Structural design and analysis of an automatic pineapple picking and collecting straddle machine

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Abstract. To maximize economic returns and reduce damages to the fruit and plant, an automatic straddle harvester for pineapples was designed, based on the planting mode and growth characteristics of the pineapple. The machine is composed of a picking manipulator, fruit transport and collection device, continuous track, and control system. The physical characteristics of pineapple fruits were investigated, and the overall structure and size of the automatic pineapple picking and collecting machine were designed based on the growth characteristics and the planting mode of the pineapple plant. SolidWorks was used for virtual modeling and then the different parts were designed based on parameters, such as the dimensions and power of the track chassis. Simulation analysis on the frame base and manipulator revealed that with a cutting sawtooth speed of 1200 r/min the cutting efficiency of the pineapple picking manipulator can reach 1636 plants/hour, i.e., double the manual cutting efficiency.

1. Introduction

The pineapple fruit is not only outstanding in taste but also rich in various vitamins and nutrients that can help digestion and improve human health. Moreover, the fiber in pineapple leaves has great potential as a material for textiles, paper, and special composite materials [1-7].

China is the world's largest producer and consumer of fruit. From 2007 to 2017, its annual fruit output has been increasing year by year. In 2017, China's fruit output exceeded 250 million tons. In recent years, crop picking efficiency has been the focus of research and with the continuous development of agricultural mechanization, automatic harvesters and robots have become a viable solution for improving crop harvest yields. In Japan, Konodo et al. [8] utilized a visual guidance algorithm for a picking robot, which updated the position of the next target fruit according to the acquired image and then harvested it. Hayashi et al. [9] developed a strawberry harvesting robot that is composed of a cylindrical manipulator, end-effector, machine vision unit, storage unit, and walking unit. This harvesting robot was used for strawberries grown by elevated matrix cultivation. Yamamoto et al. [10] developed a fixed strawberry harvesting robot combined with a mobile workbench system. Using the growth characteristics of fruits, Haifeng et al. [11] designed a picking...
manipulator that first grasps the fruit in the horizontal direction and then rotates the harvest in the vertical direction. Xia et al. [12] determined the physical size and mechanical properties of Balinese pineapple samples and designed the pineapple end actuator according to the transverse diameter of the pineapple. Li et al. [13] introduced a new recognition algorithm based on the fact that the pineapple fruit is usually located at the top of the plant, which is covered with dense young leaves. Their image processing algorithm identified the crown buds of the pineapple for positioning. Du et al [14] designed a pineapple picking end-effector according to the physical characteristics of the pineapple, such as static friction and compression characteristics. The fingers of the end-effector move step by step to capture the pineapple and reduce damage to the fruits and plants during picking. Zhang et al. [15] designed a semi-automatic pineapple picking machine which is composed of a picking system, lifting system, pineapple conveyor, pineapple collecting system, and a pineapple moving system. Operating this machine was very easy and produced little harm to the pineapple.

To efficiently harvest pineapples with no damages to the fruit and the plant, this paper proposes a continuous picking and collecting machine based on the physical characteristics of the pineapple. First, the machine was designed as a whole, and then SolidWorks simulation software was used for modeling and simulation analysis. The design and analysis of the electronic and control system of the machine were carried out based on the results of the modeling. Finally, a prototype was built and an experimental cutting test of the pineapple stalk and a collection test of the pineapple fruit were carried out to determine the efficiency of the machine.

2. Cultivation and physical characteristics of pineapples

Pineapple has a high planting density and reasonably close planting is helpful for increasing the pineapple yield [16]. Pineapple plants generally grow up to less than one meter in height with a crown width of about 140 cm.

