Design and Development of IoT-based Harvesting Robo-Vec

Diseño y desarrollo de Robo-Vec de recolección basado en IoT

Projeto e desenvolvimento de colheita Robo-Vec baseada em IoT

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Summary. - This article presents "Harvesting Robo-Vec" an IoT-based autonomous harvesting robot designed to enhance agricultural efficiency and precision. Integrating IoT technology with traditional methods, the robot automates tasks and offers real-time monitoring and control. It navigates crop fields autonomously, detects ripe produce using advanced sensing and imaging technologies, and performs precise harvesting maneuvers. Harvesting Robo-Vec features an IoT communication module for seamless connectivity with a centralized control system, enabling remote management of multiple robots. The paper outlines the robot's architecture, including its mechanical structure, sensors, control algorithms, and communication infrastructure, along with safety, power management, and robustness considerations. Iterative design, prototyping, and testing refined the robot's performance. Experimental results show that Harvesting Robo-Vec improves efficiency, reduces labor costs, and enhances productivity compared to manual methods. This study underscores the potential of IoT-based robots in agriculture, contributing to precision farming and autonomous robotics research.

Keywords: IoT, Harvesting Robot, Computer Vision, Agriculture, Automation.

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Resumen. - *Este artículo presenta "Harvesting Robo-Vec", un robot de recolección autónomo basado en IoT diseñado para mejorar la eficiencia y precisión agrícola. Al integrar la tecnología IoT con métodos tradicionales, el robot automatiza tareas y ofrece monitoreo y control en tiempo real. Navega por los campos de cultivo de forma autónoma, detecta productos maduros utilizando tecnologías avanzadas de detección e imágenes y realiza maniobras de cosecha precisas. Harvesting Robo-Vec cuenta con un módulo de comunicación IoT para una conectividad perfecta con un sistema de control centralizado, lo que permite la gestión remota de múltiples robots. El documento describe la arquitectura del robot, incluida su estructura mecánica, sensores, algoritmos de control e infraestructura de comunicación, junto con consideraciones de seguridad, gestión de energía y robustez. El diseño iterativo, la creación de prototipos y las pruebas refinaron el rendimiento del robot. Los resultados experimentales muestran que Harvesting Robo-Vec mejora la eficiencia, reduce los costos de mano de obra y mejora la productividad en comparación con los métodos manuales. Este estudio subraya el potencial de los robots basados en IoT en la agricultura, contribuyendo a la investigación en agricultura de precisión y robótica autónoma.*

Palabras clave: *IoT, Robot cosechador, Visión por computadora, Agricultura, Automatización.*

***Resumo*. -** *Este artigo apresenta o "Harvesting Robo-Vec", um robô de colheita autônomo baseado em IoT projetado para aumentar a eficiência e a precisão agrícola. Integrando a tecnologia IoT com métodos tradicionais, o robô automatiza tarefas e oferece monitoramento e controle em tempo real. Ele navega pelos campos de cultivo de forma autônoma, detecta produtos maduros usando tecnologias avançadas de detecção e imagem e realiza manobras de colheita precisas. O Harvesting Robo-Vec apresenta um módulo de comunicação IoT para conectividade perfeita com um sistema de controle centralizado, permitindo o gerenciamento remoto de vários robôs. O artigo descreve a arquitetura do robô, incluindo sua estrutura mecânica, sensores, algoritmos de controle e infraestrutura de comunicação, juntamente com considerações de segurança, gerenciamento de energia e robustez. O design iterativo, a prototipagem e os testes refinaram o desempenho do robô. Os resultados experimentais mostram que a colheita Robo-Vec melhora a eficiência, reduz os custos de mão-de-obra e aumenta a produtividade em comparação com os métodos manuais. Este estudo ressalta o potencial dos robôs baseados em IoT na agricultura, contribuindo para a agricultura de precisão e a pesquisa em robótica autônoma.*

Palavras-chave: *IoT, Robô de colheita, Visão computacional, Agricultura, Automação.*

1. Introduction. - Agriculture uses traditional manual harvesting methods that are labor-intensive, time-consuming, and prone to human error. These methods find it difficult to meet the expanding demands of a globalizing population [1-2]. In addition, the problem is exacerbated by the dire consequences resulting from a shortage of personnel in numerous sectors. Creative solutions that may automate and optimize the harvesting process are therefore desperately needed to boost output, reduce costs, and improve crop quality [3].

