Tendon Actuation Device Based On Underactuation Apple Lossless End Effector

Peishuo Bian

School of Mechanical Engineering, Shandong University of Technology, Zibo， China

21110171046@stumail.sdut.edu.cn

Abstract. With the continuous development of agriculture, people's demand for improving orchard production efficiency and fruit quality is increasing. The traditional manual method of picking apples has problems such as low efficiency and high losses. Advanced technologies are urgently needed to address this challenge. To this end, this article introduces a non-destructive apple-picking technology based on robot end effectors. Through simulation analysis, it was determined that four steps of adsorption, pulling back, clamping, and twisting were used to simulate one-handed picking. The end effector produces a spherical dynamic grasp with normal force distribution and pick-up sequence replicating selected human body patterns. By analyzing and solving the structure of the hand claw, the motion statistics of the three fingers under different drives are simulated to determine the force required for picking. This technology adds an underactuated tendon drive with a flexible flexure joint. This is to make the system work better in the event of positioning errors and to make it more resistant to changes in fruit size, shape, and orientation. Experimental results show that non-destructive apple-picking technology using robotic end effectors has higher efficiency and lower losses than traditional methods. Robots can quickly complete more picking tasks and reduce fruit waste and loss.

Keywords: End effector, underactuated, lossless picking, tendon actuation.

1. Introduction

China's apple production has steadily risen in recent years, reaching 45.973 million tons in the 2021-2022. This accounts for 56.4% of the global market, placing China at the forefront [1]. Nevertheless, harvesting has consistently been a crucial component of the apple cultivation process. Currently, hand-picking remains the primary method employed in China. Despite certain efforts towards mechanization, the efficiency remains relatively low. Harvesting high-altitude apples necessitates ladders, an inefficient, labor-intensive, expensive, and hazardous process. The selection of high-quality fruits directly impacts the preservation, processing, and sales of fruits and economic profitability. Furthermore, the growing of fruits exhibits a certain level of stochasticity, and the harvesting conditions lack total organization. Consequently, conducting a study on selecting robots has become an unavoidable decision.

Since the 1980s, researchers and technicians worldwide have been working on the advancement of automated fruit-picking robots [2]. The initial research endeavors established the fundamental operational criteria for fruit picking robots, which include: i) accurately identifying the position of fruit on the tree in three-dimensional space; ii) effectively approaching and grasping the fruit; and iii) selectively harvesting intact fruit off tree depositing it into a container. For a fruit-picking robotic system to be commercially viable, it must be both economically feasible and achieve a harvest rate (measured in fruits per second) comparable to manual picking. Additionally, the Efforts to directly apply industrial robot technology to agricultural settings for harvesting specialty crops have faced significant challenges, resulting in only partial success. These challenges mainly stem from precision, speed, and durability issues. Nevertheless, for these robots to be economically feasible, they must possess the capability to offer picking efficiency equivalent to hand-picking. Simultaneously, collisions and compression during the harvesting process must be decreased to minimize harm. Additionally, maintaining a specific length of fruit stems will aid in preserving the fruit for an

extended period. The end effector, a crucial component of the robot, necessitates interdisciplinary and cross-domain collaboration and is currently in the phase of experimental study.

This article discusses the initial findings of a study focused on addressing this issue through automation and cooperation between humans and robots. Prior projects involving robotic picking have recognized that enhancing the performance of the end-effector, namely in terms of its ability to withstand damage, is a significant area for potential enhancement. To overcome these restrictions, this study suggests the development of a prototype agricultural tool that considers the biological benefits and limitations of a typical fruit tree farming system. This is achieved through a thorough quantitative analysis of the motions and forces necessary for various methods of apple harvesting, given a higher position or rank. This research examines the construction and evaluation of an underactuated apparatus and gives empirical findings for quantifying gripping force.

