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An end-effector for robotic cotton harvesting

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ABSTRACT

Cotton, a major crop worldwide, is harvested in mechanized production systems once at the end of the growing season. To facilitate harvest and maximize fiber quality, the plants are typically defoliated when about 60% of the cotton bolls are open. Due to non-uniform maturation, the bolls that have opened early expose their fiber to weather until harvest, commonly for weeks, degrading fiber quality. Furthermore, high capacity harvesting machines are heavy, potentially compacting the soil that in turn reduces hydraulic conductivity in the wheel tracks and reducing yield. Robotic harvesting with smaller machines brings about the possibility of multiple harvests during the growing season while enabling them to pick the seed cotton soon after the boll opens, preserving fiber quality. Smaller machines would also be less likely to substantially compact the soil. Therefore, research has been conducted to enumerate and address multiple challenges associated with the design of a robotic cotton harvester. The particular focus of the research reported herein was on the design of a robotic end-effector for picking seed cotton from the open boll of a non-defoliated cotton plant. Various design concepts were considered, and some were built as prototypes and experimentally assessed. The design was selected as optimal was: a three-finger, moving pinned belt, underactuated end-effector. A refined prototype of the end-effector was indoor tested on a robotic platform with a computer-controlled three-degree-of-freedom manipulator. The end-effector could pick 66-85% of the seed cotton from a boll with a picking time of 4 s for a simple and less efficient system to 18 s for a controlled-movement and more efficient system. Further implications of this study will include adding a depth sensor on the robot to detect and localize cotton bolls and manipulate arm autonomously.

1. Introduction

As U.S. revenue stimulated by cotton revenue is greater than $120 billion annually, cotton is economically important to U.S. agriculture [1]. About 99% of cotton grown in the U.S. is harvested with large, heavy mechanical harvesters [2]. The fact that cotton bolls open at different times throughout the growing season adds some harvesting complexities. When about 60% of the bolls are open, farmers typically defoliate the cotton plants by applying defoliants, making cotton plants amenable to efficient picking [3]. Harvesting is usually done 10 to 14 days after defoliation [4]. Although conventional cotton harvesters are very effective and efficient, this once-over operation with large machines has significant drawbacks. Harvesting a field is done in one pass, so the fiber in cotton bolls that open early in the growing season can be exposed to the weather for up to 50 days, leading to significant reductions in fiber quality [5]. The machines themselves are very heavy. For instance, a 6-row John Deere round module cotton harvester weighs 30 t [7]. Such heavy machines can compact the soil in the wheel tracks, leading to reduced soil hydraulic conductivity and yield in those areas [6]. Moreover, high costs require a minimum of 600 to 800 ha of cotton available for harvest to justify the investment in a single machine [5].

Recently, agricultural robotics has been receiving considerable attention in crop production (e.g., weeding and harvesting) [7]. Over the past four decades, significant research has been conducted on developing harvesting robots as an alternative to manual and mechanical harvestings, with most of the focus on specialty crops (e.g., fruits, vegetables) [8–13]. Although a robotic cotton harvester may not be as fast as current large mechanical harvesters, it could be potentially advantageous in terms of lower equipment and maintenance costs, the capability of selective picking, flexible harvesting windows [5], etc. Such a robot could go to the field multiple times during a season and pick the seed cotton as soon as the cotton bolls open. In this case the lint quality would be higher, no chemical defoliation would be required, and yield losses caused by extended exposure to extreme weather could be reduced [5]. Furthermore, the soil would likely not be compacted by small robots, a swarm of which has the potential to replace a large conventional cotton harvester [14].

Abbreviations: FF, face to face; FS, face to side; Opt. Bl'c, optimization block; CAD, computer-aided design; Dfn, diameter of the tip of the finger; Dpn, pin diameter; Hpn, height of pin; NMW, no manipulation while picking; PMW, predefined manipulation while picking.

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Table 1
Comparison among three robotic cotton harvesters.

Harvesters	[19]	[20]	[21]
SUCCESS RATE	89% @lab 79% @field	Not reported	Not reported
DETECTION HARDWARE /METHOD	ZED camera / YOLOv3	No detection system	Stereo camera/ not reported
END-EFFECTOR	suction pipe with rotating gears	suction pipe	suction pipe with rotating gears
MANIPULATOR	3 DOF (2 linear actuator plus robot's movement)	No manipulator	3 DOF (2revoloute and 1 linear actuators)
CYCLE TIME (S/BOLL)	17 @lab 38 @field	Not reported	Not reported
END-EFFECTOR POWER CONSUMPTION	2.5 hp	Not reported	Not reported

A harvesting robot generally consists of a vision-based perception system performing object detection and localization and a manipulator that positions an end-effector which conducts the picking task. The end-effector, which is attached to the end of a manipulator (e.g., robotic arm), is used for detaching fruit (in this case the seed cotton in the boll) from plants and dropping it to a receiving device; it plays a crucial rule in harvesting effectiveness and efficiency. Various end-effector designs employ different mechanisms for grasping and other interactions including soft fingers, vacuum suction, oscillating saws, high electrical current, twisting fingers, rotating fingers, scissors, pruners, thermal knives, etc. [15–18]. Since each fruit type has specific physical and biological properties, most end-effectors for harvesting are custom-made [13]. However, some features must be kept in mind by all designers, such as adaptability, which can provide the flexibility of accommodating different fruit sizes and orientations.

No robotic cotton harvester has been commercialized to date [8], and related research literature is scant until recently, with most published articles concentrating on robot navigation and cotton boll detection. Fue et al. [19] designed a robotic cotton harvester with a prebuilt rover as the platform, in which a suction type end-effector was used with rotating gears at the tip to grasp the seed cotton. They obtained a picking success rate of 89% at a cycle of 17 s per boll in a simulated cotton field. The performance deteriorated to a success rate of 79% at 38 s per boll in an actual cotton field with defoliated plants. Maja et al. [20] used a Husky robot (ClearPath Robotics, Inc., Kitchener, Ontario, Canada) as the platform and concentrated on navigation. This robot did not have a boll detection system, and the end-effector was also the suction type, with a fixed nozzle without manipulation. A startup company in India, GRoboMac (http://www.grobomac.com/) [21], has been engaged in developing robotic harvesters for cotton and has developed an end-effector similar to that of Fue et al. [19]. Their robot has not yet extensively field tested. Overall, the research groups who have worked on robotic cotton harvesting have generally used vacuum power as a component of their end-effectors. Table 1 summarizes the major capabilities of the three above-mentioned robotic cotton harvesters.

