International Journal of Engineering Inventions
e-ISSN: 2278-7461, p-ISSN: 2319-6491
Volume 15, Issue 4 [April 2026] PP: 01-07

Design and Finite Element Evaluation of an Automated Coconut Harvesting System for Intelligent Agricultural Applications

Qingxuan Chen, Jiayan Chen, Wenming Li, Xinyu Mao, Chunyu Ding, Ying Ma and Hao Li*
Institute of Mechanical and Vehicle Engineering,Changchun University
Corresponding Author: Hao Li

Abstract: *Manual coconut harvesting is characterized by low productivity, substantial safety hazards, and rising labor costs, which restrict the modernization of the coconut industry. To address these issues, an automated coconut harvesting system integrating mechanical design, visual perception, and coordinated control strategies was developed. A three-dimensional model of the core structure was established and then simplified for finite element simulations under conventional orchard conditions and complex terrain scenarios. The static analysis results show that the maximum deformation of the end-effector occurs at the junction between the claw tip and the secondary claw segment, reaching 7.1172 mm, while the deformation of the forearm and upper arm is 0.7508 mm and 0.29245 mm, respectively. These results demonstrate that the selected materials and structural configuration satisfy the practical requirements of coconut harvesting and provide good usability and operational stability.*

Keywords*: coconut harvesting; intelligent agricultural equipment; static analysis*

Date of Submission: 20-03-2026 Date of acceptance: 03-04-2026

I. Introduction

In recent years, tropical agriculture in China has developed rapidly. As one of the representative tropical cash crops, coconuts have experienced steadily increasing market demand, and the coconut industry is moving toward large-scale and modernized production [1]. With the continuous expansion of plantation areas, the limitations of traditional manual harvesting have become increasingly evident and have emerged as an important constraint on the high-quality development of the industry. Consequently, the demand for automated and intelligent coconut harvesting equipment has continued to grow [2]. Automated coconut harvesting equipment integrates mechanical design, intelligent recognition, and motion control into an agricultural intelligent system capable of completing the full harvesting process through multi-system coordination. Such systems can provide coconut growers with continuous and stable harvesting services characterized by high efficiency, improved safety, and intelligent operation [3]. They can significantly reduce labor intensity and safety risks while improving harvesting efficiency and fruit quality, thereby lowering production costs and enhancing economic returns [4]. Therefore, automated coconut harvesting machines have broad research and application value and promising development prospects in tropical agricultural equipment.[1][2][3][4]

At present, substantial progress has been achieved in the field of fruit harvesting machinery worldwide, providing an important reference for the development of coconut harvesting systems. Ao et al. [5] proposed performance evaluation criteria for end-effectors, including harvesting success rate, harvesting time, and damage rate, thereby standardizing end-effector assessment. Zhao et al. [6] designed a rear-drive apple-harvesting robotic arm based on obstacle-avoidance postures and orchard operating requirements. Chen et al. [7] developed a dual-track harvesting system that can carry a robotic unit. Research teams at the University of Florida have also developed tropical fruit harvesting robots that integrate multi-sensor perception and path-planning algorithms to realize automated harvesting of papaya and mango [8]. In addition, Kyushu University in Japan developed a fruit and vegetable harvesting manipulator using lightweight carbon-fiber materials and high-precision servo control, which markedly improved operational flexibility and accuracy [9]. However, most coconut harvesting devices currently used in China are still simple manual tools or semi-automatic devices, lacking mature capabilities for intelligent recognition, adaptation to complex terrain, and precise high-altitude operation [10]. Under harvesting conditions in which coconut trees vary considerably in height and fruit distribution, operators still need to manually adjust position and tool angle, and some tasks require manual assistance, resulting in high labor and time consumption. Existing equipment also struggles to coordinate multiple subsystems during harvesting, and a single operating mode cannot effectively adapt to different orchards and tree ages, which limits both efficiency improvement and cost control.[5][6][7][8][9][10]

To address these issues, this study proposes an automated coconut harvesting machine with a novel overall structure capable of precise recognition, efficient harvesting, and terrain-adaptive operation. The rationality of the design is verified through static mechanical analysis and modal analysis, providing diversified harvesting modes for coconut growers and better matching the practical requirements of different coconut orchards.

