

Design and Simulation of the Climbing Mechanism for a Multi-Point Embracing Coconut Harvesting Robot

Shichao Han, Siyu Wang, Haoyu You

North China University of Science and Technology, Tangshan 063210, China.

Abstract: To address the high risks associated with manual harvesting of tall coconut trees, as well as the insufficient trunk diameter adaptability and poor conformal stability of existing climbing devices, a multi-point embracing climbing mechanism for a coconut harvesting robot was designed to enhance its adaptability to varying trunk diameters and locally irregular trunk surfaces. The mechanism comprises three crawler units arranged circumferentially around the trunk, each equipped with two driving tracks. An electric push rod drives a bionic embracing arm to achieve active clamping and positional adjustment for varying trunk diameters. Within the tracks, support wheels are designed to swing around a fixed axis, with elastic restoring forces provided by tension springs. This configuration enables the tracks to accommodate local protrusions and variations in the surface curvature of the trunk. A mechanical model for the vertical climbing of the robot was established to analyze the clamping force, anti-slip stability, and driving parameters. Furthermore, three-dimensional simulation analyses were conducted under varying trunk diameters, local protrusions, and key load-bearing structures.

Keywords: Coconut harvesting robot; Crawler climbing; Multi-point embracing; Elastic conformal adaptation

1. Introduction

1.1. Research Background and Significance

Coconut is one of the most important economic crops in the tropical regions of China, widely utilized in the fields of food, beverages, and deep processing of agricultural products. With the continuous development of the coconut industry, the planting and processing stages are gradually transitioning toward mechanization and automation; however, the harvesting stage still heavily relies on manual labor. Due to the tall trunks of coconut trees and the fact that fruits are primarily distributed near the crown, traditional harvesting methods typically involve manual climbing or cutting with long poles. These methods are highly labor-intensive and pose significant risks associated with high-altitude operations. In Hainan, factors such as tree height and diverse planting terrains mean that the harvesting of coconuts and betel nuts has long been dominated by manual labor, leading to issues such as high labor intensity and low production efficiency. Therefore, achieving mechanized harvesting holds significant practical importance [2].

Compared to large aerial work platforms or vehicle-mounted harvesting equipment, tree-climbing harvesting robots can move by directly attaching to the trunk and transporting the harvesting mechanism to the vicinity of the crown, thereby reducing their dependence on ground road conditions and operating space. Li Xingxing verified the feasibility of a climbing coconut harvesting robot through dynamic simulation and prototype testing [1]. Furthermore, Yin Xinjie et al. conducted field tests involving climbing, harvesting, and descending on actual coconut trees, demonstrating the potential of such robots to partially replace manual high-altitude operations [3]. Therefore, the clamping stability, trunk diameter adaptability, and anti-slip performance of the climbing mechanism directly determine the safety and reliability of the entire machine during high-altitude operations.

1.2. Research Background and Significance

Currently, the climbing mechanisms for harvesting robots targeting tall crops such as coconuts primarily encompass three technical approaches: Mecanum wheel-based, elastic wheel-based, and crawler-based systems. Each type exhibits distinct characteristics in terms of kinematic performance, trunk diameter adaptability, and surface conformability.

1.2.1. Mecanum Wheel-based Climbing Mechanisms

Mecanum wheel-based mechanisms utilize tilted rollers on the wheel rim to generate friction components in different directions, enabling longitudinal climbing and circumferential rotation along the trunk through combinations of left- and right-handed wheels. These mechanisms are characterized by high flexibility and maneuverability. The climbing coconut harvesting machine designed by Li Jian et al. employs eight Mecanum wheels, with left- and right-handed wheels arranged in the upper and lower sections, respectively, achieving linear climbing and circumferential posture adjustment along the trunk. Li Xingxing further analyzed the kinematic mechanism of this system and verified its feasibility through dynamic simulation and prototype testing. He pointed out that while wheel-based mechanisms offer advantages such as high moving speed and strong load-bearing capacity, the small wheel-trunk contact area limits their adaptability to variations in trunk diameter and local surface irregularities. Consequently, contact pressure fluctuations and slippage are prone to occur under complex operating conditions.

1.2.2. Elastic Wheel-based Climbing Mechanisms

To address the issue of unstable clamping caused by variations in trunk diameter, researchers have introduced elastic adjustment mechanisms into traditional wheel-based systems to enhance trunk diameter adaptability. Su Ming et al. [5] designed an elastic tree-climbing machine featuring a three-point support structure composed of a driving wheel, a balancing wheel, and an automatic adjustment wheel. The automatic adjustment wheel achieves radial movement via a movable shaft and a spring, automatically adjusting the

clamping state according to changes in trunk diameter. Compared to rigid wheel-based mechanisms, this type maintains contact between the wheel and the trunk through elastic deformation, thereby improving clamping stability under varying trunk diameters. However, its elastic adjustment primarily targets overall changes in trunk diameter, and it still lacks sufficient continuous conformability to local irregular morphologies such as leaf scars, protrusions, and depressions.

1.2.3. Crawler-based Climbing Mechanisms

Characterized by a large contact area, continuous driving force, and strong load-bearing capacity, crawler-based mechanisms have become one of the primary research directions for climbing robots of tall crops in recent years. The coconut harvesting robot designed by Wang Yuhan et al. [7] employs a crawler transmission system. Its climbing mechanism consists of tracks, driving wheels, support wheels, and tensioning devices, achieving stable climbing through the friction between the tracks and the trunk. Compared to wheel-based mechanisms, tracks can form a larger continuous contact area, which facilitates the distribution of local pressure and improves friction utilization and climbing stability. Nevertheless, most existing crawler-based mechanisms utilize rigid support structures. When local protrusions, depressions, or curvature variations exist on the trunk surface, the conformal performance of the tracks degrades, easily causing localized pressure concentration and driving force fluctuations. Thus, their environmental adaptability to complex trunk surfaces still has room for further improvement.

1.3. Existing Problems in Current Mechanisms

Based on a comprehensive review of existing research, although current climbing mechanisms for coconut harvesting robots can achieve trunk clamping and longitudinal climbing, they still suffer from the following issues: First, wheel-based mechanisms primarily form localized contact with the trunk. When the surface morphology of the trunk changes, the stress state of the contact units tends to fluctuate. Second, existing elastic wheel-based mechanisms mainly address overall variations in trunk diameter through the radial movement of the wheels, exhibiting limited adaptability to local protrusions and short-distance curvature changes. Third, a reasonable coordination is required between the clamping force and anti-slip stability; insufficient clamping easily leads to slippage, while excessive clamping may increase the resistance to movement [2]. Furthermore, Li Xingxing tested the traversal capability of the mechanism by introducing local protrusions on the trunk during dynamic simulation [1], indicating that local irregular morphologies on the trunk are also critical factors affecting climbing stability.

To address these issues, this paper proposes a crawler-based climbing mechanism that combines multi-point embracing with elastic conformal adaptation. The comparison between the existing Mecanum wheel-based climbing mechanism and the proposed multi-point embracing crawler-based climbing mechanism is shown in Figure 1.

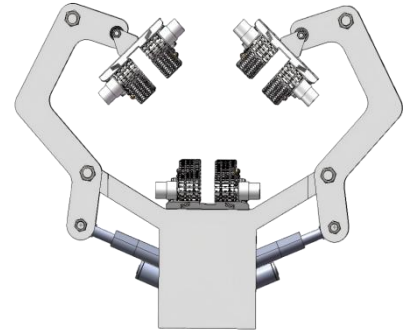
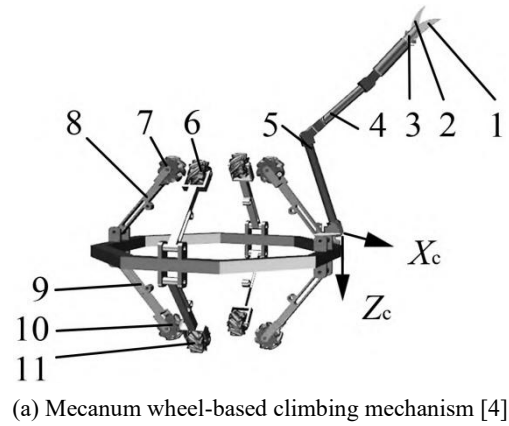


Figure 1. Comparison of typical coconut tree-climbing mechanisms

1.4. Main Research Contents of This Paper

To address the impact of overall trunk diameter variations and local surface irregularities on the stable climbing of robots, this paper designs a multi-point embracing climbing mechanism for a coconut harvesting robot. The mechanism comprises three crawler units arranged circumferentially around the trunk, with each unit equipped with two driving tracks. These multiple contact areas collectively provide clamping force and climbing driving force. Electric push rods are employed to drive the opening and closing of bionic embracing arms, adjusting the spatial positions of the crawler units according to the trunk diameter to achieve active embracing and clamping under varying trunk diameters. Compared to hydraulic drive schemes, electric push rods eliminate the need for hydraulic pumps, oil tanks, and complex pipelines, which is conducive to reducing the system volume and additional mass.

