

Prototype design and structural analysis of a variable-angle robotic gripper prototype

Yongpeng Xu ^{1, *}, Kehua Zhu ²

¹ School of Shipbuilding Mechanical Engineering, Jiangsu University of Science and Technology, Zhenjiang, China, 212100

² School of Economics and Management, Jiangsu University of Science and Technology, Zhenjiang, China, 212100

* Corresponding Author Email: xu2927731662@sina.com

Abstract. This paper describes the design of a three-finger mechanical claw, a horticultural product gripper. The design scheme adopts a systematic approach by evaluating all possible structures, selecting the most suitable motion and structure scheme, and using G.I. The proposed structure is optimized and numerically simulated by the evaluation index. The design process and test results are discussed, and the mechanical claw scheme, which is highly versatile, is designed. The three-dimensional model is established with Solidworks, and the kinematic simulation and static simulation are carried out to verify the feasibility of the design scheme preliminarily. The effectiveness of the method is proved by additive manufacturing by making an actual model for the clamping test. The experiment shows that the three-finger mechanical claw with rotating knuckles has good compatibility with the shape of the clamp, and the scheme is simple and convenient in the control process.

Keywords: Robotic design, Grasping function, Gripper, Structural analysis, Variable-angle robotic prototype.

1. Introduction

In recent decades, robotics technology has developed rapidly, with the iterative development of manufacturing technology and the increase in labor costs [1-3]. The demand for automation has increased, and the replacement of human labor by machinery has become a trend. In particular, the work of single content and harsh working conditions is replaced by robots or manipulators [4]. Among them, the need to replace human labor in agriculture and industrial production is significant and urgent [5].

The robot arm is the most common kind of robot in every scene. The main function of the robotic arm is to manipulate the end effector to the target position. Are widely used in space exploration, industrial assembly, battlefield explosion prevention and other dangerous scenes [6, 7]. The wide application of the robot arm effectively improves production efficiency and improves the working environment [8]. In the manufacturing industry, repetitive tasks such as material handling, packaging, automatic assembly of products and plate welding are mainly performed [9, 10]. In the medical scene, micro-surgery also involves the participation of robotic arms [11]. In daily life scenarios, the use of a robotic refueling arm not only improves the safety of refueling, but also greatly facilitates people's lives [12]. Use space robots to repair damaged spacecraft in time, reducing cost and efficiency while also reducing the risk of astronauts operating outside the station [13]. The wide application of robotic arms is the inevitable requirement and trend of social and technological development.

The robot is an important medium for the robot to complete the final execution requirements [5]. There are different needs in different fields and working conditions, and the structural design scheme and functional expansion of the manipulator have made great progress. However, the manipulator is designed for a specific task target in a specific working scene [14]. For example, F Dimeas and Dv Sako designed an efficient strawberry robot gripper under fuzzy control. The grasping force distribution controls the separation action, and the picking efficiency is greatly improved by reducing the grasping posture requirement [15]. Moreover, Xiong et al. also proposed a method for judging the

pickability of strawberries. The structure and control of strawberry picking were studied [16]. Zhang Yueyue et al. designed the occluding-type elliptical trajectory end-effector based on the physical characteristics of pitaya fruit. Clamping and cutting together reduce the damage to branches and leaves [17]. The compatibility and adaptability of grabbing sizes of different categories of picking objects have not been explored well.

In 1968, American scholars Schertz and Brown proposed the use of mechanical fruit and vegetable harvesting methods, which was recognized by the academic community as the beginning of agricultural picking robot research [18, 19]. Since the 1980s, Japan, the United States, the Netherlands, Italy, and other countries have researched the intelligence of picking robots and developed agricultural production robots for strawberries, apples, citrus, tomatoes, and other fruits and vegetables. Includes fingers, needles, vacuum aspirators, nozzles, scissors and robotic arms for grasping, dividing, etc., to effectively perform all biological production processes, including harvesting, seeding, dressing, primary processing, etc [20-22]. Smart agriculture has become one of the mainstream models of agricultural production. The end-effector is usually one of the core technologies of agricultural robots [19], and the requirements of mechanization production and low cost put forward new requirements for the working compatibility of the end-effector of production robots and the manipulator [1, 23, 24].

For the end effector to have good compatibility and take into account stability and easy control, Wu Jijun designed a simple underactuated hand driven by a tendon rope [25]. Park Jinsheng et al. proposed a new mechanism for the push-back rope wheel to optimize this problem [26]. However, the design has the disadvantage of uneven distribution of contact force and the grasp position control needs further optimization. Moreover, there is no further overall structural inquiry into the shape of the grasping target.

The design of this paper aims to improve the compatibility of robotic grasping work and the intelligence level of robots performing picking tasks. A structural design scheme is proposed in the end part of the actuating end, which realizes the design of a reliable grasping mechanical structure for long cylindrical strips of fruits and vegetables. By adding a degree of freedom to the mechanical finger to achieve rotation, and so that the two fingers can be rotated synchronously to adjust the grasping position of fruits and vegetables, i.e., only need to rotate a certain angle to achieve universal grasping. Preliminary fruit and vegetable grasping experiments as well as kinematic parameter simulation and finite element stress simulation verified the feasibility, stability and reliability of the end-effector design. The mechanical gripper was simultaneously simplified for gripping control through gripping index evaluation and size determination selection. The reliable gripping mechanism with low complexity and low number of components improves the compatibility of the gripper's grasping work, which in turn provides a solution for different types of fruit and vegetable harvesting by a single picking robot. It provides a solution for a single picking robot to harvest different types of fruits and vegetables.