2. Overall Scheme

2.1. Design Requirements

Mechanized fruit picking is an essential direction for developing the fruit industry. Mechanized picking can reduce labor costs, improve picking efficiency, reduce damage to fruits, and extend the shelf life of fruits, thereby increasing yield and fruit quality. Fruit tree picking is often the most significant cause of fruit tree damage. The shape, size, and growth direction of fruit trees all affect the accuracy and efficiency of picking. Many indicators of apple trees are very different, and these parameters change yearly [3]. Therefore, the termination actuator is designed based on the same physical properties of the fruit, such as the hardness, the fruit's porosity, and the stem's tensile strength. To ensure that equipment and products are not damaged, actuators must be designed with a correct understanding of these mechanical characteristics. The terminator design aimed to create a prototype that simulated picking apples by hand and addressed the limitations imposed by the fruit's growing habits. The termination actuator is optimized to correspond to five design criteria:

90% separation success rate: the ratio of the number of successfully harvested fruits to the total number of harvested fruits;

The picking time is 6 seconds—The time from picking to the storage of a single fruit, excluding the time for identification and location of the fruit;

The fruit damage rate does not exceed 10%—the proportion of successfully picked fruits damaged due to falling or excessive pressure.

It applies to various apple varieties.

It has a high cost-performance ratio and solves potential safety hazards.

2.2. Design Approach

Since the picking method determines the structure's mechanics, the design concept is reflected in the characteristics of the structure. Early apple-picking robots used the "best method" or "standard method" to identify the direction of the fruit and fruit stem and then cut off the fruit stem. Since the cut-off actuator is only responsible for limiting the movement of the fruit, the load rate is imposed on the fruit. This method is often used to increase the yield of susceptible fruits such as strawberries and grapes, as too many steps can increase picking time. It is based on the principle of minimum harm. So, I started trying to use a cutter to extract apples directly, and I found that I could reduce the picking time. The apple-picking robot's picking method determines the direct extraction's picking effect [4]. The article introduces unique research results, aiming to meet the impact of various outdoor factors on picking, improve picking efficiency, and reduce the breakage rate. An essential part of the apple picker is the end effector, which can pick apples from the tree by vacuum or manual grasping. Napier proposed a classification system that divides manual grasping into precision grasping and force-grip precision grasping. Precision grasping uses only the thumb and fingertips to attract objects, while the palm and fingers form a larger contact surface with spherical objects [4]. The end effector uses circular force to attract the workpiece and is often called a suction tip. Dynamic adsorption will

improve the robustness of positional artifacts due to the input provided by machine systems where artifacts may exist. Again, you don't need to close the fruit, as the goal is to provide a normal force distribution that replicates the human body pattern. When acting, the manipulator rotates the workpiece in real time, grabbing an object. The shape and size of the object determine the choice of gripping posture and gripping type; therefore, precision clamping is usually suitable for smaller loads.

2.3. Specific Protocols

When observing workers picking at their posts, it was found that their commonly used movements are compound movements of swinging and twisting, or they use their index fingers to hold both ends of the fruit handle and bend and pull in the opposite direction. The four basic movements are horizontal pull, vertical pull, bend, and twist. As shown in Figure 1, Fh, Fv, Tb, and Tt represent horizontal pulling force, vertical pulling force, bending force, and torsion force, respectively.

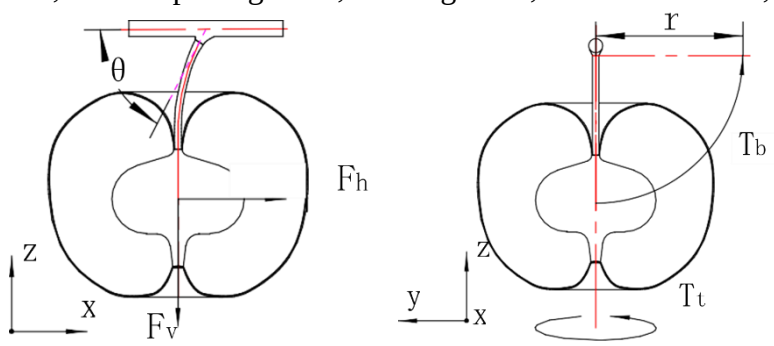


Fig. 1 Four basic actions on fruit [4]

