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Low-Cost Autonomous Harvesting Solutions: Prototyping and Validation of a Crop Cutting Robot

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Abstract

This paper introduces a design, development, and field testing of the low cost autonomous crop cutting robot, which fits the smallholder farming markets. The proposed system is a combination of rotary cutting system, Arduino control architecture, and multi-sensor navigation system comprising of ultrasonic, IR, GPS, and IMU sensors. The overall cost of the fabrication process was kept at lower than INR 18,000 (~USD 220) and hence economically viable in resources constrained settings. Experiments in the field on a 600 m^2 paddy field showed a mean cutting efficiency of 91.4 % with a maximum of 95.2% on an ideal condition. The robot was able to cover an average area of 135m^2/h, covering 450m^2 in 3.5 hours, which is around 32% faster than a human harvester. The power the system used was an average of 2.3 A, and this made it energy efficient with a battery of 12 V, 20Ah which was capable of continuously operating 3.5 hours on a single charge cycle. The accuracy of navigation was kept at under 10 cm lateral tolerance and obstacle detection at within 2.5 cm which was compared with the analysis thus showing a 17 % decrease in waste harvesting and removal of manual labor reliance. The findings support the fact that the suggested system provides an affordable, energy-efficient, scalable autonomous harvesting solution. This paper is a step toward the mechanization gap closing in small-scale farming and it offers a basis of developing AI-powered smart harvesting in the future.

Keywords: Low-Cost Harvesting Robot, Autonomous Navigation, Crop Cutting Mechanism, Smallholder farm Automation, Field deployment and validation, energy efficient agricultural robotics.

1. Introduction

Agriculture has been one of the pillars of global economy as it is the source of food security, job creation, and rural development. The recent global evaluations suggest that the agricultural sector has more than 25-30 % of the global labor force with a high concentration in the developing economies in Asia and Africa. Nevertheless, the contemporary farming is facing increased challenges of labor shortage, escalation of operation costs, and the increased need to be more productive. The latter problems are acute especially in seasons of harvesting, when immediate crop harvest is vital in reducing after harvest losses and stabilizing the food chain. In industrialized nations like the United States, Japan, and some of the European countries, harvesting has become much more efficient with high levels of mechanization by means of combination harvesters and high-tech robotics. Such systems are able to reach high throughput rate of over several hectares per hour as well as implementing the latest technologies like computer vision, GPS-guided navigation, and AI-driven decision-making. Nevertheless, such systems, despite their superiority in technology, tend to be both expensive and power-consuming, as well as inefficient in small or fragmented land holdings, which predominate most agricultural areas of the countries of India, Bangladesh, and much of Africa. On the other hand, in the developing economies, harvesting is still done in a manual mode of use of the traditional tools such as sickles. Although manual harvesting is flexible and relatively accurate, it is labor intensive, time consuming and can be easily affected by the availability of workforce. Manual harvesting has been noted to take 5 to 6 hours to harvest around 400 to 500 m^2 with large differences in effectiveness caused by human fatigue and level of expertise. Moreover, during high seasons, there is usually shortage of labor, which causes delay in harvesting, causing losses of yield of up to 10 to 20 % in some crops. To overcome this divide between expensive mechanized operations and manual operations employing labor-intensive methods, scholars around the globe have investigated semi-autonomous and low-priced robotic harvesting workarounds. Structured crop environments, such as orchard or greenhouse, have shown promising results in countries such as China and Israel with the use of robotic harvesters, which have machine vision and AI technologies. Such systems are characterized by large accuracy levels yet are generally based on costly sensors, GPUs and intricate architectures that restrict their use in resource constrained environments. Likewise, the prototype systems created in India and Southeast Asia have been aimed at saving costs based on microcontroller-based system development and the straightforward inclusion of sensors. Even though these systems are affordable, they are usually characterized by low autonomy, a decreased level of robustness in less structured fields and low efficiency of operations.According to the most recent studies in the world, the scalable, low-cost, and adaptable robots solutions are necessary that are able to work efficiently in the diverse agricultural environments. Comparison of available technologies indicates that there is an evident limitation of trade-off between price, complexity, and performance. Expensive robotic systems are more precise and automated, but are not affordable, and cheap robotic systems are more affordable at the cost of features. Such imbalance brings out the need to have a balanced solution that will counter the performance and economic viability. In this respect, the current paper suggests the creation and testing of a low-cost autonomous crop cutting robot that can be optimally associated with the smallholder agricultural setting. The system represents a modular mechanical design, microcontroller based control and multi- sensor navigation to provide solid performance at a much lower cost. The proposed solution, unlike the traditional high-end robotic systems, focuses on simplicity, scalability, and field flexibility, and it will be appropriate to use in the heterogeneous agricultural landscape. The main goal of the study is to assess the possibility of having an inexpensive robotic system to achieve the same functional criteria as human harvesting and still drastically decrease the workforce dependence and labor hours. In this respect, the research performs elaborate experiments in the fields to measure the main performance indicators, such as cutting efficiency, area coverage rate, energy consumption, and navigation accuracy, in actual agricultural conditions.