The fruit of the pineapple is oval in shape, with a longitudinal diameter of 18–27 cm and a transverse diameter of 16–23 cm. The average fruit weight is approximately 1 kg. To optimize the design and dimensions of the picking and collecting mechanisms, 10 pineapples were randomly selected for measurement. The measurement results are shown in Table 1.

| Pineapple serial number | transverse diameter | vertical diameter | quality |
|-------------------------|---------------------|-------------------|---------|
| 1                       | 18.9cm              | 22.3cm            | 1.25kg  |
| 2                       | 16.8cm              | 20.2cm            | 1.18kg  |
| 3                       | 18.2cm              | 23.1cm            | 1.26kg  |
| 4                       | 19.2cm              | 22.9cm            | 1.36kg  |
| 5                       | 23.8cm              | 26.2cm            | 1.52kg  |
| 6                       | 16.2cm              | 20.3cm            | 1.20kg  |
| 7                       | 22.7cm              | 25.6cm            | 1.47kg  |
| 8                       | 19.7cm              | 24.3cm            | 1.29kg  |
| 9                       | 21.4cm              | 26.2cm            | 1.35kg  |
| 10                      | 21.9cm              | 26.8cm            | 1.38kg  |

3. Overall structure and working principle of the pineapple and collecting machine

3.1. Overall structure
The automatic pineapple picking machine is shown in Figure 1 and is comprised of picking arms, collection mechanism, continuous track (caterpillar track or running gear), and an electronic control system.

![Figure 1. The pineapple picker showing the main components(a) Continuous track; b) Collection Mechanism; c) Electronic control system; d) Picking arms.](image)

### 3.2. Working principle and process

The operating process of the picker is as follows: (1) the operator sends instructions to control the movement of the picker through a remote-control terminal and a camera captures the position of the pineapple. (2) The distance between the picker and the pineapple is determined by two infrared sensors. The four-degree-of-freedom mechanical arm moves the picking and cutting mechanism to the vicinity of the fruit following a specific movement, and Sensor 1, which is located above the picking manipulator, detects whether it is directly above the fruit. (3) When the picker and cutting mechanism are directly above the fruit, the mechanical arm moves downward until the pineapple fruit is within the clamping range. Once the pineapple fruit is clamped as indicated by sensors the stalk is cut by the sawtooth at the bottom of the clamp. (4) After the cutting is completed, the mechanical arm places the pineapple fruit on the front of Transport Belt 1 following a specific motion. The fruit is then carried to the collection box by the transport belt. A lifting screw moves the bottom of the collection box. Sensor 2 on the edge of the collection box detects if the pineapples in the collection box are at the same level as the top of the box. When this happens the control system sends instructions to the four lifting screws to move synchronously to lower the bottom of the box and increase the volume of the collection box. At the same time, the entire machine continues to move forward and locate the exact position of the next pineapple before repeating the above steps to pick, carry, and collect pineapples in a continuous operation.

### 4. Design of main parts

#### 4.1. Design and analysis of the picking and cutting

**4.1.1. Overall design of the picking and cutting mechanism.** The overall four-dimensional model of the picking and cutting mechanism is shown in Figure 2. In the initial state, the jig is in the open state. First, it is driven and positioned above the pineapple fruit by a mechanical arm with three degrees of freedom. The telescopic rods on both sides of the picking and cutting mechanism are controlled by a single-chip microcomputer, so as to realize the clamping of a pineapple. With the
clamping device holding the fruit, the motor-driven sawtooth cutting mechanism fixed at the bottom of the clamping device cuts the fruit handle to complete the picking process.

![Figure 2](image)

**Figure 2.** The picking and cutting mechanism of the pineapple picking machine(a) Clamp; b) Pull rod; c) Fixed support; d) Linear actuator; e) Sensor 1; f) Sawtooth cutting mechanism.

4.1.2. Clamping parameters of the picking and cutting mechanism. The jig of the picking and cutting mechanism has two circular and arc slots, and a plurality of circular gaps are set outside the slots. Through the motion of the electric push rod on both sides, the clamping device can be opened and closed. The motion diagram of the mechanism is shown in Figure 3.

