

Low-Cost, TinyML-Enabled Portable Machinery for Precision Cotton Harvesting

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Abstract:

Cotton is a major crop grown worldwide, and its production requires massive labor particularly for its harvesting. Hence, mechanization of cotton harvesting can cope with labor shortage and decrease labor costs. Most of the developing countries; still have been harvesting cotton by natural means. While developed countries have been using machines to harvest most of this important crop. The interest in cotton-harvesting machinery is increasing among many countries because of the unavailability of skilled workers and increasing labor costs. In addition, manual harvesting often leads to mixing of unwanted materials such as dry leaves, stems, and dust with the cotton, which reduces its quality and market price. To tackle aforementioned problems, this paper presents a small farm land compatible low-cost lightweight energy-efficient cotton harvesting machine integrated with crop detection intelligent mechanism. An energy-efficient sensor unit which includes a camera for capturing image of mature cotton bolls and an on-device low-power AI model for processing the image and detecting the presence of cotton. If cotton is detected, the harvesting unit is turned on for cotton harvesting. In contrast to existing harvesting methods dependent on costly processors or cloud computing, the proposed system implements all processes on-chip, making it low-cost and appropriate for rural environments with scarce internet and electricity resources. More generally, this work aims to assist smallholder farmers by providing a viable harvesting alternative that demands no physically labor, incurs minimal operating costs, enhances cotton quality, and promotes the adoption of smart farming at low costs.

Keywords — Cotton Harvesting, Edge Computing, Smart Agriculture, Machine Learning, Agricultural Robotics, Computer Vision.

I. INTRODUCTION

In India, Agriculture is the backbone of the Indian economy. Cotton cultivation contributes significantly to the international textile and agricultural sectors. In agriculture, the cotton crop is mainly cultivated as a fibre crop, and it becomes the major source of income for a large number of

the population. India is the top among the leading cotton-producing countries in the world. Cultivation increases in multiple states in the country by small and marginal farmers. Though we are advanced in the technologies and cultivating methods, Cotton harvesting is one of the most labour-intensive and continues to rely heavily on manual labour. The traditional method requires a lot of physical effort,

time and multiple harvesting cycles. This leads to the shortage of labour, dependency and an increase in operational costs.

Due to complexities in the cotton picking, it requires a large number of labourers to cultivate, and each labourer should be given wages for their work. This becomes a serious challenge for the cotton growers. Maintaining the fibre quality of the cotton during collection is one of the major concerns.

Traditional methods include the selective collection of cotton balls manually. This leads to the collection of a lot of impurities, such as stems, leaves, and dust, which typically increase in the trash and lead to low market value. Over the recent years, farmers are facing issues with increased labour requirements, sudden changes in harvesting costs, and difficulties in searching for seasonal labourers. These issues delay the cotton cultivation, which creates a negative impact on the crops that need to be addressed immediately.

Since technologies are growing rapidly and the use of intelligence in all fields is also increasing, this leads to the opening of new opportunities in modern agriculture. Automation, Machine Learning, and Computer vision are the advanced techniques that have been applied in the field of agriculture in recent days. OpenCV and TensorFlow are widely used technologies in the field of agriculture, which are used for object recognition and help to provide real-time data analysis-based applications.

Our proposed solution aims to produce a low-cost and portable cotton picking machine specially designed for small and marginal farmers during the cotton harvesting process. This system uses an AI-based vision module in order to check whether the cotton bolls are mature or immature to harvest. This aims to produce lightweight, easy-to-operate and semi-automated cotton picking machinery that is suitable for all kinds of agricultural fields. The proposed system's main objective is to reduce labour dependency, improve the operational speed, enhance the cotton quality by reducing the trash content and also protect the crop from damage. Furthermore, the proposed system aligns with the

objective of Atmanirbhar Bharat and Digital India, encouraging agricultural-driven innovation to support rural development.