Support wheels capable of swinging around a fixed axis are installed inside the tracks, with elastic restoring forces provided by tension springs. When the tracks pass over local protrusions or areas with curvature variations on the trunk, the support wheels swing and induce elastic deformation of the tension springs, allowing the local profile of the tracks to adjust to the trunk surface. After passing through the irregular areas, the support wheels return to their original positions under the restoring force of the tension springs. This forms a dual-layer adaptive climbing approach characterized by "active adjustment for overall trunk diameter and elastic conformal adaptation for local surfaces."

The main tasks of this paper include the structural design of the multi-point embracing mechanism, the active crawler climbing mechanism, and the elastic conformal adaptation mechanism. A mechanical model for the robot's climbing and anti-slip performance is established. Furthermore, simulation

analyses are conducted under varying trunk diameters, local protrusions, and key load-bearing structures to evaluate the trunk diameter adaptability, elastic conformal performance, and structural reliability. Finally, the feasibility of the mechanism is verified through prototype testing. The overall research process and technical roadmap of this study are shown in Figure 2.

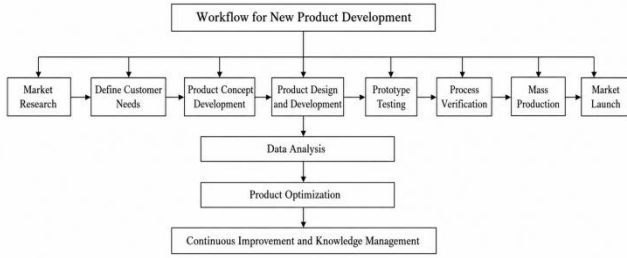


Figure 2. Technical roadmap of this research

2. Overall Scheme Design of the Multi-Point Embracing Climbing Robot

Given the characteristics of coconut tree trunks, such as a certain degree of taper, surface irregularity, and varying diameters with climbing height, this paper proposes the design of a multi-point embracing climbing robot. The robot is configured with three crawler units arranged circumferentially around the trunk. By integrating embracing arms, electric push rods, and elastic support mechanisms, it achieves a climbing mode that combines active clamping with passive conformal adaptation. Each crawler unit is equipped with two driving tracks, resulting in a total of six driving tracks in contact with the trunk. This configuration enhances the mechanism's trunk envelopment capability, driving force distribution capacity, and resistance to yaw. The overall structure of the robot primarily consists of the main frame, the multi-point embracing mechanism, the crawler climbing mechanism, the elastic support mechanism, and the upper harvesting mechanism. Modular connections are adopted among these modules to facilitate assembly, adjustment, and maintenance.

2.1. Characteristics of Coconut Tree Trunks and Design Requirements

Coconut tree trunks are generally frustum-shaped, with their diameters gradually decreasing as the height increases. As shown in Figure 3, the trunk presents obvious taper characteristics, and its surface contains leaf scars, protrusions, depressions, and other irregular structures, which affect the contact stability of the climbing mechanism. Meanwhile, the actual trunk surface exhibits irregular features such as leaf scars, protrusions, local depressions, and curvature variations, which cause the contact state of the climbing mechanism to change continuously during movement. If a fixed-size or rigid clamping mechanism is used, insufficient clamping force, track slippage, or excessive local pressure is likely to occur when the trunk diameter changes.

Therefore, the climbing mechanism must not only accommodate the target trunk diameter range but also possess a certain degree of radial adjustment capability and elastic compensation capability. Based on the characteristic that the trunk diameter gradually decreases along the height, the target trunk diameter is divided into two typical regions: the upper region (150–250 mm) and the lower region (250–400 mm), to cover the main operating range of the robot. Combining the

structural characteristics of coconut tree trunks and the operational requirements of the robot, the main design specifications are determined as shown in Table 1.

Table 1. Characteristics of coconut tree trunks and design specifications of the climbing mechanism

Parameter Name	Design Value	Design Significance
Trunk diameter	150–400 mm	Determines the adjustment range of the embracing mechanism
Trunk taper	3°–8°	Determines the adaptability of the mechanism to variations in trunk diameter
Surface features	Leaf scars, protrusions, local unevenness	Requires the tracks to possess elastic conformal adaptation capability
Track-trunk friction coefficient	0.3–0.6	Used for climbing driving force calculation and anti-slip verification
Total mass of the robot	≤15 kg	Reduces the demand for clamping force and driving power
Target climbing speed	0.1–0.3 m/s	Balances climbing efficiency and motion stability

Based on the above parameters, the climbing mechanism needs to maintain continuous and effective contact over a wide range of trunk diameter variations. Furthermore, it must ensure sufficient frictional driving force under the combined action of the robot's own weight, the load of the harvesting mechanism, and motion disturbances. Therefore, this paper adopts a composite adaptation approach of "active embracing adjustment + elastic conformal compensation," which lays the foundation for the subsequent design of the multi-point embracing mechanism and the elastic track mechanism.

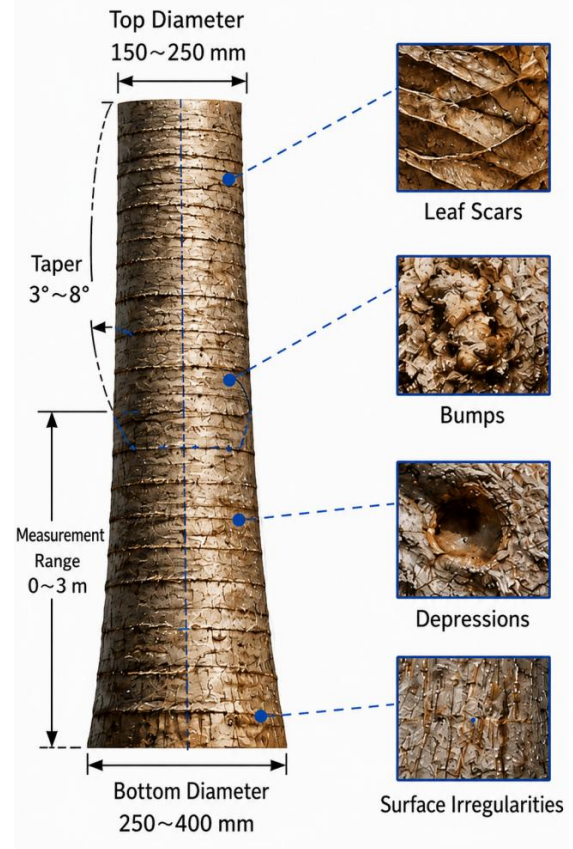


Figure 3. Schematic diagram of the structural parameters of the coconut tree trunk

2.2. Overall Structure of the Robot

The multi-point embracing climbing robot primarily consists of a main frame, two sets of embracing arms, electric push rods, three crawler units, six driving tracks, elastic support wheels, tension springs, and an upper harvesting mechanism. The overall three-dimensional structure is illustrated in Figure 5.

The main frame serves as the primary load-bearing component of the entire machine, functioning to connect the various climbing mechanisms and to mount the control system and the upper harvesting mechanism. The two sets of embracing arms are distributed circumferentially along the main frame. They are connected to the frame via revolute joints and are driven by electric push rods to open or close, thereby facilitating robot installation and enabling active adjustment in response to variations in trunk diameter.