The work on Internet of Things (IoT) [4-5] based smart agriculture monitoring systems in [6] offers a noteworthy breakthrough by employing multiple algorithms to identify, measure, and evaluate vegetable development. Integrating computer vision techniques and machine learning [7], these systems achieve over 90% accuracy, particularly focusing on tomato cultivation. The development of autonomous smart agriculture robots, such as the Agri-Bot in [8], further revolutionizes farming by performing labor-intensive tasks like planting, plowing, fertilizing, and harvesting, leveraging Arduino UNOs and NodeMCUs for seamless automation. In [9], intelligent tomato-picking robots demonstrate considerable improvements in agricultural efficiency, employing precise grasping mechanisms, enhanced color segmentation, and advanced vision positioning to achieve an 83.9% success rate. Similarly, mechanical harvesting robots for fresh-eating tomatoes in [10], equipped with stereo visual units, end-effectors, and rail-based carriers, achieve an 83% success rate, significantly enhancing productivity and reducing labor costs.

Apple harvesting robots [11], featuring geometrically optimized manipulators, pneumatic grippers, and vision-based recognition systems, further illustrate the potential of robotic technology in agriculture, successfully harvesting apples with a 77% success rate. The integration of IoT and wireless sensors [12] in smart agriculture marks a transformative shift from statistical to quantitative methods [13], exploring the potential of UAVs [14], precision farming, and wireless sensors while discussing the benefits and challenges these technologies present. In [15] the design of greenhouse tomato-picking robot chassis showcases advancements in precise positioning and cruising capabilities through kinematic models [16], simulations, and physical testing, ultimately increasing the efficiency of greenhouse harvesting. These studies highlight the advancements in IoT-based agriculture monitoring systems and robotic harvesting technologies, underscoring their potential to revolutionize modern farming practices. Considering the research gaps, we aim to create an innovative solution for the agricultural sector by developing an autonomous harvesting robot named "Harvesting Robo-Vec" that leverages IoT technology. The objectives of the proposed system include:

- Develop a robust and efficient design for the harvesting robot, equipped with necessary sensors, actuators, and control systems to perform autonomous operations in the field.
- Incorporate IoT modules to enable real-time monitoring, data collection, and communication with a centralized control system.
- Make accurate harvesting decisions with minimal crop losses by effective detection and recognition of ripe fruits and vegetables using computer vision algorithms and proximity sensors.

Through this initiative, we seek to revolutionize the agriculture sector with a cost-effective, scalable solution, leading to increased output, reduced dependence on labor-intensive farming practices, and strides toward precision farming.

2. Proposed system model.- The Harvesting Robo-Vec is an innovative harvesting robot that automates the process of picking tomatoes. It integrates multiple hardware and software (See Figure I) components to make the field more efficient and accurate.

