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Design of a Delta Configuration Tree Climbing Robot using Four-Bar Linkage

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ABSTRACT

This paper introduces the development and evaluation of a tree climbing robot (TCR) with the purpose of automating labour-intensive agricultural tasks, including coconut harvesting, agarwood collection and rubber tapping. The TCR was engineered to accommodate a wide range of tree trunk dimensions and bear loads exceeding its own weight, thereby enhancing efficiency and safety in such operations. The robot is equipped with a one-degree-of-freedom linear armature linkage, allowing it to move along both vertical and horizontal paths on tree trunks. The TCR's ability to operate on diverse tree surfaces is dependent on key design principles such as manoeuvrability, robustness, simplicity, adaptiveness, compactness and speed. The mechanical design incorporates a flexible gripping mechanism that adjusts to trunk diameters spanning from 20 cm to 50 cm, while the electrical systems guarantee accurate control and movement. The study incorporates practical experimentation of a functional prototype, which showcased the TCR's capacity to transport loads ranging from 5 to 10 kg in different circumstances. The results obtained from these tests, which were backed by design simulations, confirm the robot's efficacy and indicate potential areas for further improvement. The results suggest that the TCR provides a feasible solution for automating agricultural tasks that involve trees, which could result in substantial increases in productivity and enhanced worker safety. The TCR's pioneering design and successful testing highlight its potential influence on the agricultural robotics industry.

1. Introduction

There has been a recent increase in interest in using robotics and automation technologies in agriculture [1,2]. The driving force behind this trend is the necessity to optimize efficiency, decrease reliance on labour and enhance safety in agricultural practices [3,4]. Although many robots have been created to automate different agricultural tasks, only a small number have effectively progressed

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from being prototypes to becoming practical solutions [5]. Typical constraints encompass limited mobility, intricacy and a deficiency in user-friendliness [6]. The difficulties are especially noticeable in tree plantations, such as those engaged in coconut harvesting [7,8], agarwood extraction [9] and rubber tapping [10,11], where the work is repetitive, requires a lot of physical labour and involves a significant amount of manual effort.

Agarwood, also known as gaharu, illustrates the urgent requirement for automation in the field of agriculture [9]. Obtained from Aquilaria species, this valuable non-timber forest product is in great demand in traditional medicine, incense and perfume industries, especially in South and Southeast Asia, as well as the Middle East [12]. Excessive harvesting of Aquilaria trees due to the growing worldwide demand for agarwood is endangering their natural populations. This situation highlights the pressing requirement for creative solutions, such as robotics, to effectively and responsibly handle and gather agarwood and other tree-based resources [13,14].

With the continuous progress in climbing robot technologies, there is an increasing potential to utilize these advancements in agricultural settings [15]. From the late 1980s onwards, climbing robots have undergone substantial advancements, particularly in the areas of adhesion mechanisms and locomotion techniques [16]. Yet, the economic viability of these robots depends on their dependability and agility, which are crucial for efficient functioning in practical agricultural settings [17,18].

This paper introduces a novel TCR designed to address the specific challenges faced in arboreal agriculture [19]. TCR is engineered to adapt to various tree surfaces and conditions, overcoming obstacles such as tree sap, irregular bark and complex branch formations. TCR employs a linear armature linkage with one degree of freedom (DOF) to attain a balance of manoeuvrability, robustness, simplicity and speed. It also upholds a compact and lightweight configuration.

A key design feature of the TCR is its use of a four-bar linkage system, which plays a critical role in maintaining parallelism and ensuring a stable grip on various tree trunk sizes. Unlike prismatic or rotational joints, which have limited adaptability to irregular surfaces, the four-bar linkage offers several distinct advantages. First, it ensures that the gripping elements remain parallel to the tree surface, providing a uniform distribution of force and minimizing the risk of slippage, even on trunks with irregular or uneven bark. Second, the linkage system can easily adjust to different tree trunk sizes without requiring complex control systems, making the TCR suitable for a wide range of tree species and conditions. Third, compared to prismatic joints, which require precise alignment or rotational joints, which are prone to wear and require frequent maintenance, the four-bar linkage offers a simpler and more robust solution, minimizing mechanical complexity while enhancing durability. Finally, by maintaining parallelism, the four-bar linkage ensures that forces acting on the robot’s frame and the tree trunk are evenly distributed, reducing the risk of damage to both the robot and the tree and promoting sustainable harvesting practices.

