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Design and Mechanical Analysis of Green Plum Picking Manipulator Based on ANSYS

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Abstract

Qingmei is a small fruit, the traditional manual picking efficiency is low, mechanized picking is very important, vibration picking has a unique advantage for the picking of small fruits. On the basis of consulting a large number of materials, this paper lists the cutting-edge knowledge of the application of robot technology in green plum picking at home and abroad, summarizes the deficiencies and problems that need to be improved, and uses solidworks and ANSYS Workbench software to model and analyze the mechanical arm of green plum picking. The clamping device, etc., obtained the complete structure of the green plum picking machine, and the mechanical analysis of the key components such as the big arm and the small arm of the green plum picking machine was carried out respectively, which verified the rationality of the design and provided a reference for the innovative design of the subsequent picking machinery.

Keywords: Green plum, picker, structure design, static analysis.

1. Introduction

Green plums, serving as a fundamental pillar in the fruit industry, can be transformed into a diverse array of products, including salted varieties, candied options, plum-based beverages, and even plum wines [1]. As the scale of cultivation expands, the necessity for mechanized harvesting rises, underscoring the profound significance of developing harvesting robots attuned to the agricultural context in China [2].

Researchers at China Agricultural University have developed a greenhouse cucumber harvesting robot [3]. primarily tailored for the harvesting of cucumbers. Liu and collaborators [4] from Nanjing Forestry University have introduced a novel mountainous and hilly green plum picker equipped with a three-fingered end effector. This machine integrates nylon protective materials at its extremity to safeguard fruit integrity, enabling automated harvesting and sorting capabilities. Further advancing in this domain, the team led by Shang et al. [5] from Qingdao Agricultural University has engineered a hydraulic-controlled high-acid apple vibration picker. This innovation is derived from a meticulous kinematic analysis of high-acid apple trees and robots, culminating in the determination of optimal parameters for efficient harvesting operations amidst high-acid apple orchards.

Lang [6] established a dynamic model encompassing the interaction between cherry tree trunks and roots, and the roots with the soil. Leveraging this model, they conducted optimization design for crank-slider and eccentric wheel-type vibration pickers. At the University of Catania in Italy, Muscato and colleagues [7] delved into the research of a flexible three-finger end effector picker tailored for citrus fruits. In the United States, Amatya et al. [8] harnessed machine vision technology for precise cherry harvesting, while at Okayama University in Japan, Pu et al. [9] pioneered a tomato harvesting robot based on machine vision, allowing for automatic fruit identification and harvesting. Additionally, Magalhães et al. [10] introduced an active perception fruit harvesting robot, and Amatya et al. [11] utilized machine vision for automated cherry picking by robots. These advancements serve to significantly bolster harvesting efficiency and quality. Nonetheless, persistent challenges such as the stability and reliability of machine vision technology persist. This study, rooted in the concept of robotic harvesting, introduces a comprehensive set of equipment for green plum harvesting. Through the utilization of SolidWorks and ANSYS Workbench software, the research team modeled and subjected the mechanical arm of the green plum picker to finite element analysis, validating the rationality of the design. This innovative approach is poised to effectively enhance harvesting efficiency, setting a benchmark for future iterations in mechanical harvesting design.

2. Design Concept

Drawing from the ripeness status of green plum fruits [12], this design, based on the establishment of a tree model [13], employs vibration harvesting technology [14], with the main structure being a mechanical arm. The mechanical arm of the green plum picker stands as a highly intricate mechanical system, comprising multiple components such as the upper arm, lower arm, hydraulic cylinder, end effector, as depicted in Figure 1. These components, intertwining through a sophisticated mechanical structure and hydraulic system, synergistically achieve efficient harvesting of green plums.