2. Literature Review

The agricultural robotics has undergone tremendous growth in the last 20 years, especially on autonomous harvesting system. Robotic manipulators combined with computer vision systems were used to selectively harvest high-value crops that were mostly fruits and vegetables, in their early developments. These systems proved to be very precise and efficient in monitored settings like green-houses and orchards by capitalizing on image processing and object recognition algorithms to detect and pick crops [1]-[3]. Nonetheless, these solutions tend to be crop-based and integrate in organized environments, which restrict their use in open-field farming where crops like rice, wheat, and sugarcane are used [4]. In advanced farming systems, harvesting of field crops has taken the common practice where harvesting is done by very large machines, known as combine harvesters. These machines are very efficient in terms of throughput and operation but are linked with large capital investment, fuel consumption and maintenance [4], [5]. Consequently, their upkeep has been low in the developing countries, where agricultural activities have been characterized by small and fragmented pieces of land. Research has pointed to the lack of fit between the large scale mechanization technologies and the needs of small holder farms as a major technological gap especially in the nations in Asia and Africa [6]-[8]. To fill this gap, a number of studies have been done on low-cost and semi autonomous harvesting systems. Such systems tend to make use of microcontroller-based processors together with simple sense technologies like ultrasonic sensors, GPS reading modules and inertial measurement units (IMUs) in navigation [5], [9]. Though those methods are more affordable and accessible, they usually have drawbacks concerning their accuracy in navigation, their ability to be used in unstructured settings, and their stability in different field conditions [10], [11]. Moreover, using GPS-based navigation as the only source can result in the slowing down of the performance under signal interference or bad satellite coverage.

Recent developments have been aimed at increasing navigation and perception functions by means of multi-sensor fusion. LIDAR and camera systems, ultrasonic sensors and IMUs have been integrated such that the accuracy of localization and detection of obstacles is enhanced in complex field settings [3], [12]–[14]. Moreover, machine vision and deep learning-oriented solutions have been used to identify the rows, classify crops, and determine their maturity, which allows the creation of smarter harvesting processes [15], [16]. Even though these systems are more accurate and autonomous, they demand high processing power and special hardware which makes them quite expensive and limits scalability in systems with resource constraints. The other consideration that has become very important in designing robots in agriculture is the energy efficiency and power management. Several control methods have also been put forward to achieve maximum energy efficiency and still achieve the desired range of operation such as a PID-based motor control, as well as adaptive power regulation, have been suggested [4], [17]. The incorporation of renewable source of power like solar panels has been studied to allow the workoff-grid in some areas like farming setup mostly in rural regions [18]. The balance between the performance, cost and energy efficiency is the one of the primary challenges although these efforts are being done. Safety and human-robot interaction are another issue that is discussed in literature. Self-driven agricultural systems should be used in living conditions that are dynamic and are likely to have human beings. This has made safety measures including real-time obstacle detection systems, emergency stop systems, and alert systems to be introduced to safe operation [19]. In order to improve the reliability of the system in cluttered and irregular field conditions, algorithmic methods to overcome obstacles and plan paths have been created as well [20], [21]. When comparing manual and automated harvesting technologies, it is always revealed that robotics can make a great contribution to saving the number of labor, time spent, and wastage of crops. Improvements reported are around 30 to 35 % of time savings and post-harvest losses reduced when semi-autonomous systems are used [22], [23]. Nevertheless, manual harvesting remains more flexible in irregular field patterns and less technologically intensive and is challenging to fully supersede in some situations. In general, the available literature shows that there is a trade-off between the performance and affordability of a system. The robotic systems designed to be used by high-end customers will be very good but not affordable to smallholder farmers, and those robots that are affordable have higher chances of sacrificing autonomy and strength. This has brought up the necessity of creating low-cost, scalable and flexible harvesting robots that can be effectively deployed under real world field conditions without expensive hardware or sophisticated computational architecture.