1.1. Picking ratio

Seed cotton is different from other fruits in terms of physical properties. Other fruits commonly have one contiguous rigid component, so when the end-effector grips part of the fruit, it can control the entire fruit. On the other hand, mature cotton bolls have four to five "locks" of seed cotton [22], in each of which are multiple seeds with thousands of cotton fibers attached (Fig. 1). If an end-effector attempts to pick the seed cotton of one lock, the seed cotton in the other locks and even a part of the seed cotton on the targeted lock may be left unpicked. Therefore, in this study, the performance of a robotic cotton harvester is defined in terms of picking ratio on a weight basis, for an individual boll, as follows. The picking ratio of 30% was considered the minimum threshold for a design idea to be acceptable.

$$\text{Picking ratio} = \frac{picked\ seed\ cotton\ weight}{total\ seed\ cotton\ weight} \quad (1)$$

1.2. Transferring and doffing

Because seed cotton in a boll is not a contiguous rigid fruit, a functional end-effector must transfer picked seed cotton from the picking point to the collection point as the seed cotton deforms, without leaving any on the plant or allowing it to fall to the ground. At the end of the transfer process, the seed cotton must be removed from the end-effector and collected. The removal process is called doffing.

1.3. Easy penetration and exit

If a robotic harvester is working on undefoliated plants, leaves and branches will present obstacles to the end-effector as it attempts to access bolls on the interior of the plant. The end-effector must be able to move easily into and out of the plant's outer leaves and branches.

1.4. Targeting

Seed cotton in a boll is located inside locks (Fig. 1), and cotton bolls are located among plant foliage including leaves and stems. An end-effector with precise targeting capability would pick only the seed cotton in a boll and no other material (e.g., calyx, stems).

1.5. Boll orientation

An additional challenge to effective picking arises from the fact that cotton bolls on a plant commonly have varying orientations. Fig. 1 illustrates three possible orientations of a cotton boll on a plant with respect to an end-effector. The tip of the pencil represents the tip of an end-effector approaching the boll to pick the seed cotton. Case one (face to face) is the ideal situation, in which seed cotton can best be picked by the end effector, but a successful end-effector must be able to pick seed cotton at other orientations.

1.6. Loose and stretched out picking

Gripping a part of seed cotton in a boll may cause to stretch it out, allowing only a small portion to be picked, and leaving the rest unpicked while the gripped portion is stretched and pulled out of the boll. To meet the above-mentioned design requirements, a carefully designed end-effector must pick, transfer and doff continuously to pick a boll clean of seed cotton.

Additionally, low power consumption and hardware costs should be considered for practical application. End-effectors available on the market or described in the literature are not well suited for robotic cotton harvesting because they are not designed to address all the aforementioned challenges. Therefore, the overall objective of this research is to design and present a proof-of-concept evaluation of a novel end-effector for robotic cotton harvesting. Specific objectives are twofold:

1. To consider concepts and design, build and test preferred end-effector prototype for robotic cotton harvesting.
2. To test the prototype on a robotic platform to validate it against design requirements.

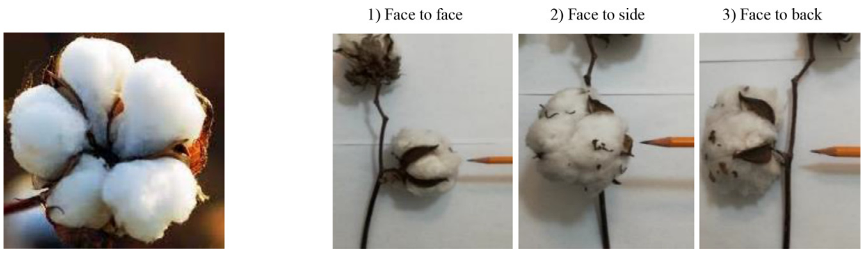


Fig. 1. Left: a cotton boll with 5 locks; Right: possible orientations of a cotton boll on a plant: 1) the end-effector targets the face of the boll, 2) the end-effector targets the side of the boll, 3) the end-effector targets the back of the boll.

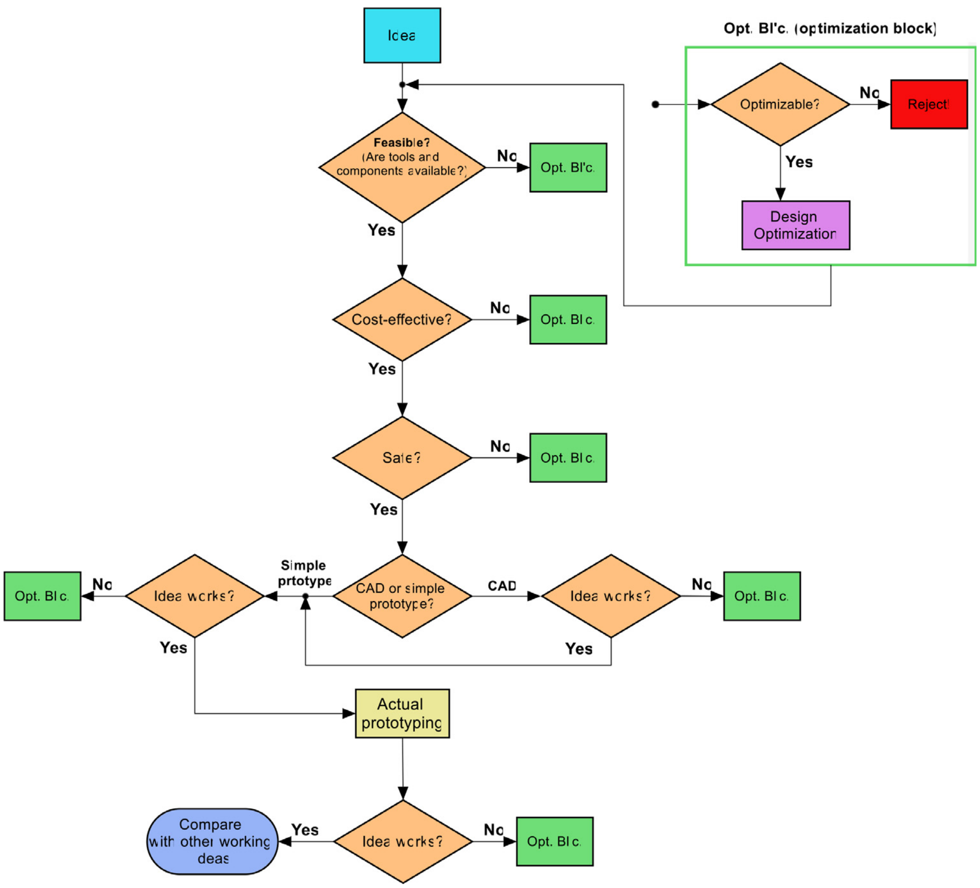


Fig. 2. The flowchart of ideas evaluation; Opt. Bl'c: optimization block.