Based on the established branch-stalk-fruit finite element model, a four-factor and three-level simulation test was conducted on horizontal speed, vertical speed, bending angular speed, and torsion angular speed. Analysis of variance and regression analysis found that sheer speed, horizontal speed, turning angular speed, and torsion angular speed significantly influence fruit separation force. Taking the fruit separation force as the optimization object, the simulation test results show that the combination of horizontal pulling, bending, and twisting may be the best separation action. Therefore, the end effector designed in this article uses four steps: adsorption, pullback, clamping, and twisting to simulate single-handed picking, which requires less force to destroy the connection and reduces the fruit damage rate. Usually, human grasping is fingertip grasping, but end effectors are designed to capture workpieces using capturing force. The actuator chooses the under-driven design of the end effector. The most significant advantage is its torque flexibility, which can realize long-distance and different pulley block transmission methods. Each end-effector finger has two links connected by flexural joints. In an early conceptual design, the authors suggested using springs instead of curved parts [5]. Flexible joints' underactuated and passively compliant compliance provides several advantages in non-formed orchard environments. For example, underactuation between finger links helps ensure shape sensitivity for fruits of variable shape, size, and orientation. And the damper compliance of the flexible joint improves its robustness against positioning errors. When unexpected collisions are expected during gain, the adjustable base can withstand out-of-plane and large deflections without damage [6].

Previously developed grasping manipulators typically have between 2 and 5 fingers, whereas a complete termination actuator contains three identical fingers. Bi-finger stretching is theoretically possible but can easily lead to stretching failure and instability. The waste of a 5-finger traction mechanism will make the mechanism complex, difficult to control, and challenging to operate. This affects stability and flexibility. Therefore, we selected three finger structures evenly distributed at 120 degrees in this study. Round handles with soft rubber inserts are arranged. To ensure that in a sphere with a stretched diameter of 80 mm (a typical apple diameter), the proximal link touches the equator of the fruit, The total length of the fingers is approximately the same as the human index finger. The bottom of each finger link has a soft rubber pad to add stiffness, enhancing the tangential

force between the fruit surface and the termination actuator. A variant of the seesaw mechanism, the disc differential provides underdrive between the fingers [7]. When one finger touches an object before the other two fingers, the differential rotates, triggering the remaining two fingers. A soft rubber pad between the power unit connects rods, and a floating pulley provides underdrive. As shown in Figure 2, the CAD model of the complete termination actuator includes support and finger independence.

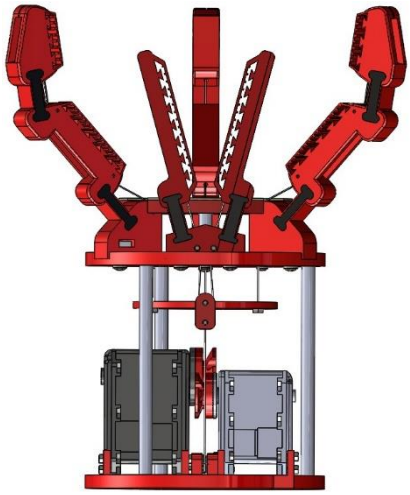


Fig. 2 Computer-aided design (CAD) model of prototype end effector [3]

A Replicator 2X printer from MakerBot Industries in New York used the physical model to create the parts that terminate the actuator. By using additive manufacturing, the required purchase quantities can be minimized, resulting in a lower overall weight of the device. As shown in Figure 3, the entire finger is made of ABS plastic. The finger pad mold is a thin shell in the solid part, using a manufacturing process similar to that of Ma, Odhner, and Dollar [8]. Vytaflex 30, Smooth-On, Inc.'s soft polyurethane, can be used in rubber palm and finger pad cavities. After the elastomer cures, the shell is molded from the mat. Place the rubber pads on your palms and the dovetail joints of your fingers. Flexible filaments (Ninjaflex, Fenner Drives, Inc.) inserted directly into the cavities of the links are used to print the gripper joints and flexures of the fingers. The design's tendons are 100-pound high-strength fishing line. The tendons of each finger are knotted at the end, traverse the link along a hollow channel, and then continuously cross in two small dowels in the proximal link.