![Figure 3](image)

**Figure 3.** Motion diagram of the picking and cutting mechanism.

In the figure, $A$ is the tie bar intersection point, $B$ is the clamp fixture fixed point, $C$ is the central marginal point of the fruit, $D$ is the center of the fruit, $L_{AD}$ is the distance from the rod intersection point to the fruit center point (cm), $L_{AC}$ is the distance from the rod intersection point to the fruit edge point (cm), $L_{DC}$ is the distance from the center to the edge of the fruit (cm), $L_{BC}$ is the distance from the fixed point of the clamp to the edge point of the fruit (cm), $L_{AB}$ is the distance from the tie bar intersection point to the clamp fixture fixed point (cm), $\beta$ is the angle between AC and DC, and $\gamma$ is the angle between AB and DB.

To obtain reasonable design embrace parameters, the parts need to be calculated, first for $\triangle ACD$ by the Pythagorean theorem:

$$L_{AD}^2 + L_{DC}^2 = L_{AC}^2 \quad (1)$$

$$L_{AC} = L_{DC}/\cos \beta \quad (2)$$

$$L_{AD} = L_{DC} \times \tan \beta \quad (3)$$

The law of cosines can be used for $\triangle ABC$:
\[ L_{AB}^2 + L_{BC}^2 - 2 \times L_{AB} \times L_{BC} \cos \gamma = L_{AC}^2 \]  \hspace{1cm} (4)

The pineapple fruit ideally has an oval shape. According to the data in Table 1, \( L_{AD} > 13 \) cm, 9 cm < \( L_{DC} < 12 \) cm, and \( L_{AD} = 20 \) cm.

The angle between AC and DC can be obtained from (3):

\[ \beta = \arctan \frac{L_{AD}}{L_{DC}} \]  \hspace{1cm} (5)

From the numerical calculation \( 59.03^\circ \leq \beta \leq 65.77^\circ \), and then substituting the values of \( \beta \) into (2), and the following are obtained:

\[ L_{AC\text{max}} = \frac{L_{DC}}{\cos \beta} \]

\[ L_{AC\text{max}} = 12/\cos 65.77^\circ \approx 29.24 \text{ cm} \]

\[ L_{AC\text{min}} = \frac{L_{DC}}{\cos \beta} \]

\[ L_{AC\text{min}} = 9/\cos 59.03^\circ \approx 17.49 \text{ cm} \]

Where, \( L_{AC\text{max}} \) is the maximum distance (cm) from Point A to Point C and \( L_{AC\text{min}} \) is the minimum distance (cm) from Point A to Point C.

For the design of the picking and cutting structure, \( L_{AB} = 3L_{BC} \) and \( 60^\circ \leq \gamma \leq 90^\circ \). Using (4),

\[ L_{AC} = \sqrt{L_{BC}^2 \times (10 - 6 \cos \gamma)} \]  \hspace{1cm} That is, \( 7.49 \leq \sqrt{L_{BC}^2 \times (10 - 6 \cos \gamma)} \leq 29.24 \). Therefore, \( 2.65 \text{ cm} \leq L_{BC} \leq 14.62 \text{ cm} \).

According to the above results, \( L_{AD} = 20 \text{ cm} \), \( L_{BC} = 5 \text{ cm} \), and \( \gamma = 60^\circ \). These dimensions will ensure the proper operation of the clamping mechanism based on the size of the pineapple fruit.

4.2. Structural design and analysis of the continuous track mechanism

The machine track system, as shown in Figure 4, includes two caterpillar tracks and a frame assembly.

\[ \text{Figure 4. The continuous track system of the machine(a)Caterpillar mechanism; b) The frame assembly.} \]  

4.2.1. The overall design and analysis of the track system. For the common two-row cropping pattern of pineapples, to ensure that the pineapple plants and immature fruits are not damaged and that a double-row of pineapples can be picked, the bicycle-straddle traveling mechanism was selected and designed. The two tracks move in the large gaps between the two rows of pineapples. The frame is connected to the caterpillar brackets. The frame is located above the two rows of pineapples, increasing the ground clearance and improving the mobility of the machine across the field.

