Design of an Agricultural Robotic System for Farm Coverage

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Abstract—The rapid evolution of agricultural technology has ushered in a new era of semi-automation aimed at enhancing productivity and sustainability in farming practices. This paper introduces an autonomous agricultural robot designed to efficiently cover large farm areas while adapting to varying plant heights and terrains. This paper details the comprehensive design considerations, mechanical and electrical components, control systems, and operational capabilities of the agricultural bot. Field tests and performance evaluations validate its effectiveness in real-world farm environments, highlighting its potential to optimize agricultural operations and contribute to sustainable food production. Overall, the development of this semi-autonomous agricultural robot signifies a significant advancement in agricultural robotics, paving the way for future innovations in smart farming technologies and addressing challenges posed by labor shortages and environmental concerns in modern agriculture.

Index Terms—agricultural robot, Farm automation, Smart farming technologies, Robotic Arm.

I. INTRODUCTION

In recent years, agricultural automation has gained significant attention due to its potential to revolutionize farming practices by improving efficiency, reducing labor costs, and enhancing productivity.The conditions for agricultural production are versatile and complex, which requires agriculture robots to be equipped with outstanding adaptability, precise navigation, and obstacle avoidance ability[1]. One promising innovation in this field is the development of Semi-autonomous agricultural robots capable of performing various tasks across diverse farm environments. The bot incorporates several innovative features to adapt to different plant heights and traverse varying horizontal distances effectively. Key components include a telescopic column for adjusting to different plant heights, a robust rope mechanism with adjustable tension for horizontal movement, and durable tires enabling mobility across different terrains.

Central to the bot's functionality is a robotic arm attached to the rope, equipped to execute various operations essential for farm maintenance and cultivation. By automating repetitive tasks and optimizing resource utilization, the agricultural bot aims to contribute to increased agricultural output while minimizing environmental impact.This paper presents the detailed design considerations, mechanical and electrical components, control systems, and operational capabilities of the agricultural bot. Additionally, field tests and performance evaluations demonstrate its efficacy in real-world farm environments, validating its potential to transform modern agriculture

At the University of Saskatchewan, Bayati et al. developed, implemented, and verified a field-based high-throughput plant phenotyping mobile robotic platform to monitor Canola plants. Wide-range images of plant canopies can be gathered and analyzed by the platform automatically. This innovation has been demonstrated to improve the productivity of farms while decreasing costs in the long run.[2]. Considering the large overshoot and long convergence time caused by large initial heading errors, Wang et al. explored a novel trajectory planning algorithm for harvesting robots that could enhance stability, thereby improving operational performance[3]. A robotic spraying system based on the SegNet model was proposed to spray pesticides in orchards, composed of hardware configuration, semantic segmentation, and depth data fused with trained RGB data. In field experiments, their environmentally friendly spraying robot showed satisfactory properties[4]. Ghafar et al. also developed a cost-saving spraying robot to satisfy the need for spraying pesticides and fertilizers[5]. Jin et al. proposed an advanced control approach using manipulators for hydraulic transplanting robots. As a result, the control accuracy and stability of transplanting was improved. Yang et al. developed a transplanting robot with three degrees of freedom[6]. Cantelli et al. invented an autonomous spraying robot containing two parts, a vehicle and a spraying control system[7].

II. SEMI AUTONOMOUS ROBOTICS SYSTEM

Our proposed system is designed to navigate and pass through a large area using a cable mechanism. The cable is attached to a telescopic pole on a 4-wheeled base drive, which provides motion in the y direction as shown in fig 1. For motion in the x direction, the robot moves on the cable attached to two such base drives.

Additionally, the telescopic pole enables height adjustment, providing motion in the z direction.

Fig 1. Robotic System for Agricultural Proposed application

This three-dimensional mobility allows the bot to adapt to varying plant heights and traverse different terrains effectively. Key components of the system include a telescopic Mechanism for adjusting to different heights, a robust rope mechanism with adjustable tension for horizontal movement, and durable tires enabling mobility across different terrains. Making the Robot cable of moving in 3 axes. The Bot can be equipped with various attachments depending on the application. The Main mechanisms of the proposed robotic system are discussed below.

