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Development of a Smartphone-controlled Robotic Arm for Automated Cotton Harvesting

Sidhant Sanjay Kulkarni[1], Yogesh Sopan Dighe[1], Abhilasha Mishra[2]

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ABSTRACT

Background: In recent years, agricultural automation has experienced rapid growth. Among these innovations, robotic arms have emerged as key instruments in reducing the need for manual labor in cotton harvesting. The increasing demand for efficient and sustainable solutions in agriculture has prompted the development of systems that enhance productivity while minimizing human intervention.

Methods: This study elaborates on the design and development of a smartphone-controlled robotic arm for selective cotton picking. The arm features six degrees of freedom (DOF) and is actuated by servo motors. A microcontroller integrated with a Bluetooth-enabled smartphone app facilitates precise arm control. The system architecture emphasizes cost-effectiveness, ease of use and portability.

Result: Experimental evaluation demonstrated that the robotic arm achieved a harvesting accuracy of approximately 70%. Despite its success, areas such as automation reliability, gripper precision and obstacle detection require further development. The proposed system shows promise for sustainable cotton harvesting with reduced labor costs and improved operational efficiency.

Key words: Cotton harvesting, DOF, Robotic arm, Smartphone app.

INTRODUCTION

The cotton harvesting operations in developing countries require substantial labor and spend large amounts of money on the same. The industry has chosen agricultural automation as its productive alternative through robotic arms that boost manufacturing output while minimizing human employment needs. Research about robotic mechanisms alongside sensor technologies and control strategies for selective cotton harvesting has been investigated by researchers over numerous years to enhance robotic arm efficiency. Robotic arms were analyzed made from Delta robots and articulated robotic arms and selective compliance articulated robot arm (SCARA) to achieve better speed and accuracy in cotton picking (Silwal *et al.*, 2017; Bac *et al.*, 2014). An economical robotic arm solution was designed which brought new automation possibilities to the farming industry (Ali *et al.*, 2023). The research examined robots featured with selective compliance while analyzing their valuable performance in agricultural applications. Modern detection technologies act as a crucial foundation for robot-based cotton harvest operations to achieve accuracy (McMorran *et al.*, 2016). The robotic arm gained enhanced cotton evaluation capabilities through the implementation of touch sensors (Nguyen *et al.*, 2020) whereas the machine vision as a key component for cotton boll identification (Zhang *et al.*, 2019). AI-based recognition algorithms that enhanced robotic object detection and selection for harvesting processes (Koirala *et al.*, 2019). The main elements responsible for robotic harvesting efficiency are the end effectors that handle and separate cotton bolls. Researchers studied soft robotic grippers because these grippers offer highly flexible and delicate handling capabilities to mitigate damage (Haghighi *et al.*, 2022). The research on vacuum suction grippers was performed for efficient cotton detachment through the use of airflow (Baeten *et al.*, 2008). The rotational and combing methods were applied to replicate hand harvesting methods in order to enhance the harvesting efficiency (Lin *et al.*, 2021). Robotics harvesting systems receive substantial improvements from the implementations of artificial intelligence and machine learning technologies. The AI applications in fruit harvesting could benefit cotton picking through better automation and decision platforms (Davidson *et al.*, 2020). Implementation of smartphone sensors for robotic control was studied which enabled remote agricultural robot control through mobile-based interface interaction (Kao and Huy, 2013).

[1]Department of Mechatronics Engineering, Sanjivani College of Engineering, Kopargaon-423 601, Ahmednagar, Maharashtra, India.
[2]Department of Electronics and Computer Engineering, Maharashtra Institute of Technology, Aurangabad-431 010, Maharashtra, India.

Corresponding Author: Sidhant Sanjay Kulkarni, Department of Mechatronics Engineering, Sanjivani College of Engineering, Kopargaon-423 601, Ahmednagar, Maharashtra, India.
Email: kulkarnisidhantmk@sanjivani.org.in
ORCID: 0000-0002-6626-8128.