Due to the loose soil and complex terrain in the field, the crawler vehicle design allows the tracks to have larger grounding area, smaller grounding specific pressure, and better adhesion performance. The crawler mechanism consists of a driving wheel, a guide wheel, a crawler, a supporting wheel, and a sprocket wheel.
Considering that the frame is the mounting base of the collecting and picking devices, it is required that the frame has a large carrying capacity and the bottom of the frame is welded to an arch pipe.

4.2.2. Specific dimension design and analysis of the crawler mechanism. The crawler pitch is an important parameter in crawler design and can be calculated by:

\[ P_b = (13.5 - 23) \sqrt[3]{G} \]  \hspace{1cm} (6)

where \( P_b \) is the crawler pitch (mm) and \( G \) is the mass of the machine (kg). Using the actual mass of the crawler machinery \( G = 625 \) kg, the resulting crawler pitch is 90 mm.

According to the actual design dimensions of the picking machine, the width of the track \( b \) is 350 mm, and the empirical ratio of the width of the track and the length of the track grounding is as follows:

\[ b/L = 0.18 - 0.22 \]  \hspace{1cm} (7)

where \( L \) is the grounding length. The design grounding length \( L \) is 1800 mm.

In order to ensure straight running and steering ability, the ratio of the grounding length to the track gauge is generally:

\[ L/B = 1.2 - 1.4 \]  \hspace{1cm} (8)

where \( B \) is the gauge between two tracks. The track gauge designed according to the designed track grounding length is 1500 mm.

The driving wheel diameter is determined according to the formula:

\[ D = \frac{P_b}{\sin \frac{180^\circ}{n}} \]  \hspace{1cm} (9)

where \( D \) is the driving wheel diameter and \( n \) is the number of teeth.

When \( n = 9 \), the diameter of the driving wheel is 263.14 mm. In general, the diameter of the guide wheel \( D_k \) is slightly smaller than that of the driving wheel \( D \) with the following ratio:

\[ \frac{D_k}{D} = 0.8 - 0.9 \]  \hspace{1cm} (10)

Then the guide wheel diameter is 236 mm.

When studying the stability of the crawler chassis and whether it can pass over the row of plants, the specific pressure of the crawler ground should also be considered. According to the literature, the average ground specific pressure can be obtained from:

\[ P = \frac{1000 \times 9.807M}{n \times W_4[L_2 + 0.35(L_6 - L_2)]} \]  \hspace{1cm} (11)

where \( P \) is the average ground specific pressure (kPa), \( M \) is the machine mass (kg), \( n \) is the number of tracks, \( W_4 \) is the width of track plate (mm), \( L_2 \) is the track grounding length (mm), and \( L_6 \) is the total length of track (mm). \( L_6 \) is determined by:

\[ L_6 = L_2 + 2d \]  \hspace{1cm} (12)

where \( d \) is the distance between the datum ground plane and the \( Z \) plane passing through the front and rear support wheel axes on the \( Z \) coordinate. The specific ground pressure is calculated to be 4.68 kPa.

The design of the support wheel should consider the distribution of the ground specific pressure. In order to make the ground specific pressure evenly distributed over a large area, the fruit picking machine design has 10 crawler support wheels distributed in two parallel rows. The diameter \( d \) of the support wheel can be obtained by the following formula:
\[ d = (1.5 - 3)P_b \]  

(13)

where \( P_b \) is the track pitch.

The diameter of the large supporting wheels connected to the independent suspension at both ends is 207 mm, and the diameter of the small supporting wheel connected to the linkage suspension is 135 mm.