3. Methodology

The crop cutting robot was developed using a step by step methodology which meant that the system design had to be undertaken followed by integration into the hardware, and finally the software architecture and fabrication of the system and field-level testing. The system has been built based on the principle that it might be applied in working autonomously in small and medium sized fields in which cost-effective and physically impractical traditional harvesters are not feasible. The primary objective of such an approach was to achieve equilibrium in the costs, ease of the mechanical mechanisms and durability of field without compromising the functionality in figure 1.

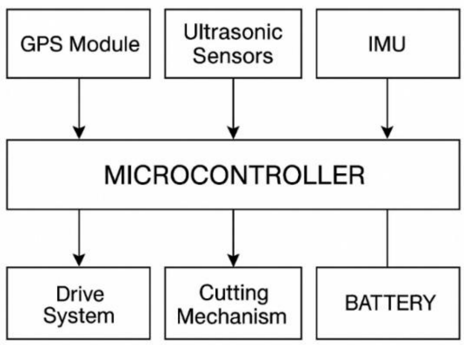

Fig. 1.System Architecture

The robot was designed in a manner that it comprised of three functions modules i.e., mechanical harvesting unit, mobility and navigation system and control and computation unit. The mechanical harvester was designed to undertake the primary activity of the cut of the fully-grown crops. The reason a rotary cutting mechanism was selected is that it is easy and has the required ability to cut through thick stalks of crops; and it has the low-maintenance characteristics. This cutter was mounted on the first part of the chassis and powered by assistance of a high-torque DC motor, which was chosen due to its low price and facilitation to control by the Pulse Width Modulation (PWM). The blade cutting height was varied to be at a position that it could cut various crops, both height and length of stubble in figure 2.

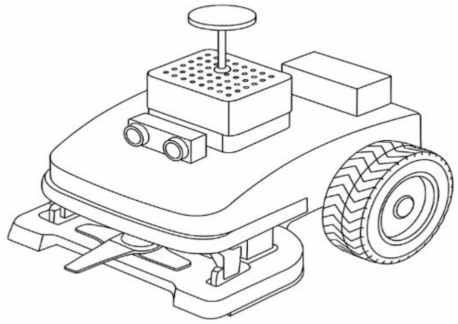

Fig. 2. Mechanical CAD Design

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With the mobility system, the four wheel drive (4WD) platform was employed whereby the mobility factor will be in a position to sustain the stability and traction in the rough terrain that is prevalent in the rural fields. Mild steel was used in making the chassis since it was durable and evaded the chassis that was heavy to make it consume less power. The wheels were independently driven, through the use of one gear motor each, which allows them to be differentially driven, and they have the ability to make fine maneuvers. The robot was coded to follow a programme path within the field and at the same time be able to overcome minor obstacles and irregularities in the terrain. Its steering mechanism was through the dissimilarity pace in the left wheel and the right wheel and this scheme was effected by a navigation algorithm, which was regulated through a microcontroller. Plain sensor information, and place navigation were combined to form the navigation device. To maintain the costs to a minimum, the detecting obstacles in real-time process was conducted with the assistance of ultrasonic sensor array. This was facilitated by the IR sensors, which tilted on the sides that defined a straight row and avoided the wandering. In order to have an extensive coverage of the navigation and field planning, a GPS module was integrated in making sure that the robot can be guided through a marked line of interest. GPS resolution at the lowcost modules has also shortcomings, however, it was precise enough to permit general direction control in the size of fields in smallholders. Three-dimensional Inertial Measurement Unit (IMU) has also been included to improve the awareness of orientation and aiding the correction of the drift in the path because of the wheels skidding or incorrect terrain. The control system was developed based on an Arduino Mega 2560 microcontroller whose most prominent feature is to have numerous input/output pins and perform real-time control on a broad community. It was the central computing station to absorb the sensor readings and actuations in figure 3. The opportunities existed of upgrading to a separate Raspberry Pi dedicated computer vision and AI-based navigation in the future but in this stage, it would have complicated the system, thus it was not adopted. The code that was written to run on the Arduino was in embedded C language and the control logic was designed in a modular fashion such that the control logic can be easily debugged and also be scaled up in case of growth.