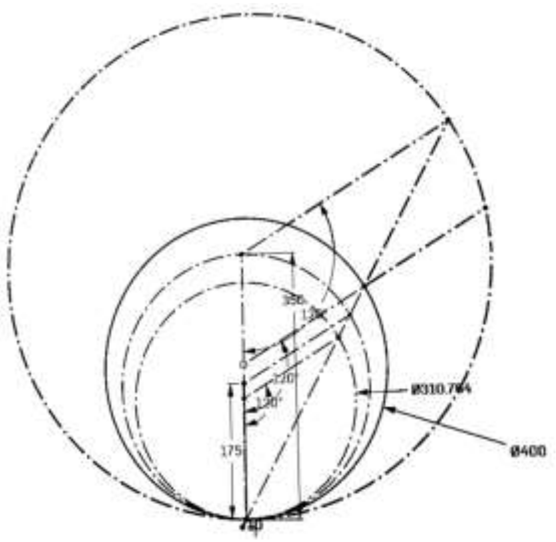
The importance of this study resides in its capacity to transform tree farming by offering a feasible and economical solution for arboreal agriculture. The TCR's capacity to manoeuvre through tree trunks of different sizes while carrying heavy loads has the potential to increase efficiency and alleviate the physical strain on workers in low-income countries where manual labour is prevalent. This research aims to advance automation technologies in sectors that traditionally rely on human labour by specifically exploring the practical application of climbing robots in agriculture.

2. Methodology

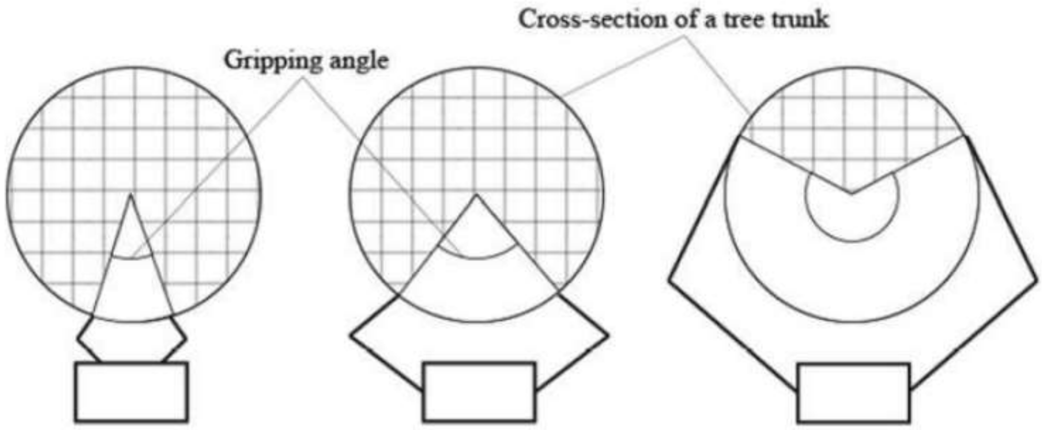
2.1 Geometry and Mechanical Design

The geometry of the TCR is essential for ensuring its stability and optimizing its performance during tree climbing. The design prioritizes the clamping arms, which have the task of fastening the robot to the tree trunk. Figure 1(a) illustrates the motion analysis required for the clamping arms to apply force linearly at a 120-degree angle from the robot's central hub. This method ensures that the clamping arms exert force effectively while preserving a direct motion trajectory. The TCR secures its grip by evenly distributing three clamping forces around the trunk, each positioned at 120-degree intervals. The deliberate deviation of the applied force by 30 degrees from the optimal angle is executed to preserve the simplicity of the arm mechanism, essential for practical application. The design prioritizes simplicity and user-friendliness, adhering to the core design principles of the TCR.