II. Modeling of the Automated Coconut Harvesting Machine

Overall Structural Model of the Automated Coconut Harvesting Machine

After the design scheme was determined, SolidWorks was used to complete the dimensional design and structural modeling of the core components of the automated coconut harvesting machine. The overall structure of the system is shown in Fig. 1, and the detailed design is described as follows.

1.Based on standardization theory, a complete equipment design methodology was established. The coordinated design approach for the technical subsystems and the optimization method for system integration were discussed and adjusted according to practical harvesting requirements. The manipulator was designed as a foldable multi-joint structure with a maximum extension height of 15,000 mm, a chassis track width of 800 mm, an operating radius of 5,000 mm, and a gripping range of 50-300 mm for the terminal clamping-cutting device [11].[11]

2.The equipment mainly consists of a high-precision vision recognition module, a telescopic multi-joint manipulator, a terrain-adaptive chassis, an end clamping-cutting actuator, an intelligent control system, and a safety protection unit. The machine is driven by a diesel-lithium hybrid power system. To ensure coordinated operation and motion accuracy, high-precision sensors are installed at the manipulator joints and on the chassis so that real-time data transmission can support interaction and coordinated control among subsystems.

3.In this study, a Weima diesel engine with a rated power of 4.78 kW was selected and installed in the power compartment behind the seat. A 250 x 160 x 200 battery pack was placed in the same compartment. The system uses five motors in total: two provide traction for the chassis; one is located between the upper arm and the major arm; one is arranged between the upper arm and the connecting rod; one is positioned between the major arm and the forearm; and two are installed between the forearm and the mechanical claw. The first three motors control rotation and extension of the manipulator, whereas the remaining two manage bending and leveling motions.

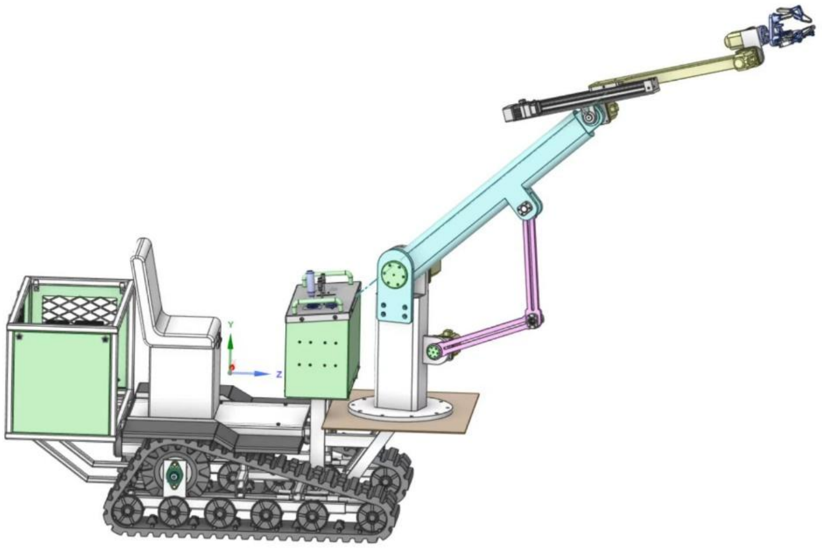


Fig. 1 Overall structure of the automated coconut harvesting machine1

Modeling of the Harvesting Manipulator

According to the operational requirements of coconut harvesting, a harvesting manipulator suitable for a large workspace was proposed, and the individual components were designed modularly. The manipulator needs to realize height adjustment, horizontal rotation, and multi-angle flexion and extension, thereby providing multi-degree-of-freedom capability. However, a fully actuated multi-degree-of-freedom manipulator, although able to satisfy operational requirements to the greatest extent, would increase both control complexity and manufacturing cost [12]. Therefore, the harvesting manipulator in this study adopts a foldable multi-joint structure in which the main degree-of-freedom drives are arranged at the manipulator base and the major-arm joint, while the forearm and wrist use a follower-type adjustment structure linked with the vision system to reduce actuation error and control-system complexity. By establishing the kinematic model of the coconut harvesting manipulator, the Jacobian condition number and manipulability index were analyzed, and reinforcement learning was introduced to reduce the number of path nodes, thereby improving robot efficiency while supporting precise rotation and extension of each joint [13][14].[12][13][14]