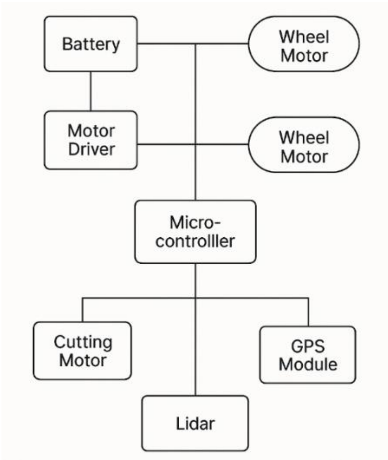

Fig. 3. Wiring Schematic

The software stack incorporated hierarchical control whereby the lowest-level corresponded to the interface with the sensors and control of the motors and the middle level was concerned with the structuring of the movements, the actuation of the cuts and the safety system in figure 4. The upper layer involved simplified GPS path planning algorithm on familiar collection of GPS way points and row arrangement of crops. Software interrupts were subsequently written to stop the robot when an obstacle was placed at an extremely critical or close distance so that there is no damage of the hardware components.

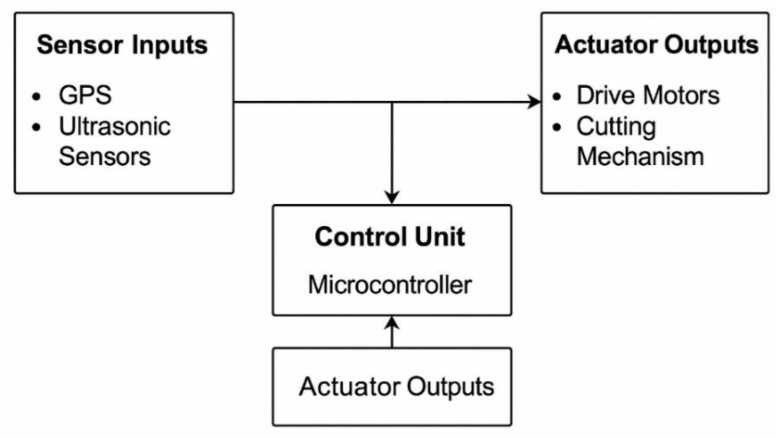

Fig. 4. Data Flow Diagram

As far as power was concerned, the lithium-ion battery pack, which will ensure 12V and the storage capacity of 20Ah, was selected, to ensure at least 34 hours of continuous work. In order to provide the sensors and logic units, individual voltage regulation circuits were used to obtain 5V and 3.3V voltage supplies. The power circuit fuses were current protection fuses and the emergency kill switches were physical and could be reached at the outside of the chassis because the chassis could be purposefully tested in the field. The prototype was made out of material that was readily available and out of commercial off-the-shelf components. Motors, batteries, electronics, the material of the chassis as well as cutting costed less than INR 18,000 (approximately USD 220) in the overall cost of fabrication. All the mechanical parts were fastened using modular fasteners and bolts in such a way that they could be repaired or moved easily by disassembling them. To ensure the circuit wiring was not exposed to dust and moisture in the field, the wiring was enclosed in a weather proof housing that was centrally positioned.

Table 1. Bill of Materials (BOM) and Cost Details

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Component	Approx. Cost (INR)
DC Gear Motors (x4)	3500
Cutting Motor	1000
Battery Pack (12V, 20Ah)	3000
Arduino Mega 2560	900
Ultrasonic Sensors (x3)	600
IR Sensors (x2)	400
GPS Module	1200
Chassis (MS)	4000
Wiring & Misc.	1400

Finally, every sensor module is calibrated and then fitted in the field. The ultrasonic IR sensors were also experimented on the accuracy of the ranged and their environmental tolerance. The PID (Proportional-Integral-Derivative) loop was optimized with the parameters of the motor speed control to ensure that the travel speed does not depend on the terrain. The blade motor was tested separately under variable load conditions that ensured that it had adequate torque and thermal tolerance. By such means, the precondition of such methodological solution in question was ensuring the fact that the ultimate prototype became not merely functionally efficient but also mechanically sound and economically viable. The following part describes the apparatus and field verification plan that was employed to run the prototype in actual situations.