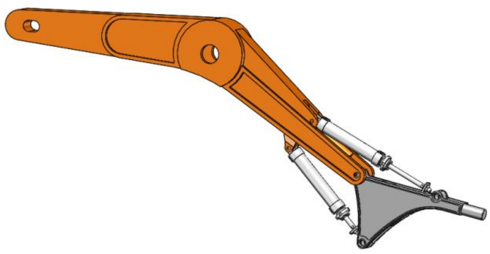

Figure 1 Schematic diagram of arm device

3. Structural Design

3.1 Design of the lower arm

In the design of the green plum picker, the lower arm stands as a crucial component assembled with the end effector, requiring the capability to withstand a weight of 36.80 kg. Considering the application in a moderately demanding work environment and cost considerations, this design opts for 6061-T6 aluminum alloy for both the upper and lower arms. The physical characteristics of this material are as follows: density: 2.70 g/cm³; modulus of elasticity: 68.9 GPa; tensile strength: 276 MPa; yield strength: 276 MPa. This selection ensures ample strength and rigidity to prevent buckling deformation, while also providing resistance to corrosion and rust. Based on the typical planting layout for green plum trees with row spacing of $4000\text{mm} \times 4000\text{mm}$ and a tree height not exceeding 2,500 mm, the design dimensions are illustrated in Figure 2.

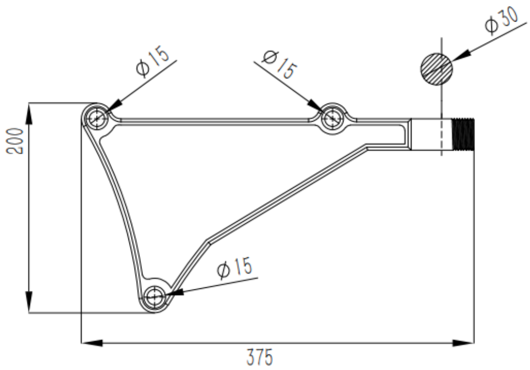

Figure 2 Geometric dimension diagram of forearm

By inputting the density parameters of aluminum alloy 6061-T6 into ANSYS Workbench software, the mass of the lower arm is calculated to be $m_{\text{lower}} = 2.37\text{kg}$.

3.2 Design of the upper arm

The middle section of the upper arm is assembled with a pillar to achieve a better distribution of weight balance. The front end of the upper arm is interconnected with the lower arm, considering that the upper arm must bear the total mass of the end effector, lower arm, and hydraulic cylinder, meeting the requirement to elevate to the desired harvesting height. Supported by the fixed support of the pillar, and in accordance with the harvesting needs, the arm's end effector's gripping clamp should be capable of gripping and vibrating before the green plum tree at a distance of 350 to 450 mm. The designed highest position reaches up to 475 mm along the main trunk of the green plum tree, while the lowest position descends to 382 mm along the main trunk, aligning with the design specifications. The motion model is depicted in Figure 3. The upper arm of the green plum picker dictates the height adjustments of the end effector, significantly influencing the range of harvesting to ensure efficiency within the designated harvest zone.