A.Telescopic Tower

In our agriculture robot system, we utilize a telescopic tower mechanism to adjust the height along the z-axis, enhancing its adaptability and functionality. The telescopic tower is raised and lowered using a leadscrew mechanism as shown in fig 1 which is driven by a DC motor.

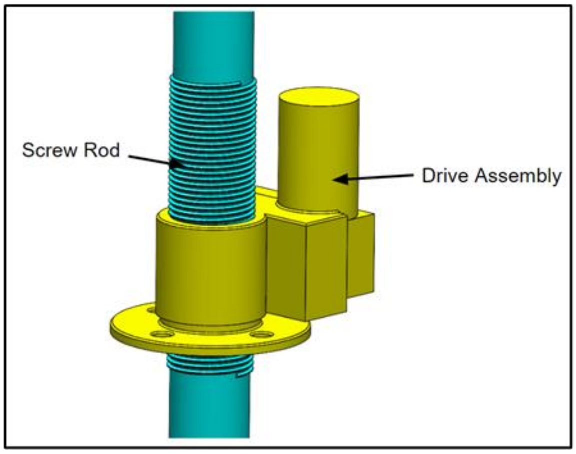

Fig 2. Lead screw mechanism

This motorized lead screw provides precise control over the vertical movement, crucial for maintaining the optimal height of the rope assembly that the robot navigates. To ensure accurate and consistent positioning, the system is equipped with an encoder and a limit switch. The encoder offers real-time feedback on the tower's position, while the limit switch initializes the system and provides end-stop detection, preventing overextension and ensuring safety Both telescopic mechanisms on the towers are identical, ensuring synchronized height adjustments. This uniformity is essential for maintaining stability and balance in the rope assembly, which is critical for the robot's navigation and operation. The use of a telescopic tower allows for dynamic adjustment of the working height, accommodating various crop heights and field conditions. This flexibility improves the robot’s ability to perform tasks efficiently across different environments. Additionally, the leadscrew mechanism provides a robust and reliable means of vertical movement, capable of handling the load and environmental stresses typically encountered in agricultural settings. This design choice enhances the robot's overall operational effectiveness and longevity.

B. Rope Tension Mechanism

To maintain the tension in the rope and guarantee steady horizontal robot extension, we have developed a rope tension mechanism. The tensioning system is actuated by two motors, each attached to the rope by a winch, which work in tandem to create and adjust the tension. By winding and unwinding the rope, the motors can dynamically alter the tension, allowing for precise control over the rope’s tautness. This rope tensioning mechanism plays a pivotal role in maintaining the tension and can adjust the rope according to the distance between the poles. The use of motorized rope tensioning enhances the robot's adaptability and precision, providing a robust solution for maintaining consistent tension and height. The ability to adjust the distance between the towers dynamically ensures that the robot can be deployed in fields of varying sizes, further enhancing its utility and efficiency in agricultural applications.

C. Base Drive

The basedrive utilizes a compound gear mechanism to drive all four wheels, ensuring efficient and reliable movement across diverse terrains encountered in agricultural operations. This robust gearing arrangement amplifies torque and regulates speed, allowing the basedrive to maintain steady horizontal movement as shown in fig 2.