2. End-effector design options considered

Multiple end-effector concepts were considered in this study. A flowchart in Fig. 2 was used to evaluate the prototypes. After evaluating the manufacturing process and estimating costs to make sure that an idea was feasible and cost-effective, the next step was to decide whether making a simple prototype or using computer-aided design (CAD) was better in terms of fabrication time and cost. In several cases it was decided to create a prototype of the idea. Rejection in any design step led to further optimizing a particular design, as shown in the optimization block in Fig. 2. Each prototype was evaluated in a preliminary experiment on 100 cotton bolls, and the picking ratio of 33% was assumed an acceptable minimum for a prototype to be considered potentially viable. Fig. 3 shows example images of the five primary end-effector prototypes, and Table 2 summarizes the test results.

2.1. Two-finger Gripper

It is a common practice to consider mimicking human hand actions when designing and developing end-effectors for robotic harvesting. Therefore, initial design emphasis was placed on finger-like gripping end-effectors. The first option considered was grasping, such as between a finger and an opposable thumb. To evaluate the concept, four layers of polyether ether ketone polymer were stacked to make a total thickness of 1.7 mm. The inner layer was covered with sandpaper to provide a jointed two-finger device with a high-friction surface, as shown in Fig. 3-A. This device could grasp the seed cotton but tended not to pick efficiently, grasping, and removing only a portion of the seed cotton in the boll (Table 2). Therefore, the next step was increasing the picking ratio, possibly by increasing the number of working fingers.

2.2. Eight-finger Gripper

Further investigation was conducted to consider a gripper with more than two fingers. Eight fingers were selected for expediency of assembly and keeping the number of fingers low enough so as not to cause difficulty in penetrating plant foliage. A prototype eight-finger gripper was constructed (Fig. 3-B), and it was expected to have a higher likelihood of grasping all the seed cotton in the boll. When picking, the gripper would expand and surround the cotton boll, then contract, and then it could be pulled backward to remove the seed cotton. Although this gripper tended to remove more of the seed cotton than the two-finger

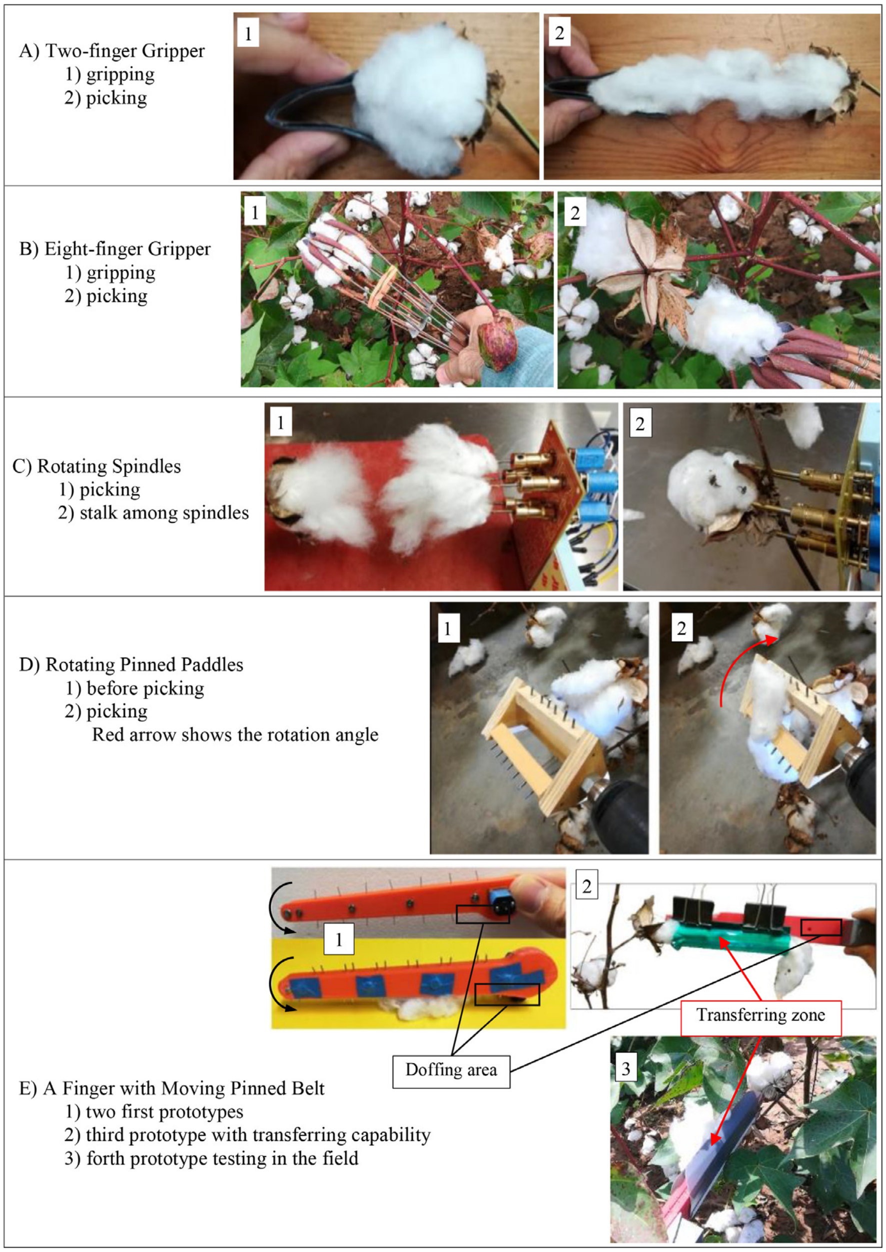


Fig. 3. Five primary end-effector prototypes.

Gripper (Table 2), it also tended to bend the associated branch and damage the boll – occasionally even plucking the entire boll – rather than simply removing the seed cotton from it. Even when only seed cotton was removed, the eight-finger design still did not remove all seed cotton from the boll. This gripper concept was also found to have difficulty in doffing (removing seed cotton from the end-effector). The main problem with this design was its tendency to bend the plant and pluck the entire boll, apparently because gripping power on the end-effector was not controlled once the fingers were in gripping position. Instead, after gripping, control was provided by a robotic arm as it pulled the entire end-effector back to pick the cotton. Based on this weakness, it was postulated that controlling fingers individually might improve the precision of the end-effector.

2.3. Rotating Spindles

One concept considered as a step toward powered fingers was a rotating mechanism such as multiple rotating spindles (Fig. 3-C). The spindle concept is currently employed in cotton harvesting machinery around the world. An end-effector based on this concept could work continuously and would be less likely to damage the cotton boll or stem. Hence, efforts were focused on prototyping and evaluation of the rotating-spindle end-effector concept. Rotating Spindles did not bend the stem or damage the boll (Table 2), but they also did not always remove all seed cotton from the boll, and doffing continued to be a challenge. This concept also had the occasional problem of removing a stem that would get stuck in the spindles (Fig. 3-C-2). A variant on the rotating spindles concept was that of rotating pinned paddles, which presented the possibility of more efficient removal of seed cotton because of deeper it engagement by the pins, and possibly also easier doffing.