2. Design procedure and structural analysis

2.1. Structural design

In the process of achieving fruit and vegetable grabbing, we need to meet the following three core requirements. Grabbing fruits and vegetables without destroying them can maintain biological quality and prevent rapid decay. 2. Steady grip 3. Simple control. The two-finger grasping mechanical claw is mainly used to complete the picking and cutting of fruits and vegetables by clamping the fruit stem [19]. Because the target object is small, the recognition and positioning requirements are high. The design scheme should meet the following specific requirements: grab fruits and vegetables of different shapes, just adjust the relevant structure of the fingers based on the design principle, use a three-finger clamping design, and combine with other design requirements for optimization. The final grasping mechanical of this design is shown in Fig 1.

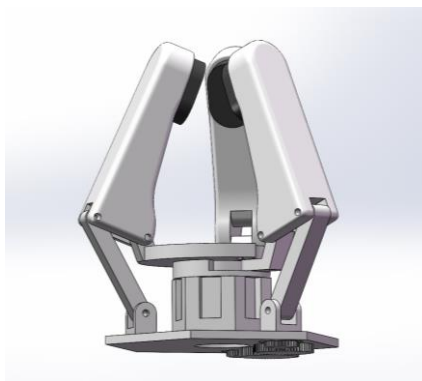


Figure 1. The design of the three-finger of the variable-angle robotic gripper

To achieve the grasping requirements of determining the position shape, the mechanical claw is composed of a base, knuckles, connecting rod 1, slider B and a connecting piece, and a rotating drive gear, which is a connecting piece between the rotating finger and the slider. Fig 1. (a) Its shape is shown in Fig 1. The base is provided with a support seat for non-rotating fingers and a limit hole for drive gear, and the middle boss is the travel groove of slider B, which is hexagonal, which is easy to assemble and position, and at the same time, prevent slider B itself from rotating during the lead screw drive.

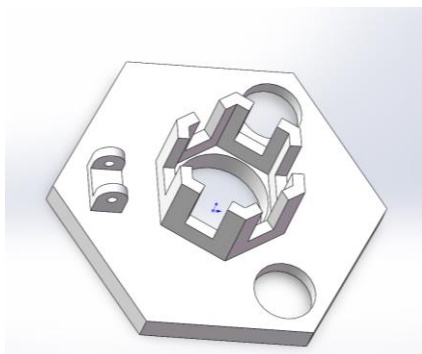


Figure 2. The design of the mount

It is mainly composed of two parts, one of which is a link knuckle, as shown in Fig 2. (a), under which there is a limit slot for connecting rotatable fingers. The other part of the link knuckles to the base, as shown in Fig 2. (b), is fitted with the hexagonal boss on the base. The link effect is shown in Fig 3.

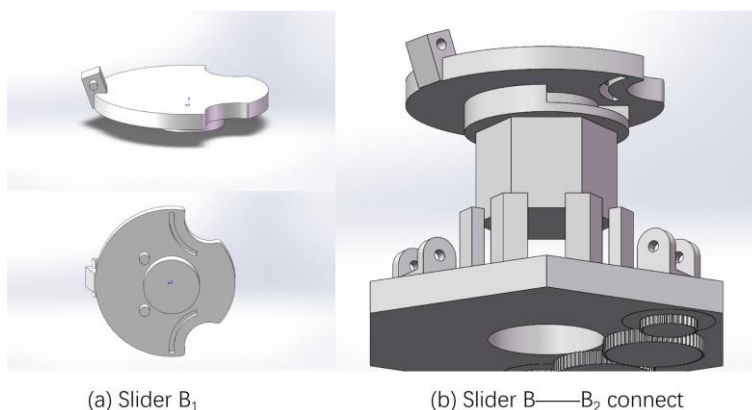


Figure 3. The design of the slider part

The other side of the knuckle is connected to the base by connecting rod 1, thereby enabling the knuckle to rotate during the movement of slider B. Fig 3. The link form is shown in Fig 3. It is connected to the bottom connector of two rotatable fingers by matching a pair of identical gears,

combined with the limit slot on the slider B to realize synchronous opposite rotation without changing the motion characteristics when grasping.

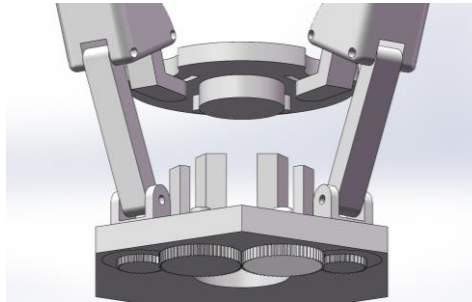


Figure 4. The function of the link rod 1 and rotary drive gear assembly

2.2. Structure analysis of the mechanical claw based on the size of the grasping target

The three-finger single joint structure is selected as the design prototype, which has better benefits and can achieve better grasping effect. On the basis of the universality of grasping targets, another mechanism is innovated to get the final model design of this paper. As show in Fig 4. (a). Slider B is connected with three knuckles, three knuckles are connected with the base through Link rod 1, two knuckles are connected with the base through a Rotary drive gear, and the corresponding slider B is also provided with a chute, so that it can rotate in the opposite direction simultaneously without changing the motion characteristics when grasping.

