Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 16, No. 3, 2025

Structural Configuration and Adaptability Research of an Intelligent Harvesting Robot for Premium Tea in Gently Sloping Hilly Areas

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Abstract: This paper aims to explore the core structural configuration of an intelligent harvesting robot for premium tea in gently sloping hilly areas, with the goal of promoting the practical application of related intelligent equipment products. By systematically reviewing the functional modules and structural characteristics of existing intelligent harvesting equipment, typical framework models were extracted. A tea row model was constructed based on the target operational scenario, and evaluation analyses of matching degree and adaptability were conducted to identify feasible structural solutions. The study focused on in-depth discussions of core components such as the locomotion chassis and harvesting manipulator to determine the optimal combination. Results indicate that gantry-type frame structures exhibit high applicability in gently sloping hilly or plain areas, whereas quadruped robots demonstrate significant advantages in complex hilly terrains. This research provides theoretical foundations and practical references for the development and application of intelligent harvesting equipment for premium tea.

Keywords: Intelligent Harvesting Robot; Premium Tea; Structural Configuration.

1. Introduction

In China, premium tea serves as the core value of the tea industry, consistently accounting for 70% to 75% of domestic sales revenue [1]. However, during the production of premium tea, tea-plucking operations account for over 60% of the total labor input in tea garden management, making it the most frequent, labor-consuming, and strenuous task in tea production [2]. The plucking standards for premium tea mostly involve a single bud (just unfolded), one bud and one leaf, or one bud and two leaves. Some high-grade products impose even stricter requirements, using only single buds or one bud with one leaf, as shown in Fig. 1. The development of intelligent harvesting equipment for high-grade premium tea is still in its early stages [3].

Key research areas for intelligent tea-harvesting robots include bud recognition, plucking point positioning, and robotic mechanism design [4]. Numerous research teams have progressed to field-testing stages, employing various technologies and intelligent methods to tackle challenges such as automated detection, precise positioning, and efficient harvesting of premium tea in field conditions. The intelligent tea harvesters developed by these teams are capable of accurately harvesting tender shoots and largely meet functional requirements. Nevertheless, the suitability of these devices for regional conditions remains under exploration as teams work toward commercial viability. This paper analyzes the functional structures of existing equipment, extends the analysis, and identifies optimal structural configurations.

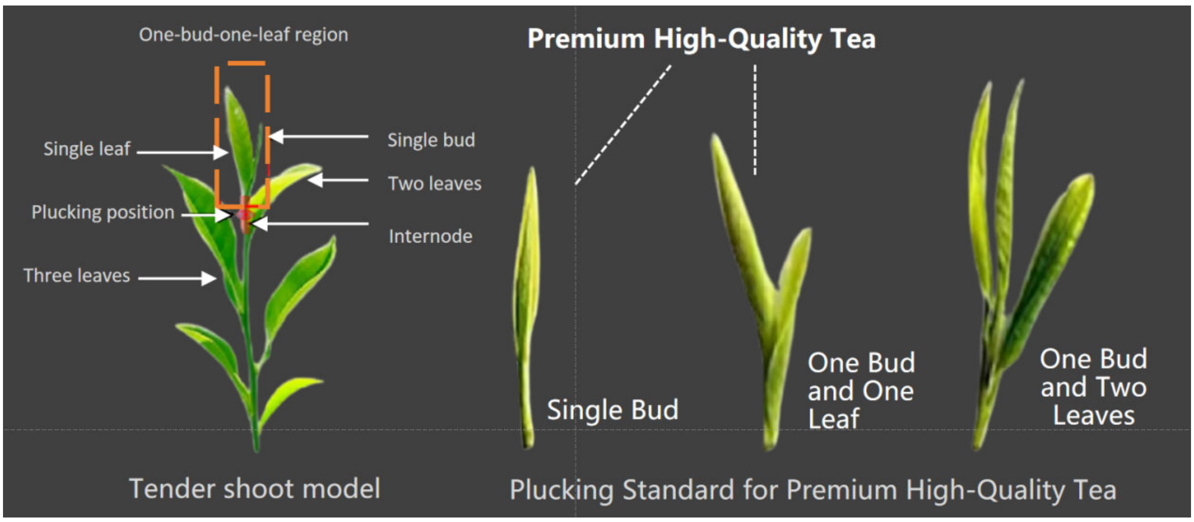


Figure 1. The structure of tea shoots is composed

2. Analysis of the Research Status of Intelligent Harvesting Equipment for Premium Tea in China

2.1. Analysis of Recognition and Positioning Technologies for Premium Tea

Domestically and internationally, technologies such as machine vision detection [5], AI-powered recognition and localization [6], robotic path planning [7], and the structure and design of end-effectors [8] have become increasingly mature. These advancements provide strong technical support for the development of intelligent harvesters for premium tea. A technical roadmap for the harvesting process is shown in Fig. 2.