2.4. Rotating Pinned Paddles

A rotating device consisting of paddles with pins protruding from them (Fig. 3-D) was designed and prototyped. Testing of the prototype showed that it did not ingest stems and get stuck like the spindle design occasionally did. However, picking ratio decreased substantially with

Table 2
Test results of five primary end-effector prototypes; Number of tested bolls and number of attempts were 100 and 1 respectively.

Considerations	Meaning	A) Two-finger Gripper		B) Eight-finger Gripper		C) Rotating Spindles		D) Rotating Pinned Paddles		E) One Finger with Moving Pinned Belt	
Picking ratio (%)	Refer to Eq (1).	22	✗	31	✓	57	✓	28	✗	39	✓
Transferring	a mechanism that transfers the picked seed cotton towards out of the end-effector	No transferring mechanism	✗	No transferring mechanism	✗	No transferring mechanism	✗	No transferring mechanism	✗	Had transferring mechanism	✓
Doffing	removing the seed cotton from the end-effector after transferring	No doffing mechanism	✗	No doffing mechanism	✗	No doffing mechanism	✗	No doffing mechanism	✗	Had doffing mechanism	✓
Penetration	penetrating through the plant without getting stuck	Not tested on actual plants	✗		✓	Branches went among the spindles and caused a problem	✗		✓		✓
Exit	The ability to come out of the plant without having got stuck	Not tested on actual plants	✗	It bent the whole branch while picking	✗	Got stuck when there was a branch among spindles	✗		✓		✓
Targeting	Grasping just the seed cotton instead of other material like leaves and calyx		✓	It grasped branches and calyx specialty when Face to Side	✗		✓		✓		✓
Boll orientation	The target bolls were at different orientations with respect to the end-effector		✓		✓		✓		✗		✓
loose and stretched out picking	The seed cotton got stretched out while picking and a part of it left on the plant		✗		✓		✗		✓		✓
Other issues	-	-		It plucked off cotton bolls in 27 tests	✗	-		Pushing the boll aside while rotation	✗	Seed cotton got stuck in transferring zone in 18 tests	✗
Outcomes	The results to be considered in the next design	increase number of fingers		Power gripping components		Do not rotate gripping components individually		Move gripping components linearly		increase number of fingers	

this design (Table 2). The pins, rotating in one direction, would sometimes push a cotton boll aside, making a part of it inaccessible to the end-effector and thus decreasing the picking ratio. The other problem was boll orientation. The end-effector could pick only with its side and not the tip. Therefore, it required Face to Side orientation (Fig. 1) to pick the boll. Doffing was also a problem. Test results with this prototype reinforced the idea of the need for an end-effector with precisely controlled fingers. A further step in that direction was to place linearly moving pins on a finger, which would likely not push a cotton boll aside, enabling picking bolls at various orientations, and also should enable easy transfer of picked seed cotton after picking.

2.5. A Finger with a Moving Pinned Belt

The concept of linearly moving pins rotating around a finger led to design and construction of multiple prototypes Fig. 3-E. The housing of the prototype finger was manufactured on a 3D printer, and the pins were attached to a belt driven with a 12V DC gear motor (Walfront, JGY-371, Shenzhen Guangdong, China). The end-effector was designed to transfer the picked seed cotton rearward and doff it. The plastic chute in Fig. 3-E-2 and 3 holds the seed cotton against the pins to help then transfer the seed cotton toward the doffing zone. During preliminary testing, this device performed picking, transferring, and doffing procedures continuously (Table 2). Compared to Rotating Pinned Paddles, the picking ratio increased because the end-effector could pick bolls both with its side and tip. However, the picked seed cotton occasionally got stuck in the middle of the transfer zone (Fig. 4). This design had two major issues that should be addressed: 1) low picking ratio, 2) transferring problems. Experimentation with a Two-finger Gripper suggested that increasing the number of fingers could lead to higher picking ratio.

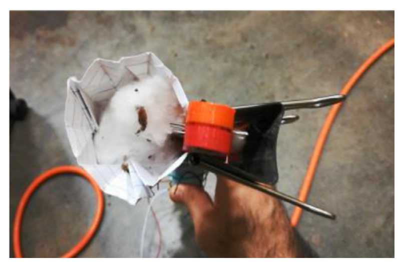


Fig. 4. The picked seed cotton got stuck while transferring to the doffing area.

If the extra fingers were properly arranged, the transferring issue could be solved as well.

3. Designing a Three-finger Moving Pinned Belt

As mentioned previously, increasing the number of fingers was expected to improve picking ratio and help solve the transferring problem experienced with the single-finger end-effector. Increasing the number of fingers increases the picking surface area of the end-effector. Also, each finger can grasp the seed cotton along one side and at the tip. Taken together, these features should lead to higher picking ratio. After picking a cotton boll, an end-effector must transfer the seed cotton toward the doffing point. In designing a picking device involving multiple fingers, the fingers must work synergistically to pull the cotton to a common point for removal from the picking unit. Otherwise, the fingers could pull the seed cotton in different directions, a situation that could force belts in the fingers to stop turning. In a three-finger configuration, the seed cotton can be held by the fingers in a roughly cylindrical configuration so that it can be transferred without becoming stuck among the

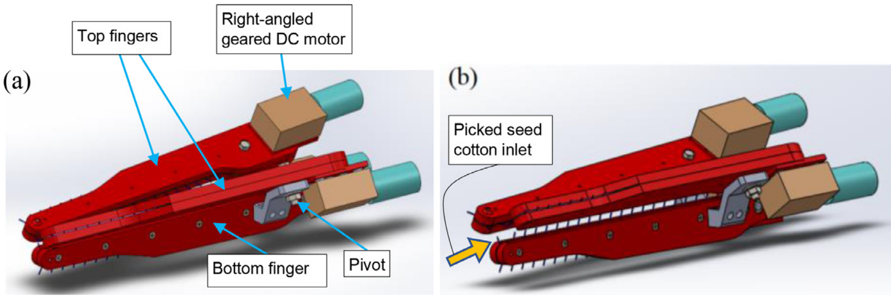


Fig. 5. CAD model of a three-finger moving pinned belt with expandable fingers; (a) fingers are contracted, (b) fingers are expanded.

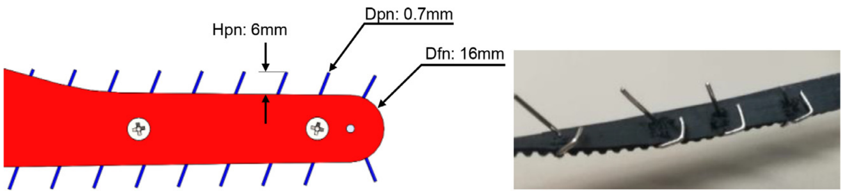


Fig. 6. Left: the sizes of the pin and tip of the finger, Right: attached pins to the timing belt.

fingers. The fingers can be arranged around a circle with 120 degrees of separation to provide the best transfer area and equal picking opportunity for all three fingers. For complete doffing by the end-effector, all fingers should doff the seed cotton at the same point. Otherwise, the seed cotton could become stuck among fingers, as occurred with the single-finger end-effector.