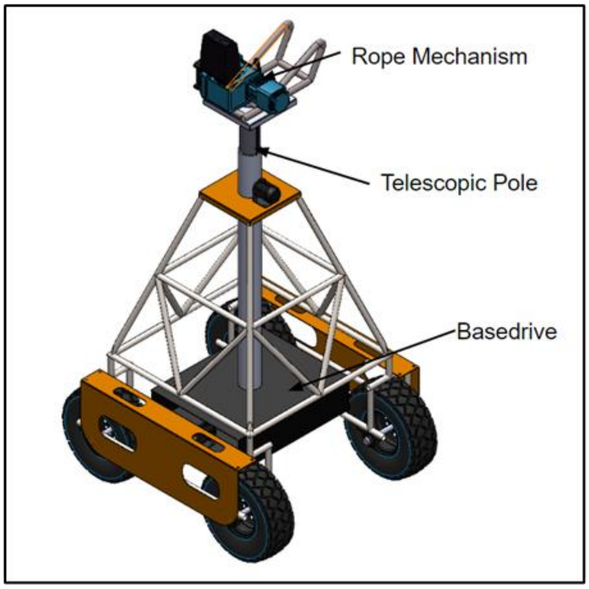

Fig 3. Base Drive

To enhance stability and prevent tipping, the system incorporates a suspension mechanism comprising shock absorbers, springs, and articulated joints. These components work together to absorb shocks and maintain consistent ground contact, ensuring the basedrive remains balanced and operationally efficient on uneven surfaces. This design provides a robust solution for modern farming, enhancing the robot's capability to perform various agricultural tasks with precision and stability.

III. ESSENTIAL COMPONENTS FOR THE EFFECTIVE FUNCTIONING OF ROBOTICS SYSTEMS

A. Localization and Navigation

As Discussed earlier The Robotic system navigates through complex agricultural environments efficiently. Assuming the rope used has negligible slag, our system can be considered the same as the overhead crane model. It is a five-degree-of-freedom mechanical system n=5 and its position is described by $q = [s1\ s2\ l\ \boldsymbol{\theta}1\ \boldsymbol{\theta}2]^T$, where s1 and s2 describe the bot position in the fixed coordinate system XYZ, l is the length of the center of mass from the cable and $\boldsymbol{\theta}1$ *and* $\boldsymbol{\theta}2$ are the swing angles as seen in the figure. The three control inputs, m = 3, are the forces F1 and F2 that actuate the bot position, that is, s1 and s2 coordinates and the winch torque Mw that changes the COM length l,$u = [F1\ F2\ Mw]^T$. In this meaning, s1, s2 and l can be regarded as controlled coordinates of the bot, whereas $\boldsymbol{\theta}1$ *and* $\boldsymbol{\theta}2$ can be called uncontrolled coordinates, and we deal with an underactuated mechanical system, m < n.

The dynamic equations of the crane model can be written in the following generic matrix form:

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{d}(\mathbf{q}, \dot{\mathbf{q}}) = \mathbf{f}(\mathbf{q}, \dot{\mathbf{q}}, t) - \mathbf{B}^{\mathrm{T}}\mathbf{u} \qquad (1)$$

here M is the $n \times n$ generalised mass matrix, d and f are the n vectors of generalised dynamic and applied forces, all M, d and f related to q, and B^T is the $n \times m$ matrix of distribution of u controls in q directions ($f_u = -B^T u$ is the n vector of generalised control forces related to q). The explicit forms of $M, d, f\ and\ B^T$ are

$$\mathbf{M} = \begin{bmatrix} m_b + m_t + m_l & 0 & m_l \sin\theta_1 \cos\theta_2 & m_l l \cos\theta_1 \cos\theta_2 & -m_l l \sin\theta_1 \sin\theta_2 \\ 0 & m_t + m_l & m_l \sin\theta_2 & 0 & m_l l \cos\theta_2 \\ m_l \sin\theta_1 \cos\theta_2 & m_l \sin\theta_2 & m_l + J_w/r_w^2 & 0 & 0 \\ m_l l \cos\theta_1 \cos\theta_2 & 0 & 0 & m_l l^2 \cos^2\theta_2 & 0 \\ -m_l l \sin\theta_1 \sin\theta_2 & m_l l \cos\theta_2 & 0 & 0 & m_l l^2 \end{bmatrix},$$