Optimizing the angle at which the robot grips and ensuring that the gripping force is perpendicular to the trunk's surface are critical for maintaining stability, particularly when the robot is moving on uneven or rough surfaces [20], as illustrated in Figure 1(b). To reduce the likelihood of slipping, ensure that the clamping force is aligned with the centre of the trunk. The literature, specifically the studies conducted by Xu *et al.,* [21] highlights the significance of optimizing these factors in climbing robots. The TCR's clamping mechanism is designed to achieve a balance between optimal gripping angles and a robust, user-friendly system by integrating geometric analysis and insights from literature [22,23]. The robot's equilibrium is improved, allowing it to securely grasp tree trunks of various surfaces, thereby enhancing its climbing performance.



(a)



(b)

Fig. 1. (a) Geometry of how the TCR will grip onto the varying sizes of tree trunk (b) Difference in gripping angle (Design of fast climbing robot for tree with multiple diverging branches)

2.2 Initial Sketches and Concepts

Figure 2 depicted the initial sketches and concepts of TCR. Utilizing additive manufacturing, also known as 3D printing, is crucial for optimizing the construction of the TCR and reducing costs [24]. This technique enables the fabrication of bespoke components utilizing a range of lightweight and long-lasting materials, thereby diminishing the overall weight of the robot [24]. A lighter TCR reduces the burden on motors and mechanical parts, thereby enhancing climbing efficiency and durability. Additive manufacturing offers the advantage of being able to choose materials that are customized to meet specific requirements. High-strength materials such as carbon fibre-reinforced polymers are well-suited for rigid components, whereas lighter, more flexible materials can be employed in areas requiring shock absorption. The meticulous choice of materials improves the TCR's performance, efficiency and structural integrity, guaranteeing durability in demanding conditions.

Moreover, the utilization of a readily accessible and reasonably priced 4V DC motor equipped with a planetary gear set as a linear actuator contributes to the TCR's cost efficiency. The planetary gear set guarantees accurate manipulation of the clamping mechanism, which is essential for maintaining a firm hold on the tree trunk. The TCR's design combines additive manufacturing, careful material selection and easily obtainable components, making it both practical and cost-effective. This enhances its feasibility and encourages its widespread use in tree climbing applications.

