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Mechanisms for Robotic Palm Climbing: A Systematic Review

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Abstract

Coconut and arecanut palm growers are facing an acute shortage of skilled human climbers for harvesting nuts, which has become a serious challenge for the plantation sector. Robotics and automation offer a promising solution to this problem. In this paper, traditional palm-climbing methods and the limitations associated with them are reviewed. In addition, the various mechanisms involved in the design and development of robotic palm climbers are discussed in detail. The study aims to provide a comprehensive overview of existing climbing techniques and to highlight technological advancements that can improve safety, efficiency, and sustainability in palm tree harvesting.

Keywords: Robot, palm climber, Gripping mechanism, Climbing mechanism, Arecanut.

1. Introduction

Palms are unbranched evergreen trees found in tropical and warm regions, characterized by a crown of long feather- or fan-shaped leaves and a trunk marked by regular patterns of old leaf scars. There are more than 2,500 species of palm trees worldwide, most of which belong to the Arecaceae family (Christenhusz and Byng, 2016). These evergreen plants may grow as shrubs, trees, or woody vines known as lianas. Palms are primarily cultivated for their nuts, from which a wide variety of products are derived, with oil being the most significant. Coconut, date palm, oil palm, and arecanut are among the most commonly cultivated commercial palms.

Coconut and arecanut palms are extensively cultivated in Kerala. In the rural regions of Karnataka and Kerala, agriculture is the primary source of livelihood, with arecanut and coconut being the major crops (Basavaraja et al., 2015). India leads the world in coconut production, despite having only two million hectares under coconut cultivation compared to the Philippines, which has 3.8 million hectares. India is also the world's largest producer and consumer of arecanut, contributing over 50% of global production. Within India, Karnataka is the largest arecanut-producing state (Hegde and Deal, 2014).

One of the main threats to this industry is the increasing cost of production coupled with a declining labor force. Another major constraint is the acute shortage of laborers for harvesting nuts. Operations such as nut harvesting and pesticide spraying must be carried out at the crown of the tree, which requires workers to climb the trees manually. Although this task may appear simple, it is in reality dangerous and labor-intensive. Moreover, only trained laborers can perform this work effectively.

Traditionally, nut harvesting has been carried out by men from economically disadvantaged sections of society. However, with increasing literacy rates and awareness of better-paying job opportunities, the number of individuals willing to climb palm trees for harvesting has declined significantly. As these workers typically lack insurance coverage, any accidents during climbing can severely affect their entire families. Furthermore, falls from great heights often leave climbers bedridden for the rest of their lives (Megalingam et al., 2015)

2. TRADITIONAL CLIMBING METHODS

Traditional climbing methods are the most commonly used techniques for nut harvesting and are practiced by local workers who are highly trained and experienced. Based on movement and technique, traditional climbing methods can be classified into frog type, walking type, pole type, and ladder type.

In the frog-type climbing method commonly used in Kerala, a climber can ascend the tree at a speed of approximately 0.5 m/s. In the walking-type climbing method, trees are connected near the crown using a multi-rope system. In this case, the climber does not need to climb each tree individually but can move from one tree to another with the help of the ropeway.

Traditional ladders made of bamboo poles, steel, or aluminum are used to climb small trees or up to half the height of taller plants to support associated crops such as black pepper climbers. In some regions, modified telescopic ladders are also in use. Pole harvesting, practiced in Karnataka, uses bamboo poles, galvanized iron (GI) pipes, aluminum pipes, and lightweight alloy pipes as harvesting poles (Kushwaha and Singh, 2015).

3. PROBLEMS ASSOCIATED WITH EXISTING CLIMBING METHODS

There are several problems associated with existing harvesting methods. These methods are dangerous, slow, and expensive. Climbing to a height of up to 24 meters and working at such heights is extremely difficult. The tree trunk is rough, and the leaves have sharp spines that can injure workers. In addition, climbers may face hazards from hidden insects and snakes in the crown of the tree.