Increasing the number of fingers increases the overall surface area of the tip, potentially causing problems in penetrating plant foliage. Therefore, the tip of the end-effector should be designed to be as narrow as possible to enable better penetration. Fig. 5 is a schematic of a three-finger end-effector. The fingers are connected to a pivot joint that enables the device to be expandable at the picking end, allowing for variation in the thickness of the material being pulled through. During picking, the pins on the fingers are moving from outside to inside as they approach the tip, thus pulling picked seed cotton into the space among the fingers and toward the doffing point at the rear of the end-effector.

As mentioned previously, most crops have individual fruits that are a solid, rigid unit, such as an apple, that can be grasped and picked. Seed cotton in an open boll is in multiple locks of fibers connected to seeds and clinging together loosely. If the seed cotton is grasped at one point in the mass and pulled, the rest of the mass may be pulled with the grasped portion, stretched out, or remain in place in the open boll. Multiple fingers should also be helpful in grasping the seed cotton at multiple points, increasing the likelihood of complete removal from the boll.

3.1. Finger's tip and pins dimensions

Two critical parameters affecting the efficacy and efficiency of the end-effector are height of pin (Hpn) and diameter of the tip of the finger (Dfn) (Fig. 6). Keeping Dfn low helps the end-effector penetrate through plant foliage more easily. On the other hand, Hpn must be high enough to grasp the seed cotton well. Higher Hpn values require larger pin diameters (Dpn) so that the pins have strength to withstand the resistive forces of the grasped cotton. A GT2 timing belt (B & B Manufacturing, Inc., La Porte, IN) with a width of 6 mm was selected to mount the pins. Based on the belt selected, market availability, and method of attaching pins to the belt, steel wire pins with a diameter of 0.7 mm were selected.

3.2. Distance to target during expansion

Accounting for the distance between the tip of the end-effector and the outer surface of a target cotton boll (Fig. 7-top-left) is critical grasping efficacy. If the distance is too short the pins may grasp not only seed cotton but also the calyx (hard outer covering) of the cotton boll, and if the distance is too long the pins may not grasp an adequate amount of fiber to pull the entire mass of seed cotton from the boll.

Since the fingers are expandable, the distance from the target changes while the fingers move relative to one another. However, the design of the end-effector should be such that when the gap among the fingers is expanding, the distance to the target remains virtually unchanged to ensure consistent engagement with the cotton fiber. Fig. 7-bottom is a CAD drawing showing the end-effector from the top view. The orange dashed line shows the trajectory of the top finger's tip while the gap is expanding, and it is apparent that the top finger will get closer to the target. The vertical gray line is tangential to the surface of the target cotton boll. Δ is the amount of the top finger's advancement while the gap is expanding, and h is the gap expansion amount, which is less than 30 mm based on lab tests. As Δ increases, D (Fig. 7-top-left) also increases. To calculate Δ an isosceles triangle can be drawn (shown in pink color in Fig. 7-top-right). α is the angle between a side (h) and the base of the triangle. Therefore, the maximum Δ can be calculated as follows:

$$\mathrm{h}_{max} = 30\mathrm{mm} \rightarrow \; 0 \le \alpha \le 86^{\circ}$$
$$\mathrm{R} = 218.9\ \mathrm{mm}$$
$$\cos(\alpha) = \frac{\mathrm{h}}{2\mathrm{R}}$$
$$h = 2 \ast 218.9 \ast \cos(\alpha) \rightarrow h = 437.8\cos(\alpha) \tag{2}$$

$$\cos(\alpha) \approx \frac{\Delta}{h} = \frac{\Delta}{437.8 \ast \cos(\alpha)}$$
$$\Delta = 437.8cos^{2}(\alpha) \tag{3}$$

To calculate the maximum amount of Δ, the derivative of Eq. (3) must equal zero.

$$\frac{d\Delta}{d\alpha} = 2 \ast 437.8 \ast\ast \cos(\alpha) \ast \sin(\alpha) = 0 \tag{4}$$

$$\rightarrow \alpha = 90^{\circ}$$

$$Since\ \alpha_{max} = 86^{\circ},\ \Delta_{max}\ \text{reaches maximum amount when}\ \alpha = 86^{\circ}\ :$$

$$\Delta_{max} \approx 30\cos(86) = 2.09\ mm$$

According to the calculation, the top fingers get 2.09 mm closer to the target while the gap is expanding by 30 mm. This level of advancement is deemed insignificant in terms of its effect on picking ratio. Furthermore, lab experiments indicated that the expansion is usually less than 15 mm, and as a result, the advancement is typically less than 2 mm.

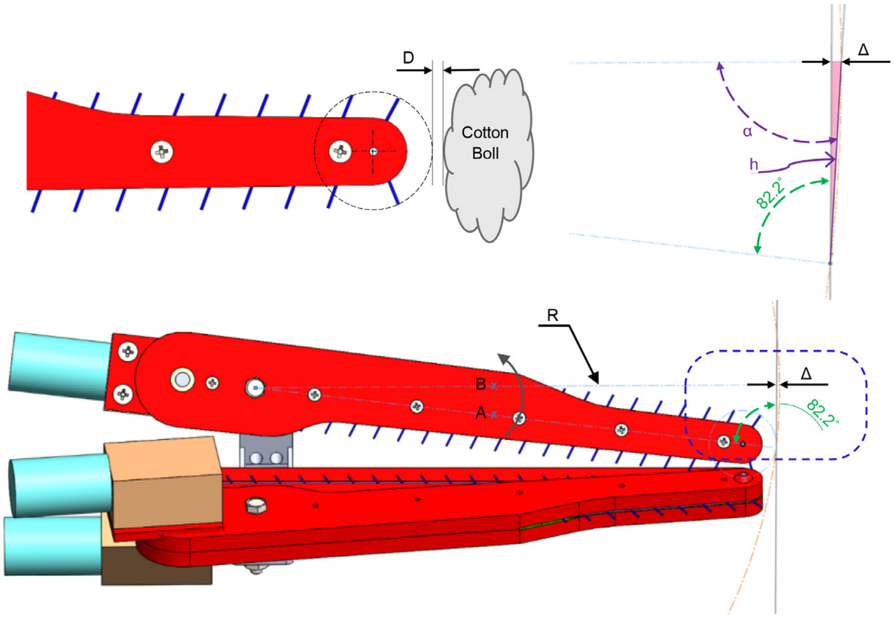


Fig. 7. Top-left: The distance between cotton boll and end-effector, Bottom-left: The three-finger end-effector from the top view, top finger's expansion effect on its distance from the target. Top- right: an enlargement of the blue dashed area on the bottom image.