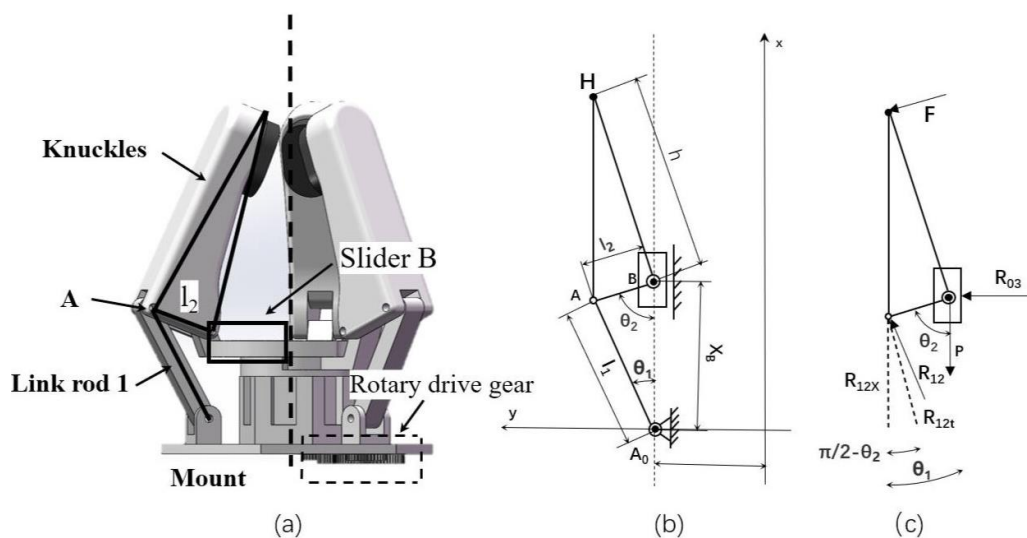


Figure 5. (a) Mechanical claw model; (b) Schematic diagram of manipulator finger design mechanism; (c) Diagram of finger stress analysis

For fruit and vegetable grabbing, there are mainly near-spherical items such as apples, oranges, nectarines, tomatoes, pears, etc. Another small can realize the approximate grasp of spherical fruits and vegetables by adjusting the grasp angle of strawberries and so on, such as long columns of cucumber and eggplant. Its size ranges from 20mm to 120mm [14]. As a reference for the grasp range of the manipulator, and the minimum range of the fingertip is required - it can pick up the smallest size of fruits and vegetables without interfering with each other. The mechanical finger is based on the crank slider mechanism, and its brief structure model is shown in Fig 1. (a). One degree of freedom has been added to the mechanical finger to improve its clamping compatibility. The finger is connected to the slider and the rocker, and a linear actuator drives and controls the grip and release action of the finger closing and opening. A rotating actuator controls the finger grasp Angle to achieve a compatible grasp.

In order to evaluate the performance and efficiency of the clamping mechanism, it is convenient to analyze its behavior by simulating the manipulator operation. Through classical mechanical

research methods, kinematics and static analysis, the proper simulation of the clamping mechanism can be achieved. Grasping Index G.I. is introduced as an indicator of grab performance [27], and the formula is defined as:

$$G.I. = \frac{F \cdot \sin \varphi}{P} \quad (1)$$

Where the shape and position angle of clamping time is P is the driving force applied by the actuator. F is the grab force. Refer to the design parameters shown in Fig 4. (c) and Fig 4. (b), the structure of the manipulator refers to has the following kinematics relationship:

$$l_1 \cdot \sin \theta_1 = l_2 \cdot \sin \theta_2 \quad (2)$$

$$\cos \theta_1 = \frac{x_b^2 + l_1^2 - l_2^2}{2x_b \cdot l_1} \quad (3)$$

l_1 and l_2 are not the length of the two connecting rods of the mechanism. x_b is describes the coordinate position parameters of the slider B . When grasping the target object is in equilibrium, grasping performance can be evaluated by the relationship between grasping force and driving force. The moment balance at point B is:

$$F \cdot h - R_{12t} \cdot l_2 = 0 \quad (4)$$

$$R_{12x} - P = 0 \quad (5)$$

Where h is the height of the finger. R_{12t} and R_{12x} are the components of the supporting force of the connecting rod along the vertical direction of the link rod 2 and the X-axis direction. The connecting rod, however, 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 along the link direction. R_{12} is the same direction as link rod 1. Moreover, they have the relationship between the two of them is:

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

$$R_{12x} = R_{12} \cdot \cos \theta_1 \quad (7)$$

You can get P from the above formula:

$$P = \frac{F \cdot h \cdot \cos \theta_1}{l_2 \cdot \sin[\pi - (\theta_1 + \theta_2)]} \quad (8)$$

And the G.I. expression can be obtained from the above formula as:

$$G.I. = \frac{l_1}{h} \cdot \tan \theta_1 \sin[\pi - (\theta_1 - \theta_2)] \quad (9)$$

On the one hand, the G.I. of the mechanical claw depends on the height of h the manipulator. However, since the minimum h height of the manipulator should exceed half the diameter of the target, it is obviously difficult and unreasonable to increase G.I. by reducing h . Another parameter l_1 is that the value can be changed to optimize, which can improve the G.I. value.