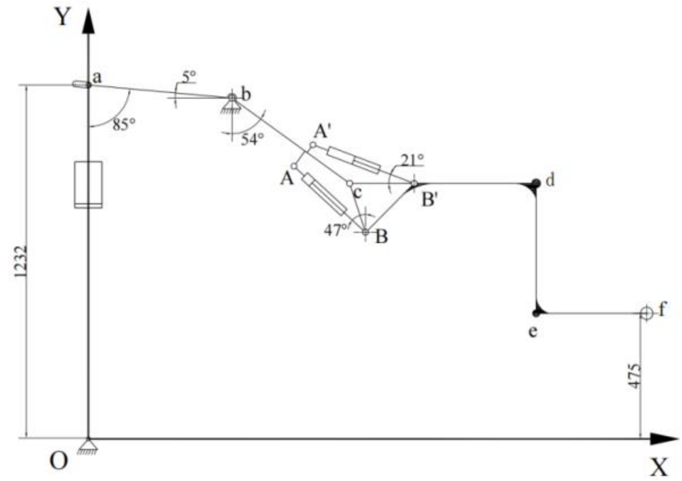

Figure (a) - State at the highest point

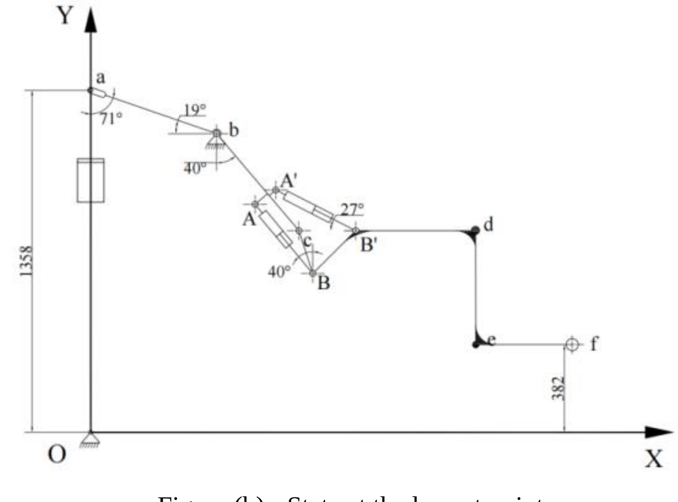

Figure (b) - State at the lowest point

Figure 3 Arm movement model

Considering the analysis of arm motion states, the angle between segments ab of the upper arm and Oa ranges from 71° to 85° concerning the horizontal direction and from 5° to 19°. Segment bc of the upper arm maintains an angle between 40° and 54° relative to the vertical direction. The hydraulic cylinder AB forms an angle between 40° and 47° with the vertical direction, while the hydraulic cylinder A′B′ positions itself at an angle range of 21° to 27° with respect to the horizontal direction. It is evident that the overall angular ranges of motion are relatively narrow, with conservative motion amplitudes, resulting in a stable state and meeting the harvesting requirements.

Given that the efficient harvesting range falls between 350 to 550 mm and within the specified angular intervals, geometric dimensions for the upper arm as shown in Figure 4 can be designed accordingly.

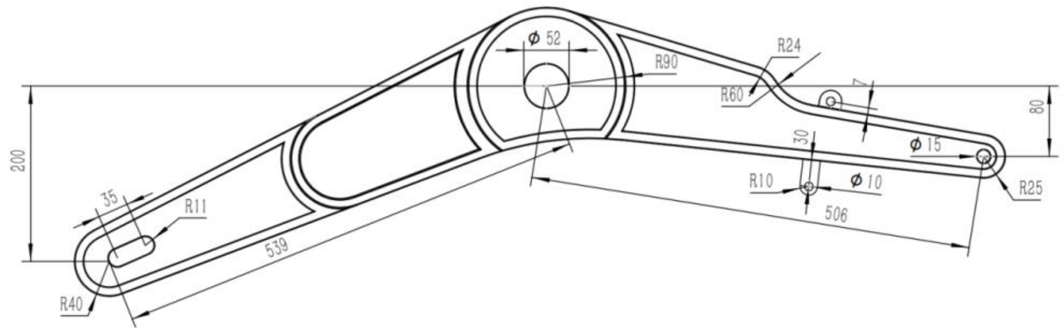

Figure 4 Geometric dimensions of the upper arm

By adhering to the properties of the 6061-T6 material and conducting mass calculations utilizing ANSYS Workbench, the mass is determined to be $m_{upper} = 12.88$kg.