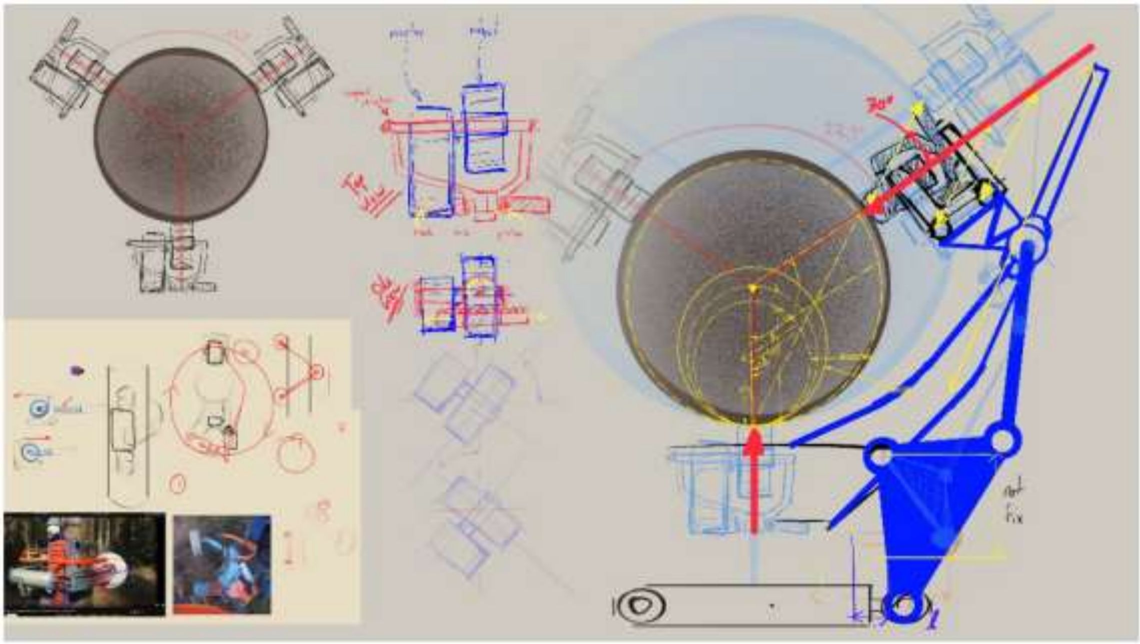


Fig. 2. Brainstorming ideas for the TCR

2.3 Model Finite Element Analysis

Finite Element Analysis (FEA) is used as a method of modelling and simulating to evaluate the structural soundness and efficiency of the TCR [25]. By subjecting the TCR design to virtual testing, any potential vulnerabilities or areas for enhancement can be detected before the creation of physical prototypes. FEA allows for the assessment of factors such as the distribution of stress, deformation and stability in response to different loads and environmental conditions. This analysis assists in improving the design and ensuring that the TCR fulfils the necessary safety and performance criteria.

2.4 Prototype and Analysis

In order to assess and improve the design of the TCR, a scaled-down prototype was created and put through a series of thorough examinations [26]. To begin, the grip force of the TCR was measured using load sensors, which allowed for a precise evaluation of the robot's clamping mechanism. This measurement was pivotal in assessing the efficacy and dependability of the TCR's traction on the tree trunk during climbing operations. After the analysis of grip force, a series of movement tests were carried out to assess the performance of the TCR under different load conditions. The robot underwent testing with payloads varying from 10% to 100% of its own weight. The tests provided valuable insights into the TCR's manoeuvrability and stability, demonstrating its ability to climb and carry various loads. This is crucial for evaluating its operational efficiency.

Additionally, durability testing played a crucial role in the analysis. The mechanical components of the TCR were subjected to conditions such as vibration, abrupt physical impacts and temperature fluctuations in order to evaluate their durability in demanding environments. The tests were conducted to verify the TCR's components' ability to endure the demanding conditions of tree climbing, thus validating the robot's durability over an extended period of time. Finally, the impact of different substances, such as tree sap, oil and water, on the mechanical parts of the TCR was investigated. The analysis played a crucial role in identifying possible weaknesses and guiding the choice of materials or protective measures to improve the robot's ability to withstand environmental challenges encountered while climbing trees. In summary, these tests yielded crucial data to facilitate the improvement of the TCR's design, guaranteeing its efficacy, longevity and dependability in practical scenarios.