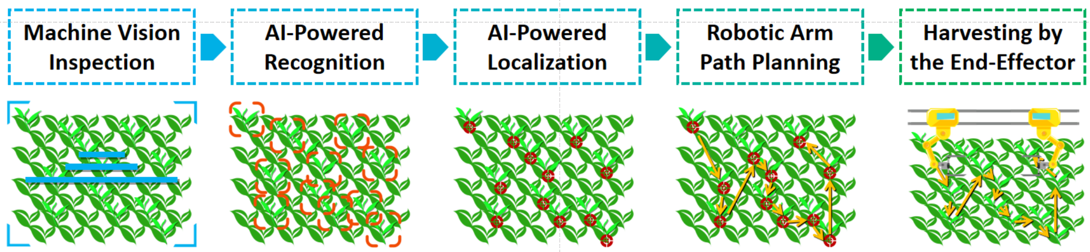


Figure 2. Famous tea mechanical picking technology roadmap

2.2. Performance Analysis of End-Effector Harvesting Devices

In the research on intelligent harvesting equipment for premium tea, some scholars have conducted a comparative analysis of different types of fresh tea leaf harvesters and handheld premium tea harvesters in terms of labor efficiency, one-bud-one-leaf harvesting rate, one-bud-two-leaf harvesting rate, and comprehensive harvesting cost [9].

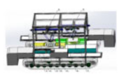
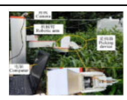
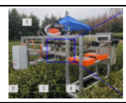
A horizontal comparison of four fresh tea harvesting devices reveals that, on the one hand, handheld premium tea harvesters achieve a harvesting rate of up to 100% for premium tea meeting the one-bud-one-leaf standard, significantly outperforming other equipment. This demonstrates their ability to consistently supply high-quality raw materials, in addition to having the lowest power consumption and energy costs. In contrast, other types of fresh tea harvesting equipment require secondary sorting after harvesting, which not only increases labor costs, service expenses, and time costs but also prolongs the exposure time of fresh leaves, adversely affecting tea quality.

On the other hand, handheld premium tea harvesters perform the worst in terms of labor efficiency, with the highest picking time and labor costs, currently unable to compete with other fresh tea harvesting equipment. Therefore, adopting intelligent harvesting robots to replace manual picking will effectively improve harvesting efficiency and reduce labor costs, thereby enhancing the quality and yield of premium tea.

2.3. Structural and Functional Analysis of Intelligent Harvesting Machines for Premium Tea

Yang Hualin et al. [10] developed a conceptual prototype for premium tea harvesting, employing a crawler chassis, a Delta parallel manipulator, and a self-designed end-effector. Shang Kaige et al. [11] conducted preliminary research on the structural design and control system of a tea harvesting robot using a cutting-type end-effector, proposing an integrated equipment structure combining a crawler mobile platform with a Delta parallel robot. Cao Chengmao et al. [12] designed a pinching-cutting combined harvesting device for premium tea tender shoots by mimicking the motion trajectory of the human hand and the finger-pinching action during manual tea plucking. Li Yatao et al. [13] constructed a prototype system for a premium tea harvesting robot tailored to the actual needs of tea gardens. The system consists of key components including a mobile sliding rail, a control system, an RGB-D camera, a 3P Delta parallel manipulator, an end-effector, and a negative-pressure recovery device. Dai Yunzhong et al. [14] developed an intelligent agricultural production device for precise harvesting of single buds in premium tea, based on new energy technology, a four-wheel drive structure, a three-dimensional picking motion device, and IoT technology. Yin Junfang et al. [15] applied human-machine-environment systems theory to analyze and design an inter-row premium tea harvesting machine. Wang Zhenwu et al. [16] designed a dog-like quadruped robotic tea harvesting machine in response to the complex conditions of the picking environment. The structural configurations of these devices are summarized in Table 1.