Although many mechanical and robotic climbers have been developed for climbing walls and trees, mechanical palm climbers are currently more popular for coconut and arecanut palms. However, there are no fully developed robotic devices specifically designed for climbing, spraying, and harvesting palms (Eliachar et al., 1992), and many of the machines designed so far are not sufficiently safe (Dhale et al., 2017). Considering this scenario, the mechanisms used in the design and development of palm climbers are reviewed in this paper. This review is intended to support future research and development of autonomous and semi-autonomous palm tree climbers.

4. LITERATURE REVIEW

Climbing robots capable of making upward and downward movements on regular structures such as poles, walls, and domes have been developed by several researchers. However, the majority of these designs are not capable of climbing trees. This limitation is mainly due to the irregular surface of tree trunks and the variation in diameter along their length (Harikrishna et al., 2014). In addition, palm and tree climbing requires greater agility and high maneuverability. Furthermore, the bark of some trees may not be strong enough to bear the weight of a climbing device (Jacob and Haridasan, 2015).

Robotic climbers can be classified into continuous-motion and discrete-motion types (Kennedy et al., 2005). In continuous-type climbing robots, the unit moves continuously along the trunk. These robots generally operate at higher speeds and consume less energy; however, implementing continuous motion is technically challenging. A common continuous-motion design is the wheeled robot, in which wheels act as both clamping and climbing components. In such models, the wheels must grip the trunk firmly while working against gravity.

Robotic climbers with discrete-type motion consist of two sets of functional components. In this configuration, one set of components is always fixed to the tree trunk. Initially, the first set grips the tree while the second set moves relative to it. Then, the second set grips the trunk tightly, and the first set moves upward or downward. This sequence is repeated to achieve continuous upward or downward movement of the unit. Most climbing robots are designed with discrete-type motion. Although this type of motion consumes more energy and operates at lower speeds, it is functionally more stable.

A review of robotic climbers shows that their motions are imitations of three natural actions: inchworm movement, ape climbing, and walking action. In inchworm movement, coordinated actions of the head and tail occur, with one always in contact with the ground. The head and tail move closer together and then apart repeatedly to achieve forward or backward motion, without crossing over each other. Ape climbing action is similar to inchworm movement, where either the upper arm or the lower arm always grips the tree. The relative movement of the upper and lower arms, along with the body, facilitates climbing upward or downward. In walking action, one leg is always in contact with the ground, and the relative positioning of the legs produces forward or backward movement. Unlike the other two actions, in walking motion one limb crosses over the other during movement.

Robotic climbers grip the trunk using either grasping mechanisms or adhesion mechanisms. Grasping mechanisms hold the tree trunk using devices such as jaws or claws. Adhesion mechanisms are more suitable for ferromagnetic or smooth surfaces and can be achieved through suction adhesion, magnetic adhesion, or similar techniques. The different mechanisms that fall under grasping and adhesion categories are discussed in the following sections.

Adhesion Mechanism

Suction cups with rack-and-pinion mechanism

Grasping Mechanism

a. Continuum body mechanism
b. Linear actuating mechanism
c. Wheels with spring mechanism
d. Screw mechanism

4.2 Adhesion Mechanism

A. Suction Cups with Rack-and-Pinion Mechanism

Lizards, which can move vertically on almost any surface, possess tiny hairs and suction-like structures along their limbs. This biological observation inspired the development of climbing robots (Subramanyam et al., 2015). Subramanyam et al. (2015) designed and developed a climbing robot for multiple applications. The robot's locomotion was achieved using a rack-and-pinion mechanism, while adhesion to the wall was accomplished using suction cups. The robot comprised two limbs, each equipped with two suction cups to adhere to surfaces. The limbs were connected to two servomotors, one for each limb.

Air removal from the suction cups was carried out using a vacuum pump controlled by solenoid valves. A microcontroller controlled the relays that switched power to the solenoid valves. Suction pipes were used to connect the solenoid valves to the suction cups. Movements in the upward, downward, right, and left directions were controlled by pulse-width modulation (PWM) signals from the controller applied to the servomotors. Gears and joints were used to convert the rotational motion of the servomotors into linear motion of the robot limbs.