$$\mathbf{d} = \begin{bmatrix} 2\,m_l \dot\theta_1 \cos\theta_1 (\dot l \cos\theta_2 - l\dot\theta_2 \sin\theta_2) \\ +m_l \sin\theta_1 \left[-2\dot l \dot\theta_2 \sin\theta_2 - l\left(\dot\theta_1^2 + \dot\theta_2^2\right)\cos\theta_2\right] \\ m_l \dot\theta_2 (2\dot l \cos\theta_2 - l\dot\theta_2 \sin\theta_2) \\ -m_l l\left(\dot\theta_1^2 \cos^2\theta_2 + \dot\theta_2^2\right) \\ 2\,m_l l\dot\theta_1 \cos\theta_2 (\dot l \cos\theta_2 - l\dot\theta_2 \sin\theta_2) \\ m_l l\left(l\dot\theta_1^2 \sin\theta_2 \cos\theta_2 + 2\dot l \dot\theta_2\right) \end{bmatrix},$$

$$\mathbf{f} = \begin{bmatrix} -k_1 \dot s_1 \\ -k_2 \dot s_2 \\ -k_3 \dot l + m_l g \cos\theta_1 \cos\theta_2 \\ -m_l g l \sin\theta_1 \cos\theta_2 \\ -m_l g l \cos\theta_1 \sin\theta_2 \end{bmatrix}, \mathbf{B}^{\mathrm{T}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1/r_w \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

where m_b,m_t and m_l are the Rope, Pulley and Robot masses, J_w *and* r_w are the moment of inertia and radius of the winch, k_1, k_2 *and* k_3 are the damping coefficients related to s_1, s_2 *and* l motions and g is the gravity acceleration.

The performance goal of the crane is to track a time-specified load motion, that is, the $m = 3$ system outputs are time-specified load coordinates,$r_d(t) =$

$[x_d(t)\ \ y_d(t)\ \ z_d(t)]^T$, which describe the desired trajectory in the inertial coordinate system XYZ. Expressed in terms of q, these task requirements lead to m constraints on the system, that is:

$$\mathbf{c}(\mathbf{q},\, t) \equiv \mathbf{\Phi}(\mathbf{q}) - \mathbf{r}_d(t) = \mathbf{0} \qquad (2)$$

called servo-constraints or control constraints, as distinct from passive or contact constraints in the classic sense.

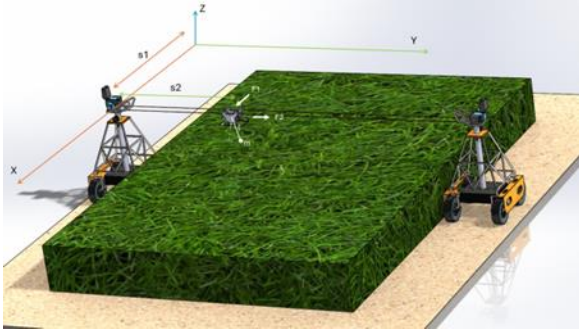

Fig 4. Proposed robotic system

After twice differentiating with respect to time, the invariant forms of servo-constraints at the position level are transformed to the constraint conditions at the acceleration level,

$$\ddot{\mathbf{c}}(\mathbf{q},\, \dot{\mathbf{q}},\, \ddot{\mathbf{q}},\, t) \equiv \mathbf{C}(\mathbf{q})\ddot{\mathbf{q}} - \boldsymbol{\xi}(\mathbf{q},\, \dot{\mathbf{q}},\, t) = \mathbf{0} \qquad (3)$$

where $\mathbf{C} = \partial\mathbf{\Phi}/\partial\mathbf{q}$ is the $m \times n$ constraint matrix and $\boldsymbol{\xi} = \ddot{\mathbf{r}}_d - \dot{\mathbf{C}}\dot{\mathbf{q}}$ is the m vector of constraint-induced accelerations. Explicit forms of servo-constraints (2) and (3) are given by the following expressions:

$$\mathbf{\Phi}(\mathbf{q}) - \mathbf{r}_d(t) = \begin{bmatrix} s_1 + l\sin\theta_1\cos\theta_2 \\ s_2 + l\sin\theta_2 \\ -l\cos\theta_1\cos\theta_2 \end{bmatrix} - \begin{bmatrix} x_d(t) \\ y_d(t) \\ z_d(t) \end{bmatrix} = 0$$