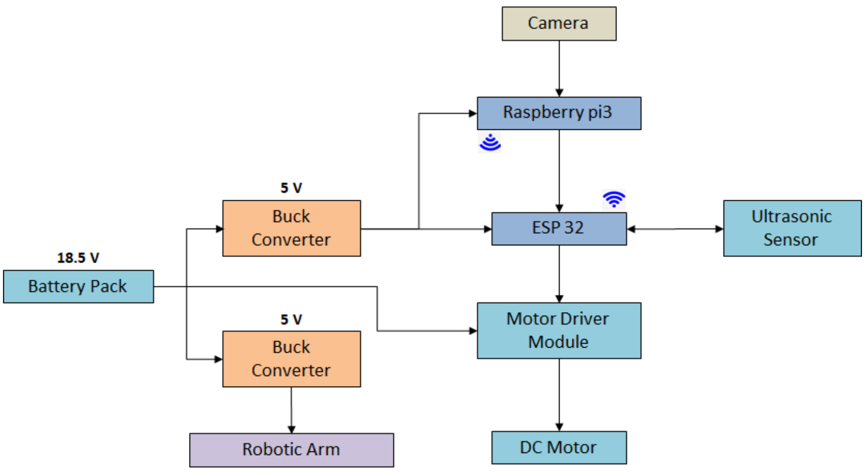

Figure I. System Block Diagram

2.1 Hardware Components

2.1.1 Microcontrollers. - The ESP32 microcontroller [17] is a low-power microcontroller, both Wi-Fi and Bluetooth capable. It is responsible for the communication line between different sensors and the robotic arm. It manages to aggregate data retrieval, and actuation as a whole well. The main processing unit is the Raspberry Pi Model 3B+ [18], which works in conjunction with the ESP32. This mini-computer has a complete Linux OS and handles complicated functionalities like image processing and computer vision algorithms

2.1.2 Sensors. - Sensors in use provide the data about the environment to the system. The Pi Camera [19] takes high-resolution images, and video of the crops, which is vital for processing visual information to identify ripe tomatoes. Ultrasonic sensors [20] send out sound waves and measure the distance to nearby obstacles using the time-of-flight of the received echo. Additionally, proximity sensors mounted on the robotic arm ensure that the distance to the tomatoes is accurately gauged for effective harvesting.

2.1.3 Actuators. - The robotic arm is powered by high-torque servomotors, which enable precise control over its movements, such as rotating and gripping. Motor driver modules interface with the microcontroller and servomotors, allowing for control over speed and direction.

2.1.4 Power Management. - The robot's operations are sustained by a battery management system (BMS) that monitors and regulates the rechargeable batteries, ensuring they are charged safely and used efficiently. Buck converters help manage voltage levels for different components, maintaining a stable power supply. Table I. presents the battery configuration for the Harvesting Robo-Vec.

Parameter	Value
Number of Cells	5
Nominal Voltage per Cell	3.7 V
Total Voltage	18.5 V
Estimated Total Current	6.35 A
Operational Duration	4 hours
Battery Capacity	25.4 Ah
Total Energy Capacity	469.9 Wh

Table I. Battery configuration

Additionally, Table II presents an analysis of energy consumption along with suggested improvements and Figure II is regarding the hardware used in the proposed model.

Energy Consumption Factor	Current Issues	Expected Amperes (A)	Suggested Improvements
Microcontrollers	High power draw from ESP32 and Raspberry Pi.	ESP32: 0.15 A	Optimize algorithms for energy efficiency. Consider edge computing to reduce Raspberry Pi load.
		Raspberry Pi: 1.2 A	
Sensors	Continuous operation leads to increased power usage.	Pi Camera: 0.5 A	Implement smart sensor activation (on-demand use). Utilize low-power modes during inactivity.
		Ultrasonic Sensors: 0.1 A each	
		Proximity Sensors: 0.1 A each	
Actuators	High energy consumption for servomotors.	2 A (per motor, typically)	Use variable torque control based on task needs. Explore energy recovery systems (e.g., regenerative braking).

Table II. Energy consumption of Harvesting Robo-Vec

Figure II. Hardware used in the proposed model

2.2. Software Components

2.2.1 Operating System. - The Raspberry Pi operates on a Linux-based system, which provides a robust platform for running applications and managing resources.

2.2.2 Programming Languages. - The software is developed using Python for applications running on the Raspberry Pi, particularly for image processing tasks. The ESP32 microcontroller is programmed using C/C++, which is ideal for handling low-level control and real-time sensor data processing.

2.2.3 Image Processing. - OpenCV [21] is a critical library used for computer vision tasks. It aids in tasks such as color detection and image filtering, allowing the robot to identify ripe tomatoes based on their color and shape. The system transforms images to the HSV color space for better color differentiation.