Table 1. Summary and Analysis of Existing Equipment

R&D Teams	Yang Hualin's team	Shang Kaige's team	Cao Chengmao's team	Li Yatao's team	Dai Yunzhong's team	Yin Junfang	Wang Zhenwu
Equipment Pictures							

Based on the summary and analysis of the aforementioned premium tea harvesting equipment, it is evident that various research teams have adopted both similar and distinctly different approaches in frame structures, drive mechanisms, and harvesting manipulator designs. Nevertheless, these three components are common to all devices, indicating that a stable frame structure is essential to ensure harvesting stability. Furthermore, the equipment must be capable of performing autonomous harvesting of premium tea via a robotic manipulator, while also achieving full coverage of entire tea rows through its drive system. This paper will focus on a comparative analysis of equipment frame structures, drive systems, and harvesting manipulators, aiming to identify the most suitable structural combination based on the topographic characteristics of gently sloping hilly areas.

3. Description of the Target Scenario and Model Construction

3.1. Product Positioning Analysis

The intelligent premium tea harvesting machine is specifically designed for large-scale standardized tea plantations to efficiently harvest premium tea (i.e., single buds and one-bud-one-leaf shoots) in a fully automated manner. The equipment requires high stability to ensure both precision and speed during the harvesting process. The target operational scenario is tea plantations in the gently sloping hilly regions of southern China, where the machine must possess certain climbing capabilities and shock absorption resistance. Additionally, as the soil in tea gardens is relatively soft, the equipment should be lightweight to prevent ground damage during long-term operation or avoid causing slope collapse due to excessive weight.

3.2. Target Scenario Description and Tea Row Model Construction

The target scenario for the intelligent premium tea harvesting machine is standardized tea plantations in gently sloping hilly areas. Taking the standardized tea plantation of Sichuan Tea Group as an example, field investigations show that the dimensions of the tea rows vary with seasons. The top width of a tea row measures approximately 1300–1400 mm, while the bottom width is about 1100 mm. The canopy height of the tea row ranges from 670 mm to 720 mm, and the inter-row spacing is between 300 mm and 500 mm. The tea canopy exhibits a flat surface, with leaves mostly growing vertically upward. During the peak spring tea harvesting season, the tea rows become fuller, which further reduces the inter-row spacing. An actual field scenario is illustrated in Fig. 3.

Figure 3. Structural analysis of tea plantations

Based on the above data, a cross-sectional model of the tea plantation was established. To ensure complete harvesting coverage and account for the certain compressibility of the edges of the tea rows, the following parameters were defined: a top width of the tea row of 1400 mm, a bottom width of 1100 mm, a canopy height of 700 mm, and an inter-row spacing of 300 mm. The top surface of the tea canopy is modeled as flat, as shown in Fig. 4.

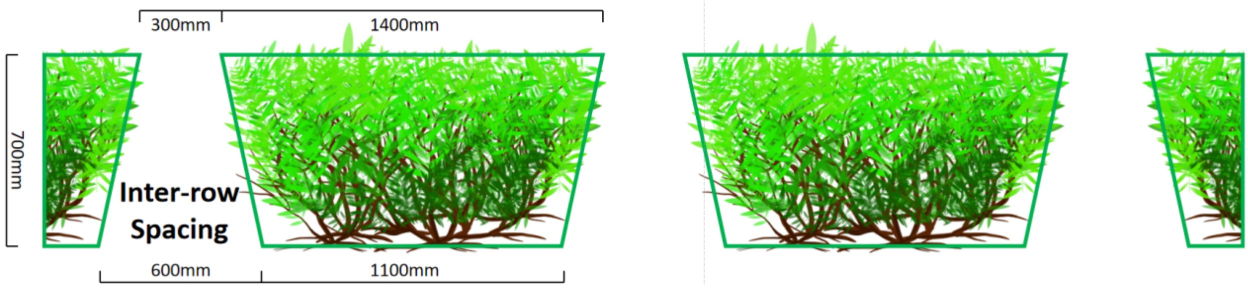


Figure 4. Chalong cross-section model

4. Extraction and Evaluation Analysis of Equipment Frame Structures

To meet the harvesting requirements of standardized tea plantations, existing intelligent premium tea harvesters can be structurally categorized into gantry-type, single-bridge-type, inter-row-type, and robotic dog configurations. Robotic dog-type harvesters can be further classified into inter-row robotic dogs and gantry robotic dogs. The locomotion framework, harvesting system, and recognition device of each configuration are extracted and summarized in terms of their form and structure, as shown in Table 2.