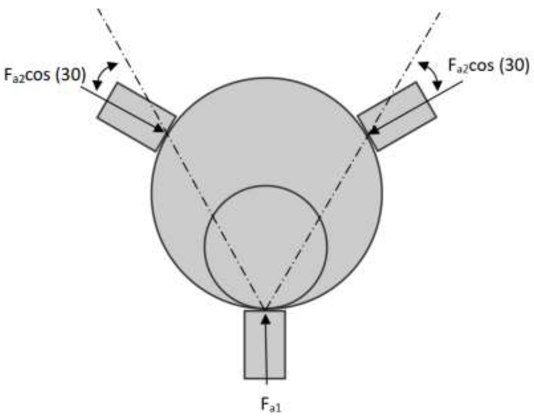
3. Results and Discussion

3.1 Geometry and Mechanical Design Analysis

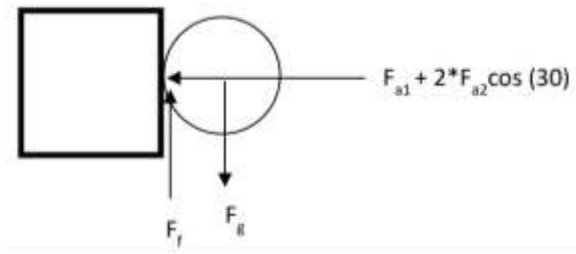
This chapter offers a comprehensive analysis of the design components and performance evaluations for the TCR. The text provides an overview of the results of the TCR's design and development process, giving a detailed explanation of the function of each component in the robot's overall operation. The mechanical design, encompassing components such as the wheel hub and robot arm, plays a vital role in enabling the robot to move and interact effectively with the surface of the tree. The mathematical model, which includes a force body diagram (FBD), is utilized to examine the forces exerted on the robot and forecast its behaviour under different circumstances. The electrical design primarily concerns the arrangement of circuits and power systems that guarantee the efficient operation and responsiveness of the TCR to control inputs. The software section provides a detailed explanation of the algorithms and programming that empower the TCR to execute intricate climbing manoeuvres and tasks.

3.1.1 Full body diagram

Figure 3(a) depicts the mechanical interaction between the TCR and the tree trunk as it ascends. The diagram illustrates a sizable circular shape representing the cross-section of the tree, with a smaller concentric circle representing a narrower trunk. The smaller circle experiences three forces: the normal force (Fa1) exerted by the TCR's body and two forces (Fa2) from the TCR's arms. The Fa2 forces are positioned symmetrically at a 30-degree angle from the tangent. This positioning ensures that Fa1 remains constant while the TCR adjusts its grip to accommodate trunk diameters of varying sizes. The FBD is vital for comprehending the TCR's clamping mechanism, which is necessary for maintaining stable tree traversal [27]. The illustrated forces exemplify the TCR's capacity to sustain a firm hold, essential for proficient climbing. Figure 3(b) demonstrates how the combined forces produce the required frictional forces to enable the wheels to achieve sufficient traction. The traction of the TCR allows it to elevate its own weight as well as any additional loads while ascending the tree [19,28].



(a)



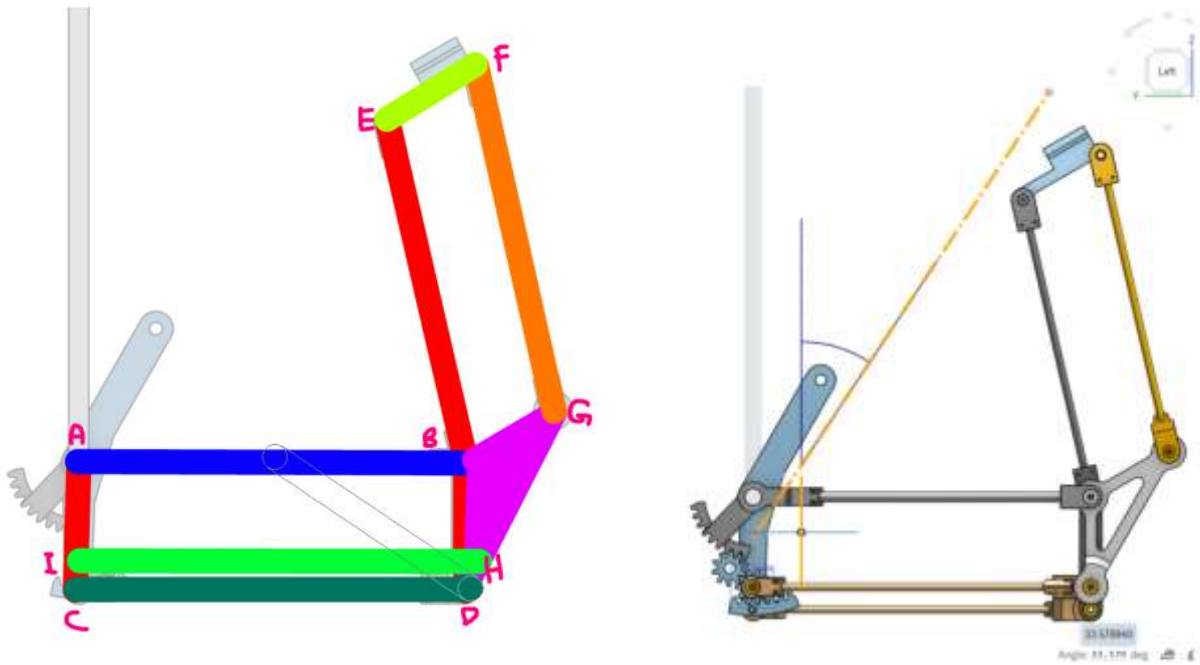
(b)