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Recent developments in agricultural robotics have emphasized the importance of combining mechanical design with intelligent control for optimized harvesting efficiency. The mechanization in cotton farming has contributed to a 25-30% reduction in labor dependency in pilot studies across India. Moreover, smartphone-controlled robotic systems enable intuitive and cost-effective interfaces, bridging the technological gap for small and medium farmers (Yadav *et al.*, 2022). There is growing relevance of Bluetooth-and app-based systems in achieving real-time, remote control of field machinery (Mishra *et al.*, 2021). In line with (Chaudhary *et al.*, 2023), artificial intelligence (AI) and machine learning algorithms now play a significant role in refining object detection, movement control and end-effector behavior in robotic systems. The successful deployment of robotic arms in agricultural harvesting requires a synergy between hardware optimization and user-friendly software controls (Patel *et al.*, 2023).

The creation of robotic arms for cotton harvesting is indicative that automation is becoming more and more common in agriculture. Research investigators have advanced robotics technology through their creation of modern processes like AI-based recognition and improved sensors and end-effectors. Current research needs to focus on enhancing both the scope of automating large systems while ensuring the robotic identification of obstacles in addition to implementing real-time responses to changing environmental conditions. The manuscript explains methods for the proposed study in Section 2 by detailing the robotic arm design and software development along with the operating principle description. The paper ends its discussion with a summary of important research outcomes and plans for future exploration.

MATERIALS AND METHODS

The experiment was conducted during the *Kharif* seasons of 2023-24 at the nearby farms of Sanjivani College of Engineering, Kopargaon, Maharashtra. This study presents the development process for creating a robotic arm that functions can be operated through smartphone applications. The initial stage involved researching different robotic arm designs and fundamental mechanism concepts. The implementation of design modeling and feasibility analysis were then carried out SolidWorks as a desktop application. The robotic arm possesses six servo motors to execute precise object manipulation by means of its gripper system while operating in various directions. The Arduino Uno microcontroller served as the choice because it provided both cost-effectiveness along with simplicity for non-professional programmers. Integrated C served as the most common choice for embedded system programming to develop the control system. A smartphone application served as an additional control system that enabled wireless robotic arm operation through mobile devices. The application connects with the ESP32 through a Bluetooth module which enables remote control operations of the arm. Silicon-based wireless interfaces enable users to achieve efficient robotic arm control through an easy-to-use system making the technology suitable for various automated systems and remote operation projects, as well as educational robotics.

Working principle

The robotic arm hardware system consists of several components shown in Fig 1 that work together to facilitate precise control functions.

The power supply unit gives the system required voltage and current levels to operate all components dynamically. The core element of the system consists of an Arduino Uno microcontroller which delivers the role of executing instructions for controlling all connected devices. The HC-05 Bluetooth module offers remote operation functionality although it does not have wireless capabilities on its own structure. The robotic arm implements servo motors through Arduino PWM pins for precise angular positioning together with a stepper motor that enables controlled rotation for accurate movement.

Design of robotic arm

Robotics engineers incorporated human arm movements as a foundational concept in the design of robotic arms to

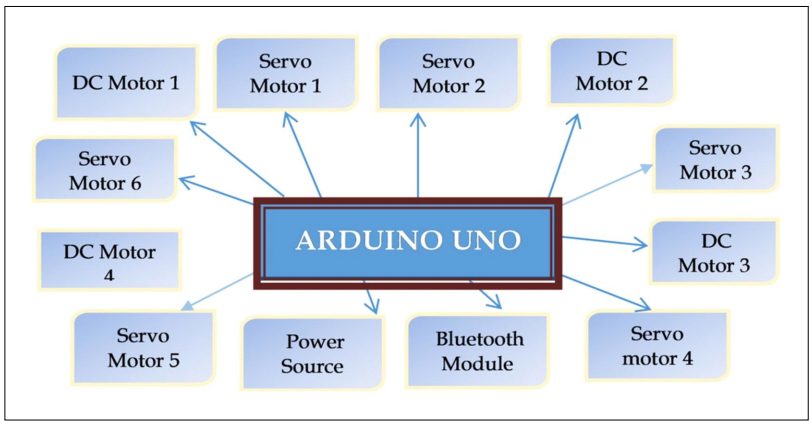


Fig 1: Block diagram of robotic arm.