End-Effector Design

The end-effector of the automated coconut harvesting machine mainly consists of a hydraulic leveling device, pressure-feedback grippers, and a high-frequency vibration cutting blade. During orchard operation, pressure-sensing contact points are arranged on the gripper at 5 mm intervals, allowing the gripping force to be adjusted automatically according to coconut size. Considering the physical characteristics of the coconut peduncle, the flexibility and adaptability of the grasping strategy determine grasping effectiveness, thereby improving cutting efficiency and reducing damage to the coconut tree [15].[15]

III. Static Analysis of the Device Based on ANSYS

Static Analysis of the Manipulator

Meshing of the Manipulator

The manipulator uses the same element type as the mechanical claw, and the tetrahedral mesh of the manipulator is shown in Fig. 2.

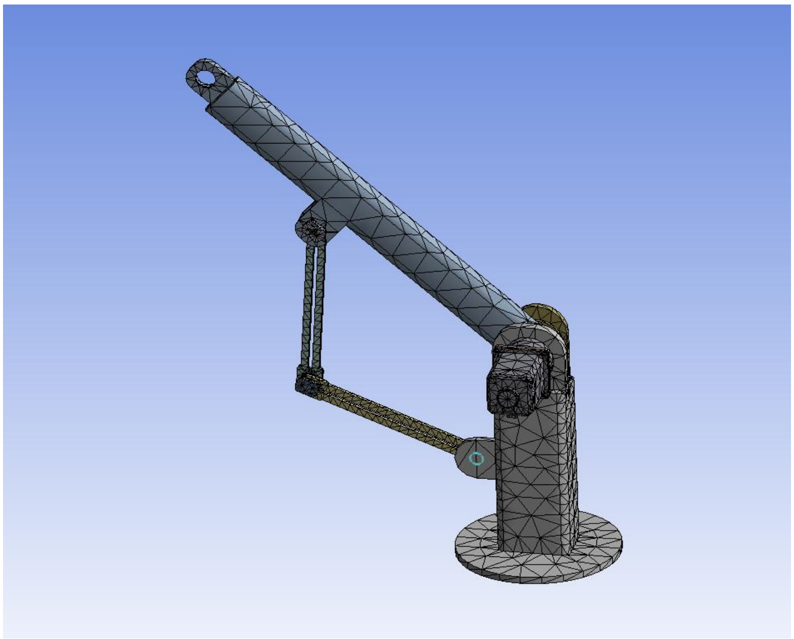


Fig. 2 Tetrahedral mesh of the manipulator

Equivalent Stress of the Manipulator

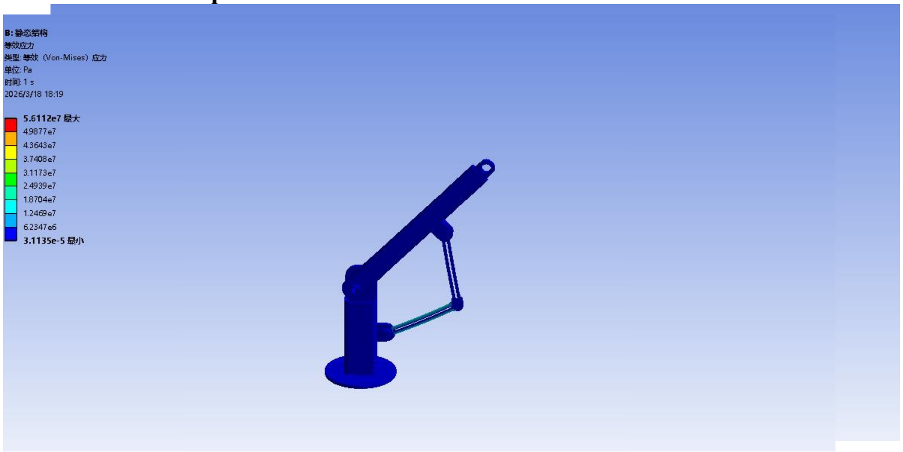


Fig. 3 Equivalent stress contour of the manipulator

The stress contour of the manipulator is shown in Fig. 3. The maximum stress appears at the connection between the major arm and the forearm, with a value of 5.611 Pa. According to the stress distribution, the yield strength of the selected material satisfies the design requirement, and both the maximum stress and deformation remain within the allowable range. This indicates that the selected material properties meet the design requirements.