2.2.4 Control Algorithms. - The gripping and harvesting algorithm modulates the final gripping strength and positioning given to feedback from the proximity sensors. This guarantees that tomatoes are taken carefully to protect them from damage during harvesting. Using the ultrasonic sensors as input, the obstacle avoidance algorithm makes sure the robot does not bump into obstacles while moving. Dijkstra's algorithm [22] calculates obstacles and determines the optimal path to get through the crop field.

2.2.5 Communication Protocols. - The communication between Raspberry Pi and ESP32 is based on RESTFull API [23] that allows command executing and data transmitting. This provides connectivity for remote control of the robot and ensures seamless communication between all components
In Figure III, the flowchart shows the entire process of the proposed system.

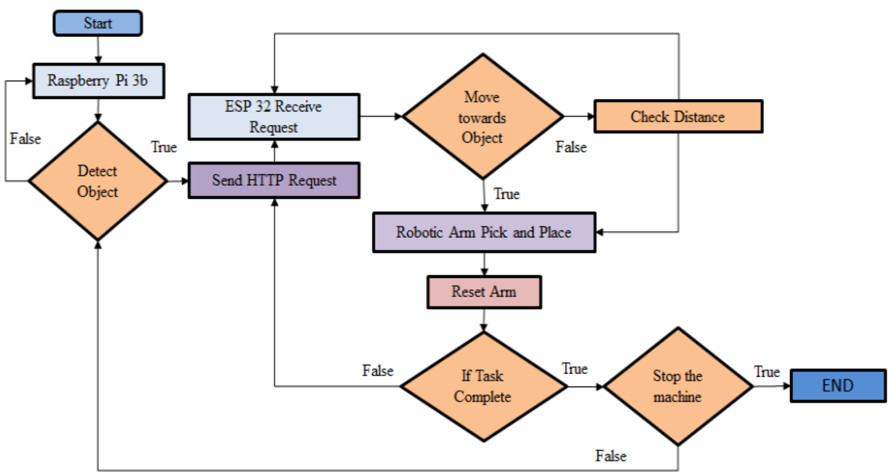

Figure III. Process flowchart.

3. Testing Procedures and Experimental Setup.- Since the testing procedure and setup will be vital for assessing the performance and functionality of Harvesting Robo Vec. The testing methods evaluate the performance parameters of Harvesting Robo Vec in tomato identification and detection. The experimental frame for testing the performance of the robot was established by simulating real agricultural environments incorporating a variety of factors. In the tomato plantation, the cultivated areas consisting of plants were organized to replicate the arrangement and density of plants in various fields, enabling a determination of robot efficiency to detect ripe tomatoes while navigating through diverse arrangements. To ensure the efficient maneuvering of the robot, different obstetrical were designed to test the real farming challenges which include soil types, and terrain variations. Moreover, the testing was performed concerning various illuminations, considering the different times of the day and weather (e.g. sunny and cloudy) conditions. Finally, the testing included levels for different soil types (e.g., clay, sandy, and loamy). This enabled us to compare the collective effects of these factors on the robot's ability to harvest in terms of stability, traction, and efficiency.

Different testing scenarios were created to assess distinct operations of Harvesting Robo Vec with different situations and are highlighted in Table III.

Condition	Description	Soil Type	Crop Variety	Lighting Condition	Obstacle Configuration
Test 1	Standard Row Planting	Loamy	Ripe Tomatoes	Clear, Midday	Few Rocks
Test 2	Cluster Planting with Intermixed Weeds	Sandy	Ripe Tomatoes	Overcast	Wooden Fences
Test 3	Row Planting with Uneven Growth	Clay	Ripe Tomatoes	Clear, Early Morning	Tall Grass
Test 4	Standard Row Planting with Different Tomato Varieties	Loamy	Cherry Tomatoes	Clear, Late Afternoon	Few Rocks
Test 5	Mixed Crop Field (Tomatoes with Other Vegetables)	Sandy	Mixed Crops	Rainy	Bushes

Table III. Experimental Conditions and Setup

Key metrics analyzed included detection accuracy, which measures the percentage of correctly identified tomatoes, providing insights into the reliability of the detection algorithms. Harvesting efficiency was also assessed, quantified by the number of tomatoes harvested per minute, offering a clear indicator of the robot's productivity.