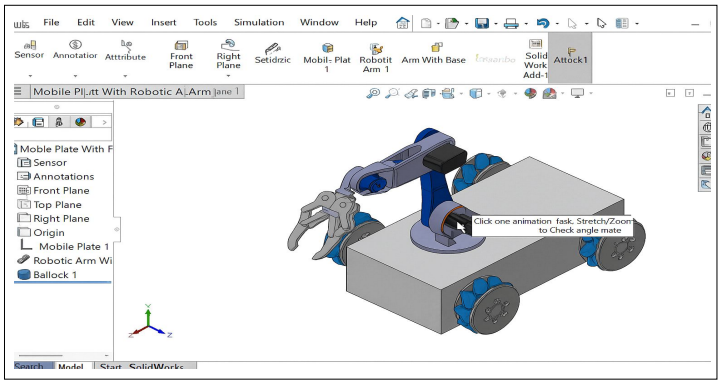


Fig 2: CAD design of robotic arm.

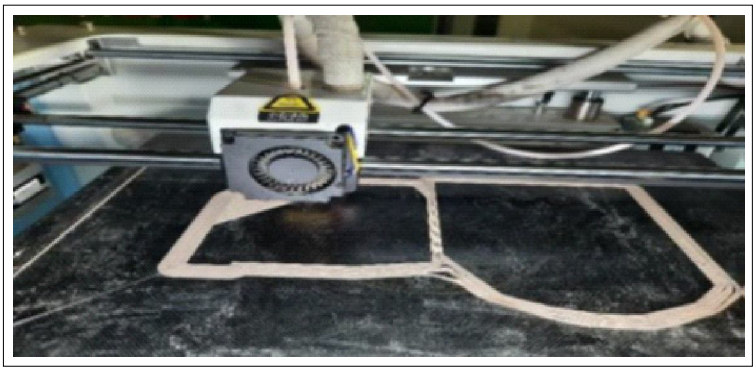


Fig 3: 3D printed part of robotic arm.

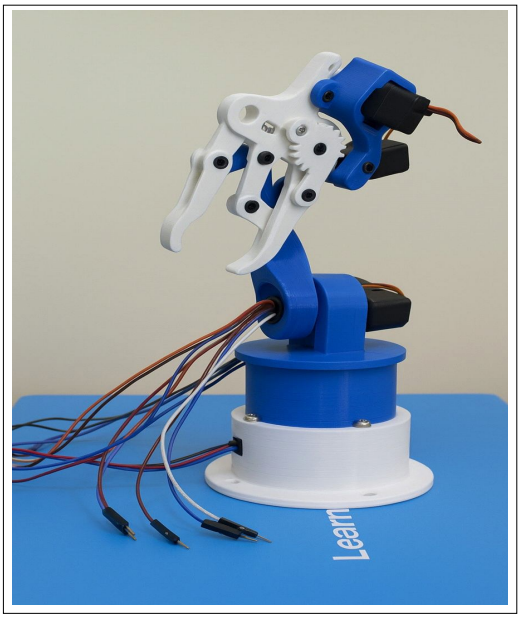


Fig 4: Fabricated robotic arm.

replicate natural motion and improve dexterity. Fig 2, generated using CAD design software (Solid Works), illustrates a robotic arm structure composed of interconnected links and joints, each equipped with sensors to enable precise motion control. The base of the robotic system provides stability and directional control, while the gripper at the distal end mimics a human hand to securely grasp cotton bolls. The arm is designed to be lightweight and compact, enabling high-speed operation and accurate movement. This ensures effective deployment in varied agricultural environments, particularly where selective harvesting and mobility are crucial. The biomimetic design enhances the robotic arm's adaptability, making it a practical and efficient solution for automated cotton harvesting.

The robotic arm was designed using SolidWorks, a parametric modeling software known for its powerful simulation, motion analysis and 3D visualization capabilities. These tools allowed engineers to evaluate joint movements, test load conditions and visualize the entire assembly in virtual environments before physical fabrication. The arm, developed specifically for automated cotton harvesting, incorporates six revolute joints that provide multi-directional flexibility, enabling it to adapt to varying positions and orientations in the field. The gripper, which functions as the end effector, was modified through iterative design to ensure gentle yet firm handling of cotton bolls, minimizing crop damage. The solid modeling approach facilitated the generation of precise 3D design files suitable for additive manufacturing. These designs were then 3D printed, as shown in Fig 3 and assembled into a fully functional prototype depicted in Fig 4.