$$\mathbf{C} = \begin{bmatrix} 1 & 0 & \sin\theta_1\cos\theta_2 & l\cos\theta_1\cos\theta_2 & -l\sin\theta_1\sin\theta_2 \\ 0 & 1 & \sin\theta_2 & 0 & l\cos\theta_2 \\ 0 & 0 & -\cos\theta_1\cos\theta_2 & l\sin\theta_1\cos\theta_2 & l\cos\theta_1\sin\theta_2 \end{bmatrix}$$

$$\boldsymbol{\xi} = \begin{bmatrix} \ddot{x}_d + l[(\dot{\theta}_1^2 + \dot{\theta}_2^2)\sin\theta_1\cos\theta_2 - 2\dot{\theta}_1\dot{\theta}_2\cos\theta_1\sin\theta_2] \\ -2\dot{l}(\dot{\theta}_1\cos\theta_1\cos\theta_2 - \dot{\theta}_2\sin\theta_1\sin\theta_2) \\ \ddot{y}_d + l\dot{\theta}_2^2\sin\theta_2 - 2\dot{l}\dot{\theta}_2\cos\theta_2 \\ \ddot{z}_d - l[(\dot{\theta}_1^2 + \dot{\theta}_2^2)\cos\theta_1\cos\theta_2 - 2\dot{\theta}_1\dot{\theta}_2\sin\theta_1\sin\theta_2] \\ -2\dot{l}(\dot{\theta}_1\sin\theta_1\cos\theta_2 + \dot{\theta}_2\cos\theta_1\sin\theta_2) \end{bmatrix}$$

Which is a five degree of freedom mechanism

B. System Architecture

The system architecture of the robotic system is designed to efficiently control its integral components and subsystems.

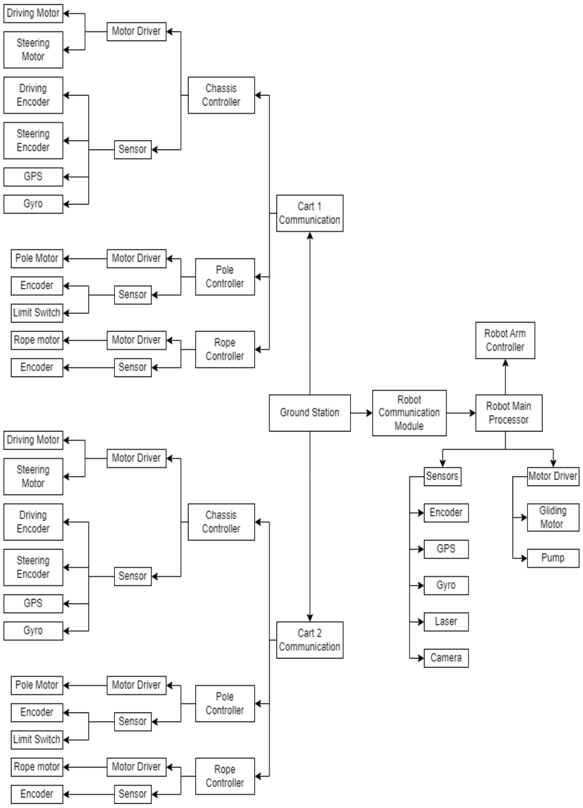

Fig 5. System Architecture

The robot's movements are coordinated through integrated actuators, each of which operates within its own feedback loop. The control system for these subsystems is managed by separate microcontrollers dedicated to each subsystem. These subsystem microcontrollers communicate with the cart module, which contains the communication interface with the ground station. This cart module processes inputs from various sensors, executes control algorithms, and sends commands to the actuators. The control algorithms encompass a range of functions including navigation, data collection, analysis, path planning, obstacle avoidance, and data processing.

The sensor system includes position and orientation sensors like GPS, IMU (Inertial Measurement Unit), and encoders help track the robot's position and orientation, ensuring accurate navigation and data collection. Communication within the system is facilitated by the communication system, which typically uses wireless technologies such as Wi-Fi, Bluetooth to enable data transmission between the robot and a remote base station.