A crawler unit is mounted at the end of each embracing arm. Each crawler unit is equipped with two driving tracks, resulting in a total of six driving tracks. The tracks are powered by independent driving motors, allowing multiple contact areas to collectively bear the robot's weight and climbing resistance. Elastic support wheels are installed within the crawler units, with tension springs providing a preload. This configuration allows the tracks to undergo a certain degree of radial displacement when encountering minor protrusions, depressions, or curvature variations on the trunk surface.

The control system is centered around an STM32H743 microcontroller, which interfaces with the track driving motors, electric push rods, rotary joints, telescopic components, and various sensors, forming a collaborative hub for the climbing, sensing, and harvesting modules. The hardware composition and signal interaction relationship of the control system are shown in Figure 4. Regarding the sensor configuration, pressure sensors are deployed at the track-trunk contact points to acquire real-time data on clamping force variations. A six-axis Inertial Measurement Unit (IMU) is mounted on the fuselage to monitor posture and vibration states, while infrared ranging sensors are utilized to obtain distance information between the robot, the trunk, and the end effector. Based on multi-sensor fusion feedback, the control platform adjusts the output of the electric push rods to ensure that the embracing mechanism maintains stable clamping and continuous climbing in complex coconut forest environments. Furthermore, limit detection and overload protection mechanisms are implemented to guarantee operational safety at high altitudes.

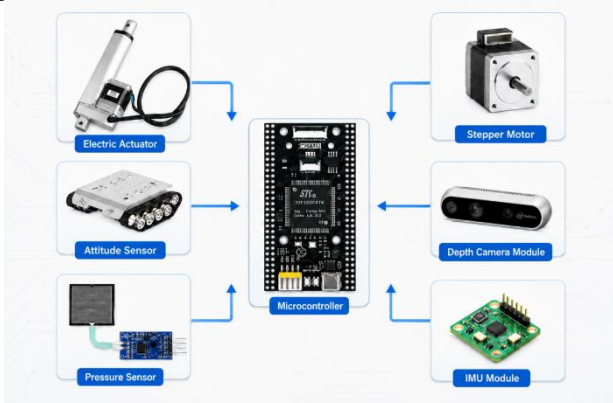


Figure 4. Block diagram of the control system hardware composition

A mounting platform for the harvesting mechanism is

situated above the main body of the robot. It is designed to carry the robotic arm and the end-effector harvesting device, thereby forming an integrated structure capable of trunk climbing, position holding, and coconut harvesting.



Figure 5. Overall three-dimensional structure of the robot

2.3. Layout of the Multi-Point Embracing Structure

To enhance the clamping stability of the robot on coconut tree trunks, this paper employs a multi-point embracing layout with three crawler units arranged circumferentially around the trunk. The three crawler units are connected to the main frame via independent embracing arms, forming multiple discrete contact areas between the robot and the trunk.

Compared to single-sided pressing or two-point clamping configurations, the multi-point embracing structure distributes the required clamping force across different contact points, thereby reducing the local pressure exerted on the trunk by a single track. Meanwhile, the six driving tracks collectively output the climbing driving force. While meeting the total driving force requirement, this configuration reduces the driving load borne by each individual track and improves the friction utilization rate between the tracks and the trunk.

When the robot tends to yaw due to the movement of the upper harvesting mechanism, trunk bending, or uneven force distribution on the tracks, the crawler units arranged in different directions form mutually constraining support relationships. The normal support forces generated at each contact point constitute a stable embracing load-bearing system, which can effectively inhibit the tilting and rotation of the fuselage around the trunk. Therefore, the multi-point embracing layout is not only used to generate the clamping force required for climbing but also enhances the robot's anti-yaw, anti-overturning, and posture-holding capabilities during high-altitude operations.

2.4. Working Principle

The working process of the multi-point embracing climbing robot mainly consists of four stages: installation and clamping, preload fitting, active climbing, and trunk diameter self-adaptation.

After the robot is installed on the coconut tree trunk, the extension and retraction of the electric push rods are first controlled to drive each embracing arm to close toward the

trunk around the connecting rotation axis, gradually bringing the three crawler units closer to the trunk. Once the tracks make contact with the trunk surface, the electric push rods continue to apply a certain clamping force, allowing multiple track contact points to collectively form an embracing state. Simultaneously, the tension springs located inside the crawler units exert a preload, pushing the elastic support wheels to keep the tracks in close contact with the trunk.

After clamping is completed, the six driving tracks operate synchronously. The driving wheels drive the tracks in a continuous loop, generating an upward frictional driving force between the tracks and the trunk. This force overcomes the robot's own weight and motion resistance, enabling the entire machine to climb upward along the trunk.

During the climbing process, when the trunk diameter undergoes significant changes with height, the system adjusts the opening and closing positions of the embracing arms via the electric push rods to achieve active adaptation to the trunk diameter variations. When the tracks pass over local irregular areas such as leaf scars, protrusions, and depressions, the elastic support wheels undergo minor floating under the action of the tension springs. This achieves passive conformal adaptation to the trunk surface through localized displacement of the tracks.

This forms a collaborative working mode of "active diameter adjustment via electric push rods—elastic preload via tension springs—passive conformal adaptation via tracks—active driving via multiple tracks," enabling the robot to maintain a relatively stable clamping state and climbing driving force under varying trunk diameters and irregular trunk surfaces.

3. Design of the Multi-Point Embracing and Elastic Conformal Mechanism

The multi-point embracing and elastic conformal mechanisms are the core components enabling the climbing robot to achieve stable tree embracing and continuous climbing. Considering the characteristics that coconut trunk diameters gradually change along the height and that the trunk surface features leaf scars and local protrusions, this paper adopts a combined design concept of "active embracing for diameter adjustment and passive elastic conformal adaptation." Specifically, the bionic embracing arms and electric push rods are responsible for large-scale trunk diameter adaptation and clamping force adjustment; the crawler units are responsible for outputting the climbing driving force; and the elastic mechanism composed of swinging support wheels and tension springs is used to compensate for local dimensional variations on the trunk surface. Through the collaborative work of these two types of adjustment mechanisms, the robot can maintain a relatively stable contact state under varying trunk diameters and irregular surface conditions.

3.1. Bionic Embracing Arm and Electric Push Rod Mechanism

The bionic embracing arm is the primary load-bearing component for the robot to form a multi-point embracing state. Its structural form is inspired by the joint movement characteristics of animal limbs embracing a trunk, and it consists of a main connecting arm, an intermediate rotating arm, and a crawler unit mounting end. The arm segments are hinged via pins, enabling the embracing arms to perform

opening and closing movements around a fixed rotation axis. The structural configuration of the bionic embracing arm and electric push rod mechanism is shown in Figure 6. The three embracing units are distributed circumferentially along the robot's main body, collectively forming a multi-point clamping structure that surrounds the trunk in the closed state.

The opening and closing range of the embracing arms is determined based on the target coconut trunk diameter range. During robot installation or when the trunk diameter is large, the arms expand outward to form a large enveloping space among the three crawler units. As the electric push rods retract, the embracing arms rotate toward the trunk around the hinge points, gradually bringing the crawler units closer to the trunk to establish contact. The maximum expanded state must meet the requirement for rapid robot installation, while the minimum closed state must ensure sufficient clamping margin on thinner trunks, thereby covering the aforementioned target trunk diameter range of 150–400 mm.

The electric push rod is installed between the main frame and the embracing arm, with one end hinged to the frame and the other end connected to the driving point of the embracing arm. The push rod utilizes a stepper motor and a worm gear screw transmission mechanism to convert the rotational motion of the stepper motor into linear displacement, driving the crawler bracket to achieve radial expansion and contraction adjustments. The stepper motor is controlled via pulses, and the relationship between the push rod displacement and the number of input pulses satisfies the following equation:

$$S = NP / i \quad (1)$$

where S is the displacement distance of the push rod; N is the number of input pulses; P is the lead of the screw; and i is the subdivision multiplier of the driver. By controlling the number of input pulses, the system can precisely adjust the expansion and contraction distance of the push rod, allowing the embracing mechanism to quickly adapt to trunks of different diameters. Compared to hydraulic drive schemes, hydraulic systems typically require additional auxiliary components such as hydraulic pumps, oil tanks, valve blocks, and pipelines, resulting in a relatively complex system composition[6]. For the small-scale tree-climbing robot in this study, the use of electric push rods can reduce the number of auxiliary components in the power system and facilitate direct connection with the electronic control system. In terms of structural compactness, mass control, layout flexibility, and maintenance convenience, this approach better meets the lightweight requirements of the entire machine. Therefore, this paper adopts electric push rods as the active adjustment components of the embracing mechanism. This satisfies the clamping requirements while reducing system complexity, providing an execution foundation for subsequent trunk diameter adaptive control.