Table 2. Structural extraction of modeling

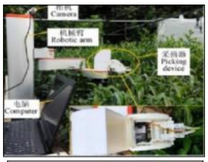
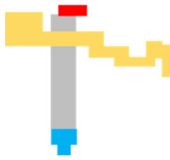
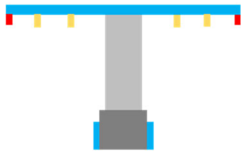
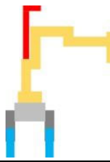
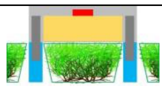
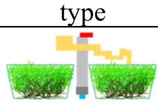
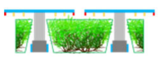
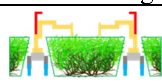
Equipment Pictures	Structural Classification	Form Factor Extraction	Locomotion Framework Harvesting System Recognition Device
	Gantry-type		
	Single-bridge-type		
	Inter-row-type		
	Gantry-type Robotic Dog		
	Inter-row Robotic Dog		

Table 3. Styling Structure Rating Scoring Sheet

Structural Classification	Gantry-type	Single-bridge type	Inter-row type	Gantry-type Robotic Dog	Inter-row Robotic Dog
Application Scenario Simulation					
Environmental Adaptability	8	4	6	9	9
System Reliability	9	6	4	8	6
Harvesting Range	8	9	8	8	7
Harvesting Efficiency	9	5	9	8	5
Design Rationale of the End-effector	98%	94%	23%	35%	87%
Composite Score	8.425	5.8	3.475	5.65	6.35

Following the extraction of structural configurations from existing equipment, structural models of five categories were obtained. Each model was applied to the cross-sectional tea row model. Through panel discussions and based on research into relevant equipment data, a comparative analysis was conducted on environmental applicability, equipment stability, harvesting range, harvesting efficiency, and rationality of the harvesting device. The evaluation method was determined as follows:

Composite Score = [Environmental Applicability + Equipment Stability + (Harvesting Range + Harvesting Efficiency) × Rationality of the Harvesting Device] / 4

In this formula, Environmental Applicability, Equipment Stability, Harvesting Range, and Harvesting Efficiency are rated on a 10-point scale, while the Rationality of the Harvesting Device is rated as a percentage coefficient. The rationale for this design is that the structural rationality of the harvesting device directly affects both the harvesting range and efficiency. Therefore, this coefficient is multiplied by the sum of the scores for harvesting range and efficiency, effectively serving as a weighting factor. The detailed evaluation analysis and scoring results are presented in Table 3.

Based on the above evaluation and analysis, the following conclusions are drawn regarding the five structural configurations:

(1) The gantry-type structure is well-suited for standardized tea plantations in gently sloping hilly areas. It offers the highest equipment stability and can fully cover the entire top surface of the tea row. Furthermore, it provides ample driving space for the harvesting system, allowing for diverse choices in robotic arm types. Additionally, multiple harvesting systems can be installed based on operational needs, significantly improving picking efficiency. Consequently, this structure received the highest overall score.

(2) The single-bridge-type structure requires track installation, resulting in high construction costs and poor suitability for widespread adoption. Its stability is moderate. Although it can cover the top surfaces of tea rows on both sides, offering the widest coverage, it is typically equipped with only one harvesting system. While it provides sufficient driving space for the picking system, its structural limitations restrict the selection of robotic arms, mostly to multi-axis models, leading to relatively low harvesting efficiency.

(3) The inter-row-type structure features a T-shaped expansion, using deployed arms to cover the top surfaces of tea rows on both sides. However, due to proportional constraints of the tea row structure, each arm can only cover half of the top harvesting area of a single tea row. Moreover, to maintain balance, both arms must be deployed simultaneously, greatly limiting its effectiveness when harvesting single tea rows on slopes. Additionally, the main body of the inter-row structure travels between tea rows, and its movement can be hindered during the lush growth period in spring or in plantations with narrow inter-row spacing. Finally, the harvesting system design in this structural model is inadequate for handling the complex and multi-dimensional harvesting environment of premium tea.