Static Analysis Results of the Manipulator

A finite element model of the manipulator was established in Workbench, and static analysis was carried out. In the Workbench post-processing module, the total deformation contour of the first-stage manipulator of the coconut harvesting machine was obtained, as shown in Fig. 4.

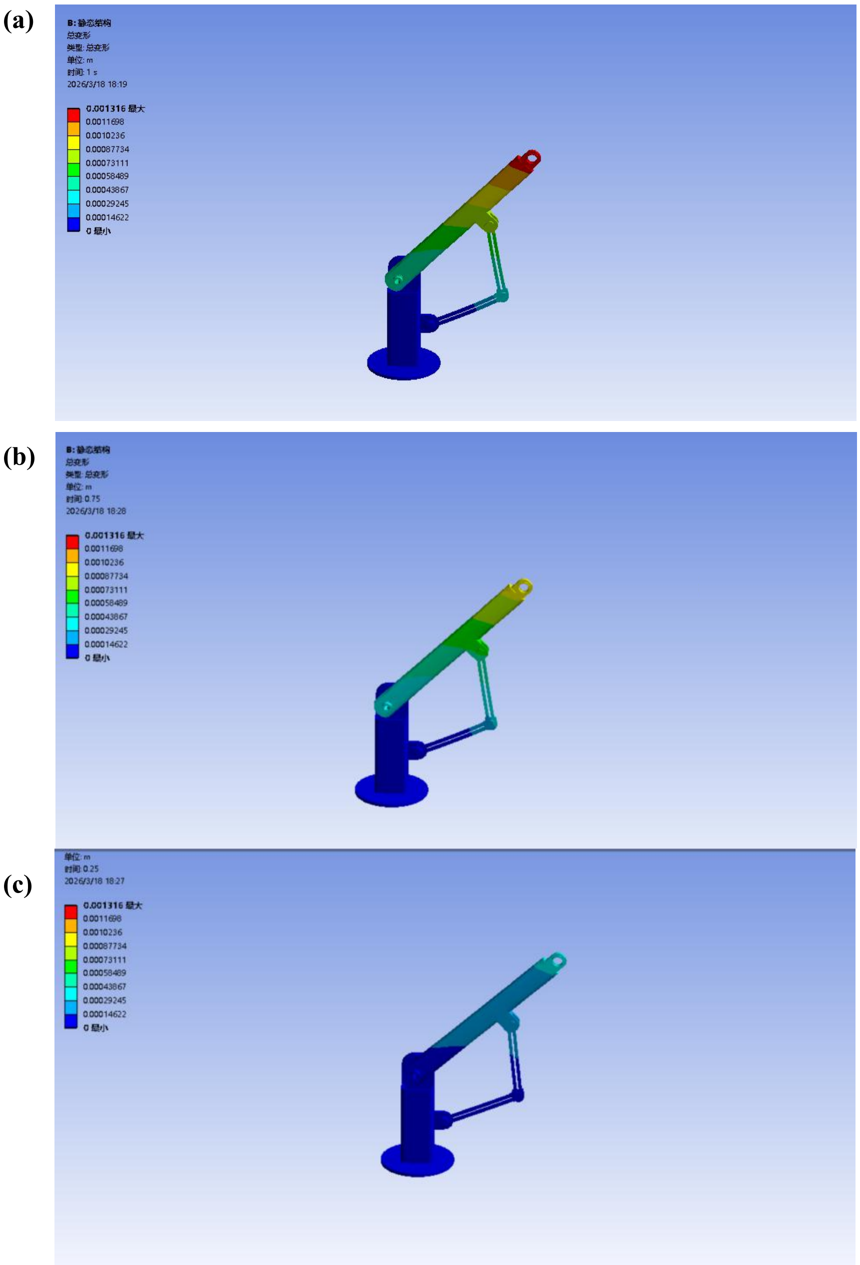


Fig. 4 Total deformation contour of the manipulator

As shown in Fig. 4, the maximum deformation of the manipulator occurs at the connection between the major arm and the forearm, with a value of 1.316 mm. The deformation displacement of the major arm is 0.29245 mm, and that of the upper arm is 0.14622 mm. The overall displacement trend gradually decreases from top to bottom.