C.Control

The control system is designed to manage movement across the x, y, and z axes. The system includes two telescopic towers for adjusting height in z-axis, mounted on basedrive moving along x-axis and the robot motion along y-axis is achieved by rope mechanism.

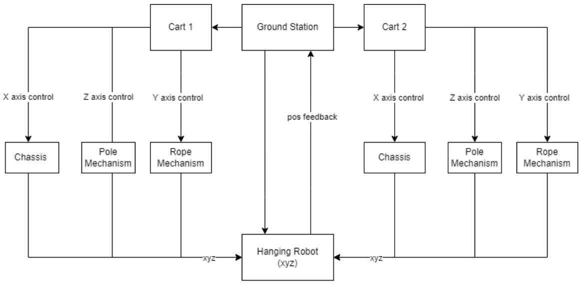

Fig 6. Control strategy.

In this system, cascade PID control is used for each cart. The primary loop controls the desired output of actuators, while the secondary loop could manage the control along the X, Y, and Z axes of the robot. This multiple input with single feedback of robot coordinates efficiently controls all the mechanisms.

D.The Human-Robot Interaction

At the core of the HRI system is a high-resolution touchscreen interface that provides clear and detailed visual feedback on the robot's operational status, task progress, and environmental conditions. The user-friendly navigation menu allows operators to easily access various functions, settings, and real-time data, with customizable interface layouts enabling them to prioritize information relevant to specific tasks and preferences. This enhances situational awareness and decision-making, making the system highly intuitive.To facilitate precise manual control, the HRI system includes an ergonomic handheld controller. Wireless connectivity ensures that operators can maintain control while moving freely around the field, further enhancing operational flexibility.

IV. ROBOTIC SYSTEM FOR AGRICULTURAL APPLICATIONS

This robotics system is highly adaptable, designed to accommodate various modular attachments on hanging robots, enabling the robot to perform a diverse array of agricultural tasks such as planting, weeding, fertilizing, and harvesting making it an ideal Multi-Purpose Agricultural Robotics System.

The hanging robot serves as the end effector, equipped with a comprehensive array of sensors and surveillance modules. This end effector is pivotal for the robot's functionality, integrating essential tools and technologies to perform a variety of agricultural tasks efficiently. The hanging robot is outfitted with a high-resolution camera for crop surveillance, enabling real-time monitoring and data collection on crop health and growth.

Fig 7. Hanging Robot

Additionally, it features a laser distance measurement system, providing accurate data on the spacing and height of plants, which is crucial for precise operations and navigation.It can traverse across the field using a chain-sprocket driven pulley system. One of the standout features of the hanging robot is its modular design, allowing for the integration of various attachments such as,

A.Robotic Arm

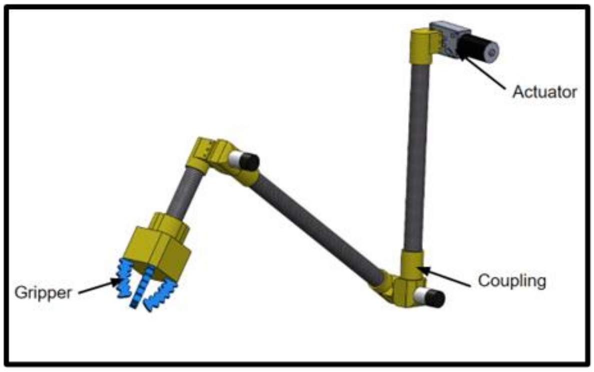

Fig 8. Robotic arm

This robotic arm as shown in fig 8 is engineered for tasks such as cultivation, precise planting, and maintenance activities. It has four joints, providing it with four degrees of freedom. These joints are typically driven by actuators, allowing the arm to move in multiple directions—up/down, left/right, forward/backward, and rotation. The arm's structure is designed to be lightweight yet robust, capable of reaching various positions in a controlled manner. The gripper is made of soft silicone material (Ecoflex 00-50), which is flexible and compliant. The robotic arm is equipped with advanced vision-based sensors that enable it to autonomously detect and navigate toward the desired object. This automated process not only reduces the labor required for manual harvesting but also ensures consistent quality by selectively picking fruits based on ripeness and size.