Fig. 3. (a) Top view FBD of the TCR (b) Side view FBD for the TCR

Figure 4(a) illustrates a four-bar linkage mechanism featuring a double parallelogram configuration. This configuration features crucial joints that connect movable links, creating a closed circuit. The double parallelogram configuration ensures that the input and output links remain parallel, irrespective of the mechanism's position [29]. This feature is particularly advantageous for preserving a uniform orientation in specific applications. The tree-climbing robot can employ this mechanism in its gripping system to guarantee a firm hold on the tree trunk during ascent.

The objective of this study is to examine the motion and force at a specific node in the double parallelogram linkage, identified as point E in Figure 4(a), when a horizontal force is exerted at point I. The analysis employs static equilibrium principles, focusing on the fixed point at AI and the structural attributes of the linkage. Understanding the behaviour of mechanical linkages under external loads is crucial for the design and improvement of mechanical systems like the TCR [19].

This study analyses the direction and magnitude of displacement at a designated node (point E) in a double parallelogram linkage when a horizontal force is exerted at point I. The analysis relies on the principles of static equilibrium, taking into account the fixed-point artificial intelligence and the structural complexities of the linkage. The reaction of mechanical linkages to external forces is crucial for the design and evaluation of mechanical systems. The TCR employs two identical and symmetrical arms, each featuring two double parallelogram linkages and a fixed-point AI. A horizontal force is exerted at point C. The integration of the gear chain with this system will yield a singular DOF, resulting in the end effector's movement towards point A at a 30-degree angle. This corresponds with the assessment of the delta configuration of the TCR, as illustrated in Figure 4(b).



(a) (b)

Fig. 4. (a) Double parallelogram four-bar linkage used in the TCR (b) Dash and dotted line in orange shows the path of the end effector from its starting position towards the centre point (33.58 deg.)

It was also done at two speeds, 18 m/s and 36 m/s, which correspond to 1×106 and 2×106 Reynolds numbers, as calculated from Eq. (1) and Eq. (2) and shown in Table 1. This was done so that the Reynolds number's effects could be separated. By substituting the given values into the formula, the maximum linear force that can be applied is approximately 25132.74 N. This is a significant amount of force, demonstrating the power of such a setup [19,21,27]. Note that this is a theoretical value and actual results may vary depending on factors such as friction and system efficiency.

The normal force FN exerted by the tree climbing robot (TCR) is given by:

$$FN = Fa1 + 2 \cdot Fa2 \cdot \cos(30) \quad (1)$$

The frictional force F_f, which is critical for maintaining grip, is calculated using:

$$F_f = \mu_s \cdot FN \quad (2)$$

where μ_s is the static friction coefficient. These equations are fundamental for assessing the TCR's grip and stability during climbing operations.

Table 1
Specifications of the robot based on calculations

Parameter	Value with Max Fl (25132.74 N)
Friction Force (Ff)	17165.98 - 34331.96 N
Total Normal Force (FN)	68663.92 N
Carrying Load	1749.85 kg (min) – 3499.69 kg (max)

It is crucial to note that this analysis does not factor in any decreases in the μ_s caused by environmental elements like slippery organic substances, weather disruptions and mechanical inefficiencies [30]. Generally, mechanical systems of this kind exhibit an efficiency ranging from 80% to 90%. Nevertheless, due to the presence of lenient tolerances and subpar construction, the losses can reach up to 95%, indicating a mere 5% efficiency. The input energy can be determined by multiplying the maximum force applied by the actuator with the distance it moves. Table 2 provides a summary of these estimations. However, it is important to note that the actual mechanical losses may differ due to variations in the system's efficiency and other factors, such as friction coefficients, which can be influenced by different environmental conditions.