According to the above calculation and analysis, the parameters of the crawler device are summarized in Table 2.

| Parameter Item                     | Determined Value |
|------------------------------------|------------------|
| Track grounding length             | 1800mm           |
| Track pitch                        | 90mm             |
| Number of drive gear teeth         | 9                |
| Drive wheel diameter               | 263.14mm         |
| Guide wheel diameter               | 236mm            |
| Large support wheel at both ends   | 207mm            |
| Small roller                       | 135mm            |
| Tug diameter                       | 200mm            |
| Number of large supporting wheels  | 2                |
| Number of small supporting wheels  | 8                |
| Number of tugboats                 | 4                |
| Caterpillar track                  | 1500mm           |

\* All parameters in the table refer to a unilateral track.

4.2.3. The power design of the track system. Considering the actual working environment of the picking machine, it is not necessary to have a high crawling speed and the crawler line speed is set to 0.5 m/s. According to the relationship between track speed and line speed:

\[ v = \frac{\pi r n_d}{30i} \]  

(14)

where \( v \) is the track line speed (m \cdot s\(^{-1}\)), \( r \) is the radius of the driving wheel (m), \( n_d \) is the motor speed (r \cdot \text{min}\(^{-1}\)), and \( i \) is the total transmission ratio. This design is set to a total transmission ratio of 10 and the corresponding motor speed can be calculated as 182 r \cdot \text{min}\(^{-1}\).

The linear running resistance of the track can be calculated according to the following formula:

\[ F_s = \frac{mgf}{\eta} \]  

(15)

Where \( F_s \) is the linear running resistance of track (N), \( m \) is the full load mass (kg), \( \eta \) is the transmission efficiency and is set to \( \eta = 0.85 \), \( g \) is the acceleration due to gravity (9.8 m \cdot s\(^{-2}\)), and \( f \) is the rolling friction resistance coefficient of the track. Considering the actual working environment of the pineapple picking and collecting machine, the rolling resistance coefficient is set as 0.25. The calculated \( F_s \) is 2206 N, so the driving resistance of the unilateral track is 1103 N.

Theoretically, the driving force of a unilateral track is calculated as follows:
Where $F$ is the driving force of unilateral crawler (N), $i$ is the transmission ratio, $T_d$ is the output torque (N · m), and $r$ is the radius of the driving wheel (m). From $F = F_x$, the calculated output torque $T_d$ is 29.02 N · m.

According to the relationship between traction and power:

$$P = \frac{F \times v}{\eta}$$

(17)

Where $P$ is the driving power (W), $F$ is the traction force (N), $v$ is the walking speed of the tracked chassis (m · s$^{-1}$), and $\eta$ is the transmission efficiency coefficient, which is 0.85. Therefore, the driving power is 648.82 W.

Considering the internal friction and power loss of the machine, in order to ensure sufficient driving capacity, two independently driven tracks are used. Each side is equipped with a servo motor with a rated power of 1.2 kw, rated speed of 3000 rpm, and rated torque of 4 N · m.

### 4.2.4. Finite Element Analysis of the Frame

TB6 titanium alloy (Ti-10V-2Fe-3Al) was selected in order to reduce the overall weight of the picking machine and improve its bearing capacity. See Table 3 for the specific parameters.

| property               | numerical value | unit         |
|------------------------|-----------------|--------------|
| elasticity modulus     | 110000          | N/mm$^2$     |
| The poisson's ratio    | 0.33            |              |
| Medium shear modulus   | 45600           | N/mm$^2$     |
| mass density           | 4650            | kg/m$^3$     |
| tension strength       | 1160            | N/mm$^2$     |
| yield strength         | 1070            | N/mm$^2$     |

Using the finite element analysis methods for related mechanical designs and applications [17, 18], the SolidWorks Simulation module was used to carry out static stress analysis of the frame. Figures 5 and 6 shows the frame considering its own gravity, at the same time, under the external load of 2000 N, the maximum stress of $2.038 \times 10^6$ N · m$^{-2}$ the maximum yield stress is far less than $1.07 \times 10^9$ N · m$^{-2}$, thus the design of the frame strength conforms to the actual requirements.