There are two specific parameters for the optimization evaluation index, one is the G.I. $_{mean}$. That is the average of the Grasping Index. The optimization goal is to maximize the G.I., which means maximizing the grasping ability in the process. The formula can be expressed as follows [27]:

$$\max G.I._{mean} \quad \text{subject to} \quad l_{i,min} < l_i < l_{i,max} \quad \text{for } i=1,2 \quad (10)$$

Another parameter is to minimize the average deviation of the Grasping Index, which can be expressed as follows [27]:

$$\min \frac{G.I._{max} - G.I._{min}}{G.I._{mean}} \quad \text{subject to } l_{i,min} < l_i < l_{i,max} \quad \text{for } i=1,2 \quad (11)$$

The mean deviation of the holder is the ratio of the G.I. change in the grasping process to the G.I. mean in the grasping process. This index reflects the stability of grasping ability in the grasping process, which is the mechanical claw grasping process. Or we could say the stability of the grasping force. Through the above two indexes, we can evaluate a manipulator finger structure parameter with the maximum grasping ability G.I. in the acquisition process and the stable G.I. value in the grasping process. According to the requirements of grasping the target size, the boundary conditions of the size parameters of each part of the mechanical claw are preliminarily made, as shown in Table 1.

Table 1. Limits of ranges of design parameters of the gripper.

Variable:	Min.(mm):	Max.(mm):
l1	30	60
l2	15	20
r	30	30

Finally, two reasonable design schemes are obtained. In scheme 1, l1 and l2 lengths correspond to 30mm and 20mm, respectively. Its Grasping Index Daviation is 0.541751, and G.I._{mean} is 0.286937. In Scheme 2, the length of l1 is 39mm, the length of l2 is 20mm, the Grasping Index Daviation is 0.400687, and the G.I._{mean} is 0.279419.

The result of the G.I._{mean} from scheme 1 is better, but the average deviation of Grasping Index of scheme 1 is greater, while the average deviation of G.I. and flat Grasping Index of scheme 2 is more reasonable. Therefore, a scheme with a relatively large average and the minimum average deviation of the Grasping Index is selected. The final mechanical claw structure parameter is l₁, equal to 39 mm. l₂, equal to 20 mm. The X-axis direction coordinate motion range of block B is from 27mm to 43.5mm. Its change value is 16.5mm. As in Fig 4. (b), the motion range of the mechanical grip can be expressed by the following formula:

$$r_H = r + h \cdot \sin\left(\frac{\pi}{2} - \theta_2\right) \quad (12)$$

The motion range of mechanical claws and fingers can be obtained by formula analysis. The diameter range of the target object that it can grab is from 9.18mm to 122.06mm. The structure of the mechanical claw is shown in Fig 4. (a). In order to increase the grasp range and improve the adaptability of the grasp object shape, the index finger and middle finger can be rotated 90° around the normal line of the fixed base. Moreover, through the lead screw and the lead screw nut to complete the lifting and falling of slide B, and then to complete the grasp. The two gears are matched with the gears at the lower end of the two rotating fingers, respectively, and a motor is matched with one of the gears to complete the opposite or reverse rotation of the two fingers, and then the adaptive grasping of the shape of the grasping object is realized. Grasp effects and finger rotation effects are shown in Fig 5 and Fig 6.

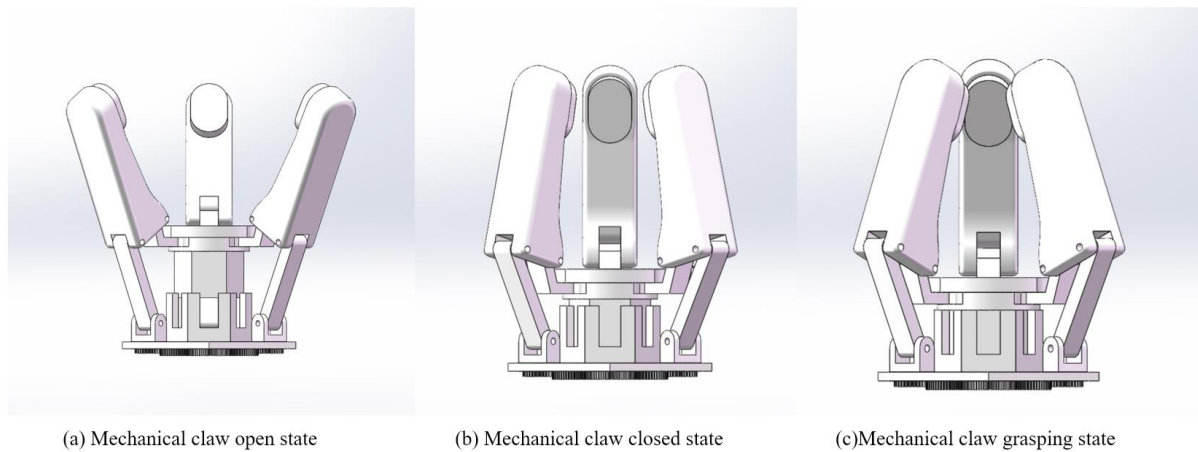


Figure 6. Mechanical claw state

When BarrettHand grasped, the finger faces of the two rotating fingers were not toward the center of the circle because the middle and index fingers were rotating around their respective fixed center of the circle, that is, their respective driving motor positions so that the finger faces toward their respective rotation centers. The design in this paper directly fixed the three fingers at 120° around the center of the circle, and the two rotatable fingers only rotated around the normal axis of the fixed base, which could always keep the surface contact of the finger surface, which effectively solved the problem when BarrettHand was used for fruits and vegetables to grab spherical fruits. Three fingers can not make each finger touch the skin of the fruit, which increases the pressure problem. Compared with BarrettHand, the cost is low, the structure is simple, and the control is easy. The position of the rotation axis of the three fingers is an equilateral triangle distribution, and the three fingers can bear the load evenly when grasping.