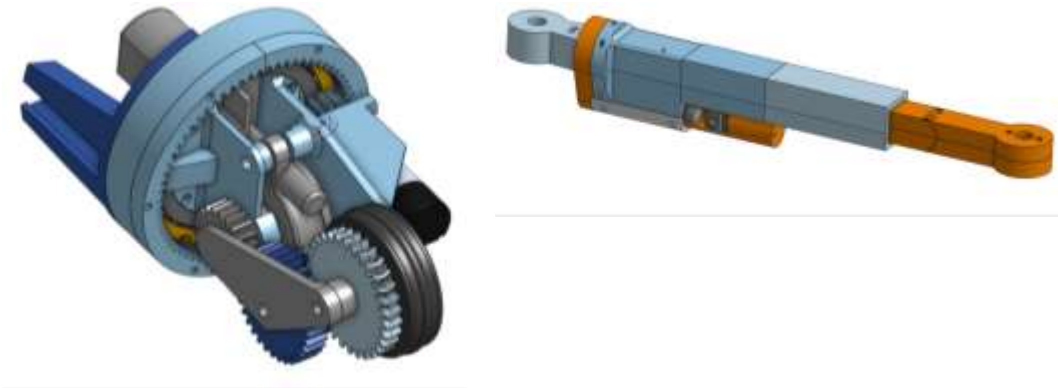
Table 2
Specifications of the robot based on calculations (5% efficiency)

Parameter	Value with Max Fl (1256.64 N)
Friction Force (Ff)	858.40 - 1716.90 N
Total Normal Force (FN)	3433.20 N
Carrying Load	87.50 kg (min) – 175.00 kg (max)

3.1.2 Mechanical design

The wheel hub of the TCR depicted in Figure 6(a) is engineered with a dual DOF system to augment its climbing capabilities. The initial DOF allows for rotation along the x-axis, enabling vertical upward movement along the tree trunk. Meanwhile, the second DOF allows rotation along the z-axis, facilitating horizontal movement around the trunk.

The hub is equipped with an 80mm Neoprene castor wheel that is driven by a MYBOTIC Power Window Motor. The motor functions at a voltage of 12VDC, with a specified speed of 60 revolutions per minute (RPM) and a specified torque of 2.9 Newton-meters (N·m) or 30 kilogram-force centimetres (kgf·cm). The device has a no-load speed of around 85 RPM and draws less than 3A of current when not carrying any load. When under load, the current consumption increases to less than 7A. The motor is connected to a gear system consisting of a driving gear with 15 teeth and a driven gear with 30 teeth, resulting in a gear ratio of 2:1. This gear ratio guarantees optimal power transfer and facilitates efficient vertical ascent.



(a) (b)

Fig. 6. CAD model of (a) wheel hub used (b) linear actuator

The TCR utilizes an SPG30E-270K motor for horizontal motion. This motor functions at a voltage of 12 volts, generates a rotational speed of 16.7 revolutions per minute and produces a torque of 1.37 Newton meters. The wheel is powered by a motor located inside a frame that is 3D-printed using a PLA composite material. The gear ratio of the wheel is 2.357:1. This configuration enables seamless and accurate navigation around the tree trunk.

The wheel hub design prioritizes modularity and simplicity in manufacturing. This approach facilitates future modifications and enhancements, in accordance with iterative design principles, to improve the performance and adaptability of the TCR [17,19].

In addition, the TCR includes a solitary linear actuator depicted in Figure 6(b) that is powered by a 4.2V motor that has a gear ratio of 10:1. The actuator has a maximum extension of 30 cm and can exert a linear force of approximately 25,132.74 N. The robot arm exerts a significant perpendicular force on the tree's surface. Nevertheless, the theoretical upper limit could be diminished in real-world scenarios because of factors like friction and inefficiencies within the system.