II. LITERATURE REVIEW

A. Comparative Analysis of Cotton Harvesting Mechanisms

Harvesting cotton in developing countries—India especially—is still mostly a hands-on job. Laborers go out and pick the bolls straight from the plants. It takes forever. "There's no Whitewash it: hand-picking cotton is backbreaking labor. Every harvest season brings the exact same stress for farmers. They can't find enough hands, and the cost to hire help just keeps climbing. It takes a year of hard work that should finally put them in the green, and turns it into a financial nightmare." That's exactly why engineers and researchers have been racking their brains for years to find a better way. They just want to make the job faster and easier on everyone's bodies, which is why we're now seeing everything from basic, handheld tools to some seriously advanced farming robots."

Deshmukh and Mohanty [4] took a good look at how different parts of the world handle this. They weighed traditional hand-picking against modern mechanical options. Their takeaway? Those massive, spindle-based harvesters are absolute beasts when it comes to speed. They can clear out huge farms in almost no time. But there is a catch. These giants cost a fortune to buy and keep running, and they only really make sense on massive, flat estates. For an average Indian farmer working a small plot, buying one of those is a pipe dream.

Looking for something that actually fits local farms, Rao et al. [11] focused on portable, manually operated pickers designed with India in mind. Turns out, these lighter mechanical tools actually do take a lot of the physical strain off workers, and they speed things up too. They won't break the bank and are easy enough for anyone to use. The problem? They aren't very smart. Without intelligent sensors, these machines basically grab whatever is in front of them. You end up with a messy mix of good cotton, dried leaves, and tough stems.

Going in a completely different direction, Gharakhani et al. [6] built a high-tech robotic harvester. It used an automated arm with a three-fingered gripper. It actually worked pretty well, boosting efficiency and using smart tech to pick only the mature bolls. But again, there is a tradeoff. You've got complex robotic parts, fragile sensors, and complicated software. It's just too expensive and finicky for daily farm life.

Another group recently tried to improve this robotic approach by focusing on how the arm actually moves [9]. By throwing some heavy math at it—specifically clustering algorithms and shortest-path models—they figured out how to stop the robot from making useless movements. This definitely made the picking faster.

Modern farming gadgets are doing a great job at taking the heavy lifting out of agriculture. But for the millions of everyday families running small farms in India, these "advanced" tools simply don't fit. They are usually expensive, take up too much space, or require an technical degree to fix. It is time we create a new, inexpensive generation of harvesting gear that is designed specifically to help these everyday farmers. To genuinely support local farming communities, future designs must be inexpensive, easy to carry, and intuitive to use, possessing just enough practical intelligence to pick clean cotton without relying on overly complex, inaccessible technology.

B. Machine Vision for Maturity and Feature Detection

Machine vision technology is one of the most widely used in smart agriculture. The image processing technique enables its use as an automated system that identifies crops in the field and agricultural-based products. The main purpose of using computer vision is to detect the mature and immature cotton balls during harvesting. Then the machine tries to collect only the mature cotton bolls and reduce the trash content during the harvesting process. Research papers aim to advance the technologies for better harvesting, efficient collection of cotton, and reducing manual methods and time.

A paper titled "A Research for Intelligent Cotton Picking Robot Based on Machine Vision" developed computer vision, image segmentation, and feature extraction methods that offer accurate detection of cotton balls in different environmental conditions. The system successfully harvests the mature cotton balls [15].

Gharakhani et al. developed a robot for cotton harvesting that uses a dual-camera vision setup to identify where the cotton is located, its distance, and how to pick it accurately. The system also uses a YOLOv4-tiny deep learning model to achieve accurate detection of cotton balls [8].

Another paper uses morphological vision characteristics, such as the dimensions of the cotton balls, the structure of the surface, and geometric properties. The system mainly focuses on digital image processing methods for cotton extraction from the crops[2].

From the above research papers, we can observe that all systems focus on using machine vision and AI-ML technologies to detect the mature cotton bolls and to harvest accurately. The existing system uses AI-based agricultural machinery that uses powerful hardware and requires the internet for cloud-based data processing for operation. Therefore, by integrating TinyML, the system enables modules to run and process the collected data in real time on an embedded system. This proposal improves efficiency and produces low-cost, portable machinery for cotton picking.