3.3 Design of the end effector

The end effector employs a shock-absorbing suspension chain-type gripper, enhancing harvesting efficiency while ensuring precision control of gripping force without damaging the tree bark. A vibratory device, driven by a motor-driven eccentric block, has been devised to facilitate this functionality. The gripper's opening is shielded with flexible material to prevent harm to the vital trunk area, promoting gentle handling. The shock-absorbing suspension disk connects to the mechanical arm and is linked below to three damping chains. When the gripper and vibrator operate below to lessen vibration-induced damage and prolong operational longevity, as illustrated in Figure 5. In pursuit of stability and durability for the tracked vehicle, the overall selection of materials comprises aluminum alloy. Special materials are reserved for specific components like high-demand grippers and unique flexible parts to ensure performance excellence.

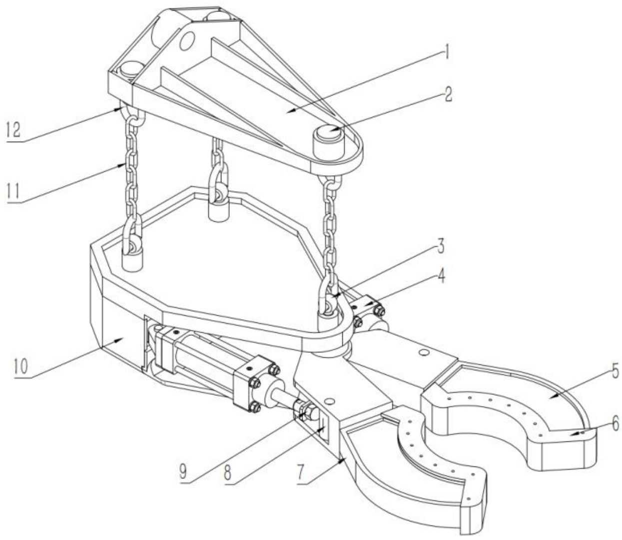

Figure 5 Structural diagram of end clamping pliers

Notes: 1. Shock-absorbing suspension frame; 2. Chain suspension pin; 3. Articulated bolt; 4. Hydraulic cylinder; 5. Gripper (left); 6. Flexible sheath; 7. Gripper (right); 8. Hydraulic cylinder securing hook; 9. Dome nut; 10. Rear cover of vibratory device; 11. Chain; 12. Shock-absorbing link ring.

3.3.1 Design of the vibratory device

In the harvesting process of the Vibratory Green Plum Picker, the pivotal component is the vibratory device responsible for inducing vibration. By leveraging an electric motor and a rotating unbalanced [15] eccentric block, vibratory force is generated to establish the requisite vibration frequency [16] for the vibratory system composed of the vibratory device and the gripper. A fixed right-angle [17] semi-cylindrical eccentric block is employed, as depicted in Figure 6.

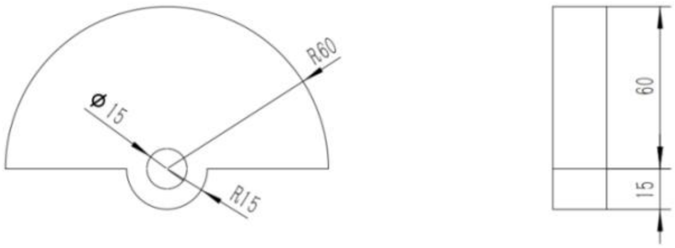

Figure 6 Schematic diagram of geometric dimensions of eccentric blocks

Selected geometric dimensions of the eccentric block:

Large circle radius R_1 = 60 mm

Small circle radius R_2 = 15 mm

Inner hole radius r = 7.5 mm

Thickness d = 20 mm

Based on the analysis of eccentricity design criteria outlined by Shang et al. [5] and the design insights by Zhang et al. [18], the calculation formula for the eccentricity of the fixed right-angle semi-cylindrical eccentric block is expressed as:

$$e = \frac{4(R_1^3 - R_2^3)}{3\pi(R_1^2 + R_2^2 - 2r^2)} \quad (1)$$

Where:

e =the eccentricity of the eccentric block (mm);

R_1=the large circle radius of the eccentric block (mm);

R_2= the small circle radius of the eccentric block (mm);

r=the inner hole radius of the eccentric block (mm).