(4) Compared to the gantry-type structure, the gantry robotic dog offers stronger adaptability to complex terrain and can access most tea garden areas. However, the drive mechanism of large robotic dogs generates significant vibration, which may cause long-term damage to precision harvesting systems. Furthermore, insufficient vertical working height limits the extension of the harvesting system and restricts the diversity of available robotic arm types and end-effector designs.

(5) Similar to the gantry robotic dog, the inter-row robotic dog exhibits excellent environmental adaptability and can perform harvesting tasks in most tea plantation areas. However, like the inter-row-type structure, it is also affected by dense tea bush growth or narrow inter-row spacing. It can only cover half of the top area of a tea row for bud and leaf picking, and increasing the number of devices would be necessary to improve efficiency. Nevertheless, due to its compact size and simple structural design, it holds promise as an optimal structural solution for harvesting premium tea in complex hilly areas once robotic dog technology matures and costs decrease.

In summary, the gantry-type framework offers the most stable functionality and supports the widest range of compatible harvesting and drive systems, which explains its widespread adoption by numerous research teams. The following discussions on harvesting systems and drive systems will focus on options compatible with the gantry framework.

5. Evaluation and Analysis of Harvesting and Drive Systems

5.1. Structural Analysis and Evaluation of the Harvesting System

The harvesting system is the core functional component of an intelligent premium tea harvesting machine, serving as the key structure and end device responsible for plucking operations. Its core elements include the harvesting manipulator and the end-effector. Due to the complexity of premium tea harvesting, the manipulator must have a workspace capable of covering the entire top surface of the tea row while ensuring stability and precision during operation when equipped with the end-effector. Based on a review of relevant literature, equipment websites, and consultations with industry experts, five types of manipulators that meet both functional requirements and operational conditions have been selected for further analysis.

(1) Cable-Driven Redundant Manipulator: This type of manipulator is a bionic robot inspired by flexible biological structures such as elephant trunks and octopus tentacles. It uses cable-driven mechanisms to simulate the movement of biological tendons and can be categorized into three structural types: discretely rigid fully-driven, continuously flexible segment-driven, and rigid-flexible coupled segment-driven. Its advantages include high flexibility, a large workspace, and strong operability, making it suitable for precision tasks. However, it also has limitations such as structural complexity, insufficient stiffness, limited load capacity, and challenging control. This manipulator is widely used in aerospace inspection and maintenance, nuclear power plant operations, minimally invasive surgery in the medical field, and deep-sea high-pressure environments, demonstrating excellent adaptability and development potential [17].

(2) Cartesian Manipulator: This type of manipulator is a linear motion robot with three degrees of freedom, moving along the X, Y, and Z axes. It consists of a fixed base and a movable worktable, featuring a simple and easy-to-control structure. It is widely used in automation fields such as welding, assembly, and material handling. Its functional advantages include high precision, adjustable workspace, low cost, and strong reliability, making it particularly suitable for rectangular spatial characteristics, such as in kiwifruit orchards, where it performs end actions accurately. However, its flexibility is lower than that of articulated manipulators, its workspace is limited to a rectangular area, and its load capacity may be insufficient for special requirements. This manipulator is widely used in automated production lines, agricultural harvesting, scientific research laboratories, and logistics warehousing, demonstrating efficiency and economy, though its application in fields requiring high flexibility and complex operations is limited [18].

(3) Multi-Axis Serial Manipulator: A multi-axis serial manipulator is an industrial robot composed of multiple joints connected in series. The coordinated movement of these

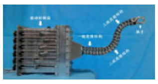
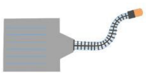
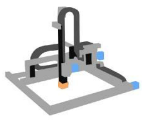
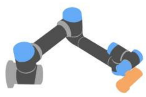
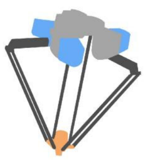
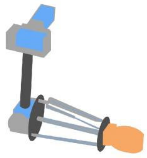
joints enables the end-effector to reach any position in three-dimensional space. It is commonly used in manufacturing, medical, and service industries. Its functional advantages include high flexibility, high precision, diverse applicability, and substantial load capacity, making it suitable for tasks such as assembly, welding, and surgical assistance. However, its workspace is limited by the range of joint motion, its control system is complex and costly, and it suffers from singularity issues and accuracy limitations due to mechanical constraints. While multi-axis serial manipulators play a key role in modern production and life due to their strong adaptability and efficiency, further optimization in precise control and stability remains a direction for future development [19].