C. Robotic Mobility and Navigation in Unstructured Fields

In Agricultural fields there is uneven land, arrangement of crops is irregular and there are obstacles that make it difficult for the robots to move in the field. There are different robotic mobility and navigation techniques that help in navigating the robot in the field. Researchers have proposed some techniques that help reduce the time and move through the fields efficiently.

Gharakhani et al. developed different types of end effector that works differently. Their study emphasized about the robotic movement and also the type of end effector used. Based on the type of end effector and the orientation of the plant the efficiency differs [6].

A recent research paper on robotic arm path planning proposed clustering-based optimization algorithms to improve the traversal path of robotic arms during harvesting operations. The method reduced unnecessary robotic movement and improved overall operational efficiency [9].

Zhang et al. presented an overview of Edge Computing technologies in agricultural IoT systems and discussed how real-time processing at the edge can improve autonomous agricultural operations. Their study highlighted the advantages of edge computing like low power consumption and low latency [17].

Another study by Sanchez-Iborra and Skarmeta discussed TinyML-enabled smart devices and their applications in low-power intelligent systems. Their work demonstrated that TinyML-based edge devices can support real-time decision-making while consuming minimal energy, making them highly suitable for autonomous agricultural applications [12].

These studies indicate that robotic mobility and navigation are critical for automated harvesting systems. However, many systems still face difficulties in operating effectively in small, uneven, and fragmented Indian agricultural lands. Therefore, lightweight portable systems with simple navigation mechanisms and low-power processing capabilities are more suitable for practical farming applications.

D. Socio-Economic Impact and Frugal Innovation in Small Landholdings

Cotton cultivation in India is mainly done by small and regular farmers who has their own agricultural land. These farmers mainly depend on labors who work for their land for cotton harvesting, but due to this lot of time gets wasted, dependent on labors, and mainly economically challenging. In

case of increasing labor daily wages, shortage of labour according to seasonal crops and rise in harvesting crops has also created serious Impact on farmers during peak harvesting seasons. Because of this Impact, there is a necessity of efficient and affordable harvesting technologies , which is suitable for small and large-scale farmers.

The already existing cotton harvesting machines are mainly designed for large-scale farming and due to which they require huge field space, operators and high cost. Such type of harvesting machines are not affordable for small-scale farmers in India. Due to machines structure, high power consumption and more maintenance make machines inaccessible for small/poor farmers.

Frugal innovation play a vital role in solving different agricultural problems by implanting a low-cost, affordable and an efficient technological solution. These technologies main goal is to reduce difficulty, reduce production cost, improve efficiency of energy, and also make sure that it is available for all type of farmers. In case of cotton harvesting, frugal innovation main goal is to implement a portable harvesting system that can do efficient harvesting methods without any huge machines or skilled operators.

The proposed low-cost, tinyml enabled portable and precision machinery for cotton harvesting mainly depend on supporting frugal innovation by including lightweight embedded system, computer vision, and low power ai technologies into affordable and efficient agricultural machine.

Another major socio-economic Impact of proposed system is reducing the dependency on labors. Manual cotton harvesting require humans help and due to which it leads to lot of time consuming during peak harvesting seasons. Smart harvesting technological solutions can improve the speed , efficiency and reduce the physical working of human in land. This leads to increase in agricultural development, productivity and reduce dependency of manual labor,

III. PROPOSED MODEL

Building on existing models, the following section proposes a new model. The objective, purpose, and work will be proposed:

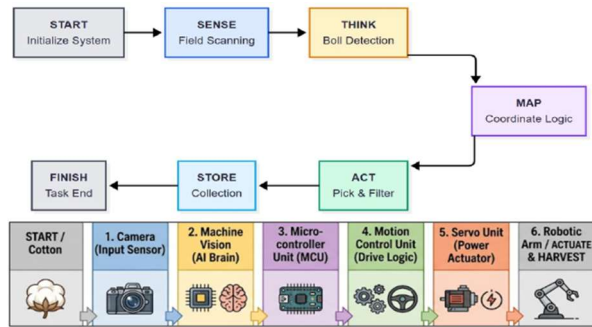


Fig.1. Autonomous Harvesting Workflow

A. Scope of the model

The proposed model is an autonomous robot designed to assist with cotton harvesting, reducing labor and time while offering a cost-effective alternative. It enhances cotton quality and enables farmers to gather premium cotton more efficiently. Farmers can monitor the robot's activity directly. The robot operates on a solar-powered battery and connects to the cloud, making information accessible through a dashboard. Equipped with an onboard camera, the robot captures images of cotton bolls. A machine learning model classifies mature bolls, immature bolls, and flowers, with processing handled at the edge device to minimize latency. After classification, the robotic arm collects the cotton, ensuring minimal trash content. The robot then navigates autonomously using integrated sensors, covering fields quickly.

B. Implementation

The robot can be either controlled by the user or work autonomously. It starts with locating the



Fig.2. Autonomous Cotton Harvesting Robot

field with cotton to be harvested. The camera and the sensors attached help in navigating the

cotton on the plant. The attached camera captures the cotton and classifies it into 3 categories: mature boll, immature boll, and a flower. The dataset collected for this classification will be real-time data. The machine learning model will be trained with the dataset and also be tested using some real-time data. This processing will be done on the edge device, i.e., on the microcontroller, which takes less time and less computing power. During the processing, there is a limited internet connection. Only the cotton bolls will be collected with less trash content using the end effector. The basket placed on the robot will collect all the cotton and will notify the farmer when it fills up. After all this, it starts navigating to the next crop. This model uses Edge Computing, which is processing data at the edge. The real-time robot for the field requires flexible mechanical wheels that can navigate in the field.

C. Edge Computing in the proposed model

Firstly, Edge Computing will allow us to analyze information about the cotton field collected by our robot right here, on its premises. The reason behind it is that in an agricultural environment, there is not always the possibility of stable internet access. Thus, we will process data locally which means that we will increase speed, efficiency, and stability. Moreover, our robotic system will be supplied with an onboard camera that constantly will scan the environment in order to take pictures of the cotton plant. After that, our machine learning algorithm will classify cotton into one of three types: mature boll, immature boll, and flower.

As a result, we will make our decisions without transmitting all data on a cloud server. Such an approach will decrease the time required for classification, thus increasing efficiency of picking the required products. Also, our robot will become faster as it will pick only mature bolls from the field, therefore decreasing both labor costs and percentage of trash among the cotton. What is also important, we will use Edge Computing to minimize the consumption of our

bandwidth as no unnecessary images will be sent to the cloud dashboard.

Besides, edge computing will enable us to save energy in our robot that operates with a battery supplied with energy by a solar charger. In addition, edge computing is a technology based on which we will make our robotic arm function autonomously. That is why the robot won't need any external communication in case it loses connection to the internet. Besides, we will improve the privacy of our robot in case someone wants to track its movements.

Finally, our robot will become able to navigate through cotton field using its onboard cameras for obstacle recognition, path planning, and crop identification. With this method, we will increase productivity and the size of our robot's area of operation. Overall, edge computing will make our robotic system work more efficiently and productively.

IV. CONCLUSION

Using lightweight machine learning models on low-power microcontrollers makes the system cost-effective, energy-efficient, and particularly suitable for rural scenarios where internet connectivity and power resources are major concerns. The selective picking mechanism facilitates reducing trash content with the harvested cotton, hence enhancing the quality and market price of the cotton.

Our proposed solution also offers significant advantages in terms of both portability and usability. The machine has been conceptualized considering small and marginal farmers who cannot afford heavy agricultural machinery/equipment. A rechargeable battery with support from the solar panel also promotes the concept of green energy in agriculture.

Basically, this project states that advanced technologies do not always need costly infrastructure and can be adapted into normal and affordable tools for agriculture. The proposed machine has the potential to support smart farming,

boost efficiency, reduce costs, and provide better economic support for farmers in the future.

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