For the material selection of the eccentric block, typically, 45# steel is chosen, with a density ρ $7.85\times10^3 kg/m^3$. The mass of the eccentric block is calculated as:

$$m_1 = \frac{\pi}{2}(R_1^2 + R_2^2 - 2r^2)d\rho \quad (2)$$

Where:

m_1=the mass of the eccentric block (kg);

d= the thickness of the eccentric block (mm);

ρ= the density of the eccentric block (kg/m^3).

By calculation, the mass of the eccentric block is determined to be m=0.931kg=931 g. With these calculations, the design parameters for the eccentric block are summarized in Table 1.

Table 1 Eccentric block design parameters.

Parameters	Values	Unit
Large circle radius R_1	60	mm
Small circle radius R_2	10	mm
Inner hole diameter r	7.5	mm
Thickness	20	mm
Eccentricity e	24.31	mm
Mass m	0.931	kg
Density ρ	7.85×10^3	kg/m3

According to the relationship between vibrational force and angular velocity [15], as well as the connection between rotational speed and angular velocity:

$$F = \omega^2 m_1 e \tag{3}$$

$$n = \frac{60\omega}{2\pi} \tag{4}$$

Where:

ω=the rotational angular velocity in radians per second (rad/s);

n= the operational speed of the eccentric block in revolutions per minute (r/min).

The relationship between angular velocity and frequency is:

$$\omega = 2\pi f \tag{5}$$

Where f denotes the vibrational frequency of the vibratory device. Through these equations, it is determined that the eccentricity of the eccentric block is e=23.65 mm, and the calculated mass of the eccentric block is m=0.931 kg=931 g. Based on the analysis of the vibration characteristics of the green plum tree, it is concluded that the natural frequency for green plums to detach is achieved at 10.4 Hz. To enhance the harvesting efficiency of green plums without causing harm to the fruits or tree trunk sections, and considering the physical properties of the green plum tree, a vibrational frequency of $f = 12$ Hz is chosen for the vibratory device. By simultaneously solving equations (1) to (5), the harvesting speed of the eccentric block is computed as$n = 720 r/min$, and the vibrational force exerted by the eccentric block picker amounts to $F = 1{,}026.60N$.

3.3.2 Design of the gripper clamp

In order to minimize damage to the main trunk section of the green plum tree and enhance control accuracy in gripping strength, the picker employs a gripper clamp to securely hold and grip the tree trunk [19], complementing the vibratory device. The structural design is depicted in Figure 7.

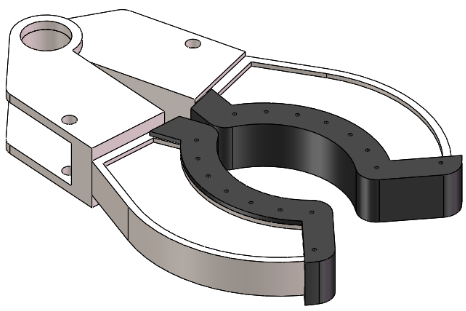

Figure 7 Schematic diagram of clamping pliers and flexible sheath

Based on the physical characteristics of the green plum tree, it is known that the diameter of the tree trunk is approximately 100 mm. Therefore, the sizing specifications for the end gripper clamp are designed as illustrated in Figure 8.