(4) Parallel Delta Manipulator: This type of manipulator is an indispensable equipment in industrial automation due to its high speed, high precision, stability, and compact structure. It consists of a static platform, a moving platform, driving arms, and driven arms, providing three degrees of freedom for movement along the X, Y, and Z axes. Its closed-loop design and multi-chain collaborative operation enable excellent grasping precision and extremely high operating speeds, making it particularly suitable for high-speed sorting tasks in food, pharmaceutical, packaging, and logistics industries. The servo motors are installed on the fixed platform, reducing the load on the moving platform and further enhancing dynamic performance and stability. Additionally, its efficient structural design makes it outstanding in applications requiring high-precision positioning and dynamic performance. Although limited by workspace and singularities, its advantages are fully demonstrated in high-speed sorting and high-precision operations, making it an important tool for improving efficiency and quality in modern industrial fields [20].

(5) Hybrid Serial-Parallel Bionic Manipulator: This type of manipulator combines the advantages of serial and parallel structures, offering high compliance, high stiffness, and environmental adaptability, making it an innovation in the field of collaborative robots. The arm mimics the skeletal structure of the human arm, using a serial design to achieve a large motion space and operational flexibility. The wrist employs a 3SPS-1S parallel mechanism to enhance stiffness and load capacity. The use of Series Elastic Actuators (SEA) enables high compliance and environmental adaptability even when transmitting high torque, making it suitable for complex and uncertain working environments [21].

The structural configurations of the above five manipulators were extracted, and experts were invited to discuss and evaluate their performance in terms of accuracy, speed, stability, lightweight nature, workspace coverage, spatial adaptability, and load capacity on a 10-point scale. The evaluation process fully considered compatibility with the equipment framework, and comprehensive scores were calculated as average values, as shown in Table 4.

Table 4. Function evaluation and analysis of robotic arm

Designation	Cable-Driven Redundant Manipulator	Cartesian Robot	Multi-Axis Serial Manipulator	Parallel Delta Robot	Hybrid Serial-Parallel Bionic Manipulator
Image					
Form Factor & Structure Extraction					
Accuracy	9.5	9.5	8.3	9.7	9.3
Speed	3.2	6.8	8.5	9.9	4.5
Stability	7.5	9.5	9.6	9.5	9.5
Lightweight Nature	4	6.5	8.3	9.5	6.5
Workspace Coverage	8.2	9.8	9.7	8.8	8.6
Spatial Adaptability	4.3	9.7	9.8	8.5	8.5
Payload Capacity	2.3	9.8	9.8	9.2	9.4
Composite Score	5.57	8.8	9.14	9.3	8.04

Based on the functional structure and performance evaluation of the five manipulators, the following conclusions can be drawn: The cable-driven redundant manipulator exhibits the slowest driving speed, an overly bulky drive control box, poor end-effector load capacity, and low compatibility with harvesting end-effectors, making it poorly suited for this product. The hybrid serial-parallel bionic manipulator, despite its complex control output and relatively slow operating speed, shows moderate applicability. The Cartesian manipulator demonstrates excellent performance in accuracy, stability, workspace coverage, spatial adaptability, and load capacity. However, its speed and lightweight nature are moderate. Overall, it received a good comprehensive rating for product applicability and can be considered as a viable option. The multi-axis serial manipulator performs well in accuracy, speed, stability, and end-effector load capacity, with outstanding workspace coverage and spatial adaptability. It also received a good comprehensive rating for product applicability and can be selected as a candidate for integration. The parallel Delta manipulator excels in accuracy, speed, stability, and load capacity. Its top-drive unit can be mounted on a supporting structure, further reducing the weight of suspended components and achieving the best lightweight performance. Although its workspace and spatial adaptability require consideration of its motion range, adjustments can be made to achieve full coverage of the harvesting area. With an excellent comprehensive rating for product applicability, it is recommended as the preferred choice for integration.

