. As shown in Fig. 5, an object might push 1, 2 or 3 pins inwards. The pin marked in deep color will push the object from side.

By linear pattern of this pin unit, a pin array is formed, as shown in Fig. 6. The base of each pin is fixed on the top frame, where the pin swing direction is in accordance with its slot. Slots are cut at the base frame, along which pins are able to slide. Figure 6 (a) shows the initial state of pin array before grasping, where pins are parallel to each
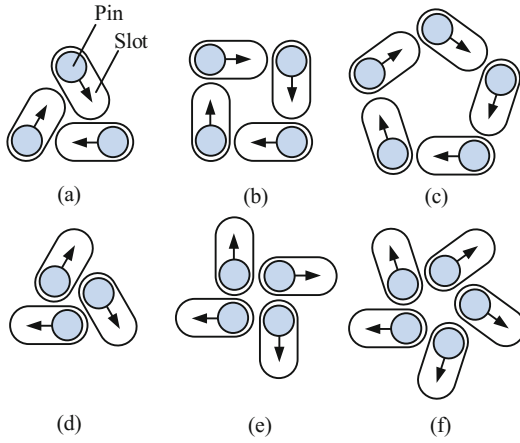
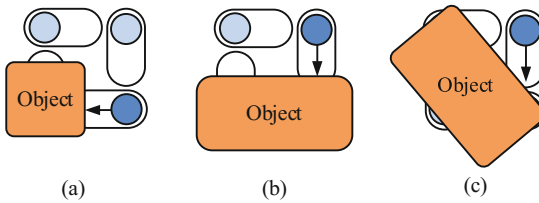Fig. 4. Possible pin unit configurations.

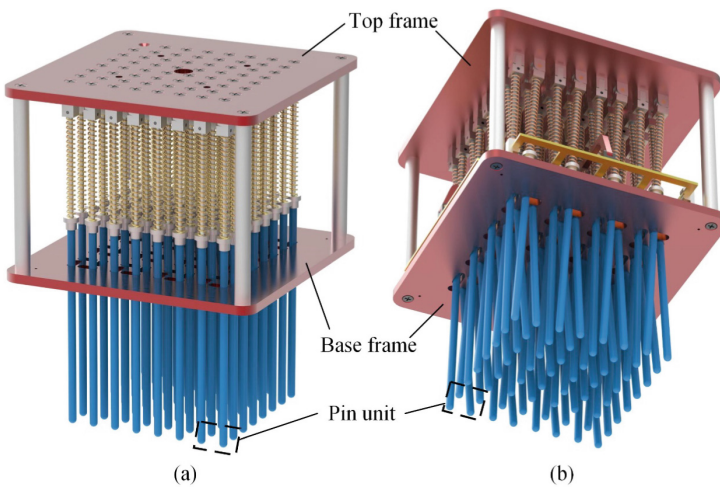Fig. 5. Lateral contact scenarios of 4 pin configuration

Fig. 6. Pin array design

other. When actuated, all pins swing simultaneously, as shown in Fig. 6(b). In this design, 16 pin units are implemented with 64 pins in total. A correspondent actuation system is presented in the next section.

4   Actuation System

Note that the motion of a quarter of pins is identical, that is, towards a same direction. Therefore, each set of pins with the same swing direction can be driven by a same power transmission system.

A sliding frame mechanism is proposed to actuate these 4 pin sets. As shown in Fig. 7(a), the sliding frame is perpendicular to the pins. Each sliding frame only connects with the same set of pins via elastic bands. The elasticity of the connection is essential for underactuated shape adaption. When a pin is blocked by target object, the connected elastic band deforms as a spring. Hence, the frame keeps sliding so that other pins contact with the object consecutively. The pins marked in dash lines are connected with other frames. The elastic bands are array arrange on the frame with twice of the spacing of pins to provide pin actuation forces F_{pi}. The frame slides at horizontal direction, which is enable by the traction force F_t applied at one of its end.