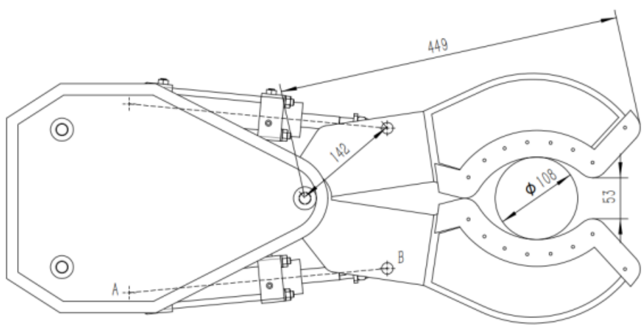

Figure (a) Schematic of the minimum opening size of the gripper clamp

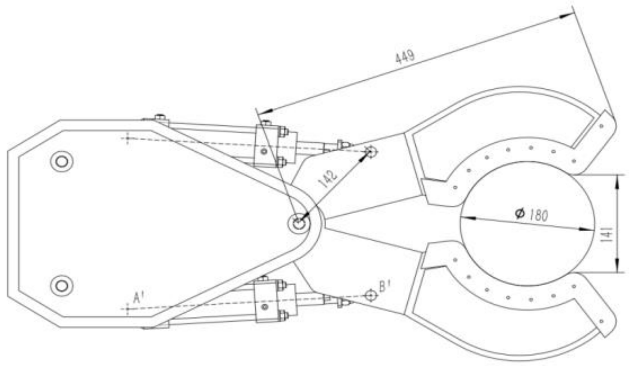

Figure (b) Schematic of the maximum opening size of the gripper clamp

Figure 8 Geometric dimension diagram of clamping pliers

Considering the mountainous terrain environment where exposure to intense sunlight and rain erosion is frequent, the material for the gripper clamp can be selected as aluminum alloy due to its lightweight nature compared to conventional steel materials, along with its excellent strength and corrosion resistance properties [20]. In accordance with the GB/T 1591-2008 standard for low-alloy high-strength structural steel, this design opts for Q345B, with a density of 7.85 g/cm³, offering superior toughness, wear resistance, and machinability. For the flexible sheath, considering the growth environment of green plums, materials such as polytetrafluoroethylene (PTFE) or fluoroelastomer are chosen for their high-temperature tolerance and resistance to chemical erosion, both of which contribute to extending the operational lifespan of the gripper clamp.

3.4 Overall assembly

By modeling the green plum picker, the comprehensive design of the machine is derived, leading to the three-dimensional modeling and assembly as depicted in Figure 9.

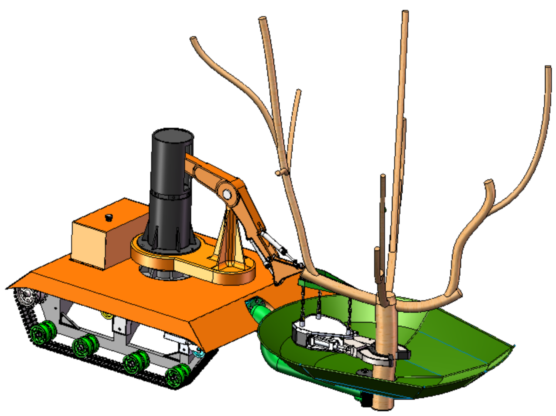

Figure 9 3D schematic diagram of the entire vehicle

The green plum picker maneuvers beneath the fruit tree using a tracked locomotion system. It employs a vertical lifting mechanism composed of a vertical lifting cylinder and a sizeable arm to elevate the gripper clamp, which serves as the terminal actuator capable of generating vibrational force. Through the vibratory device, fruits are dislodged, and a folding fan-shaped umbrella structure is utilized as the collection apparatus, facilitating the harvesting of green plums.

4. Finite Element Analysis

4.1 Static stress analysis of the lower arm

In order to validate its capacity to withstand the 36.80 kg terminal actuator, this design employs ANSYS

Workbench software to conduct a static stress analysis of the lower arm. By configuring material parameters and fixing three-point constraints within the lower arm model, a force of 36.80 kg, equivalent to a weight of 360.64 N, is applied in the Z-axis direction at the assembly point of the terminal actuator and gripper clamp. The displacement transformation cloud map is depicted in Figure 10.