Static Analysis of the Mechanical Claw

Before the static analysis of the coconut harvesting machine in Workbench, the most important task was geometric modeling because modeling quality directly affects the correctness of the computational results. In general, geometric modeling occupies a large amount of time and plays a critical role in the entire finite element analysis process.

Initially, the model of the coconut harvesting machine under different states was simplified in SolidWorks. Because this study involved static analysis, flexible binding structures without practical effect could be removed before importing the model into ANSYS Workbench, and the simplified model was then saved in STP format.

Meshing of the Mechanical Claw

Element types include tetrahedral meshes, hexahedral meshes, and automatic mesh generation. Because tetrahedral elements are suitable for different structures and can represent arbitrary shapes in three-dimensional space with good numerical stability, they are not prone to computational error even under relatively large deformation and can provide high computational accuracy. The mesh of the mechanical claw is shown in Fig. 5.

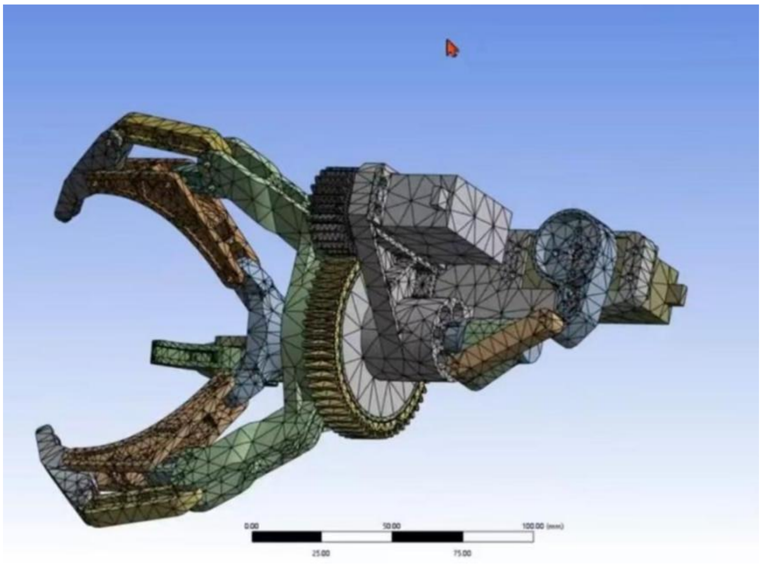


Fig. 5 Tetrahedral mesh of the mechanical claw

Equivalent Stress of the Mechanical Claw

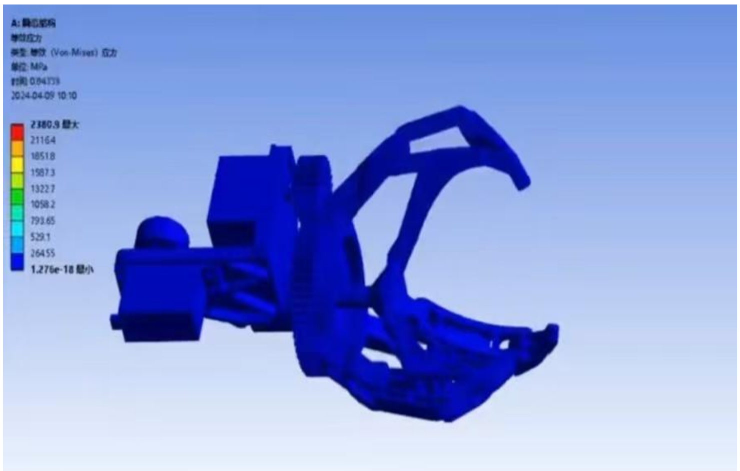
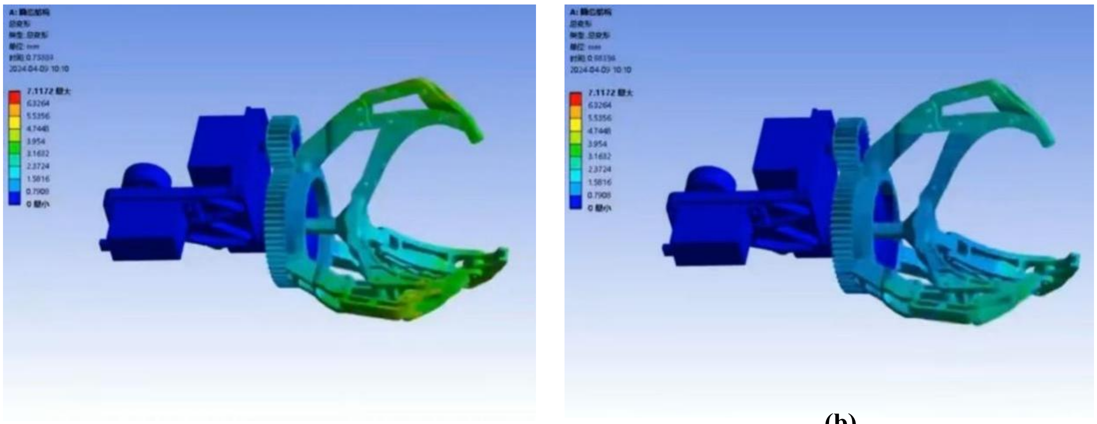


Fig. 6 Equivalent stress contour of the mechanical claw

The stress contour of the mechanical claw is shown in Fig. 6. The maximum stress appears at the connection between the claw tip and the second claw segment, with a value of 2380.9 MPa. According to the stress distribution, the yield strength of the selected material satisfies the design requirement, and both the maximum stress and deformation remain within the allowable range, indicating that the selected material properties are suitable for the design.

Static Analysis Results of the Mechanical Claw

A finite element model of the mechanical claw was established in Workbench, and static analysis was carried out. In the Workbench post-processing module, the total deformation contour of the mechanical claw of the coconut harvesting machine was obtained, as shown in Fig. 7.



(a) **(b)**

Fig. 7 Total deformation contour of the mechanical claw