A freely rotating pulley at the base of each finger tower directs the tendons to their ends on the disc differential to reduce friction with the plastic components. The connecting rod is tilted and secured to a single stainless steel bundle on the stem clamp via a floating pulley. Sturdy bundles connect the disc differential and floating pulleys to the pulleys on each actuator corner. The differential, floating pulley, and extreme pulley are also printed parts. The Dynamixel MX-64AR and MX-28AR from Robotis, Irvine, Calif., are actuators for braces and fingers. Stirring gears, motor drives, PID controllers, DC motors, and data networks are the components of the Dynamixel servo system. The stall data of the MX-64AR is 7.3 Nm, and the stall data of the MX-28AR is 2.5 Nm. The Microsoft Visual Studio C++ development environment uses the software development kit (SDK) provided by the manufacturer to manage the server system. The actuator servo system uses 12 volts of DC voltage, while the manipulator uses 24 volts of DC voltage.

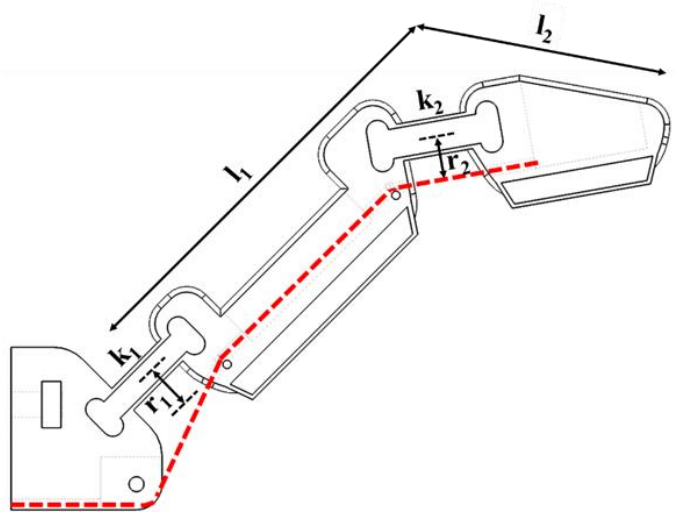


Fig. 3 Schematic diagram of end effector fingers [3]

Dynamixel MX-64AR (Robotis Inc., Irvine, CA) and MX28AR are grippers and finger actuators. Dynamixel servers include data networks, DC motors, load gear heads, PID controllers, and motor drivers. The MX-64AR and MX-28AR have stall torques of 7.3 Nm and 2.5 Nm, respectively. The crane load actuator requires a separate power supply as it operates on 12 VDC, while the manipulator uses 24 VDC.

In the Microsoft Visual Studio C++ development environment, manufacturers provide software development kits (SDKs) for managing server systems. After assembly, the actuator weighs 0.4kg. Based on the average mass of tomatoes harvested during the handpicking analysis, the total tariff for the final actuator and harvested fruit was less than 0.7kg. Table 1 lists some important physical parameters and the logic of the end effector. The orthogonal distance from the bend midline to the tendon entry point corresponds to the calculated range of the pulley radius. Please assume the joint is a torsion spring and then use a load cell to measure its rotational stiffness. Compared with k2/k1, the stiffness between the two joints is crucial to the motion properties of the connection between the links. The arrangement of the fingers gives the fruit sculptural power. In this abstract sequence, the proximal link comes into contact with the object before the distal link bends to cage the fruit. By conducting experiments, the stiffness of a curved bow can be determined. Table 1 shows the physical and geometric parameters of the end-effector prototype.