3.2 FEA Result

The Finite Element Analysis (FEA) simulation of the mechanical linkage system reveals minimal deformation of the parts under applied forces [25]. These findings indicate that the linear actuator and linkage mounts are operating within the elastic limit of the material, which is advantageous for preserving the structural integrity during use. The young modulus value of 2.3 GPa indicates that the parts possess a high level of stiffness, which is characteristic of certain printed materials and guarantees dependable performance in real-world scenarios, such as exerting pressure on tree trunks. The low levels of deformation are advantageous as they suggest that the system is likely to maintain its functionality and shape under the simulated conditions.

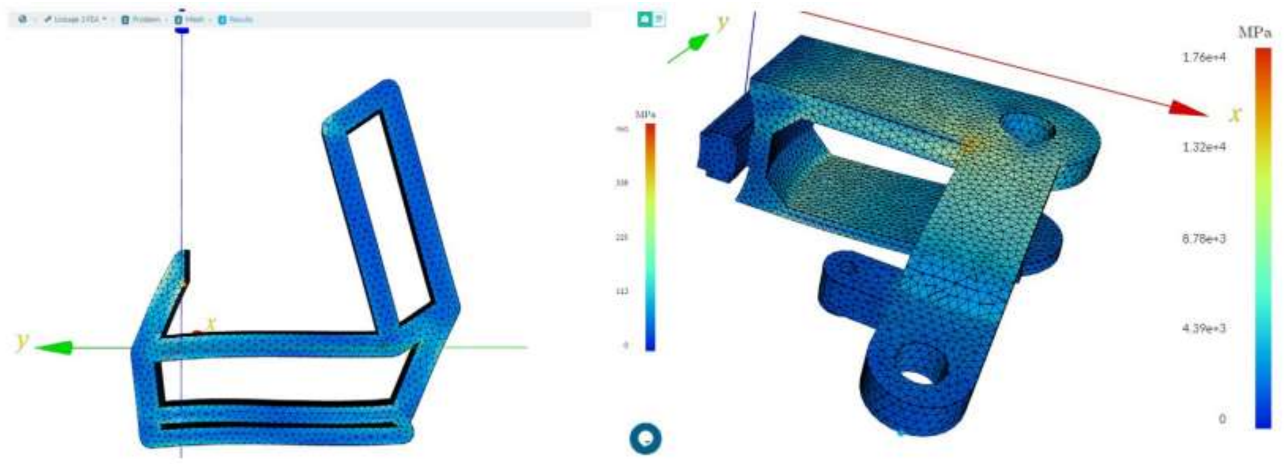


Fig. 7. FEA simulation result

4. Conclusions

The initial computations and simulations of the Delta Configuration TCR have shown encouraging outcomes, validating that the design satisfies the necessary weight-carrying requirements. The robot's capacity to bear both its own weight, which is estimated to be between 3 and 8 kg, as well as extra loads, highlights its durability and effectiveness. However, in order to guarantee the dependability and effectiveness of the design, additional empirical testing is necessary. Physical tests will verify the theoretical predictions and offer essential insights into the performance of the fully assembled prototype in real-world scenarios, which is crucial for improving the design and progressing towards the final stages of development.

The TCR, which employs a four-bar linkage mechanism, is a notable breakthrough in agricultural robotics, specifically for use in tree plantations. The design of this product effectively tackles important operational obstacles by integrating qualities such as agility, durability, ease of use, flexibility, small size and velocity. This versatile approach guarantees efficient performance on various tree surfaces and activities, including harvesting, agarwood collection and rubber tapping.

The effective application of these design principles, combined with practical experimentation, verifies the TCR's capacity to improve efficiency and safety in labour-intensive agricultural activities. Through the implementation of automation, the TCR has the potential to significantly decrease the need for manual labour and enhance the management of plantations. As the adoption of the TCR increases and development continues, it has the potential to revolutionize agricultural practices, resulting in safer and more efficient operations, while also tackling major challenges in the sector. The combination of empirical testing outcomes with inventive design principles emphasizes the revolutionary influence of the TCR on agricultural robotics.

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