As shown in Fig. 7, the maximum deformation of the mechanical claw occurs at the connection between the claw tip and the second claw segment, reaching 7.1172 mm. The deformation displacement of the fixed plate is 1.5816 mm, and that of the forearm is 0.7508 mm. The overall displacement trend first increases and then decreases from left to right.

IV. Conclusion

In this study, SolidWorks was used to complete the three-dimensional design of the automated coconut harvesting machine. One servo motor controls rotation and extension of the manipulator, and another servo motor manages flexion, extension, and leveling so that coconuts at different heights and positions can be harvested. The end-effector is equipped with an independent drive motor to achieve precise gripping and rapid cutting of the fruit stalk. Coordinated control of the motors significantly improves the working range and motion coordination of the harvesting machine. For coconut growers, the equipment provides multiple operating modes, including conventional flat-ground harvesting, complex-terrain harvesting, and precise high-altitude harvesting, so that different practical orchard requirements can be met.

After structural design was completed, simulation software was used to perform finite element analysis of the equipment, including static mechanical analysis and modal analysis. The static results show that the maximum deformation of the mechanical claw occurs at the connection between the claw tip and the second claw segment, reaching 7.1172 mm, while the deformation displacement of the fixed plate is 1.5816 mm and that of the forearm is 0.7508 mm, with an overall trend that first increases and then decreases from left to right. The maximum deformation of the manipulator occurs at the connection between the major arm and the forearm, reaching 1.316 mm, while the deformation displacement of the major arm is 0.29245 mm and that of the upper arm is 0.14622 mm, with an overall trend that gradually decreases from top to bottom. All indicators remain within the allowable range of the material, demonstrating that the strength and stiffness of the main structure satisfy the operational requirements. Modal analysis further determined the first three natural frequencies of the device. Because these frequencies do not overlap with the vibration frequency generated during operation, resonance can be effectively avoided, thereby ensuring structural stability and control accuracy.