The robotic arm, designed with five degrees of freedom (DOF), can precisely position its end effector along the x, y and z axes, enabling accurate manipulation during harvesting operations. This specialized version is equipped

with an agricultural gripper tailored for delicate cotton handling, ensuring minimal crop damage. The system executes control commands with high reliability, maintaining consistent performance across various tasks. Embedded control functionality is programmed using Integrated C, a widely adopted language for hardware-level programming due to its efficiency in managing time-sensitive operations and real-time control.

Software development

The robotic arm control application runs through MIT App Inventor as shown in Fig 5. This platform accompanies a simple application development process through its features allowing users to build their UI layouts by dragging components and coding tasks using blocks as a visual language.

Real-time control of the robotic arm is achieved through a Bluetooth-based communication protocol that facilitates seamless interaction between the smartphone application and the microcontroller. The application allows users to adjust multiple motion parameters, including wrist pitch, wrist roll, elbow, shoulder, grip, waist rotation and arm speed. This flexible interface ensures precise and efficient control of the robotic system, enabling responsive and accurate execution of harvesting tasks.

RESULTS AND DISCUSSION

The robotic arm implements a systematic workflow for cotton harvesting according to Fig 6.

The robotic arm follows a programmed sequence to carry out cotton harvesting operations with high precision and efficiency. It navigates along pre-defined paths to pick cotton bolls while minimizing damage to the surrounding plant structure. The fixed gripper is engineered to balance firm gripping force with delicate handling, ensuring optimal fiber preservation during collection. The system operates in sync with cotton boll ripening schedules, enabling time-based harvesting for improved productivity. When unexpected obstacles such as plant stems or debris are encountered, an obstacle response mechanism is activated, allowing the user to manually intervene and adjust the arm's movements. This feature ensures continuous and adaptive harvesting, significantly enhancing the robotic arm's performance in real field conditions.

Robotic arm configuration and motion

The robotic arm is equipped with six independent degrees of freedom (DOF), each controlled by a dedicated servo motor to enable precise and flexible motion. Four of the servo motors operate within a voltage range of 4.8V to 6.6V, while the remaining three require a slightly higher range of 4.8V to 7.2V. These six rotational joints allow the arm to achieve smooth and accurate positional adjustments, facilitating complex movements necessary for effective cotton harvesting. Table 1 below outlines the range of motion for each DOF.

Table 1: Range of motion of robotic arm joints.

Servo part	Maximum angle (°)
Waist	0-180
Shoulder	0-60
Elbow	0-85
Wrist roll	0-180
Wrist pitch	0-180
Grip	0-90

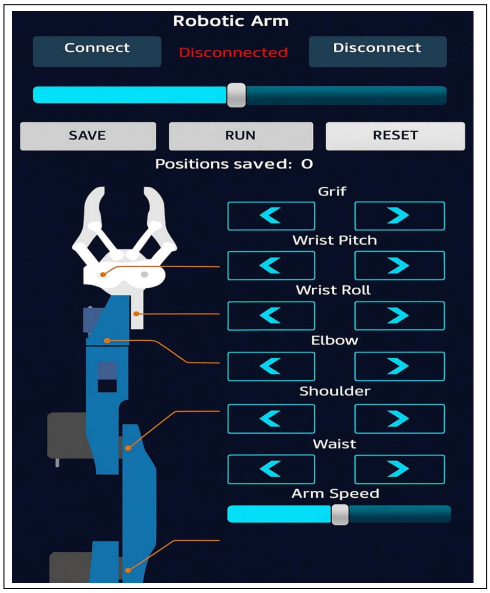


Fig 5: Robotic arm user interface.