All sensor data, camera data, and performance logs were used to analyze how well the robot performed in the agricultural environment. The use of detection accuracy, which explains the percentage of correctly identified tomatoes, provides information about the reliability of the detection algorithms and thus, it will be one of the key metrics analyzed in this work. We also evaluated harvesting efficiency (i.e., the number of harvested tomatoes per minute), providing a direct measure of the productivity of the robot. Moreover, the time spent performing the harvesting task was also recorded to assess the overall efficiency. Finally, the damage rate was measured as the percentage of damaged tomatoes during harvesting, which is crucial for understanding the impact of the robot's operations on crop quality as can be seen in Table IV.

Test Condition	Detection Accuracy (%)	Harvesting Efficiency (Tomatoes/Min)	Time Taken (Min)	Damage Rate (%)
Test 1	92	10	15	5
Test 2	85	8	20	10
Test 3	78	6	25	15
Test 4	90	9	18	6
Test 5	80	7	22	12

Table IV. Performance Metrics under Different Conditions

For this purpose, a comparative analysis between the proposed Harvesting Robo Vec and traditional manual harvesting methods was carried out as shown in Table V which demonstrates the effectiveness and efficiency of the proposed Harvesting Robo Vec over the traditional manual tomato harvesting method.

Method	Average Detection Accuracy (%)	Average Harvesting Efficiency (Tomatoes/Min)	Average Time Taken (Min)	Average Damage Rate (%)
Manual Harvesting	90	8	15	6
Robo Vec Harvesting	92	10	12	4

Table V. Comparison of Harvesting Methods

4. Results and Analysis. - In the results and analysis of Harvesting Robo-Vec, a more complex analysis of objectives was performed on the robot's live-operating performance against multiple metrics.

4.1 Tomato Detection Accuracy. - In regard to tomato detection accuracy results, the confusion matrix [24] (see Table. VI), summarizes the performance of the algorithm in terms of true positive (TP), true negative (TN), false positive (FP), and false negative (FN) detections. The confusion matrix shows the classification results and is used to assess the accuracy of the tomato detection algorithm.

Predicted	Actual Tomato	Actual Not Tomato
Tomato	True Positive (TP)	False Positive (FP)
Not Tomato	False Negative (FN)	True Negative (TN)

Table VI. Confusion Matrix Key Term

To obtain the essential parameters, we used the following formulae:

$$\text{Accuracy: } (TP + TN) / (TP + TN + FP + FN) \quad \text{Eq (1)}$$

$$\text{Precision: } TP / (TP + FP) \quad \text{Eq (2)}$$

$$\text{Recall: } TP / (TP + FN) \quad \text{Eq (3)}$$

By using data of TP = 120, TN = 700, FP = 150, and FN = 10, an accuracy of 83.67%, precision of 44.44%, and recall of 92.31% was obtained. The result for the tomato detection with other objects placed and with only tomato(s) can be seen in Figure IV.