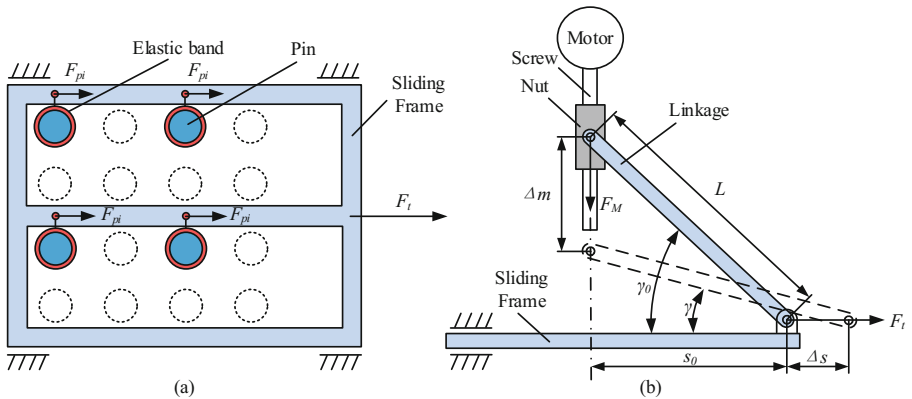$$F_t = \sum_{i=1}^{n} F_{pi} \tag{5}$$

Fig. 7. Sliding frame mechanism

To avoid collision of frames, frames can be parallel to each other. The power transmission from motor can also be parallel to the frames. As shown in Fig. 7(b), motor shaft is connected with a screw, which drive a nut to translate vertically. The nut is connected with the 4 sliding frames via 4 linkages (only one is shown). When the nut

is driven down a distance of Δm with motor output force of F_M, the sliding frame will translate Δs with traction force F_t. With the dimensions described in Fig. 7(b) and Table 1, there are

$$L\cos\gamma_0 = s_0 \tag{6}$$

$$L\cos\gamma = s_0 + \Delta s \tag{7}$$

$$F_M\cos^2\gamma = F_t \tag{8}$$

The CAD embodiment of the sliding frames is shown in Fig. 8. (a) illustrates the initial state before sliding, where 4 frames link to the nut by respective linkage. Note that the connection on the nut is not at a same level, which is correspond to the spacing between frames. It is beneficial to uniform force transmission and same structure of linkage. (b) shows the sliding direction of the frames, which is the same with the swing direction of 4 pins in a pin unit.
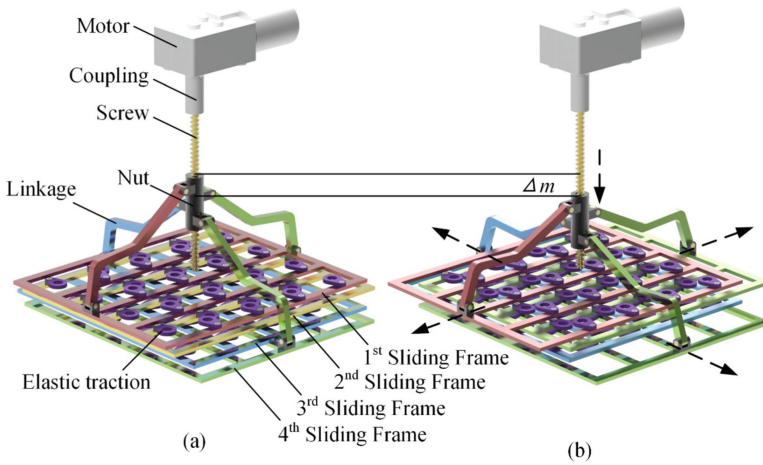

Fig. 8. Actuation system design

Combing the sliding frames and pin array, the proposed pin array gripper is shown in Fig. 9. The frames are placed at the middle of pins, in order to increase the pin actuation force.
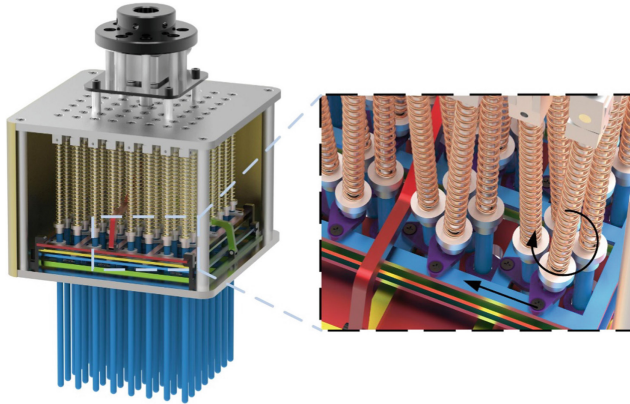
Fig. 9. Universal gripper base on pivoted pin array with chasing tip

5 Grasp Analysis

The grasp performance of pin array gripper is judged by two criteria. The first one is universal grasp capability, which is characterized by pin density. In a denser pin array, more pins are likely to contact with target object. Thus, the shape of the object is better adapted and grasped. The second one is payload of the gripper, which is benchmarked by grasp force. Since pin density is mainly limited by manufacturing, we analyzed how the grasp forces is influence by different dimension of the design.