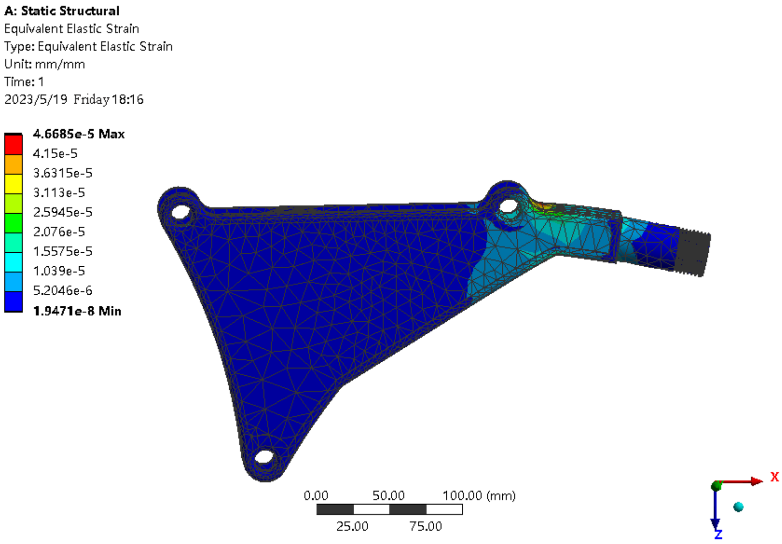

Figure (a) Cloud map of equivalent elastic strain in the lower arm

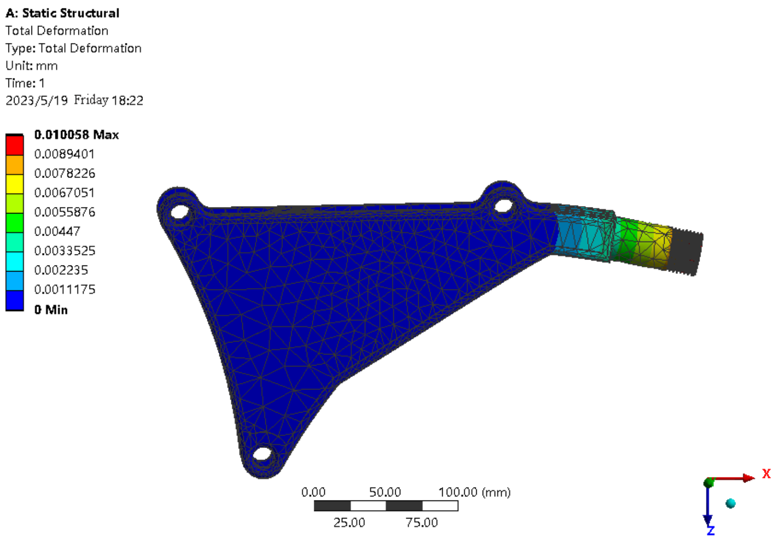

Figure (b) Cloud map of overall deformation in the lower arm

Figure 10 Static analysis deformation cloud map of forearm

Observing a maximum deformation of 0.010058 mm, it is apparent that there is minimal alteration in shape, aligning closely with the actual form. This outcome satisfies the requirements for stiffness and strength, affirming that the structural design of the lower arm meets the specified criteria under the chosen material.

4.2 Static stress analysis of the upper arm

Based on the dimensional design of the upper arm, a model is crafted using SolidWorks, followed by stress analysis utilizing the static analysis capabilities of ANSYS Workbench. With the selected material in mind, material parameters are finalized, and constraints are applied at the groove and mid-support of the upper arm. To ensure the safety and reliability of the upper arm, an external force of 370 N is exerted in the Z-axis direction. The overall deformation cloud map is presented in Figure 11.