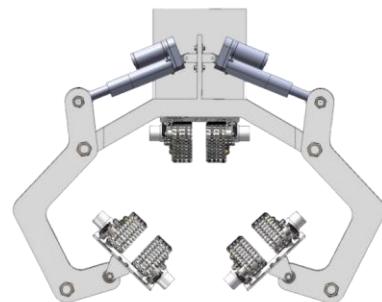


Figure 6. Structural diagram of the bionic embracing arm and electric push rod

3.2. Kinematic Relationship of the Embracing Mechanism Under Varying Trunk Diameters

During the upward climbing process of the robot along the coconut tree, the trunk diameter typically decreases gradually. Therefore, the embracing mechanism needs to adjust the spatial positions of the three crawler units in real time according to the trunk diameter variations. When the trunk diameter is relatively large, the electric push rods are in a relatively extended state, the embracing arms exhibit a larger opening angle, and the crawler units are positioned farther away from the robot's center. As the trunk diameter gradually decreases, the push rods drive the embracing arms to rotate inward through extension and retraction, synchronously bringing the three crawler units closer to the trunk center to maintain reasonable contact pressure. Letting θ represent the rotation angle of the embracing arm relative to the main frame and s represent the extension/retraction displacement of the push rod, a definite geometric constraint relationship is formed among the two variables, jointly determined by the hinge point position of the embracing arm, the installation point position of the push rod, and the connection dimensions. Ultimately, the trunk diameter variations are compensated through the kinematic chain of "push rod length variation—embracing arm angle variation—crawler unit radial position variation."

During the mechanism design process, it is necessary to critically verify three typical states: the maximum trunk diameter, the intermediate trunk diameter, and the minimum trunk diameter. A kinematic check of the entire opening and closing process of the embracing arms is conducted using a 3D assembly model to ensure that necessary structural clearances exist among the embracing arms, the main frame, the electric push rods, and adjacent crawler units. This prevents issues such as linkage jamming, component collisions, and mutual interference between crawler units during the opening and closing processes, thereby ensuring that the mechanism can continuously and smoothly complete the diameter adjustment actions within the target trunk diameter range.

3.3. Multi-Track Active Climbing Mechanism

The climbing drive section consists of three structurally identical crawler units. Each crawler unit is equipped with two parallel driving tracks, resulting in a total of six driving tracks arranged on the entire machine. A single crawler unit mainly comprises a track frame, a driving wheel, support wheels, tracks, a transmission shaft, and a driving motor, with its structure illustrated in Figure 7. The driving motor is installed at the end of the track frame and transmits torque to the driving wheel via a transmission mechanism. After meshing with the track, the driving wheel drives the track in a continuous loop, while the support wheels are used to support the working span of the track and maintain its basic motion trajectory. After the embracing mechanism generates the normal clamping force, frictional contact is formed between the tracks and the trunk. When the driving wheel drives the track to move, the trunk exerts a reverse frictional force on the track, thereby generating the climbing driving force for the robot along the trunk direction.

The three crawler units are distributed circumferentially around the trunk, and all six tracks are actively driven. Compared to schemes with only partial driving wheels, multi-

track active driving can distribute the required climbing traction force of the entire machine across multiple contact areas, reducing the load on individual driving units while enhancing the driving redundancy when friction conditions in a specific contact area degrade. Compared to conventional rigid wheel-based climbing methods, tracks possess a greater contact length and contact area with the trunk, forming a more continuous frictional contact region under identical clamping conditions. Particularly when the coconut tree surface features leaf scars, shallow protrusions, and local curvature variations, the tracks can rely on their multi-segment structure to achieve a certain degree of geometric conformability. Therefore, this study selects the dual-track crawler units as the primary climbing actuators for the robot, providing a structural foundation for the subsequent elastic conformal adaptation design.

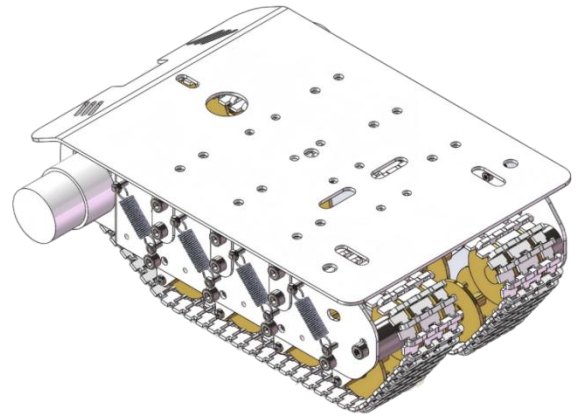


Figure 7. Three-dimensional structure diagram of a single crawler unit

3.4. Tension Spring-Based Elastic Conformal Mechanism

Relying solely on electric push rods to adjust the embracing arms can accommodate the overall diameter variations of the trunk. However, the surface of coconut trees also exhibits local irregularities such as leaf scars, protrusions, and depressions. During continuous climbing, if the track support structure is entirely rigidly connected, local protrusions can cause an instantaneous increase in contact pressure, potentially lifting the tracks off the surface. Conversely, passing over depressions may result in insufficient local contact, compromising the continuity of the frictional driving force. To address this, a swinging support wheel and tension spring-based elastic conformal mechanism is designed within the crawler units. The detailed structure of the swinging support wheel and tension spring mechanism is shown in Figure 8.

The support wheels are mounted at the ends of swinging components, which are hinged to the track frame via a fixed axis, allowing the support wheels to undergo small-angle rotations around the fixed axis. One end of the tension spring is connected to the swinging component, while the other end is fixed to the track frame, with a certain preload set during assembly. During normal climbing, the preload of the tension spring continuously pushes the support wheels toward the inner side of the tracks, thereby keeping the working spans of the tracks in close contact with the trunk surface. When the tracks pass over protrusions on the trunk, the protrusions first push the tracks outward, which in turn drives the support wheels and swinging components to deflect around the fixed

axis. As the swing angle increases, the length of the tension spring increases, generating a corresponding elastic restoring force. This restoring force is reapplied to the tracks through the swinging support wheels, allowing the tracks to yield outward to pass over the protrusion while maintaining a certain clamping force, thus preventing the tracks from completely detaching from the trunk surface.

The force exerted by the tension spring can be expressed as:

$$F_s = F_0 + k\Delta l \quad (2)$$

where F_s is the actual elastic force of the tension spring; F_0 is the preload generated by the initial pre-tension during assembly; k is the stiffness of the tension spring; and Δl is the additional elongation of the tension spring caused by the swinging displacement of the support wheel. According to this equation, as the height of the protrusion increases and the displacement of the swinging support wheel enlarges, the elongation of the tension spring increases accordingly, generating a greater restoring force to maintain the necessary conformal pressure on the tracks. After passing the protrusion, the external force decreases, and the tension spring releases part of its elastic potential energy, pulling the swinging component back to restore the support wheel to its original position. For local depressions, the support wheels can compensate by moving toward the trunk under the action of the tension spring, keeping the tracks in close contact with the surface. Therefore, this mechanism can achieve passive compensation for local terrain relying solely on mechanical elasticity without the need for additional sensors or independent actuators. It features a simple structure, direct response, and minimal mass increment. Its core function is not to alter the overall embracing size of the robot, but to adjust the local position of the track's working span within a small range, enabling the tracks to continuously conform to irregular trunk surfaces.