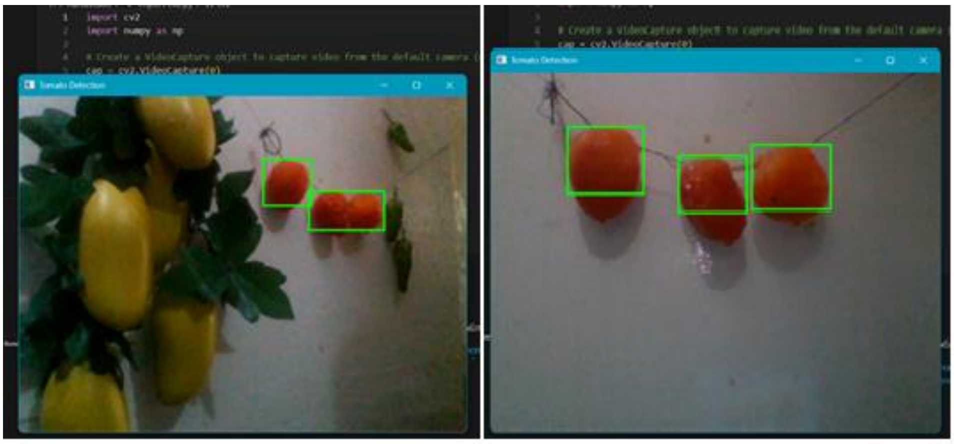

Figure IV. Tomato detection.

4.2 Obstacle Avoidance Performance. - In terms of obstacle avoidance, the robot successfully navigated around 95% of obstacles, with only 2 near misses and 3 collisions out of 100 encounters. This high success rate highlights the effectiveness of the obstacle detection and avoidance systems, though further fine-tuning could enhance performance.

4.3 Robotic Arm Manipulation Efficiency. - The robotic arm's manipulation efficiency was impressive, achieving a 90% success rate in gripping attempts and an 85% success rate in harvesting tomatoes. These metrics underscore the arm's reliability and effectiveness, with potential for further optimization in control algorithms and gripper design to improve precision and reduce damage to the product. Figure V represents the gripping and dropping of tomato from the robotic arm at the predefined location.

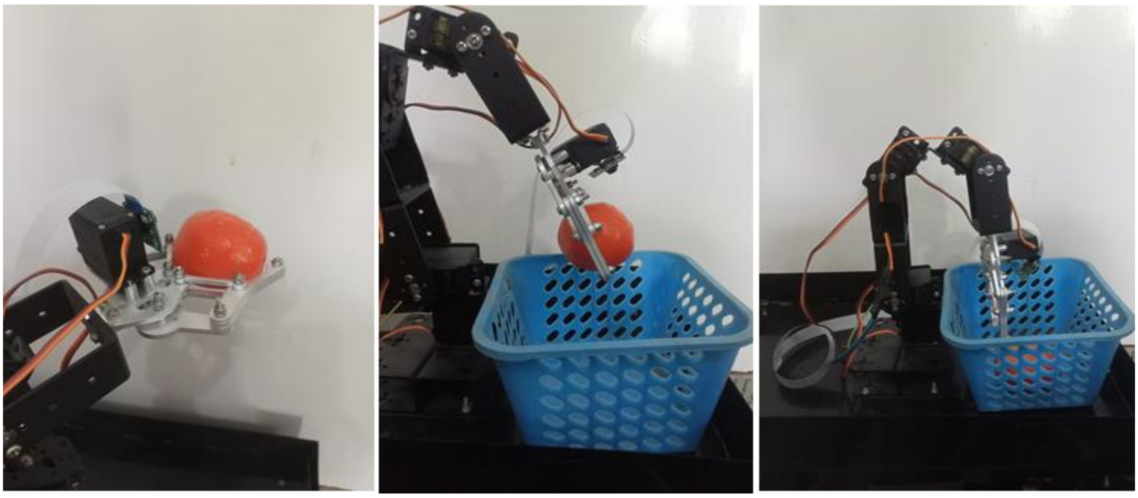

Figure V. Robotic Arm Manipulation.

The chassis of the vehicle, its charging port, and the resting position of the robotic arm placed in the final product can be seen in Figure VI.