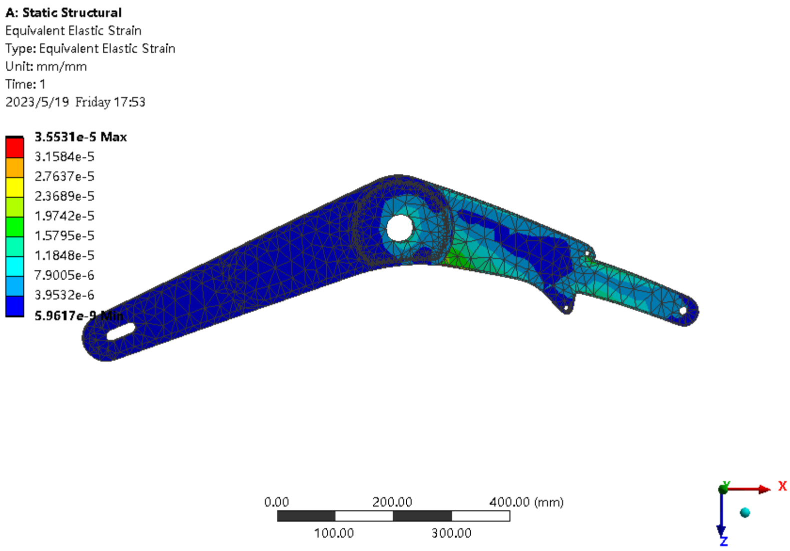

Figure (a) Cloud map of equivalent elastic strain in the upper arm

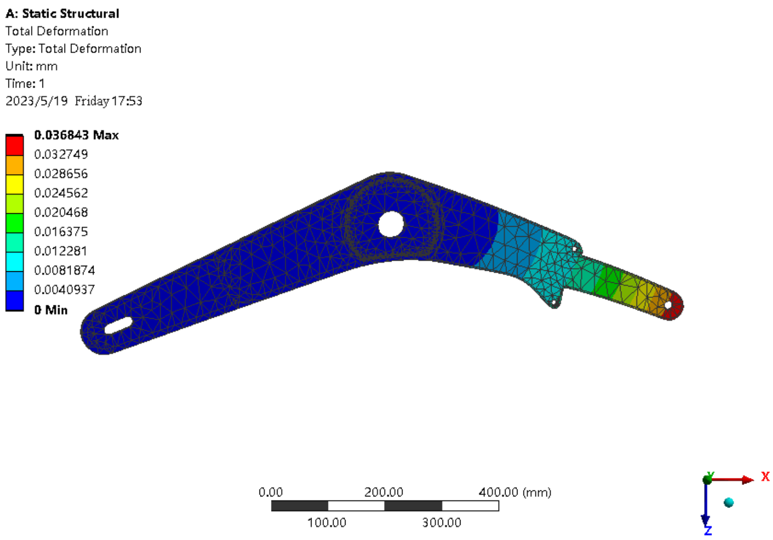

Figure (b) Cloud map of overall deformation in the upper arm

Figure 11 Cloud diagram of static analysis of the upper arm

Analysis data indicates that under the influence of gravity from the lower arm and terminal actuator, as depicted in Figure 11 (a), the maximum elastic strain force at the critical point registers at 3.5531×10-5 N. Figure 11 (b) highlights significant deformation at the load-bearing end, with the maximum overall deformation measuring at 0.03684 mm. Notably, the actual analysis reveals relatively minor deformations, affirming the upper arm's design sufficiently meets the stipulated requirements for stiffness.

5. Conclusion

The design presented here is a mechanical plum picker developed for the field of robot harvesting. Through experimentation and model verification, it is evident that this plum picker design is well-suited for conducting plum harvesting work in hilly terrains. It boasts high harvesting efficiency, stability, and reliability, while minimizing damage to the plants. Notably, the design does not delve into the systematic design of the mobile chassis, power system, and fruit collection mechanism. It is hoped that in subsequent iterations, there will be a plethora of more rational design solutions to collectively advance the healthy and stable development of the green plum industry.

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4. Collaborative Innovation Project Supporting the Construction of Anhui Intelligent Agricultural Machinery Equipment Research Institute by Anhui Provincial Department of Education (GXXT-2023-111)

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