Prudvi Raj and Nayak (2014) designed and developed a wall-climbing robot capable of climbing vertical and rough planes, such as stucco walls. Such capability offers significant civilian and military advantages, including inspection, surveillance, search-and-rescue, and even recreational applications. Similar to the earlier design, this robot used a rack-and-pinion mechanism for locomotion and suction cups for adhesion. One of the main drawbacks of suction-based adhesion is that it requires time to develop sufficient vacuum to generate adequate adhesion force. Another drawback is that any gap in the seal can cause the robot to lose grip and fall (Sadegi and Moradi, 2008). In vacuum suction systems, achieving precise gripping is difficult due to surface irregularities (Yoon and Rus, 2007).

4.3 Grasping Mechanism

A. Continuum Body Mechanism

This type of robot operates using two sub-mechanisms: gripping and climbing. Its movement resembles that of an ape climbing a tree (Shen et al., 2005). First, the upper pair of arms grips the tree; then the body moves upward. Next, the lower pair of arms grips the tree, the upper pair releases contact, and the body moves upward again (Segal et al., 2008). With appropriate equipment, such robots can assist workers in arboriculture tasks such as inspection and tree maintenance.

Lam and Xu (2011) developed a tree-climbing robot with high maneuverability in irregular tree environments, surpassing the performance of many existing tree-climbing robots. The robot body featured a novel continuum maneuvering structure with high degrees of freedom and superior extension capability. It was also equipped with a pair of omni-directional tree grippers that enabled it to adhere to a wide variety of trees with different trunk curvatures.

Raj et al. (2015) designed and developed a semi-autonomous coconut-harvesting robot inspired by the inchworm mechanism. The grippers were designed such that, regardless of the tree diameter, each gripper made contact at four points. This autonomous tree-climbing robot could perceive its environment and climb trees independently.

Nallusamy et al. (2015) proposed a tree-climbing robot that autonomously perceived its environment and climbed trees using an inchworm-inspired mechanism. The algorithm reconstructed the shape of the tree using only limit switches. With its well-balanced mechanical design, the robot could climb tree surfaces using minimal sensing resources. However, it was capable of climbing only regular and irregular shaped trees without branches. The robot was also equipped with a pair of omni-directional tree grippers, enabling it to adhere to a wide variety of trees with a wide range of gripping curvatures.

B. Linear Actuating Mechanism

Harikrishna et al. (2014) designed a tree-climbing mechanism inspired by a shrimp species known as *Stomatopod*, whose entire body acts like a distributed foot, enabling it to move with agility over rugged terrain. This biological locomotive mechanism was imitated to develop an efficient climber.

Rahul et al. (2015) designed a semi-automated coconut tree climber using three linear electric actuators—two for gripping and one for vertical motion. Each actuator was capable of carrying up to 400 kg. Asfar (2016) proposed a palm tree-climbing robot that employed three pneumatic actuators: one main actuator and two auxiliary actuators, along with two encircling arms, springs, and pneumatic valves. The arms embraced the tree trunk, while the springs and auxiliary actuators maintained suitable arm positions either to allow upward movement or to support the robot's weight during climbing.

C. Wheel Mechanism

Mohankumar et al. (2013) developed a tree-climbing device for maintenance of trees with single, unbranched trunks such as palm and coconut trees. The wheel drum of the device was designed to move along the trunk without causing damage and could safely carry a human up and down the tree. Harikrishna et al. (2013) proposed a similar system using a power engine that was easy to operate and ensured safety. Sumitomo (2010) developed a tree climber that used a steel wire belt to climb coconut or palm trees safely, which could also be used for fruit plucking and pesticide application. Kacer (1988) proposed an automatic climber capable of climbing palms to any desired height and carrying tools for operations such as cutting coconut bunches, leaf trimming, and pesticide spraying.

In wheel-type designs, or wheeled robots, wheels replace grippers for climbing up and down trees. The robot engulfs the tree, locks onto it, and moves as the motor rotates. The sizes of these robots are typically comparable to the diameter of the tree, making them suitable for trees with straight and smooth trunks.

Baghani et al. (2005) proposed a kinematic model for a wheel-based pole-climbing robot (UT-PCR), in which an appropriate coordinate system was selected to describe the robot's state. Kawasaki et al. (2008) developed a pruning robot with a climbing method similar to that used by timber jacks in Japan. The main features included positioning the center of mass outside the tree and an innovative vertical climbing strategy. The robot used four active wheels placed at regular intervals around the tree, with each wheel driven by a DC servomotor through a worm gear.