Table 1. Physical and geometric parameters of the end effector prototype [3]

Link	Length *l (m)*	Joint Stiffness k (N-m/rad)	Pulley Radius r (m)	Resting Angleθ (o)
1	0.07	0.055	0.00956	45
2	0.04	0.111	0.00716	35

2.4. Structural Analysis

In most grasps, the proximal normal force is located at or near the fruit's equator. The driving force that generates the normal force in the human picking pattern must be determined. Figure 4 illustrates a balanced shear configuration that a human actuator calculated. This is a complex process because the normal force depends on the kinematics of the underconfigured actuating finger. During the harvesting process, changes in fruit shape, size, and position will result in changes in the configuration of the multiple interception actuators. Likewise, hostile regular forces can develop in specific configurations, indicating a loss of contact between the corresponding links [9]. Open-loop control should ensure that, in all possible configurations, the object is not damaged when grasped. Matlab simulations (Mathworks Inc., Natick, MA) were used to evaluate the effect of proximal normal force on positioning the tray. The center diameter of the circle is 80mm at different positions on the X-Y plane. The pallet in the X direction is -10 to +10 mm, and the pallet in the Y direction is 0 to 10mm.

There are four hundred different fruit locations throughout the grid. At each point, the stem/branch system is assumed to limit yield. Use the solver to estimate the configuration of the finger links tangent to the circle and then determine the change in link position Δθ and contact points b1 and b2, assuming one contact point on each link.

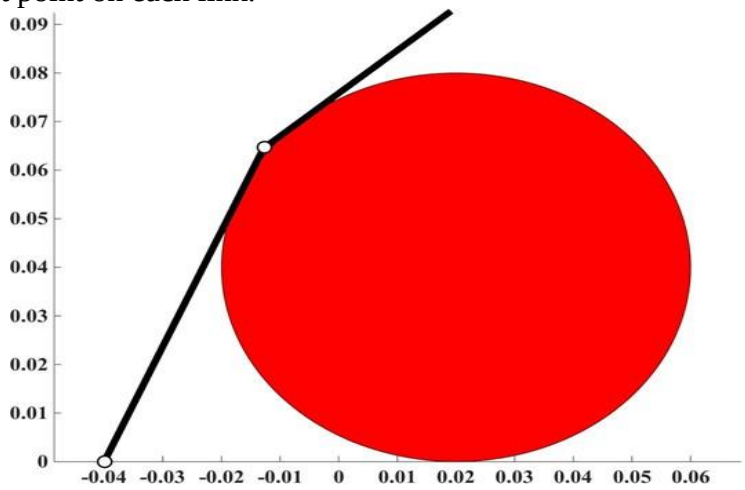


Fig. 4 Grab a configuration example from Matlab Solver [3]

The solution is then used to determine the proximal normal force. Without considering the tangential forces generated by the difficulty, the proximal normal force should increase the pullout force required to remove the fruit from the termination actuator. As shown in Figure 5, the force data scaled using unit-based normalization show that for a constant actuation force, the proximal normal force increases with increasing Δθ1 as shown in Figure 4, when the x value at the finger's base increases, the proximal link must rotate further to reach the fruit.

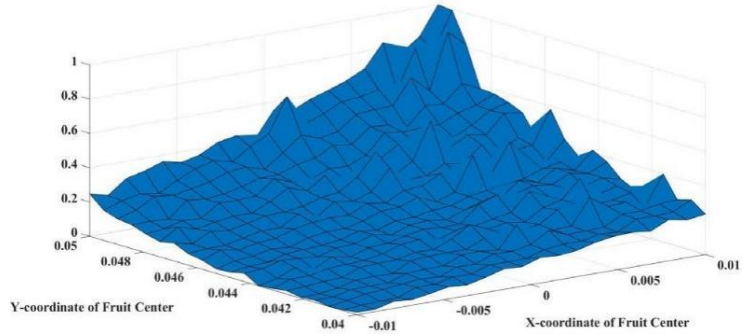


Fig. 5 Normalized proximal force produced during static balancing of a single finger [3]