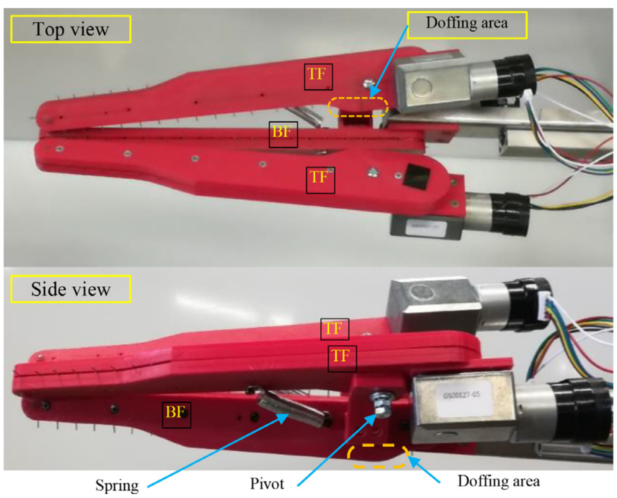


Fig. 8. The three-finger configuration of the end-effector, TF: top finger, BF: bottom finger.

Fig. 8 shows a fabricated three-finger end-effector. The housing is 3D printed, and the moving pinned belt is powered with a 12V DC gear motor (Walfront, JGY-371, Shenzhen, Guangdong, China). The bottom finger serves as a base that attaches to the manipulating arm, while the top fingers are attached to the bottom finger by a pivot joint. Two springs hold the fingers together, allowing the gap between the bottom and top fingers to expand as required for the current volume flow, but maintaining inward force to preserve contact with the seed cotton. While the distance between the fingers is expandable, the action of expansion is not controlled by an actuator, so the end-effector is considered underactuated, meaning the number of DOF is more than the number of actuators. A commercial example of an underactuated end-effector is Kinova Robotics' three-finger gripper [23], which has a gripper capable of picking different objects with various shapes and sizes. The top fingers of the robotic cotton end-effector are designed so as to doff the seed cotton sooner than the bottom finger. After doffing by the top fingers, the bottom finger continues transferring the picked seed cotton to the base of the end-effector and then doffs it there.

The belts on the fingers can run in either forward and reverse directions. Moving in reverse can help the end-effector penetrate easily through the plant by moving away leaves and branches while approaching the target boll. An elastic fabric was installed around the pin channel of each finger to help seal it and prevent cotton fiber and dust from coming inside the finger and causing problems inside the mechanism.

4. Test end-effector prototype

4.1. Robotic platform

The three-finger picking device was attached to a mobile platform (Fig. 9) for testing as a robotic cotton harvesting end-effector. The platform's autonomous positioning system included three linear actuators to provide motion with three DOF. A GPU-based computer (Jetson TX2, Nvidia Corp., Santa Clara, CA, USA) controlled the linear actuators as well as the end-effector and limit switches.

While most researchers have utilized 3 DOF manipulators for harvesting robots [13,15], a 2 DOF manipulator could be used, relying on vehicle motion as the 3rd DOF, but this configuration can be difficult to control precisely. A robotic arm with more than 3 DOF has better access to targets at different orientations and can avoid obstacles more easily, but more DOF leads to higher costs and lower manipulation speed [13,15]. Agrobot [24] and FFrobotics [25] are examples of commercialized robotic harvesters that utilize 3 DOF manipulators. In the research reported here, three linear actuators (igus Inc, East Providence, RI) were selected to provide a 3 DOF manipulator for the robotic platform (Fig. 9). Motion in the X and Z directions is driven by two NEMA 23 stepper motors (igus Inc, East Providence, RI and motion in the Y direction is driven by a NEMA 34 stepper motor (igus Inc, East Providence, RI) The length of motion in the X, Y, and Z directions is 60, 54, and 53 cm, respectively. The end-effector is attached to the Z-axis actuator. Limit switches (Shenzhen Longruner Digital co.Ltd, Shenzhen, Guangdong, China) were connected to both ends of each linear actuator to ensure they would not overextend.

Fig. 9 shows the platform with components attached. An aluminum frame was constructed as the chassis of the platform. Since the robot is stationary, and there was not a significant dynamic load on the platform during testing, the only structural-component property that was considered while designing the chassis was the cross-sectional moment of inertia. Extruded aluminum (Misumi, Schaumburg, IL) with a square cross-section of 50 × 50 mm^2 was used, and its cross-sectional moment of inertia was 38e+4 mm4, easily enough to bear the weight of the actuators and other components. Since this structure had four wheels to provide mobility, a ballast weight was attached opposite the actuators at the bottom of the chassis to bal-

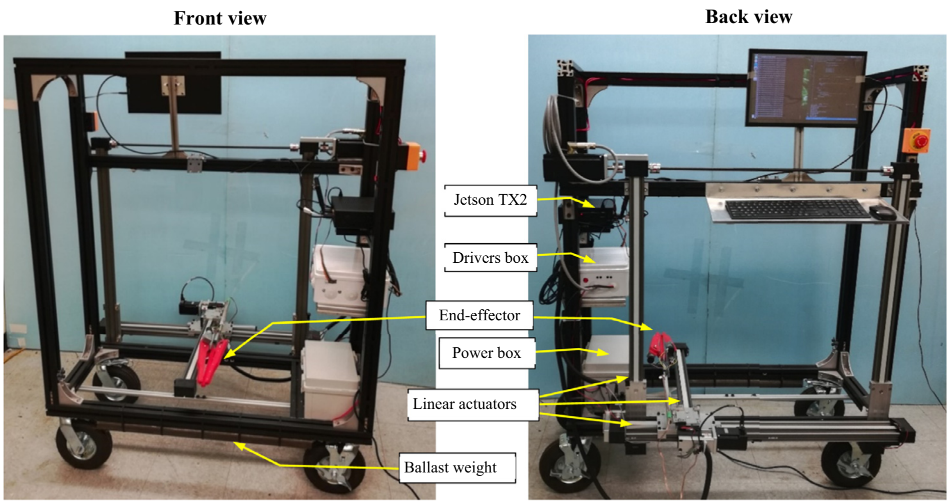


Fig. 9. The fabricated platform to test the end-effector of the robotic cotton harvester.