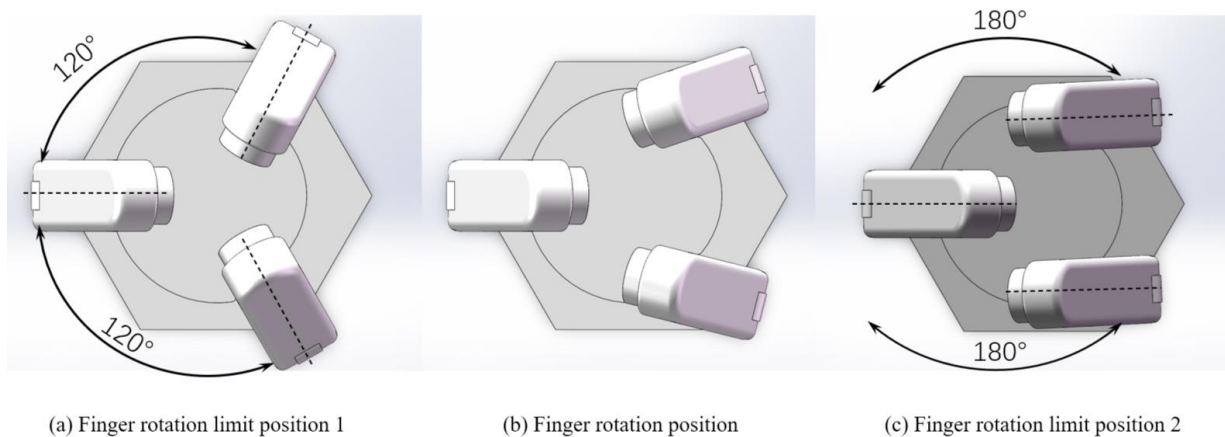


Figure 7. Finger rotation position

3. Finite element modelling

Finite Element Analysis (FEA) is a computer analysis system widely used in engineering numerical analysis of powerful tools, especially in the field of solid mechanics and structural analysis, to solve a large number of significant engineering problems. By discretizing the continuous solution domain, that is; by dividing it into finite elements connected by a certain shape, interpolation is an approximate method for numerical computation. SolidWorks Simulation uses a fast Finite element algorithm (FFE) to improve the solution speed significantly. It is Fully integrated with the Windows environment and seamlessly integrated with Solidworks simulation. A static stress-strain distribution stress analysis can be performed on the model.

3.1. Motion of analysis of robotic gripper

Open the three-dimensional model of the three-finger manipulator assembly in Solidworks, load the Solidworksmotion plug-in, and only solve the motion parameters of the kinematic simulation. Moreover, the constraint relationship of the assembly does not need to be re-added; it directly uses the constraint during the establishment of the assembly. Moreover, since the three fingers are identical in bending motion, So we only need to simulate one finger. The driving member can set the motion speed of the corresponding member of the slider B, as shown in Fig 8.

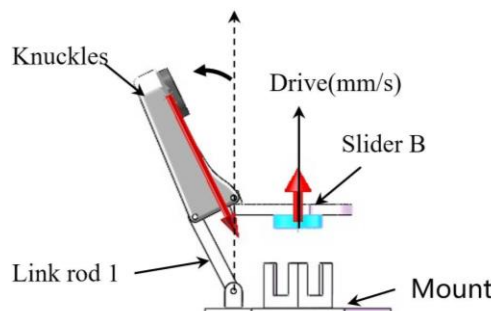


Figure 8. Motion simulation parameter

Three different driving speeds are selected for slider B: 5mm/s, 10mm/s and 15mm/s. The kinematic simulation was carried out, and the angular velocity and angular acceleration images under three different driving speeds were drawn on the knuckles. The results are shown in Fig 7.

3.2. Structural analysis of robotic gripper

The quality of fruits and vegetables is mostly between 0.5N and 2N [14]. Through Eq. (8) and Eq. (4), it is assumed that the friction coefficient is 0.5, the knuckle loading torque can be given, and the given P is 40N for the convenience of calculation. The knuckle material is set on ABS engineering plastic, and the convex material at the fingertip to grab fruits and vegetables is set on rubber. The performance parameters of the respective materials are shown in Table 2 respectively.

Table 2. ABS and Rubber material properties and applications

Stats	Stats
Name: ABS	Name: Rubber
Yield strength: 5e+07 N/m ²	Yield strength: 9.23737e+06 N/m ²
Tensile strength: 3e+07 N/m ²	Tensile strength: 1.37871e+07 N/m ²
Modulus of elasticity: 2e+09 N/m ²	Modulus of elasticity: 6.1e+06 N/m ²
Poisson's ratio: 0.394	Poisson's ratio: 0.49
Mass density: 1,020 kg/m ³	Mass density: 1,500 kg/m ³
Shear modulus: 3.189e+08 N/m ²	Shear modulus: 2.9e+06 N/m ²

It is added the fixture to the position in Fig 9. (a). A 40N normal uniform load is added to the surface at the position shown in Fig 9. (b). Triangular mesh elements with the side length of 0.2mm and tolerance of 0.01mm were selected for grid division. Finally, an example of static stress analysis is given. The result is shown in.