**Figure 5.** Stress nephogram of the frame.  
**Figure 6.** Frame strain diagram.
4.3. Design of the collection device

As shown in Figure 7, the collection device is comprised of two conveyor belts and a collection mechanism. One conveyor (Transport belt 1) is used for the process of moving the fruit from the picking device to the collection mechanism and the other conveyor (Transport belt 2) is used for the delivery of the pineapple collection box.

Picking collecting machine according to the actual length of batteries and other devices with placement location to determine the length of the conveyor belt 1 is 850 mm. In order to prevent the pineapple fruit from falling out of the conveyor belt after being released by the clamping mechanism, baffles are installed on the sides of Transport belt 1. In addition, Transport belt 1 is funnel-shaped with an angle of $\alpha = 3.5^\circ$. Transport belt 1 runs at $v = 0.4 \text{ m/s}$ and, assuming that the pineapple on the conveyor belt does not roll, can carry two pineapples with a total weight of 3 kg.

According to the relationship between the conveyor belt speed and power, the power of the drive motor is:

$$P = k_1 F_v \sin \alpha = 0.03 \times 30 \times 0.4 \times 0.061 \text{ kW} = 0.022 \text{ kW}$$

(18)

where $k_1$ is the friction factor between pineapple and conveyor belt. Considering the power loss of the conveyor belt, the total power of the drive motor for Transport belt 1 is 0.03 kW.

Because the pineapple collection box should be lifted by the action of the lifting screw, the initial position of the collection box is close to the center of the picking machine. A conveying track 2 with a length of 1180 mm is designed for transporting the collection box to the back of the picking machine. Therefore, the power required for transport belt 2 is:

$$P = k_2 F_v = 0.25 \times 500 \times 0.01 \text{ kW} = 1.25 \text{ kW}$$

(19)

Where, $k_2$ is the friction coefficient between the collection box and Transport belt 2. Considering the power loss of the conveyor belt, the total power of the drive motor for Transport belt 2 is 1.3 kW.

The collecting mechanism is comprised of a collecting frame and a lifting screw. In order to maximize the picking efficiency and avoid a high round-trip frequency of the picker in the field due to insufficient collection space, the size of the collection box (frame) as shown in Figure 8 is 500 mm x 500 mm x 500 mm. The bottom of the collection frame has a moveable bottom plate. The moveable bottom plate is initially located on the upper part of the collection box. The height of the barrier around the box is less than the width of a pineapple. When the pineapple rolls down from the Transport belt 1, the pineapple will not be damaged because the bottom of the box is not very deep and the pineapple will not fall out of the box because the box wall is sufficiently high. The removable bottom plate is placed on the lead screw. When the lead screw rises, the bottom plate...
can be lifted to rise with it. When the lead screw falls, the removable bottom plate will fall with the lead screw tightly under the action of gravity.

Figure 8. The fruit collection box (a) Box; b) Moveable bottom plate.

5. Control system design
Pineapple is planted artificially, and the growth direction and position are relatively regular. The picker, straddling on the plants, picks two rows of pineapples simultaneously. In order to effectively identify the pineapple fruit position through the camera in real-time detection, access to relevant information [19-23], and based on Visual c++ and OpenCV libraries as a development platform to write pineapple harvest collection machine image processing system, as shown in Figure 9.

Figure 9. Software interface for pineapple picking and collecting machine.

The software operation interface is mainly composed of 6 parts, which are as follows:
- Image block control area: mainly used for the display, background segmentation, and feature extraction of the acquired pineapple image.
- Image display area: the pineapple images collected by cameras on both sides are displayed. The image background segmentation and feature extraction patterns can also be displayed.
- Serial communication area: Indicates the data transmission between the machine and the software.
- Position coordinate display area: displays the central coordinate position after feature recognition.
- Machine control area: automatic control of the machine and one-step control of each part.
- Information acquisition area: displays machine parameter information.
When the operator needs pineapple picking image information, the "pause" button in the image control area can be used to acquire the current frame for subsequent research. The operation interface is shown in Figure 10.