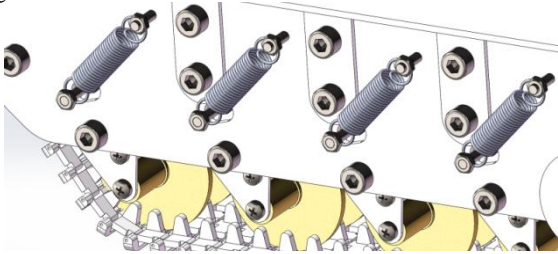


Figure 8. Detailed structural diagram of the swinging support wheel and tension spring

3.5. Dual-Layer Adaptive Mechanism

Integrating the aforementioned structures, the climbing robot in this paper forms a dual-layer adaptive mechanism comprising both active adjustment and passive compensation. The first layer is large-scale active adaptation targeting overall trunk dimension variations. When the robot climbs from a thicker to a thinner section, or is installed on coconut trees of different diameters, the electric push rods drive the embracing arms to open or close by altering their extension length. This further adjusts the positions of the three crawler units relative to the trunk center, enabling them to re-establish a stable clamping state over a wide range of radial dimension variations. The second layer is small-scale passive adaptation targeting local trunk surface variations. When the tracks pass over leaf scars, protrusions, or shallow depressions, the swinging support wheels undergo local floating around the fixed axis, and the tension springs expand and contract to provide restoring forces. This allows the tracks to complete local conformal compensation without altering the overall

posture of the embracing mechanism. The two adaptation methods complement each other in spatial scale and function. The electric push rods and embracing arms primarily solve the problem of "overall thickening or thinning of the trunk," while the swinging support wheels and tension springs mainly address the issue of "local unevenness of the bark." Together, they constitute the dual-layer adaptive climbing mechanism of "active embracing for diameter adjustment and passive elastic conformal adaptation," which ensures sufficient clamping and driving forces while enhancing the robot's adaptability to complex coconut tree surface conditions and its continuous climbing stability.

4. Mechanical Analysis of the Climbing Mechanism

To verify the clamping and driving capabilities of the multi-point embracing climbing mechanism on the surface of coconut trees, this chapter presents a mechanical analysis of the robot's stable climbing process. The robot relies on three crawler units to form a multi-point embrace, with each unit equipped with two driving tracks, resulting in six primary driving contact areas. By establishing a mechanical model for the entire machine, the normal clamping force, track-trunk friction, climbing resistance, and eccentric loads are analyzed. Furthermore, the anti-slip conditions, clamping force of the embracing arms, and parameters of the track driving system are determined, providing a theoretical basis for subsequent simulation analysis and motor selection.

4.1. Force Analysis During Whole-Machine Climbing

When the robot climbs upward along the coconut trunk at a constant velocity, its main forces include the total weight of the machine (G), the normal force on the tracks (N_i), the friction force exerted by the trunk on the tracks (F_{fi}), the climbing resistance (F_r), and the eccentric load generated by the upper harvesting mechanism, as illustrated in Figure 9.

The total weight of the machine acts vertically downward and can be expressed as:

$$G = mg \quad (3)$$

where m is the total mass of the robot and g is the acceleration due to gravity. Under the action of the embracing mechanism, the three crawler units press against the trunk, and the six tracks obtain normal forces N_i . The normal forces themselves do not directly provide the upward climbing driving force; rather, they generate tangential driving forces through the friction between the tracks and the trunk. The maximum friction force that can be provided by the i -th contact area satisfies:

$$F_{fi} \leq \mu_i N_i \quad (4)$$

where μ_i is the friction coefficient between the corresponding track and the trunk.

During actual motion, the robot must also overcome the equivalent climbing resistance F_r caused by internal track transmission, local deformation, and trunk surface irregularities. Additionally, the upper harvesting mechanism, robotic arm, and end effector are typically located above the climbing mechanism. When their center of mass deviates from the central axis of the trunk, an eccentric moment is formed:

$$M_e = Ge \quad (5)$$

where e is the eccentric distance between the center of mass of the entire machine and the central axis of the trunk. This

moment can easily cause the robot to yaw or overturn. Therefore, the three crawler units are arranged circumferentially at multiple points to utilize the normal forces at different contact positions to jointly form a constraining moment, thereby improving the posture stability of the entire machine.

4.2. Anti-Slip Stability Conditions

The fundamental condition for the robot to climb upward stably is that the total effective frictional driving force generated between the tracks and the trunk must overcome the total weight of the machine and the climbing resistance. Considering uncertainties such as changes in bark conditions, vibrations, and load fluctuations, a safety factor S is introduced. To prevent the robot from sliding downward, the following condition must be met:

$$\sum_{i=1}^6 F_{fi} \geq S(G + F_r) \quad (6)$$

Meanwhile, the friction force that each track contact area can generate is limited by the Coulomb friction condition, i.e., $F_{fi} \leq \mu_i N_i$

Therefore, when the forces on the six tracks are approximately uniform, the track-trunk friction coefficient is uniformly taken as μ , and the normal force borne by a single track is N , the equation becomes:

$$6\mu N \geq S(G + F_r) \quad (7)$$

From this, the minimum normal clamping force required for a single track to maintain stable climbing can be derived:

$$N_{\min} = \frac{S(G+F_r)}{6\mu} \quad (8)$$

This relationship indicates that the required clamping force of the robot is jointly affected by the total load, climbing resistance, friction coefficient, and safety factor. As the friction coefficient μ increases, the tracks can obtain sufficient frictional driving force under a smaller normal force; thus, $N_{\min}$ exhibits an inversely proportional decreasing trend with the increase of the friction coefficient. In practice, the friction conditions of actual coconut bark fluctuate due to moisture content, roughness, and surface attachments. Therefore, the mechanism should not be designed based solely on an ideal friction coefficient.

The safety factor S is used to compensate for dynamic factors such as local smoothness of the bark, uneven track loading, startup impact of the robot, and movement of the harvesting mechanism. Increasing S can enhance the anti-slip capability of the robot, but it simultaneously increases the required normal clamping force, subjecting the embracing arms, electric push rods, and trunk surface to greater loads. Therefore, a balance must be struck between anti-slip reliability and clamping load during design.

Based on the above relationship, the minimum normal clamping force under different friction coefficients can be calculated. The relationship curve between the friction coefficient and the minimum normal clamping force is shown in Figure 9, providing a basis for determining the rated thrust of the electric push rods and the clamping range of the embracing mechanism.

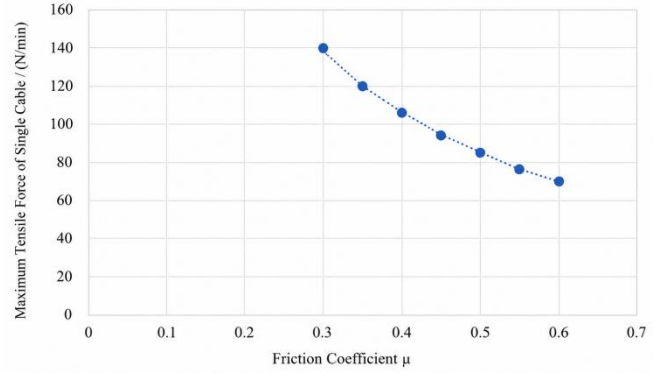


Figure 9. Relationship curve between friction coefficient and minimum normal clamping force

4.3. Clamping Force Analysis of the Embracing Arms

The axial thrust output by the electric push rods needs to be converted into the normal clamping force exerted by the crawler units on the trunk surface through the linkage structure of the embracing arms. Therefore, the relationship between the push rod thrust and the track normal force is not a simple linear correspondence but is jointly affected by the geometric dimensions and motion angle of the arms.

Taking a single embracing unit as the research object, let the output thrust of the electric push rod be F_a , the rotation angle of the embracing arm be θ , the effective angle between the push rod action line and the embracing arm be β , the distance from the push rod action point to the rotation axis of the embracing arm be l_a , and the effective moment arm from the normal force action line of the crawler unit to this rotation axis be l_N . Neglecting the minor moments generated by hinge friction and the weight of the components, the moment equilibrium at the rotation axis yields:

$$F_a l_a \sin \beta = N l_N \quad (9)$$

Therefore, the normal clamping force at a single track contact area can be expressed as:

$$N = \frac{F_a l_a \sin \beta}{l_N} \quad (10)$$

This can be further generalized as:

$$N = f(F_a, \theta, L) \quad (11)$$

where L represents the main geometric dimensions of the embracing arm. Since β , l_a , and l_N may all change with the arm angle θ during the rotation of the embracing arm, the mechanical force transmission ratio of the mechanism will also change with the trunk diameter.

When the trunk diameter is large, the embracing arms are in a largely expanded state, and the length of the electric push rod and the arm angle change accordingly. As the robot climbs to a thinner trunk area, the push rod gradually adjusts its length, the embracing arms close inward, and the crawler units move toward the trunk center. During this process, even if the electric push rod maintains the same output thrust, the final normal clamping force will still change due to variations in the moment arm ratio and the action angle.