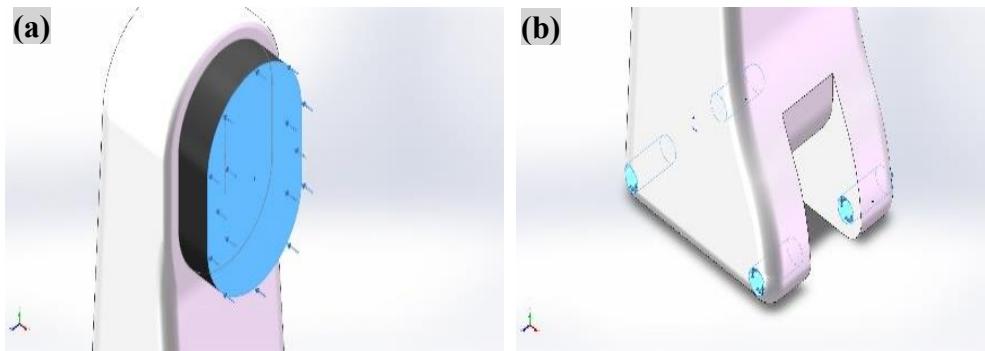


Figure 9. (a) fixture (b) normal uniform load

4. Results and discussion

4.1. Motion results of analysis of robotic gripper

The angular velocity and angular acceleration of knuckles obtained through Solidworks motion and motion simulation are shown in Fig 10. It can be seen that within the limited range of motion of the three-finger mechanical claw, although the total grasping motion time is 2-3 times longer under the driving speed of 5mm/s, the angular velocity change is more stable. At 10mm/s and 15mm/s drive speeds, the knuckle response speed is doubled, but so is the reduction in angular velocity in the second half of the motion. For precise position control, it is more difficult, and the precision requirements for transmission parts are also higher. Therefore, the driving speed of 5mm/s is more appropriate. The angular acceleration response is also more stable in the drive speed of 5mm/s, which is beneficial for the grasping force control. The simple control logic has a better grasping effect, and the damage to fruits and vegetables is also less.

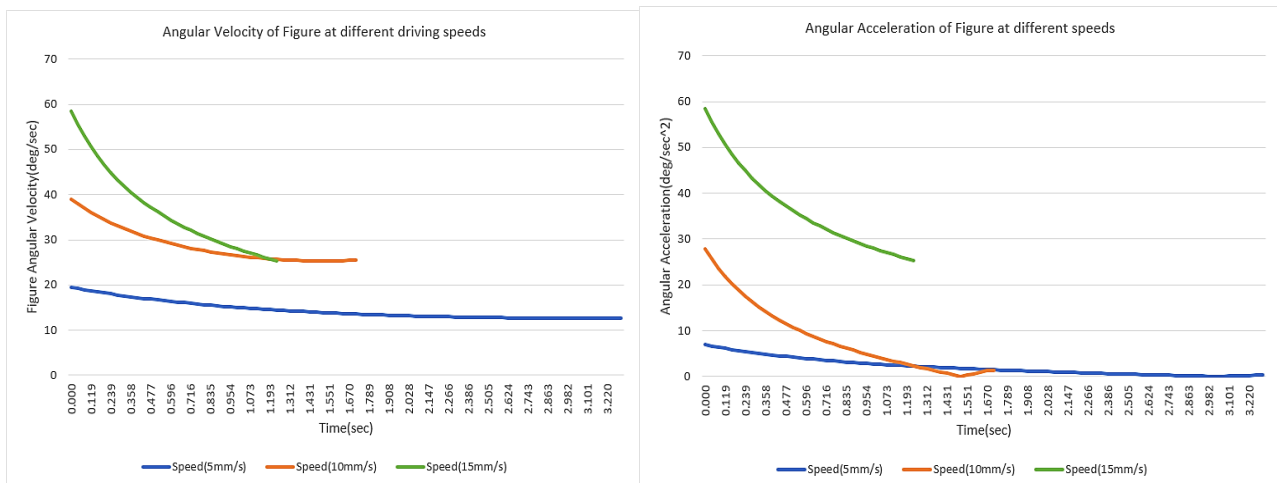


Figure 10. (a) angular velocity at different driving speeds (b) angular acceleration at different speeds

4.2. Structural analysis results of analysis of robotic gripper

The stress and displacement results of knuckles obtained through Solidworks Simulation static stress simulation analysis are shown in Fig 11.(a). It can be seen in Fig 13 that the maximum stress is in the fixed position of the knuckle, and the value is far less than the yield strength of ABS engineering plastic, which is completely suitable for grasping. In the static stress analysis and displacement simulation shown in Fig 11.(b), the maximum displacement at the fingertip grasping fruit and vegetable convex is 0.322mm, which is also reasonable for grasping, especially for protecting fruit and vegetables.