![Image of the operation interface](image.png)

**Figure 10.** Video frame pause to acquire a single-frame image.

In the process of picking pineapples, it is necessary to extract features and classify the background of the collected pineapple information in order to control the machine. The obtained pineapple information can be segmented by clicking the background segmentation button.

### 6. Experimental prototype of the automatic pineapple picking and collecting mechanism

A prototype of the picking and cutting mechanism is shown in Figure 11. Considering the influence the rotation speed of the sawtooth on the cutting time of the fruit handle, a cutting test of the pineapple handle, and a picking test were carried out in a laboratory environment. The test data are shown in Table 4.

| The sawtooth speed | Clipping time | Cutting efficiency |
|-------------------|---------------|--------------------|
| 400 r/min         | --            | --                 |
| 600 r/min         | 3.1 s         | 1162 plant/hour    |
| 800 r/min         | 2.8 s         | 1286 plant/hour    |
| 1000 r/min        | 2.6 s         | 1385 plant/hour    |
| 1200 r/min        | 2.2 s         | 1636 plant/hour    |
| 1400 r/min        | 2.2 s         | 1636 plant/hour    |

The test experiments verified that the mechanism could complete the basic functions of picking and collecting pineapples. The stalk could not be cut off when the sawtooth rotation rate was below 400 r/min and the cutting time was reduced when the rotation rate was increased above 400 r/min. The cutting process was stable at a cutting time of 2.2 s.
7. Conclusion

Based on the analysis of several types of picking machines, the physical characteristics of the pineapple fruit, and the growth characteristics and planting pattern of pineapple plants, a next-generation pineapple picking and collecting machine was designed, which is composed of a picking manipulator, fruit transport and collecting devices, continuous track system, and control system.

Using motion diagram analysis, the picking and clamping mechanisms were designed based on the typical size of pineapples. Therefore, the pineapple fruit can be tightly gripped by the picking mechanism. At the same time, the parameters of the crawler mechanism and the power required for crawling were calculated, ensuring the good mobility of the picking machine when moving across the field. A collection frame which could be lifted vertically was designed, and the transport power was optimized to reduce fruit damage during the collection process. A reasonable chassis height and a manipulator picking from the top of the pineapple can ensure that the pineapple and the plant are not damaged during the picking process. The collection device was also designed to reduce secondary damage.

The SolidWorks Simulation module was used to analyze the static stress of the frame. With an external load of 2000 N, the maximum stress of the frame was $2.038 \times 10^{28} N \cdot m^2$, which was far less than the maximum yield stress of $1.07 \times 10^{29} N \cdot m^2$. The design strength of the frame meets the actual requirements in the field.

Modeling and simulation of the automatic picking mechanism followed by pineapple fruit stalk cutting and pineapple fruit collecting experiments verified that the machine can achieve continuous harvesting operation when the cutting sawtooth speed is above 400 r/min. The cutting efficiency is as high as 1636 plants/hour which is 2 times the manual cutting efficiency of a human picker. When the driving sprocket wheel speed is 30 r/min, collection efficiency of 195 plants/hour can be achieved. This study lays the foundation for further design optimization and promotion of mechanized and automated picking of pineapples.

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References

[1] Iewkittayakorn J, Khunthongkaew P, Wongnoipla Y, Kaewtatip K, Suybangdum P and Sopajarn A 2020 Biodegradable plates made of pineapple leaf pulp with biocoatings to improve water resistance J. Mater. Res. Technol. 9(3) 5056-66

[2] Devi L U, Bhagawan S S and Thomas S 1997 Mechanical properties of pineapple leaf fiber-reinforced polyester composites J. Appl. Polym. Sci. 64 1739-48

[3] Campos D A, Coscuetá E R, Vilas-Boas A A, Silva S, Teixeira J A, Pastrana L M and Pintado M M 2020 Impact of functional flours from pineapple by-products on human intestinal microbiota J. Funct. Foods 67