3. Programme implementation

3.1. Hand Jaw Construction

The end effector is mounted circumferentially by three sets of identical support claw units. Each set includes a horizontal slider, an upper link, a lower link, and a clamping claw. The level is fixed on each slide of the three-claw slide block and can be extended or retracted radially simultaneously. One end of the upper and lower connecting rods is connected to a horizontally fixed clamping claw to form a rotating pair. The other end is connected to the upper and lower ends of the center to create a rotating pair: vacuum suction cup and center reset fixation. The three slide tables extend or retract simultaneously when the three-claw slider moves. This causes the central rotation of the claw to drive the vacuum suction cup to expand and retract during the opening and closing processes. When prompted by an active part, the mechanism can carry out the two sequential actions of clamp jaw closing and vacuum suction cup retraction. A clamp on the top of the termination actuator holds the stem down during fruit separation. The angle between the grip and the linkage is 30 degrees when it

is open. There is a soft rubber pad between the supporter links, and a floating pulley provides underdrive [10].

3.2. Simulation Tests

The experiment used a plastic sphere with a radius of 40 mm to measure the normal force. Due to the transfer of the sphere and the termination actuator, the termination actuator's center line coincides with the steering sphere's center. The contact sites on the proximal link had three piezoresistive force sensors made by Tekscan Corporation, Boston, MA. The actuator executing the terminator (not reversible) is in data mode and driven to its stall point to complete the kinetic adsorption. Static equilibrium measurements are then used to determine the directional force. As the resulting load increases, the measurement is repeated several times. The experimental equipment provided is shown in Figure 6.

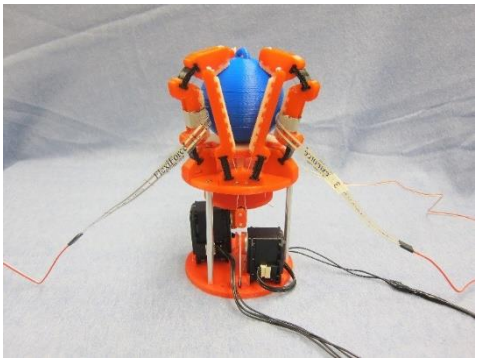


Fig. 6 Experimental setup for contact force measurement [3]

The same experiment was performed for the terminal normal force. Figure 7 shows the experimental results and normal force measurements at five actuator loads. Expectation: To increase tendon tension, the proximal normal force will be significantly more potent than the distal normal force. The distal force changes were irregular, indicating jumps at both ends interspersed in horizontal steps; the proximal force changes were relatively linear with increasing tendon tension. The proximal link remains stationary during surface contact, but the distal link frequently adjusts its equilibrium configuration under reduced loads. Figure 8 compares the proximal normal force when ten different differential loads were measured simultaneously on three fingers. Results are shown for six iterations. The closest normal force produced when picking apples is about 7N, requiring 10% of the maximum Bluetooth value [11]. According to the simulation results in Figure 5, the contact force generated by actuating the workpiece should be below the 11 N force threshold for undesired extraction configurations. This force threshold resulted in bruising during field testing in handpicking mode. Future research will focus on whether the control inputs developed through this novel abstract analysis can successfully extract fruit from the tree. This will consider the external interference the experimental rhizomes' tensile and rotational strengths provide in non-novel configurations. The grip is not force-isotropic as expected for the ultimate grip, although the normal force distribution is similar for each finger. Since the normal force is highly dependent on the configuration, any minor adjustment in the sensor position can significantly impact the final result.