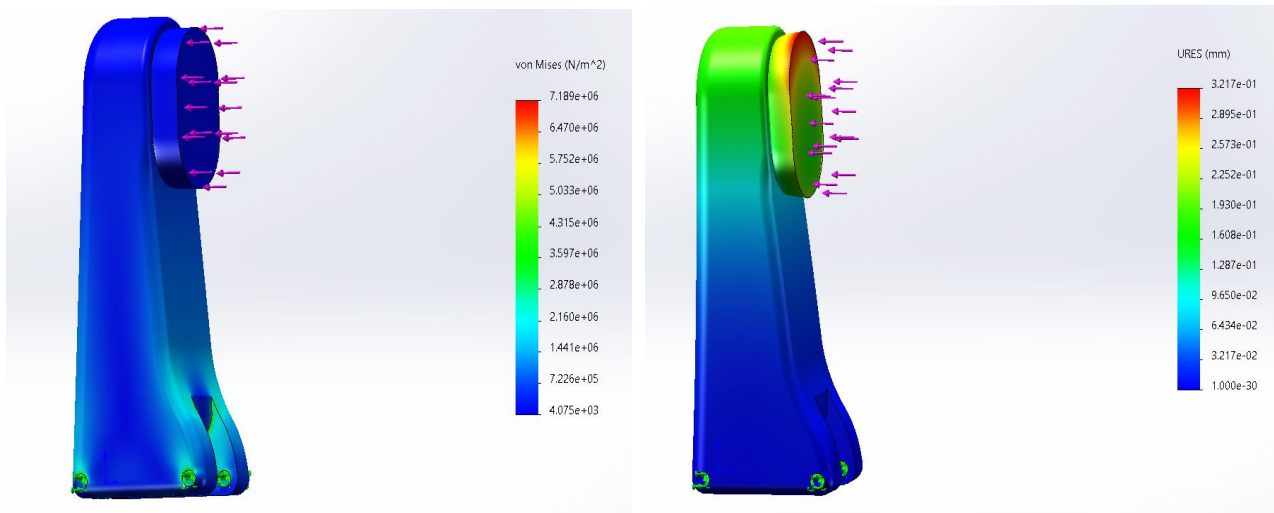


Figure 11. (a) Static stress analysis – Stress (b) Static stress analysis – Displacement

4.3. Results of grasping performance of robotic gripper

The design model is printed one by one, and the assembled mechanical claw is used to grab fruits and vegetables. The differences in grasping stability and grasping compatibility of fruit and vegetable shapes were demonstrated. The better circular feature selects three fingers to grasp each other at about 120° and fine-adjusts the rotation Angle to make the fingers more closely fit the surface of the grasping object. The kinds of fruits that were successfully captured are shown in Fig 12. Then, the mechanical claw was moved and shaken, and the grasp was stable, and there was no obvious damage to the surface of the fruit.

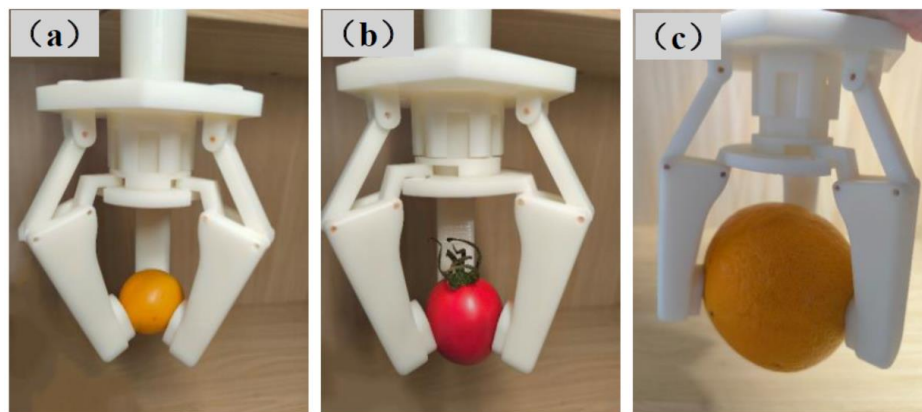


Figure 12. The grasping condition of different objects: (a) loquat; (b)cherry tomatoes; (c) citrus

A completely cylindrical cherry fruit is selected for the grasping test. For the grasping Angle of three small spherical fingers close to symmetry, the whole mechanical claw needs to be rotated so that the grasping attitude can be successfully and stably grasped. It is complicated to identify and adjust grasping, and it is not conducive to improving grasping efficiency. By rotating two rotating fingers, the contact area with the fruit surface is adjusted. The grasping effect is shown in Fig 13 (a).

The compatibility of mechanical claws was further explored for grasping large, long, columnar-shaped fruits. The grasp effect is shown in Fig 13 (b). Grasp is stable and reliable in moving and shaking state.

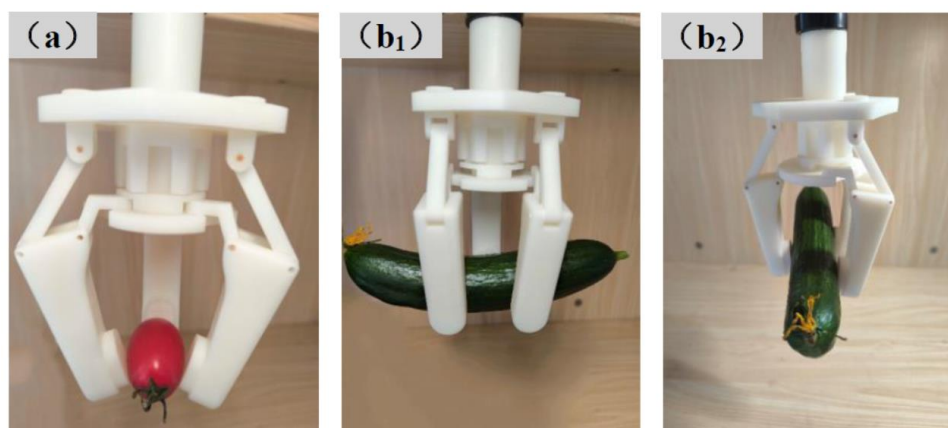


Figure 13. The grasping condition of different objects: (a) cherry tomatoes; (a) loquat;

5. Conclusion

Considering the requirements and characteristics of horticultural product grips, new horticultural product grips are proposed through specific selection analysis and design process. G.I. index was used for numerical simulation analysis, and a three-dimensional model was established according to the analysis results, and its kinematics and static analysis were studied. 3D printing manufacturing was used for prototype construction, and the actual capture test proved that the scheme could meet the task requirements. In the future, the finger structure and the grasp of the motor drive control can be further optimized.