5.2. Structural Analysis and Design of the Locomotion Framework System

As a core functional component of the intelligent premium tea harvesting machine, the performance of the locomotion framework system directly determines the equipment's stability, terrain adaptability, reachable areas, and suitability for different tea row configurations. Based on field investigations of the harvesting environment, the primary operational scope of the intelligent premium tea harvesting machine includes tea plantations, as well as transit between tea gardens, tea farmers' residences, enterprise warehouses, and equipment storage facilities, as shown in Fig. 5. It is essential to account for challenges such as discontinuous road surfaces, changes in ground structure, slopes, obstacle avoidance, and obstacle crossing that may be encountered during transitions between tea gardens and roads, as well as between different types of roads.

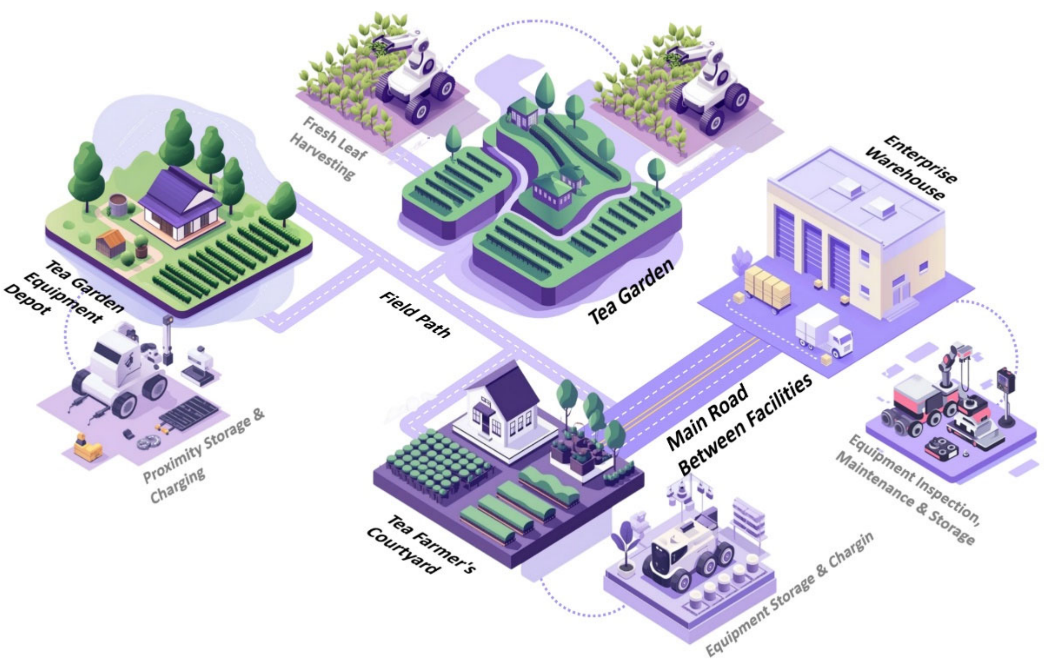
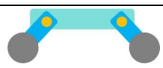
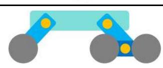
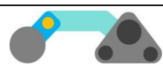
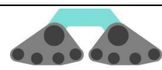


Figure 5. Roundtrip Scene Presets

The core components of the locomotion framework system include the support frame structure, shock absorbers, and drive units. To adapt to the complex environment of gently sloping hilly areas in southern China, the drive system often incorporates self-adaptive joint structures and walking mechanisms that combine multiple legs, multiple drives, or hybrid drive modes. Through a review of literature, patents, and existing equipment, drive systems suitable for the operational environment of the intelligent premium tea harvester were selected, including four-wheel drive [22], six-wheel drive [23], semi-tracked [24], and multi-segment tracked [25] configurations. Locomotion chassis models were extracted and evaluated on a 10-point scale based on the functional characteristics of their drive devices, to identify the most suitable drive structure for the intelligent premium tea harvesting machine. The evaluation results are presented in Table 5.

Table 5. Function evaluation and analysis of drive system

Product Image				
Locomotion Chassis Extraction				
Stability Performance	9.6	9.6	9.7	9.5
Balance Performance	9.5	9.7	7.5	7.5
Obstacle Negotiation Ability	8.5	9.3	9.3	9.4
Load-Bearing Capacity	8.5	9.5	9.8	9.9
Lightweight Design	9.1	9.0	5.5	3.5
Composite Score	9.04	9.42	8.36	7.96

Based on the evaluation and analysis of the functional structures and performance of the four drive systems, the following conclusions can be drawn:

(1) The four-wheel drive system is slightly deficient in obstacle-crossing ability and load-bearing capacity, yet it still meets the operational requirements of the intelligent premium tea harvesting machine. It demonstrates excellent stability and balance performance. Its independent movable joints allow the main harvesting equipment to maintain horizontal balance even on rugged terrain, fulfilling lightweight requirements. Overall, it shows good applicability.