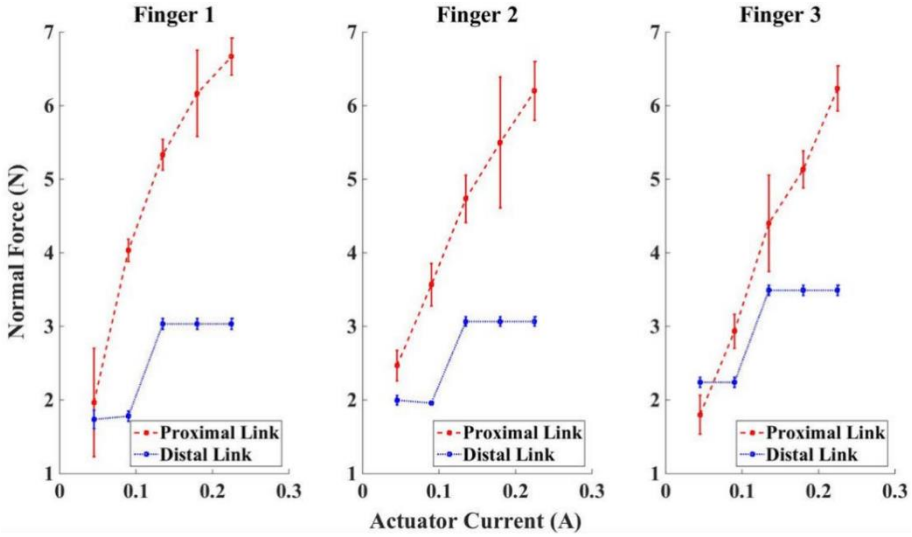


Fig. 7 Proximal and distal regular forces for each finger at five different actuator loads [3]

Additionally, the proximal contact point sometimes adjusts slightly when tendon tension is increased. Changes in normal contact position relative to the sensor may be the source of some differences between proximal force values. Finally, some of the outer layers of the proximal elastic flexure tend to delaminate under the actuation loads described above. This process may lead to inconsistencies between joint stiffnesses and maybe another source of force variation. The authors intend to address delamination in curved sections by adjusting part orientation and other printing parameters during manufacturing.

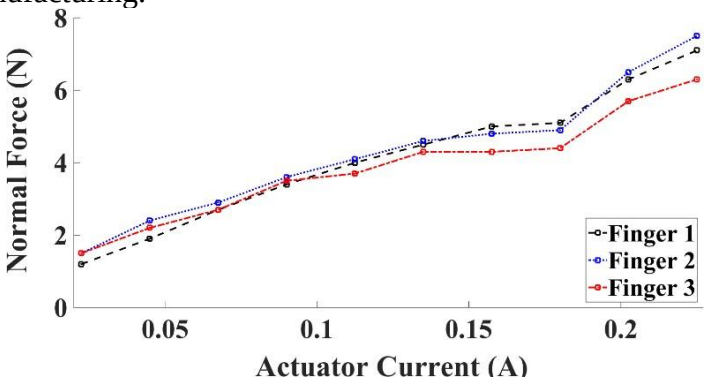


Fig. 8 Plot of normal force versus actuator load [3]

4. Conclusion

This paper presents the design of a prototype actuator for a robot that can pick up products from fruit trees. The innovative design of the multi-link spatial three-claw mechanism enables the action to pull back and support two movements driven by an active piston, thus reducing the number of main movement mechanisms. An underactuated design with flexible joints and flexible compliance is used to improve the position pallet's robustness. Positional pallets severely hampered previous fruit yield pallet operators. This achieves shape-sensing device stretching and contact force through open-loop control, constituting the optimal hand stretching mode. Additionally, this design is relatively lightweight, low-cost, and straightforward.

Future research will address the robustness of the end effector for the position slider. A separate system will be used to measure the fixture during workpiece positioning. Focus on the ability of the end effector to maintain instantaneous grip despite interference from external signals representing the strength of the valve stem rotation. Preliminary results show that when the termination actuator is subjected to a pulling force of more than 35 N along the normal axis of the device, it can continue to capture images. Field trials have been arranged for apple orchard production. These comprehensive

tests will use quantitative performance measurements to evaluate the ability of machine vision systems, robotic arms, and inertial actuators to harvest apples at the fresh market successfully.

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