References

- [1] JIN Y. Research Progress Analysis of Robot Selective Harvesting Technologies [J]. 2020, 51 (9): 1 - 17.
- [2] QILIN W, HAN2 Z, XIAOFEI2 C, et al. Review of Technology, Application Status and Development Trend in Multi-arm Cooperative Robots [J]. 2023, 59 (15): 1 - 16.
- [3] HUIZHI W. Application of industrial robot in intelligent manufacturing [J]. 2022, 53 (02): 78 - 80.
- [4] ERFANI S, JAFARI A, HAJIAHMAD A. Comparison of two data fusion methods for localization of wheeled mobile robot in farm conditions [J]. Artificial Intelligence in Agriculture, 2019, 1 (48 – 55).
- [5] ZHANG B, XIE Y, ZHOU J, et al. State-of-the-art robotic grippers, grasping and control strategies, as well as their applications in agricultural robots: A review [J]. 2020, 177 (105694).
- [6] MENG W J L C Y Y C Y Q H L. Hybrid Control Strategy of Manipulator for Spacecraft Component Assembly [J]. 2022, 33 (02): 90 - 6.
- [7] QI W, ZHIGANG W, YU Y, et al. Review on Development and Application of Structure of Manipulator [J]. 2024, 35 (05): 60 - 73.
- [8] XIE D, CHEN L, LIU L, et al. Actuators and sensors for application in agricultural robots: A review [J]. 2022, 10 (10): 913.
- [9] GUOFA W, FENG L, YIHUI P, et al. Coal mine intellectualization: The core technology of high-quality development [J]. 2019, 44 (2): 349 - 57.
- [10] RUNQUAN X, YANLING X, SHANBEN C, et al. Key technologies and application development status of welding robots [J]. 2020, 10): 24 - 31.
- [11] YILI F, BO P. Research progress of surgical robot for minimally invasive surgery [J]. 2019, 51 (01): 1 - 15.
- [12] HONGPU C, GUOYONG Y. Robotic refueling machine [J]. 2020, 03): 65 - 7.
- [13] LIANGLIANG Z, XUEAI L, JINGDONG Z, et al. Development Strategy of Space Robots for Autonomous Repair and Maintenance of Spacecraft [J]. 2024, 26(01): 149 - 59.
- [14] RUSSO M, CECCARELLI M, CORVES B, et al. Design and test of a gripper prototype for horticulture products [J]. 2017, 44 (266 - 75).

- [15] DIMEAS F, SAKO D V, MOULIANITIS V C, et al. Design and fuzzy control of a robotic gripper for efficient strawberry harvesting [J]. 2015, 33 (5): 1085 - 98.
- [16] XIONG Y, PENG C, GRIMSTAD L, et al. Development and field evaluation of a strawberry harvesting robot with a cable-driven gripper [J]. 2019, 157 (392 - 402).
- [17] YUEYUE Z, JIAQUAN T, WENXIANG W, et al. Design and experiments of end-effector for dragon fruit picking robot [J]. 2023, 8 (04): 144 - 50.
- [18] JIDONG L. Research on Visual Measurement and Obstacle Avoidance Control of Apple Harvesting Robot [J]. 2012.
- [19] JIANQIAO W, SHENGZHE F, LIANG G, et al. Research Status and Development Direction of Design and Control Technology of Fruit and Vegetable Picking Robot System [J]. 2020, 2 (4): 17.
- [20] GORJIAN S, EBADI H, TROMMSDORFF M, et al. The advent of modern solar-powered electric agricultural machinery: A solution for sustainable farm operations [J]. 2021, 292 (126030).
- [21] TSOLAKIS N, BECHTSIS D, BOCHTIS D J A. Agros: A robot operating system-based emulation tool for agricultural robotics [J]. 2019, 9 (7): 403.
- [22] XIONG Y, GE Y, GRIMSTAD L, et al. An autonomous strawberry-harvesting robot: Design, development, integration, and field evaluation [J]. 2020, 37 (2): 202 - 24.
- [23] SUNCHENGYU, YANJIANWEI, ZHANGFUGUI, et al. Research progress of vegetable picking robot and itskey technologies [J]. 2023, 44 (11): 63 - 72.
- [24] SHI XIAOJIE W S, LIU HUIMIN, WANG SHAOWEI, QU HUIXING, LI NING, WU JIE, YANG HUAWEI. Current status and prospects of research on forest fruit picking robots [J]. 2024, 1 - 9.
- [25] JIJUN W. Study on the Design and Grasping Characteristics of the End-effector of Picking Robot [D]; Tianjin Agricultural University, 2018.
- [26] JINSHENG P, JIANCHUAN Z, WEI P, et al. Structure Design and Static Analysis of the Underactuated Three-knuckle Manipulator with a Reverse Rope-pulley Mechanism [J]. 2023, 47 (12): 60 - 8.
- [27] CECCARELLI M. Fundamentals of mechanics of robotic manipulation [M]. Springer, 2022.