B.Sprinkler mechanism

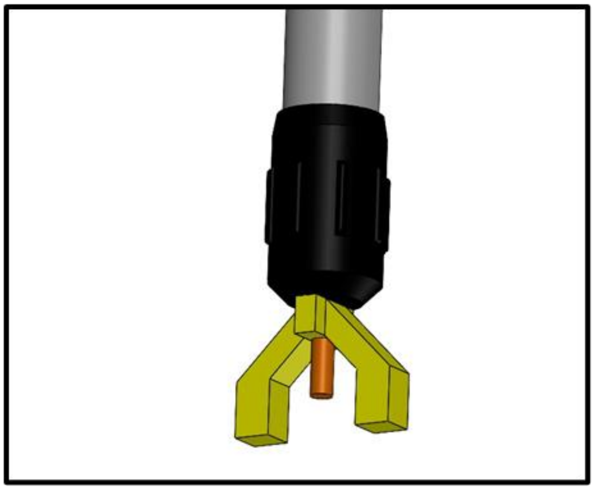

Fig 9. Sprinkler mechanism

Sprinkler mechanism as shown in figure 9, capable of delivering pesticides and water directly to the plants. The robot can traverse the field and evenly distribute the necessary substances, ensuring thorough coverage and effective pest control. This dual-functionality makes the robot a valuable asset in modern agriculture, enhancing productivity, reducing costs, and promoting sustainable farming practices.

VI. SENSOR ATTACHMENTS

This robot is designed to accommodate different sensors based on specific requirements, making it versatile for various tasks. For instance, proximity sensors, ultrasonic distance sensors, LiDAR sensors, IMUs, and 3D cameras are attached for obstacle detection and navigation, enabling the robot to safely maneuver through fields and avoid damaging crops. Meanwhile, temperature, humidity, and soil moisture sensors can monitor environmental conditions and soil health, providing crucial data for irrigation and climate control. Air quality sensors, CO2 sensors, and pH sensors are integrated to assess atmospheric conditions and soil chemistry, helping optimize growing conditions and detect potential issues like pests or diseases early. This modular design allows for quick swapping or addition of sensors, enabling the robot to perform a wide range of tasks, from planting and monitoring to harvesting and crop maintenance, tailored to the specific needs of different agricultural environments.

CONCLUSION

The development of this semi-autonomous agricultural robot represents a significant advancement in agricultural robotics, addressing the challenges of labor shortages and the need for sustainable practices. By integrating innovative features such as a telescopic mechanism for height adjustment, a robust rope tensioning system, and versatile attachments like a robotic arm and sprinkler, the robot demonstrates exceptional adaptability and precision in various farm environments. Field tests and performance evaluations confirm its effectiveness in automating repetitive tasks and optimizing resource utilization. This robot not only enhances operational efficiency but also contributes to sustainable agriculture by minimizing environmental impact and maximizing productivity. Overall, the agricultural robot's capabilities mark a step forward in smart farming technologies, offering a scalable solution for modern agricultural challenges and paving the way for future innovations in the field.

FUTURE SCOPE

Mechanism improvements could focus on increasing the precision and speed of movement, as well as enhancing the durability and weather resistance of the components. Implementing advanced materials and robotics technologies can further optimize the system's efficiency and longevity.

For IoT alternatives, incorporating low-power wide-area networks (LPWANs) like LoRaWAN and NB-IoT can facilitate reliable long-range communication, even in remote agricultural fields. This connectivity can be leveraged for real-time monitoring and control, providing farmers with detailed insights and timely alerts.

AI and machine learning (ML) can be integrated to enhance the system's capabilities in crop management and predictive maintenance. AI algorithms can analyze sensor data to predict crop growth patterns, detect anomalies, and optimize resource allocation. ML models can improve the system's decision-making process by learning from historical data, leading to better yield predictions and automated adjustments to environmental controls.

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