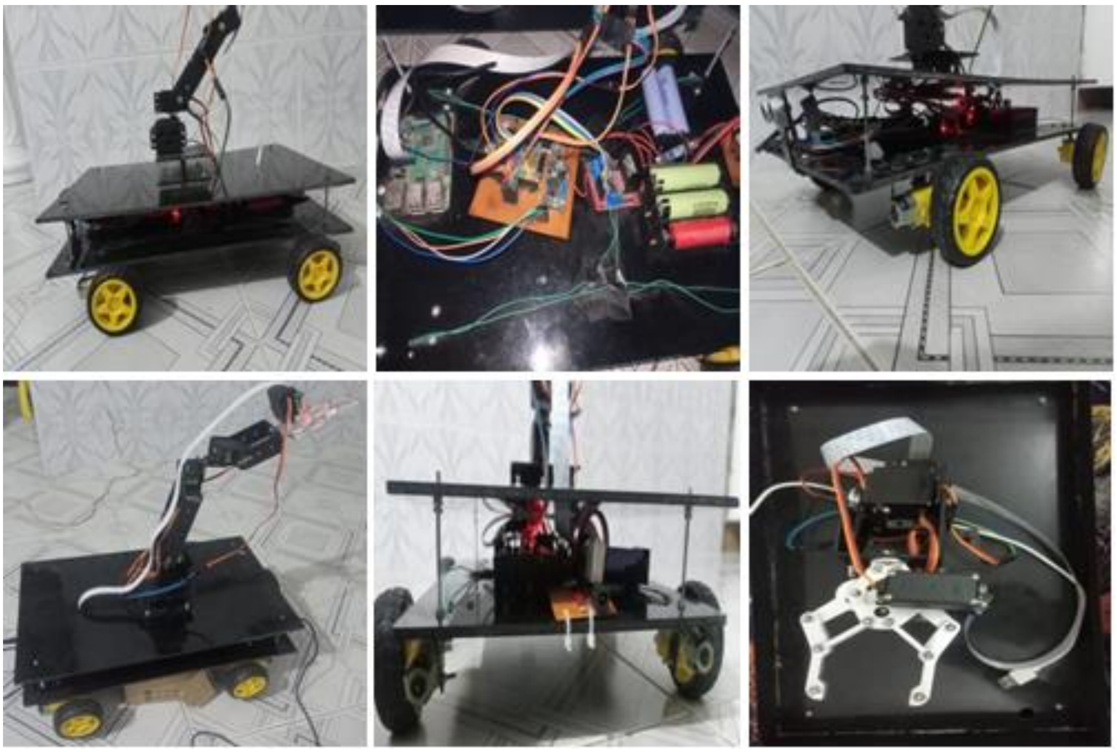

Figure VI. Robotic Arm Manipulation.

4.4 User Interface. - The prototype is controlled remotely using an Android application named "Harvesting Robot" (see Figure VII). To operate it, the Android phone connects to the access point of the ESP-32 module named "Harvesting Robot".

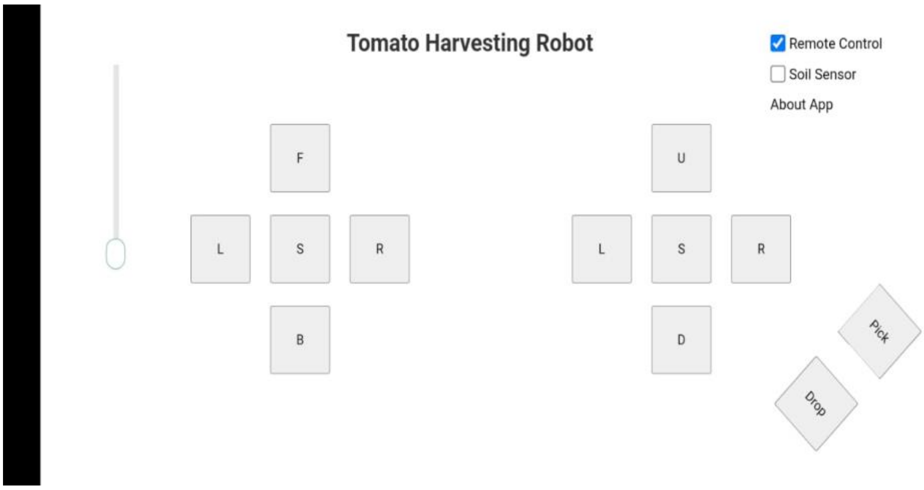

Figure VII. Remote Control of Robo-Vec.