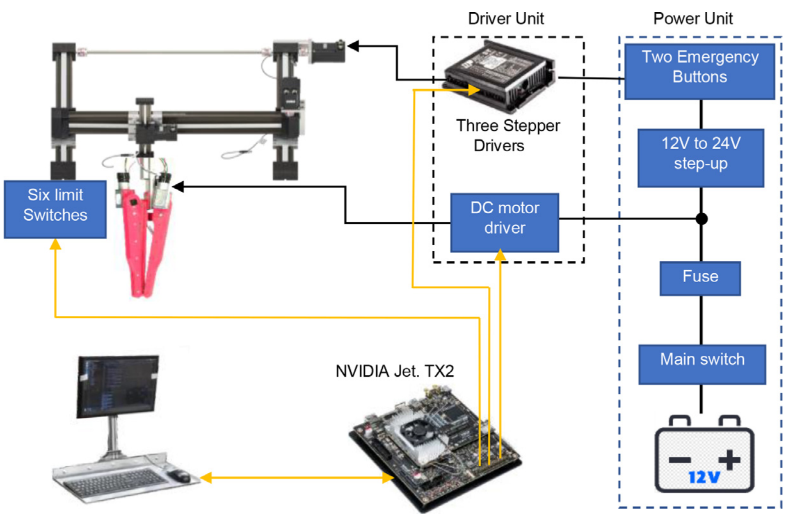


Fig. 10. The power and signal circuits of the robot.

ance the robotic platform and lower the center of gravity to increase stability.

Fig. 10 illustrates the control logic of the harvesting platform. The Jetson TX2 computer sends and receives signals through its GPIO pins to control the linear actuators and the end-effector (yellow lines in Fig. 10). Power was supplied to the system by a 12V battery (model and manufacturer info). A 12V-to-24V DC step-up converter was used to power the stepper motors (for what control). Two emergency buttons were installed to enable easy manual disconnection of the manipulator's power in case of an unsafe situation. The stepper motors were driven by three ST10-S micro-stepping drivers (Applied Motion Products, Inc., CA 95076, USA) that have advanced current control to save power while the actuators are in idle status. The end-effectors' three 12V DC motors were also controlled by a driver.

The manipulating arms were operated remotely through the keyboard on the robot computing device, but the action of the end-effector was autonomously controlled by the system.

4.2. Laboratory tests

Since the tests were done after harvest season, simulated cotton plants with real cotton bolls were used. The bolls were attached to a piece of wire that was connected to an aluminum bar (Fig. 11). Four treatments – two boll orientations relative to the end-effector tip, and two end-effector control algorithms – were considered, and 100 bolls were used for each treatment. Regarding boll orientation, Face to Face tests were conducted in which the end-effector's tip faced the cotton boll's face, and Face to Side tests were conducted in which the end-effector's tip faced the side of the cotton boll. Regarding end-effector control algorithms, No Manipulation While picking (NMW) tests involved the end-effector's approaching the cotton boll with manual control such that the end-effector's center touched the center of the boll. Then the end-effector worked for 4 seconds before being retracted. With Predefined Manipulation While picking (PMW), the robot first completed the NMW procedure, and then it moved the end-effector around the open surface of the cotton boll to cover a greater area in order to increase picking ratio [26]. Fig. 12 shows the working algorithm of the PMW tests.

After each test, the picked and unpicked seed cotton were weighed to the nearest mg. All picking attempts led to a completed test cotton unless the calyx was ingested during picking (Fig. 11-c). In such cases the end-effector was stopped manually, and that attempt was recorded as a failure. The picking time was measured with a stopwatch from the time the end-effector reached the boll until completing the picking procedure, retracting the Z-axis actuator, and stopping all motion.

5. Results

5.1. Design and fabrication

Incomplete picking, doffing, and transferring were the most common problems among several end-effector prototypes. The three-finger device with pins moving around the fingers overcame these problems and

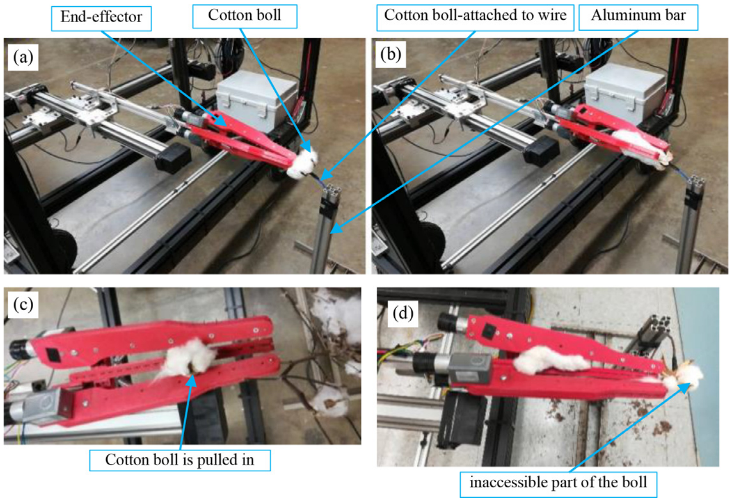
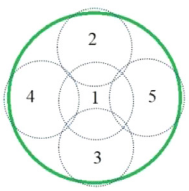


Fig. 11. The end-effector while lab tests, Face to Side situation; (a) seed cotton is unpicked, (b) seed cotton is being pic ked, (c) whole cotton boll is pulled in, (d) end-effector cannot get access to the rear part of the cotton boll in Face to Side situation.




```
manipulate the arm to the target boll
function PMW():
    pick point 1; run end-effector for 4 second
    retract the Z axis

    for points 2 to 5:
        go to the point
        pick point; run end-effector for 1 second
        retract the Z axis for 10 cm
        swallow; run the end-effector for 1 second
    end
```

Fig. 12. Left: cotton boll is divided into 5 parts. The end-effector targets point 1 and then it targets the rest of the points consecutively; Right: the pseudocode of multiple boll position (PMW) algorithm.

Table 3
Results of four test sets.

Test mode		# of bolls	# of calyx in failure	Picked bolls‡ (g)	Losses		Total weight (g)	Average weight of a boll (g)	Picking ratio (%)	Losses		Picking time (s)
					Left on boll (g)	Calyx in (g)				Left on boll (%)	Calyx ingestion failure (%)	
1	**FF*, NMW**	100	10	391.188	148.809	51.027	591.024	5.910	66.2	25.2	8.6	4
2	**FF, PMW**	100	11	507.710	35.965	55.156	598.832	5.988	84.8	6.0	9.2	18
3	**FS†, NMW**	100	23	286.200	170.406	130.589	587.195	5.872	48.7	29.0	22.2	4
4	**FS, PMW**	100	24	334.442	123.707	135.126	593.275	5.933	56.4	20.9	22.8	18

* FF refers to Face to Face orientation.
† FS refers to Face to Side orientation.
‡ Picked Bolls refers to picking without failure.

so was rigorously designed, constructed, refined, and tested. Although the fabrication procedure was time consuming, especially manually attaching the pins to the belt, it was not overly complex. Initial testing of the prototype showed that the end-effector's configuration enabled it to pick seed cotton at different boll orientations, and being underactuated helped it to adapt to different seed cotton thicknesses. Providing power to each finger independently enabled each finger to pivot independently, mitigating any difficulty in transmitting power to the other fingers.

5.2. Testing

Testing of the end-effector showed that it can pick seed cotton with reasonably high picking ratio, depending on the method in which it is controlled. Table 3 summarizes the test results across the four treatments, which included two boll orientations and two end-effector control methods.