Therefore, the design of the embracing mechanism cannot rely solely on the maximum thrust of the electric push rod for component selection. The force transmission relationships must be calculated separately for three typical states: maximum trunk diameter, intermediate trunk diameter, and minimum trunk diameter, ensuring that $N \geq N_{\min}$ is satisfied throughout the entire target trunk diameter range. At the same time, excessive clamping forces that cause additional

climbing resistance or damage to the trunk surface must be avoided.

4.4. Track Driving Force and Motor Parameters

The six driving tracks collectively bear the driving force required for the robot to climb upward. Considering the safety factor, the total driving force F_d required by the track system must satisfy:

$$F_d \geq S(G + F_r) \quad (12)$$

When the six tracks share the load approximately equally, the effective driving force required for a single track is:

$$F_{di} = \frac{F_d}{6} \quad (13)$$

Letting the pitch circle radius of the track driving wheel be r_d and the track transmission efficiency be η_t , the output torque required for the driving wheel of a single driving track is:

$$T_d = \frac{F_{di} r_d}{\eta_t} \quad (14)$$

If the target climbing speed of the robot is $\mathcal{V}$, the theoretical mechanical power required for the entire track driving system can be expressed as:

$$P = \frac{F_d \mathcal{V}}{\eta} \quad (15)$$

where η is the comprehensive efficiency composed of the motor, reduction mechanism, and track transmission. If the six tracks use identical driving units, the rated power of a single driving unit should have a certain reserve for startup and impact based on the theoretical average power.

If the rated output torque of the motor is T_m , the transmission ratio of the reduction mechanism is i , and the transmission efficiency is η_g , the output torque of the driving wheel satisfies:

$$T_d = T_m i \eta_g \quad (16)$$

From this, the required minimum reduction ratio can be determined:

$$i_{\min} = \frac{T_d}{T_m \eta_g} \quad (17)$$

When selecting the actual motor and reduction mechanism, the rated speed must also be verified to ensure that the linear velocity of the driving wheel meets the robot's target climbing speed requirements. By integrating the calculation results of driving force, torque, power, and speed, the main parameters of the track driving system can be determined.

5. Simulation Analysis

To verify the mechanical performance of the key load-bearing components of the multi-point embracing climbing mechanism under working loads, finite element models of the support arms and the connecting plates of the embracing arms were established to conduct static structural analyses. The simulation primarily focused on analyzing the stress distribution, deformation, and elastic strain levels of each component under the rated clamping force condition. Combined with material properties, the structural strength and stiffness were verified to provide a basis for subsequent prototype manufacturing and testing.

5.1. Simulation Model and Conditions

The support arms and connecting plates were extracted as the primary analysis objects based on the 3D assembly model of the robot. The support arm is the core load-bearing component in the bionic embracing arm that transmits the thrust of the electric push rod to the crawler units, while the

connecting plate is the critical connecting component between the embracing arm and the main frame. To reduce the computational scale, features such as threaded holes, small-size chamfers, and minor geometric details that have little impact on the overall stiffness were appropriately simplified without affecting the primary load transfer paths.

The finite element analysis was conducted using the Static Structural module in ANSYS Workbench. The material was set as 2A12 aluminum alloy, with an elastic modulus of 70 GPa, a Poisson's ratio of 0.33, and a yield strength of 265 MPa. Tetrahedral elements were used for meshing, with local refinement applied at the edges of the pin holes, geometric transitions, and load transfer locations to enhance the reliability of the stress and strain results. The boundary conditions were set according to the actual assembly relationships: fixed constraints were applied to the inner surfaces of the pin holes, and loads corresponding to the actual working conditions were applied at the electric push rod connection points and the crawler unit load-bearing points.

5.2. Static Analysis of the Support Arm

5.2.1. Equivalent Stress

The equivalent stress distribution of the support arm under the rated load is shown in Figure 10. As can be seen, the maximum equivalent stress of 28.13 MPa appears near the pin connection hole. This region is the primary load transfer path, and the stress concentration phenomenon is consistent with the mechanical characteristics of hole-edge load bearing. The stress distribution in the main body region is relatively uniform, with most areas exhibiting a low stress level.

The support arm is made of 2A12 aluminum alloy with a yield strength of 265 MPa. Calculated based on the maximum equivalent stress, the safety factor of the structure is:

$$n = \frac{\sigma_s}{\sigma_{\max}} = \frac{265}{28.13} \approx 9.4 \quad (18)$$

The safety factor is greater than the 1.5 to 3 times generally required in mechanical design, indicating that the support arm has sufficient strength margin under the rated load and will not undergo yield failure.

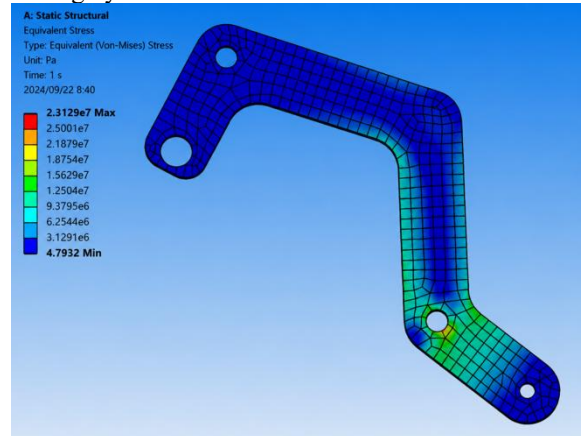


Figure 10. Equivalent stress nephogram of the support arm

5.2.2. Equivalent Elastic Strain

Equivalent elastic strain is an important indicator reflecting the degree of structural deformation under load. The distribution of equivalent elastic strain of the support arm under the rated load is shown in Figure 11. The maximum equivalent elastic strain is 3.9713×10^{-4} , located at the stress concentration area on the edge of the pin connection hole. The elastic strain in the main body region approaches zero, and the deformation distribution is uniform.

In engineering, a plastic strain of 0.2% is typically used as

the conditional yield criterion for materials without an obvious yield point. The current maximum elastic strain of 3.9713×10^{-4} is far below this threshold, indicating that the stress level of the support arm under the rated load is low, and the overall structure remains in the linear elastic working stage without plastic deformation. This result corroborates the conclusions of the equivalent stress analysis, further verifying that the support arm has sufficient structural safety margin under the rated load.

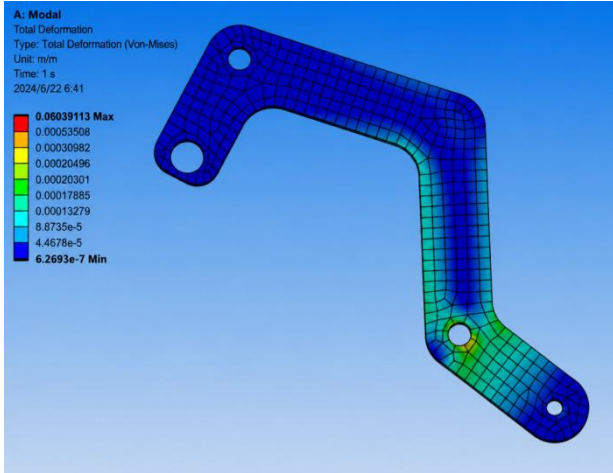


Figure 11. Equivalent elastic strain nephogram of the support arm

5.2.3. Total Deformation

The total deformation distribution of the support arm under the rated load is shown in Figure 12. The maximum deformation is 3.2814×10^{-4} m, occurring at the end of the support arm away from the constraint. The deformation in the main body region is between 0.05 and 0.15 mm, and the deformation trend is consistent with the mechanical characteristics of cantilever loading.

The total length of the support arm is approximately 300 mm, and the maximum relative deformation is about 0.11%. This deformation has a negligible impact on the clamping position of the crawler units and will not affect the normal opening and closing of the embracing arms or the conformal contact state between the tracks and the trunk. The results indicate that the support arm possesses sufficient stiffness reserve.