The User Interface for controlling and monitoring the Harvesting Robo-Vec is designed as an intuitive Android application, enabling remote operation of the robot. Key features include straightforward control options that allow users to remotely direct the robot's movements and harvesting actions. The app provides manual control capabilities, as well as options for pausing and resuming operations as needed. Additionally, users can adjust specific parameters, such as speed and harvesting sensitivity, to tailor the robot's performance to various field conditions or crop types. The total cost analysis of IoT-based Harvesting Robo-Vec is presented in Table VII.

Component	Cost Estimate (Pkr)
Development and Prototyping	15,000
Microcontrollers (ESP32, Raspberry Pi)	37,500
Sensors (camera, ultrasonic, proximity)	2,600
Actuators (servomotors)	5,000
Battery (Li-ion system)	750
Chassis and Frame	5,000
Software Development	5,000
Contingencies	6,000
Total Initial Investment	**76,850**

Table VII. Cost analysis of IoT-based Harvesting Robo-Vec

5. Limitations and Failure Modes. - While the Harvesting Robo-Vec indeed works autonomously and can be a useful tool in agricultural scenarios, it does have its limitations and possible problems that could arise with its operations. We, therefore, explore these hurdles and propose solutions.

5.1 Obstacle Proximity Challenges. - The robot may have a problem identifying obstacles that are too close, which can cause collisions, or the robot to unexpectedly stop. This can be compensated for by adding additional sensors and moving their position

5.2 Detection Errors in Tomato Identification. - Tomato harvesting depends on precise detection with no leading fault. Such reliability can also be achieved using advanced image processing and methods of machine learning.

5.3 Energy Consumption and Limited Battery Life. - Prolonged operation can lead to quick battery depletion, especially under heavy workloads. Implementing energy-saving modes and optimizing operational paths can help extend battery life.

5.4 Mechanical Wear and Tear. - If the robot has run for some time there can be wear in the robotic components that can affect the performance. This problem can be minimized by making use of durable materials and also by following regular maintenance schedules.

6. Ethical and Social Implications. - Harvesting Robo-Vec will raise real ethical and social considerations that need to be addressed.

6.1 Impact on Jobs. - Automation will improve efficiency and help reduce service costs; It will also decrease the traditional demand for farm workers. Conversely, this tech can also generate employment in terms of maintaining, operating, and managing the robot systems, which can assist workers with the transition into new positions.

6.2 Environmental Considerations. - The Robo-Vec is designed to be energy-efficient, helping to lessen its environmental impact through smart power management and low-energy components. Future models might even use renewable energy sources, such as solar panels, to further decrease reliance on traditional power, supporting more sustainable farming practices.

6.3 Workers Safety. - Proximity sensors and emergency stop buttons are also added to Robo-Vec to ensure the safety of human workers around it. They even have sensors that are sensitive enough to detect anybody walking by, ultimately stopping the robot from doing its task to avoid an accident

With the continuous expansion of agricultural robotics, it is necessary to consider these ethical and social dimensions to ensure these advancements benefit society and the environment.

7. Conclusion and Future Work. - The proposed system model successfully achieved its goals and made significant advancements in automated tomato harvesting. The meticulous design and integration of the robotic system's components resulted in an effective and reliable outcome. The implementation of a Raspberry Pi-based color recognition algorithm enabled accurate tomato detection, while the integration of the ESP32 microcontroller facilitated seamless movement control, obstacle detection, and robotic arm manipulation. The findings indicate that the IoT-based Harvesting Robo-Vec has the potential to revolutionize tomato harvesting by reducing manual labor, increasing productivity, and ensuring consistent results through the successful integration of hardware, software algorithms, and IoT capabilities. Future work could enhance the tomato detection system's accuracy and robustness using machine learning techniques or advanced image processing algorithms and improve control through real-time data analytics and remote monitoring via IoT connectivity. Future iterations might also incorporate renewable energy sources, such as solar power, to enhance the system's sustainability and operational efficiency.

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Author contribution:

1. Conception and design of the study
2. Data acquisition
3. Data analysis
4. Discussion of the results
5. Writing of the manuscript
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