Shokripour et al. (2010) developed an automatic self-balancing control system for a four-wheeled tree-climbing robot. A wireless data link module was used to transfer data between the remote control and the robot. The robot could climb and overcome trunk irregularities, achieving a maximum tilt angle of 8° and 6° along the Y and X axes, respectively, at a climbing speed of 4.6 m/min. Shokripour et al. (2012) later developed an automatic cutting system for harvesting oil palm fresh fruit bunches (FFB), in which a mechanized motor system moved the cutting machine forward and backward along the tree trunk radius.

Mani and Jothilingam (2014) developed a semi-autonomous tree-climbing and harvesting robot (COCOBOT) with an octagon-shaped chassis and four active wheels placed at specific intervals around the tree. Springs were used for clamping, and the entire system was remotely controlled. Shenoy et al. (2014) developed a remote-controlled tree-climbing machine for arecanut trees using four stepper motor sets and a spring-based gripping mechanism. Jacob and Haridasan (2015) developed an autonomous tree-climbing robot inspired by human pole climbers, using a wheel mechanism for smooth and fast climbing. This design was proposed as a basis for improvements in seed harvesting, maintenance, fumigation, and harvesting of tall trees.

Senthilkumar et al. (2015) developed an automated coconut harvester prototype in which stability was achieved using three wheels on either side that tightly gripped the entire circumference of the tree. Tony et al. (2016) designed and fabricated an arecanut tree-climbing and spraying machine using nylon tires with rubber grippers, offering a safe, reliable, and efficient solution. Prasad et al. (2016) designed a wireless palm tree harvester that employed a wheeled-leg mechanism to improve harvesting efficiency.

D. Screw Mechanism

Sadeghi and Moradi (2008) designed and fabricated a column-climbing robot known as the Koala robot. It used two linear mechanisms for gripping, with each gripper consisting of a DC motor and a power screw mechanism guided by a linear bushing. Two pneumatic jacks were used as actuators for climbing. This robot was intended for inspection and surveillance of pipes in oil and electric power industries.

Jain (2010) proposed a tree climber built to address challenges associated with manual climbing. The climbing speed depended on the pitch of the ball screws used for arm movement and top and bottom gripper assemblies. The robot's motion resembled that of an ape climbing a tree, using screw mechanisms for both clamping and climbing.

Mittal et al. (2014) designed a semi-autonomous arecanut tree-climbing robot that used a screw mechanism for clamping and an X-bar mechanism for climbing. Widanagamage et al. (2014) developed an autonomous tree-climbing robot (Treebot) utilizing a four-bar linkage system and screw mechanisms for gripping. The Treebot could successfully climb trees with diameters ranging from 15 cm to 25 cm.

Peter et al. (2015) designed and constructed a tree-climbing robot consisting of two segments joined by a retractable spine. Each segment had four legs with sharp-ended feet for gripping. The robot could successfully climb trees and had potential applications in harvesting, tree maintenance, and wildlife observation.

Dubey et al. (2016) developed an autonomous coconut tree-climbing and harvesting robot. The kinematics and motion were inspired by the movement of traditional coconut harvesters. The robot consisted of two segments joined by a pair of threaded rods coupled to motors, enabling climbing and harvesting operations.

5. Conclusions

As agricultural robotics continues to revolutionize the agricultural sector in developed countries, developing nations such as India should not miss the opportunity to adopt these technologies and keep pace with innovations in agriculture. Considerable research has already been carried out in this area; however, there is still no device that is both completely safe and highly accurate. Although several designs have shown positive results, they often involve significant complexity. Many existing designs are also limited by tree size, as they are suitable only for particular trunk diameters.

In this context, this paper has presented a review of the various mechanisms used in existing palm climber models. The advantages and limitations associated with these mechanisms have also been discussed. This review is expected to serve as a useful reference for future research and development of safer, more versatile, and more efficient autonomous and semi-autonomous palm tree climbers.

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