The grasp force is provided by the contact friction of pins according to Eqs. (2)–(4). The swing angle α_i will determine the length of pin and slot, therefore is to be investigated. The contact point P might vary from pin to pin. Contact length ratio l_{OP}/l_{OA} indicates how far the contact point is with respect to the pivot point. Assuming the friction coefficient $\mu = 0.5$, pin actuation force $F_{pi} = 1\ N$ and lateral contact angle $\beta_i = \pi/6$, the single pin grasp force F_{gi} is shown in Fig. 10(a), where $\alpha_i = 1 \sim 20\ deg$, $l_{OP}/l_{OA} = 1.5 \sim 2$. Results shows that both swing angle and contact length ratio have significant impact on the grasp force. A larger swing angle introduces higher grasp force. The contact length ratio should be smaller as a result of the principle of leverage.

Pin actuation forces come from motor via the sliding frame mechanism. Output ration is defined as F_t/F_M, indicating the actuation performance. It is influenced by the dimensions of linkage and sliding frame, according to Eqs. (6)–(8). Assuming the overall dimension of the gripper is predefined with half-length of sliding frame $s_0 = 50$ mm. The output ratio is determined by the displacement of sliding frame Δs and initial pressure angle γ_0, as shown in Fig. 10(b). The displacement of sliding frame has little impact, which means the length of slot can be extended to increase the swinging angle therefore grasp force. The initial pressure angle has considerable impact. The smaller it is, the better the output ratio. Note that it cannot be too small, due to the possible interference of linkages with frames. For this reason, the linkage shown in Fig. 8 is in a curved shape to avoid collisions.
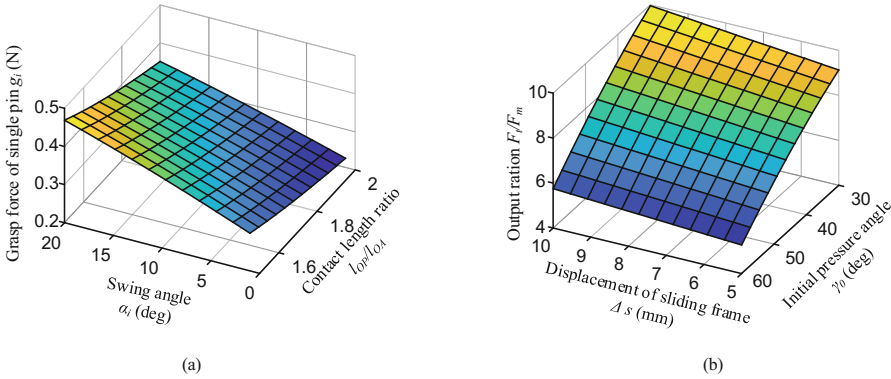
Fig. 10. Grasp performance analysis

For a target object, if m pins are pushed at axial direction and n pins contact the object from sides, the total grasp force grasp F_G is estimated:

$$F_G = \sum_{i=1}^{n} F_{gi} - \sum_{i=j}^{m} F_{vj} \tag{9}$$

To gain a maximum total grasp force, the friction coefficient should be as large as possible while the spring constant as small as possible. In the proposed design shown in Fig. 9, supposing $\mu = 0.8$, $F_{pi} = 2$ N, $\alpha_i = 10$ deg, $\beta_i = 30$ deg, $k = 0.5$ N/mm, $\Delta x_j = 10$ mm, *length ratio = 2*, $n = 6$, $m = 10$, the total grasp force could be 38.32 N theoretically. With higher pin density, the grasp forces can be further increased, which is feasible for many applications.

6   Conclusion

This paper has presented a universal gripper based on pin array. Objects in different shape, size or pose can be adapted vertically and horizontally. It is suitable for complex grasping tasks in unstructured environment.

Passively slidable pins are hinged at a frame in a matrix form. When forced over object, pins slide towards the frame so that the object is covered by pin array. Then pins swing across each other like chasing, building lateral contacts with the objects from sides. The object is therefore grasped. Different configurations of pin unit is proposed, among which a preferable one is chosen for CAD embodiment. Grasp performance is analyzed through the force transmission, from the perspective of grasp force. The feasibility of the presented pin array gripper is verified theoretically.

Future attentions will be placed on prototyping and testing. A physical prototype will be built and used to validate the predicted performance, especially the universal grasp capability.

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