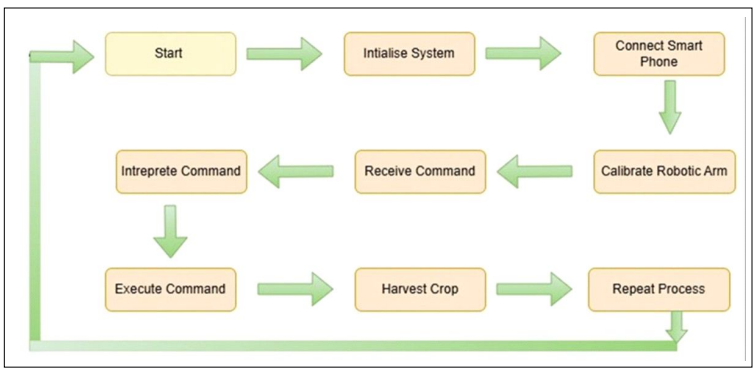


Fig 6: Process flow of robotic arm.

Table 2: Performance metrics for cotton harvesting.

Aspect	Observation
Performance	The success rate reached 1 in 4 attempts but pendulum movement reduced it and the success improved when the gripper movement occurred at a lower frequency.
Smartphone control	70% accuracy, with minor failures due to insufficient gripping pressure.
Efficiency	Energy efficiency aspect against manual labor operations should be considered when considering this technological advancement.
Comparison with manual harvesting	Automation delivers both fast operation together with standardized processes although human involvement achieves better adjustment capabilities.
Harvesting process	The system operates through pre-defined paths in combination with structured drop-off locations and empower users to handle obstacles manually.

The precision-based agricultural tasks require complex manipulations that the robotic arm achieves easily because of its six degree of freedom configuration. Further improvements in both motor control devices and power distribution systems and motion algorithm optimizations will lead to better accuracy along with higher energy efficiency performance of the robotic arm.

Performance evaluation

While operating the robotic arm achieved satisfactory cotton harvesting results but it also faced operational difficulties. The swinging arm motion sometimes created misalignment between the robot's grasp point and cotton clusters so that successful gripping occurred only once out of each four attempts. The precision issue was partially fixed by slowing down gripper movements while additional precision tools need development. Better alignment of the pan-tilt unit used for cotton boll tracking demanded supplementary modifications. The smartphone-controlled operation achieved a success rate of 70% but minor failures happened because of inadequate force during cotton fiber gripping. The key element of energy efficiency needs more study before comparing the robotic system with human-operated cotton picking procedures. Manual cotton harvesting holds better adaptability since it lets workers choose mature bolls effectively during collection. The robotic arm operates in three stages including its programmed pathways and human manual interventions and points to drop the harvested cotton but requires sensors and obstacle detection systems for improvement. The robotic arm achieved its performance outcomes while processing cotton according to data shown in Table 2.

Advanced gripper designs and obstacle detection systems and automated systems installed onto the robotic arm will maximize its efficiency for major harvest operations.

CONCLUSION

Robotics arm systems developed for crop harvesting resolve modern agricultural difficulties through their reduction of manual labor and their 70% precision level and their wireless Android app-based control. The technology boosts both operational effectiveness and exactness with environmentally friendly characteristics which increase output levels. Robot arms utilize modern sensor applications along with advanced computer vision systems to perform autonomous navigation in fields while accurately detecting crops followed by minimum human-assisted harvesting. The smartphone-operated robotic arm proposed in this work offers an efficient harvesting system that combines low implementation expenses with minimum operational labor costs and large-scale potential which supports current digital agricultural and precision farming tendencies. Several issues including uncontrolled arm waving and imprecise grasping along with the high price need to be resolved. Future research needs to concentrate on AI-processing of images with advanced sensor networks and machine learning systems that will advance operational efficiency together with affordability and large-scale implementation within the agricultural market.

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Disclaimers

The views and conclusions presented in this article are solely those of the authors and do not necessarily reflect the official policies or positions of their affiliated institutions. While the authors have ensured the accuracy and completeness of the information provided, they disclaim any responsibility for potential losses or damages arising from the use of this content.

Informed consent

This study did not involve human participants or animal experimentation. Hence, ethical approval and informed consent were not required. All development and testing procedures were limited to the use of mechanical and electronic components.

Conflict of interest

The authors declare that there are no conflicts of interest related to the publication of this manuscript. The study was

conducted independently and no external funding, sponsorship, or commercial support influenced the design, execution, analysis, or reporting of the research.

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