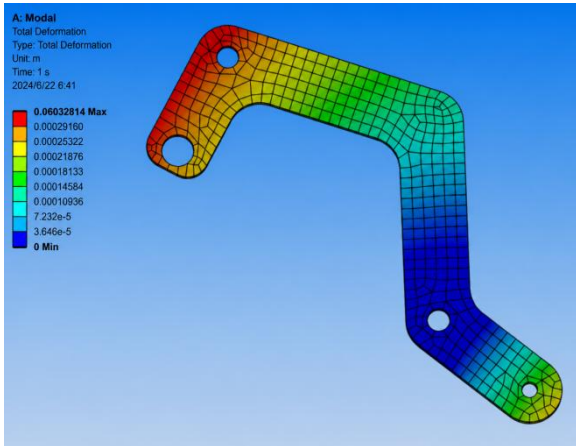


Figure 12. Total deformation nephogram of the support arm

5.3. Static Analysis of the Connecting Plate

The connecting plate is the critical connecting component between the bionic embracing arm and the main frame, and its strength directly affects the effective transmission of the clamping force of the entire machine. A static analysis was conducted on the connecting plate under the rated clamping

force condition to extract the equivalent elastic strain distribution.

The overall strain distribution of the connecting plate is relatively continuous, with most areas at a low strain level. The maximum equivalent elastic strain is 3.4167×10^{-6} , appearing in the area around the connecting holes, while the minimum equivalent elastic strain is approximately 2.2818×10^{-8} . From the nephogram, the main body region of the plate is dominated by the low-strain blue areas, with no large-scale high-strain concentration observed. This is consistent with the structural characteristic that the connecting plate bears local load transmission through the pin holes.

Based on the maximum equivalent strain and the elastic modulus of 2A12 aluminum alloy, the maximum equivalent stress of the connecting plate can be estimated as:

$$\sigma_{\max} = E \cdot \varepsilon_{\max} = 70 \times 10^9 \times 3.4167 \times 10^{-6} \approx 0.24 \text{ MPa} \quad (19)$$

This stress value is far below the yield strength of 265 MPa for 2A12 aluminum alloy, indicating a sufficient safety factor and that the structural strength of the connecting plate meets the requirements under the rated load. The connecting holes and geometric transition areas are regions of relatively concentrated stress. In future optimizations, priority should be given to increasing the fillet radius at the hole edges or appropriately enlarging the local cross-sectional dimensions to further improve the stress distribution. The equivalent elastic strain distribution of the connecting plate under the rated load is shown in Figure 13.

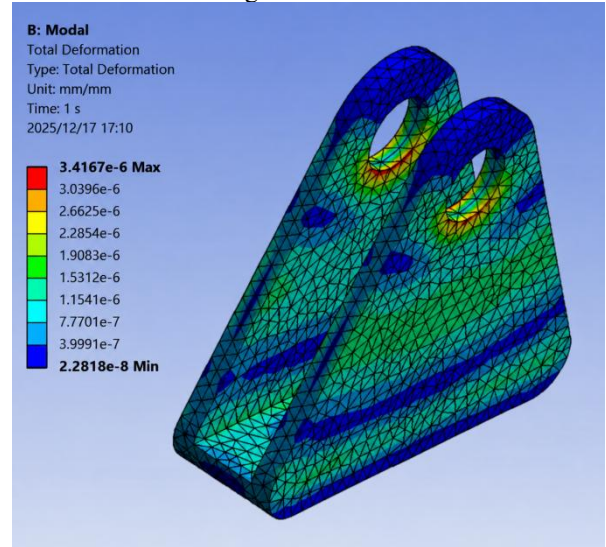


Figure 13. Equivalent elastic strain nephogram of the connecting plate

5.4. Simulation Conclusions

Based on the above simulation analyses, the following conclusions can be drawn:

(1) Under the rated clamping force condition, the maximum equivalent stress of the support arm is 28.13 MPa, which is far below the yield strength of 265 MPa for 2A12 aluminum alloy, yielding a safety factor of approximately 9.4. The maximum deformation is 0.328 mm, with a relative deformation of about 0.11%; both stiffness and strength meet the design requirements. The maximum equivalent elastic strain of the support arm is 3.9713×10^{-4} , which is far below the material's yield strain threshold of 0.002, indicating that the structure is completely in the linear elastic stage under working loads and will not undergo plastic deformation.

(2) The maximum equivalent elastic strain of the connecting plate is 3.4167×10^{-6} , corresponding to a maximum equivalent stress of approximately 0.24 MPa, indicating sufficient structural strength. The area around the connecting holes is a region of relatively concentrated stress.

Overall, the key load-bearing components of the designed multi-point embracing climbing mechanism possess sufficient strength and stiffness margins under the rated load. The structural design is rational and meets the safety and reliability requirements for the robot's high-altitude climbing operations.

6. Prototype Testing and Result Analysis

To verify the actual working performance of the multi-point embracing climbing mechanism under varying trunk diameters and local irregular surface conditions, a prototype testing platform was established based on the theoretical analysis and simulation research. Climbing tests under different trunk diameters and local protrusion traversal tests were conducted. The tests primarily focused on evaluating the robot's stable clamping capability, climbing speed, track slippage and mechanism jamming conditions, and the elastic conformal adaptation effect of the swinging support wheel and tension spring mechanism. The results from theoretical calculations, simulation analyses, and prototype tests were compared.

6.1. Prototype and Testing Platform

A prototype of the multi-point embracing climbing robot was built according to the aforementioned structural scheme. The prototype mainly consists of a main frame, bionic embracing arms, electric push rods, three sets of dual-track crawler units, six driving tracks, a swinging support wheel and tension spring elastic mechanism, and a drive control module. The tests utilized cylindrical simulated trunks, and three typical operating conditions with diameters of 150, 275, and 400 mm were selected to cover the design trunk diameter range of the mechanism.

The physical prototype of the multi-point embracing climbing robot is shown in Figure 14. The prototype consists of the main frame, bionic embracing arms, electric push rods, dual-track crawler units, elastic conformal mechanisms, and control modules, which are consistent with the structural design described above. During the testing process, the effective climbing distance for a single run was set to 1.5 m. A ruler was used to measure the climbing distance, and a timing device was used to record the motion time. The adjustment displacement under different trunk diameters was recorded via the displacement of the electric push rods. For the local protrusion tests, protrusion blocks of varying heights were set on the surface of the simulated trunk. The motion state of the swinging support wheels was observed frame-by-frame via video, and the elongation of the tension springs and the maximum swing angle were measured simultaneously. Repeated tests were conducted for each operating condition, and the average values were taken as the analysis results.



Figure 14. Physical photograph of the prototype

6.2. Climbing Tests Under Different Trunk Diameters

To verify the active adaptability of the electric push rod and bionic embracing arm mechanism to different trunk diameters, climbing tests were conducted on simulated trunks with diameters of 150, 275, and 400 mm, respectively. Before the tests, the opening and closing positions of the embracing arms were adjusted by controlling the electric push rods to ensure that the three sets of crawler units stably conformed to the trunk. Subsequently, the six driving tracks were activated to move the robot vertically upward along the trunk.

The average climbing speed of the robot was calculated using the following equation:

$$v = \frac{h}{t} \quad (20)$$

where v is the average climbing speed, h is the actual climbing distance of the robot, and t is the time required to complete this distance. The test results under different trunk diameter conditions are presented in Table 2.

Table 2. Prototype climbing test results under different trunk diameter conditions

Trunk Diameter (mm)	Push Rod Position Change (mm)	Climbing Distance (m)	Average Climbing Time (s)	Average Climbing Speed (m/s)
150	42	1.5	7.82	0.192
275	76	1.5	7.54	0.199
400	113	1.5	7.91	0.190

As shown in Table 3, the robot was able to complete the embracing clamping and continuous climbing under all three typical trunk diameter conditions. The average climbing speed ranged from 0.190 to 0.199 m/s, falling within the design target range of 0.1 to 0.3 m/s. As the trunk diameter increased, the position change of the electric push rod increased correspondingly, indicating that the embracing mechanism can adjust the spatial positions of the crawler units by altering the push rod stroke. Under the 400 mm trunk diameter condition, slight instantaneous slippage occurred, but no continuous downward sliding or mechanism jamming was observed, and the overall climbing process remained stable.