Through structural innovation and multi-system coordination, the automated coconut harvesting machine designed in this study addresses the major industry challenges of low harvesting efficiency, high safety risks, and poor terrain adaptability. The selected materials and structural configuration satisfy the practical operational requirements of coconut harvesting. Future work can further optimize the intelligent recognition algorithm and control system, improve autonomous operating capability and harvesting efficiency, and reduce manufacturing cost through lightweight design, thereby promoting large-scale application and industrialization.

References

[1] Yang D, Zhu Y, Liu S. Focusing on Characteristic Industries: Research on the Optimization of the Value Chain of Hainan's Tropical High-Efficiency Agriculture Driven by Big Data [J]. Innovation Series: Advanced Science, 2025, 2(6).

[2] Zeyu J, Kai H, Qun W, et al. Real-time litchi detection in complex orchard environments: A portable, low-energy edge computing approach for enhanced automated harvesting [J]. Artificial Intelligence in Agriculture, 2024, 11:13-22. DOI:10.1016/J.AIIA.2023.12.002.

[3] Cheng'en L, Yunchao T, Xiangjun Z, et al. A Novel Agricultural Machinery Intelligent Design System Based on Integrating Image Processing and Knowledge Reasoning [J]. Applied Sciences, 2022, 12(15):7900. DOI:10.3390/APP12157900.

[4] D K S, A A M, P A O. Evaluation of the efficiency of apple picking using a flexible manipulator [J]. IOP Conference Series: Earth and Environmental Science, 2022, 949(1). DOI:10.1088/1755-1315/949/1/012008.

[5] Ao J, Ji W, Yu X, et al. End-Effectors for Fruit and Vegetable Harvesting Robots: A Review of Key Technologies, Challenges, and Future Prospects [J]. Agronomy, 2025, 15(11):2650. DOI:10.3390/AGRONOMY15112650.

[6] Zhao X, Liang H, Liu Z, et al. Research on design and experiment of rear-drive apple harvesting robotic arm based on obstacle avoidance posture conditions [J]. Smart Agricultural Technology, 2025, 11:101028. DOI:10.1016/J.ATECH.2025.101028.

[7] Chen J, Wang K, Zhou L, et al. Design of an intelligent Camellia oleifera fruit picking robot system with a dual-track transport [J]. Smart Agricultural Technology, 2025, 12:101308. DOI:10.1016/J.ATECH.2025.101308.

[8] Burks T F, Alchanatis V, He Y. Machine vision systems for agricultural robotics: A review [J]. Computers and Electronics in Agriculture, 2021, 183:106069.

[9] Noguchi N, Takanishi T, Ishii K. Development of a lightweight robotic arm for fruit picking [J]. Journal of Field Robotics, 2019, 36(7):1234-1250.

[10] Liu S, Cai Y. Research and Application of Optimization on Safety Protection Structure for High-Altitude Operations Based on Utility Model [J]. GBP Proceedings Series, 2025, TMEM2025:49-57. DOI:10.70088/ZMB5H695.

[11] Mai L. Design Method of Equipment Optimization Development Based on Standardization Theory [J]. Defence Technology, 2013, 9(3):140-145. DOI:10.1016/j.dt.2013.09.012.

[12] Zhao X, Liang H, Liu Z, et al. Research on design and experiment of rear-drive apple harvesting robotic arm based on obstacle avoidance posture conditions [J]. Smart Agricultural Technology, 2025, 11:101028. DOI:10.1016/J.ATECH.2025.101028.

[13] Wang M, Zhou Z, Wang Y, et al. Design and experiment of facility elevated planting strawberry continuous picking manipulator [J]. Computers and Electronics in Agriculture, 2025, 228:109703. DOI:10.1016/J.COMPAG.2024.109703.

[14] Fang Z, Liang X. Intelligent obstacle avoidance path planning method for picking manipulator combined with artificial potential field method [J]. Industrial Robot, 2022, 49(5):835-850. DOI:10.1108/IR-09-2021-0194.

[15] Sut J D, Sethuramalingam P. Deep learning-based object identification for grasping force control of a robotic soft end effector [J]. Robotics and Autonomous Systems, 2026, 199:105367. DOI:10.1016/J.ROBOT.2026.105367.