[4] Taussig S J and Batkin S 1988 Bromelain, the enzyme complex of pineapple (Ananas comosus) and its clinical application. An update J. Ethnopharmacol. 22 191-203

[5] Hossain M A and Rahman S M M 2011 Total phenolics, flavonoids and antioxidant activity of tropical fruit pineapple Food Res. Int. 44 672-6

[6] Mishra S, Mohanty A K, Drzal L T, Misra M and Hinrichsen G 2004 A Review on Pineapple Leaf Fibers, Sisal Fibers and Their Biocomposites Macromol. Mater. Eng. 289 955-74

[7] Ekanem U F, Umoren S A, Udousoro I I and Udoh A P 2010 Inhibition of mild steel corrosion in HCl using pineapple leaves (Ananas comosus L.) extract J. Mater. Sci. 45 5558-66

[8] Kondo N 1996 Visual Feedback Guided Robotic Cherry Tomato Harvesting Transactions of the Asae 39 2331-8

[9] Hayashi S, Shigematsu K, Kobayashi K, Yamamoto S, Kamata J, Kohno Y and Kurita M 2010 Evaluation of a strawberry-harvesting robot in a field test. Biosyst. Eng. 105 160-71

[10] Yamamoto S, Hayashi S, Yoshida H and Kobayashi K 2014 Development of a Stationary Robotic Strawberry Harvester with a Picking Mechanism that Approaches the Target Fruit from Below J.agr.-Jpn Agr. Res. Q 48 261-9

[11] Wang H F, Li B, Liu G Y and Xu L M 2012 Design and test of pineapple harvesting manipulator Transactions of the Chinese Society of Agricultural Engineering 28 42-46

[12] Xia H M, Li Q R and Zhen W B 2012 Design of a Pineapple Picking End-Actuator Appl. Mech. Mater. 1867 134-9

[13] Li B and Wang M 2013 In-Field Recognition and Navigation Path Extraction for Pineapple Harvesting Robots Intell. Autom. Soft Co. 19 99-107

[14] Du X, Yang X, Ji J, Jin X and Chen L 2019 Design and Test of a Pineapple Picking End-effector Appl. Eng. Agric. 35 1045-55

[15] Zhang L, Tang S, Li P, Cui S, Guo H and Wang F 2018 Structure Design of A Semi-Automatic Pineapple Picking Machine IOP conf. series. Mater. Sci. Eng. 452 42155-6

[16] Dass H C, Reddy B M C and Prakash G S 1978 Plant-spacing studies with “Kew” pineapple Sci. Hortic-Amsterdam 8 273-7

[17] Chen X, Wang D, Qiu Y, Wang J, Li Y and Li B 2018 Finite element analysis of cotton ginning state based on Ansys Text. Res. J. 89 2142-53

[18] Miklos I Z, Miklos C and Alic C I 2018 Finite element analysis of cylindrical gear with mechanical event simulation IOP conf. series. Mater. Sci. Eng. 393 12046

[19] Lv J D, Zhao D A, Ji W B and Ding S H 2016 Recognition of apple fruit in natural environment Optik 127 1354-62

[20] Ji W, Zhao D, Cheng F, Xu B, Zhang Y and Wang J 2012 Automatic recognition vision system guided for apple harvesting robot Comput. Electr. Eng. 38 1186-95

[21] Zhao J, Tow J and Katupitiya J 2005 On-tree fruit recognition using texture properties and color data IEEE Xplore pp 263-8
[22] Li B, Wang M and Wang N 2010 Development of a Real-Time Fruit Recognition System for Pineapple Harvesting Robots. In: 2010 Pittsburgh, Pennsylvania, June 20 - June 23, 2010, (St. Joseph, MI: ASABE)

[23] Zawbaa H M, Abbass M, Hazman M and Hassenian A E 2014 Automatic Fruit Image Recognition System Based on Shape and Color Features Communications in Computer and Information Science (Cham: Springer) vol 488