6.3. Local Protrusion Traversal Tests

To verify the adaptability of the tension spring-based

elastic conformal mechanism to local irregular trunk surfaces, protrusion blocks with heights of 5, 10, and 15 mm were set on the surface of the simulated trunk, and the robot was controlled to pass through the protrusion areas stably. During the tests, the focus was placed on observing the swinging condition of the support wheels, the elongation of the tension springs, the continuity of track contact, and the stability of the robot while passing over the protrusions.

The elastic force of the tension spring during operation can be expressed as:

$$F_s = F_0 + k\Delta l \quad (21)$$

where F_s is the actual elastic force of the tension spring; F_0 is the initial preload force of the tension spring; k is the stiffness of the tension spring; and Δl is the additional elongation of the tension spring relative to the preloaded state.

When the tracks contacted the local protrusions, the protrusions pushed the tracks and support wheels outward. The support wheels swung around the fixed axis, and the tension springs elongated further to generate a restoring force. After passing the highest point of the protrusion, the tension springs gradually contracted and pulled the support wheels back to their initial positions. The test results are presented in Table 3.

Table 3. Test Results of Local Protrusion Passability

Protrusion Height (mm)	Max Swing Angle of Support Wheel (°)	Max Additional Elongation of Tension Spring (mm)	Track Contact State
5	4.8	2.3	Continuous conformal contact
10	8.7	4.6	Basically continuous conformal contact
15	12.9	6.8	Weakened local contact

As the protrusion height increased, both the maximum swing angle of the support wheels and the elongation of the tension springs increased significantly. When the protrusion heights were 5 mm and 10 mm, the tracks were able to maintain continuous or basically continuous conformal contact. When the protrusion height increased to 15 mm, the local contact state weakened, but the remaining support areas were still able to maintain effective contact, and no complete detachment of the tracks occurred. Under all three operating conditions, the support wheels were able to return to their normal positions under the restoring force of the tension springs after passing the protrusions, indicating that the swinging support wheel and tension spring mechanism possesses a certain degree of local passive compensation capability.

6.4. Comparison of Theoretical, Simulation, and Experimental Results

To comprehensively evaluate the working performance of the multi-point embracing and elastic conformal mechanisms, the results from theoretical calculations, simulation analyses, and prototype tests were compared. First, based on the anti-slip stability conditions mentioned above, the minimum normal clamping force required for a single driving track is:

$$N_{\min} = \frac{S(G+F_r)}{6\mu} \quad (22)$$

The total weight of the machine is:

$$G = mg \quad (23)$$

where $N_{\min}$ is the minimum normal clamping force for a

single track; S is the safety factor; G is the total weight of the robot; F_r is the equivalent climbing resistance; μ is the friction coefficient between the track and the trunk; m is the total mass of the machine; and g is the acceleration due to gravity, taken as 9.81 m/s^2 . According to the design conditions, taking $m = 15 \text{ kg}$, $S = 1.5$, $F_r = 20 \text{ N}$, and $\mu = 0.45$, G is calculated as 147.15 N . Substituting this into the equation yields $N_{\min} = 92.86 \text{ N}$.

The relative error between the simulation values and the experimental values was calculated using the following equation:

$$\delta = \frac{|X_{\text{test}} - X_{\text{sim}}|}{X_{\text{sim}}} \times 100\% \quad (24)$$

where δ is the relative error; X_{test} is the prototype test value; and X_{sim} is the simulation result. A 275 mm trunk diameter and a 10 mm protrusion were selected as typical operating conditions, and the simulation and experimental results are presented in Table 4.

Table 4. Comparison of simulation and prototype test results

Comparison Indicator	Simulation Value	Experimental Value	Relative Error (%)
Normal Clamping Force per Track (N)	101.6	98.7	2.85
Climbing Speed (m/s)	0.205	0.199	2.93
Max Additional Elongation of Tension Spring (mm)	4.4	4.6	4.55
Max Swing Angle of Support Wheel (°)	8.4	8.7	3.57
Track Contact State	Basically continuous	Basically continuous	—

As shown in Table 5, under the typical operating condition, the normal clamping force per track obtained from the test was 98.7 N , which is slightly lower than the simulation value of 101.6 N but higher than the theoretical minimum clamping force of 92.86 N , thus satisfying the basic anti-slip requirements. The actual average climbing speed was 0.199 m/s , with a relative error of approximately 2.93% compared to the simulation value of 0.205 m/s . Under the 10 mm protrusion condition, the relative errors between the experimental and simulation results for the maximum elongation of the tension spring and the maximum swing angle of the support wheel were 4.55% and 3.57% , respectively, and their variation trends were basically consistent.

There are certain deviations between the experimental and simulation results, which are mainly related to actual hinge clearances, track transmission losses, tension spring stiffness errors, and variations in contact surface friction conditions. Overall, the results of the climbing tests under different trunk diameters and the local protrusion traversal tests demonstrate that the designed mechanism can utilize electric push rods to achieve active adjustment of the overall trunk diameter and employ the swinging support wheel and tension spring mechanism to accomplish passive conformal adaptation to local surfaces. This verifies the fundamental feasibility of the dual-layer adaptive scheme of "active embracing for diameter adjustment and passive elastic conformal adaptation."

7. Conclusions

Focusing on the issue of stable climbing under the conditions of overall trunk diameter variations and local

surface irregularities of coconut trees, this paper conducted structural design, mechanical analysis, and simulation research on a multi-point embracing climbing mechanism. The main conclusions are as follows:

A multi-point embracing climbing mechanism composed of three crawler units, six driving tracks, and bionic embracing arms was designed. The three crawler units form a stable envelopment around the trunk, collectively sharing the clamping force and climbing driving force. This design is conducive to improving the clamping stability of the robot on the trunk surface and enhancing its constraining capability against yaw and overturning tendencies.

Electric push rods are employed to drive the opening and closing of the bionic embracing arms, adjusting the positions of the crawler units relative to the trunk center by altering the push rod stroke, thereby achieving active adaptation to varying trunk diameters. This scheme can complete the adjustment of the embracing size within the target trunk diameter variation range, while taking into account structural compactness, lightweight design, and control convenience.

A swinging support wheel and tension spring elastic conformal mechanism is designed within the tracks, utilizing the preload of the tension springs to maintain contact between the tracks and the trunk surface. When passing over local protrusions or depressions, the support wheels can swing around a fixed axis, driving the tension springs to deform. Local profile compensation is achieved through the elastic restoring force, thereby realizing passive conformal fitting.

Through simulation analyses under varying trunk diameter conditions, local surface undulations, and key connecting structures, the geometric adaptability, elastic conformal capability, and structural response of the mechanism were

verified. The current simulation results indicate that the key connecting parts generally exhibit a low level of elastic strain. Subsequent prototype climbing and traversal tests can be conducted to further verify the consistency between the theoretical analysis and the actual working conditions.

References

- [1] Li, H. X. (2024). Research on key technologies of a climbing coconut harvesting robot [Doctoral dissertation]. Northeast Forestry University. <https://doi.org/10.27009/d.cnki.gdblu.2024.000896>.
- [2] Su, M. (2018). Research on development of a new type of coconut and areca nut harvesting machine. *China Equipment Engineering*, (17), 102–103.
- [3] Yin, X. J., Zhang, X., Zheng, H. C., et al. (2026). Design and experiment of a climbing coconut harvesting robot. *Journal of Fruit Science*. <https://doi.org/10.13925/j.cnki.gsxb.20250591>.
- [4] Li, J., Li, H. X., Zhang, W., et al. (2025). Design and experiment of a climbing coconut harvesting machine. *Chinese Journal of Agricultural Mechanization Science and Technology*, 46(8), 1–6, 21, 361. <https://doi.org/10.13733/j.jcam.issn.2095-5553.2025.08.001>.
- [5] Su, M., Han, H. M., & Song, Y. P. (2019). Design of an elastic tree-climbing machine for coconut and areca nut trees. *Modern Agricultural Machinery*, 46(11), 115–116.
- [6] Liang, D., & Zhang, J. (2010). Hydraulic system design for a coconut harvesting machine. *Hydraulics & Pneumatics*, (5), 27–28.
- [7] Wang, Y. H., Shao, L. Y., Jiang, S. D., et al. (2023). Mechanical system design of a coconut harvesting robot. *Construction Machinery*, 54(12), 111–114,12.