Comparing corresponding boll orientation treatments – 1 with 3 and 2 with 4 – picking ratio is clearly higher when boll orientation is Face to Face (FF). The difference is 17.5% higher with NMW control and 28.4% higher with PMW control. As expected, FF provides much better access to the seed cotton in the boll and leads to much higher picking ratio.

Comparing corresponding control algorithm treatments – 1 with 2 and 3 with 4 – suggests that regardless of orientation, moving the end-effector up and down and side-to-side while picking increased its picking ratio, but it also required more time, roughly 3 times as long. Manipulation reduced the amount of unpicked seed cotton in both the FF (19.2%) and Face to Side (FS) (8.2%) situations. Manipulation in FS orientation resulted in a lesser reduction, because the end-effector's access to the rear part of the boll was not improved by the control system's manipulation, as it moved only left, right, up, and down (Fig. 11-d).

With the FS orientation, the end-effector is more likely to ingest the calyx because the calyx is more accessible in this situation. Treatments 1 and 2 had far fewer Calyx In failures than treatments 3 and 4.

Furthermore, manipulation didn't lead to significantly more Calyx In failures. Fig. 12 shows that, after working at the center of the boll for 4.0 s, the end-effector is worked at points 2 through 5 for 1.0 s each, giving a very short time for boll material to be pulled in. As soon as the end-effector grabs the boll and tries to pull it in, the robot stops the end-effector, retracts it, and moves it to the next point.

Regardless of whether the manipulator is in NMW or PMW control mode, Calyx In failure in the FS orientation was more than twice that in FF, because the end-effector has more contact with the calyx in the FS orientation.

Calyx In failure causes 9 to 23% loss. A simple remedy to reduce it is to move the end-effector back and forth while picking so as not allow time for calyx to be ingested. The fact that PMW control mode did not increase Calyx In failures significantly suggests that the first part of the algorithm (Fig. 12) that runs the end-effector for 4.0 s could be divided to multiple sections such that instead of working for a long time, the end-effector could work at multiple short sessions. For instance, the end-effector could work for 1.0 s, then stop, then be pulled back and push forward and work again for another 1.0 s. This procedure can lead to fewer Calyx In failures but would sacrifice time to move the end-effector back and forth.

5.3. Discussion and Future Research

A trained laborer can pick about 300 lb of seed cotton in an 8-h workday (E. Barnes, personal communication, Jan. 20, 2022). An average cotton boll contains 4.5 grams of seed cotton [27], so such a laborer can pick over 30,000 boll/d, or just over 1.0 boll/s. This cycle time includes arm manipulation, picking and moving from one plant to another. Ideally, a small robotic cotton harvester could at least mimic human performance by picking 1.0 boll/s.

For the end-effector developed in this study to be practically useful, it must be able to harvest a boll of seed cotton much more quickly than it did during lab tests, in which the end-effector and manipulator were operated at low speeds to allow careful monitoring of the robot and to prevent potential damage. Because the PMW control-mode tests involved more operational steps than the NMW tests, low operational speed compounded the lengthy picking time.

A major consideration for practical work in a cotton field is selective harvesting, in which machine vision (MV) will be needed to guide an end-effector. Each time the end-effector picks and is retracted, an MV system could collect and process images of the cotton bolls of interest and guide the end-effector to the exact point where unpicked seed cotton remains so it can pick as much seed cotton as possible. In this case the picking ratio could be increased. However, it could increase the picking time. The time required for image processing would need to be minimized to maximize harvesting speed. Image processing speed could potentially be enhanced by using an optimized image processing pipeline (e.g., with the aid of OpenCV library) on GPU-accelerated computing hardware.

Another major consideration for work in a cotton field is the end-effector's energy requirement. A vacuum-type end-effector requires at least 1 kW power to pick seed cotton [28]. Based on the voltage and current used by the motors during operation, the three-finger moving pinned belt end-effector requires only about 12 W. On the other hand, a vacuum-type end-effector can move the seed cotton to a remote storage tank in addition to picking it. Therefore, to make a sensible comparison between the vacuum-type end-effector and the end-effector introduced here, the required power to convey the picked seed cotton from the end-effector to the tank must be considered as well. If a mechanical conveying system were designed to work in conjunction with this mechanical end-effector, its required power would likely be much lower than that of a vacuum type. Accordingly, the overall power required for a mechanical end-effector with a mechanical conveying mechanism should be significantly less than for a vacuum-type end-effector with pneumatic conveyance.

Follow-on research issues that have been identified are as follows:

- As mentioned previously, adding a camera could help the robot pick seed cotton more precisely and in a shorter time. Having an "eye-in-hand" camera could give a better view of a target cotton boll, but using this camera configuration by itself in a bushy cotton plant might be problematic, because if a stereo camera is used its added volume would make the end-effector larger. Using a small camera and a distance sensor could be a good alternative to a stereo camera.
- When the end-effector ingests hard material like calyx, the pins around the finger can bend. Some optimization of the end-effector design may resolve this issue.
- Adding a sensor to the end-effector capable of detecting calyx could prevent ingestion.
- The PMW control method has higher picking ratio but longer picking time, which could be decreased by increasing actuator and computing speeds.
- The weather during harvesting can be very hot or very cold, and field conditions can be wet and dusty. Various parts of the robot must be made of appropriate materials to resist harsh weather and field conditions.
- The fingers' housings were 3D printed with polylactic acid filament. This material should likely be replaced to deal with issues such as temperature variation and exposure to severe sunlight.
- The pins are made of steel and they were rigid enough to perform primary tests. However, they must be designed stronger in future versions of the end-effector to handle the collisions with plants in real-world field conditions.

6. Conclusion

This article has reported on research, design, testing and evaluation of a novel robotic end-effector for cotton harvesting. Various end-effector concepts for robotic cotton harvesting were considered, and a three-finger, moving pinned belt, configuration was selected, designed, and developed. The end-effector prototype meets the design requirements which were picking ratio, transferrin, doffing, penetration and exit, targeting, picking at different orientations, and clean and complete picking. Its picking ratio was improved with a control algorithm that moved the end-effector around the boll to engage all the seed cotton in the boll. Picking failures, which involved ingesting the calyx of the boll, were more common when boll orientation was sideways to the end-effector. The picking time for picking seed cotton from a boll was longer when the control algorithm was used, but future refinement and optimization can minimize the time requirement.

Authors contributions

Conceptualization, H.G. and J.T .; methodology, H.G. and J.T .; formal analysis, H.G.; software, H.G.; writing— original draft preparation, H.G. and J.T.; writing—review and editing, H.G., J.T ., and Y.L.; supervision, J.T.; project administration, J.T. All authors have read and agreed to the published version of the manuscript.

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Declaration of Competing Interest

The authors declare no conflict of interest.

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