(2) The six-wheel drive system further improves upon the four-wheel drive system in terms of obstacle-crossing ability, load-bearing capacity, stability, and balance performance, while still meeting lightweight requirements. It exhibits the best overall applicability.

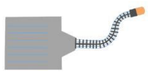
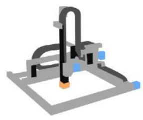
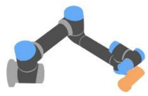
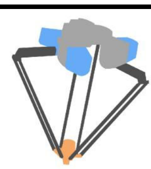
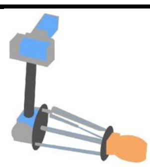
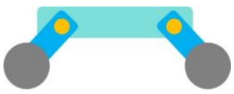
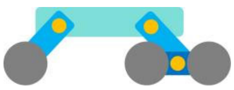
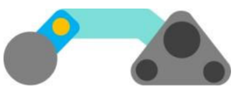
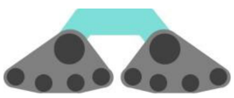
(3) The half-track drive system outperforms wheeled drives in stability, obstacle-crossing ability, and load-bearing capacity. However, due to the lack of independent movable joints and the large surface coverage of the tracks, its capability to maintain the balance of the main harvesting equipment on uneven terrain is significantly inferior to that of wheeled systems. Additionally, although it is a half-track structure, the weight of the track system poses challenges to meeting lightweight requirements. Overall, it demonstrates relatively good applicability.

(4) The multi-segment track drive system offers the best performance among the four systems in terms of stability, obstacle-crossing ability, and load-bearing capacity. Nevertheless, its ability to maintain equipment balance is the poorest among the four, and it is the heaviest, failing to meet lightweight requirements. Overall, its applicability is moderate.

5.3. Comprehensive Evaluation Analysis

Based on the evaluation coefficients obtained for different structures of the harvesting system and the drive system, an evaluation matrix was established. The final evaluation scores for each structural combination were calculated by multiplying the respective coefficients of the two systems, as shown in Table 6.

Table 6. Scoring of Key Functional Combinations Based on Gantry Frame Structure

Actuation System Harvesting System					
	50.35	79.55	82.63	84.07	72.68
	52.47	82.90	86.10	87.61	75.74
	46.57	73.57	76.41	77.75	67.21
	44.34	70.05	72.75	74.03	64.00

It is evident from the table that, under the gantry frame structure, five structural combinations have scored above 80 points. These can be prioritized as preferred equipment configurations in the practical design of premium tea harvesting devices. Among them, the multi-axis serial manipulator can be effectively paired with the robotic dog framework, serving as a reference design combination for harvesting premium tea in complex hilly areas.

6. Conclusion and Outlook

This study systematically analyzed the structural configuration of an intelligent tea-harvesting robot suitable for gently sloping hilly areas. By extracting typical frame structures, constructing a tea row model, and conducting adaptability evaluations, the comprehensive advantages of the gantry-type structure in plains and gently sloping hilly areas were clarified, along with the potential of quadruped robots in complex terrains. The research further demonstrated that, under the gantry framework, the combination of a parallel Delta manipulator and a six-wheel drive system delivered the best performance. Looking ahead, future work should focus on investigating multi-robot collaboration strategies, optimizing human-robot interaction and productization design, and enhancing robustness testing in complex terrains. These efforts will help promote the transition of intelligent tea-harvesting equipment from the laboratory to the market and advance the tea industry toward intelligent and precision development.

Acknowledgements

[1] Key Project of Yibin Vocational and Technical College: Development and Application of Intelligent Mountain Tea Harvesting Robot (No. ZRZD24-15)

[2] Project of Yibin Science and Technology Bureau:

Multi-Degree-of-Freedom Adjustable Z-Source Crystalline Silicon Photovoltaic Grid-Connected Inverter Topology and Its Leakage Current Suppression Technology (No. 2024MZ003)

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