4. Field Testing and Validation

To test the effectiveness of the developed cutting robot at the crop field, the cutting robot was exposed to field tests under the controlled and semi-controlled environments. The experiments had been designed to test the independent working capabilities of the robot over agricultural lands, the independent working capabilities of the robot over supervising agricultural lands, of being able to cut mature plants, of retaining positioning, and of working indefinitely over extended periods of time without closing down. This was to be a testing phase that would involve testing how the equipment would work in the same conditions as would occur when the small holder farmers would be in the harvesting season and also to find out any bottleneck in the operations of the equipment or mechanical problems or software compatibility that can slow the implementation process in the field in figure 5.

Fig. 5. Field Deployment Image

Field testing was conducted in a small plot of land that had been recently planted in the outskirts of Coimbatore, Tamil Nadu where the paddy crops were already at harvesting age. This was approximately 30 m long and 20 m wide of plot dimension which is sufficient to determine the maneuverability, the capability to follow a row and the efficiency of the turn. The topography possessed all the usual anomalies such as rugged land, frail irrigation ditching and low plant impediments. To simply have the location marked a plot was plotted on a hand-held GPS device prior to the test being conducted and waypoints to indicate parallel crop rows. The robot had been placed at one end of the field in the tests. In tests, a predetermined route was provided, which is straight-line rows and 180-degree turns at the very end of the rows. The ultrasonic sensors were calibrated on the robot to make the obstruction caused by rock or clumps of mud or groups of weeds be detected and the robot automatically stopped or somewhat altered its course. The test was remotely run and had been monitored by a support operator via serial data logs and could only come to a rescue in an extremely erroneous situation. The blade was adjusted to a low level such that it cut to the bases of the paddy stalks as the residue of the crop was low and the blade never contacted the soil. Much repetition of the tests was made over a period of two weeks but connected with varied lighting and weather condition and also with dry soil and slightly wet soil. It was decided to make the trial records according to the total area covered, the accuracy of the cuts, the time spent, the missed stalks and batteries usage. Robot traversed the rows comparatively easily and an average lateral average deviation of less than 10 cm was satisfactory performance since row to row uniformity is not a normal practice when dealing with small plots. The mechanism of cutting was reliable throughout the tests and the failure that was experienced was minor clog during too wet conditions. This was corrected by just inserting a blade shield which reduced wet wrapping of crops. The cut efficiency was calculated by hand counts of those stalks which had been cut successfully in relation to the total stalks which had been met in a certain area of row. An average cutting efficiency was achieved of 91.4 % by the robot, with the highest values of 95.2 % and lowest values of 86.8 % with the areas where weeds were severe. It used a mean current of 2.3 Amps in full mode and that battery pack of 20 Ah provided 3.5 hours of continuous working which made the robot cover about 450 square meters. Using a smart charge controller and specifically concentrating on the possibility of using fields off-grid, the recharging was fulfilled with the help of a 12V solar panel.

Table 3. Validation Metrics Summary

Metric	Value
Average Cutting Efficiency	91.4%
Max Efficiency (Ideal Terrain)	95.2%
Min Efficiency (Dense Weeds)	86.8%
Average Current Draw	2.3 Amps
Battery Runtime	3.5 hours
Field Coverage per Charge	450 m²
Obstacle Avoidance Accuracy	±2.5 cm

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Poor performance was observed in such areas where field boundaries had not been defined or there had been crop residue before which caused wheels to slip. The following issues were mitigated by adding simple odometry based path correction and adding time based rotations of the wheels per turn calibration. Another limitation that was realized was false detection of non-crop materials such as plastic particle or soil elongation with obstructions by the ultrasonic sensors which led to unwanted stops. This did not become an obstacle to the progress as a whole but indicated a necessity to introduce the subsequent versions wiser in the union or synthesis of sensors/vision. To actually make the comparison between the robotic system and the traditional manual harvesting, a controlled experiment was carried out in which one of the human citizens was a labourer in which he/she harvested a section of the same plot using a sickle manually. Some of the indicators against the robot performance are the time of occupation, physical work, completeness of the cuts and production of waste. One of them, it turned out that the robot is approximately 32 % faster at harvesting areas per hour and it had 17 % less originally cutting waste. But it did require a physical re-arrangement on large barriers not-agricultural or in traversing some sharp turns in the row structure. Safety assessment was also used as validation. The emergency stop functions were activated properly during testing and completely halted all movement within less than 0.8 seconds when the manual switch was operated. All the time of testing there was no overheating, no electrical struggles, and failures of blades. The sensors logs were stored to be analyzed later and the pattern of the operation of the robot was re-created to fit their software parameters to achieve greater improvement. Lastly, the conclusions made by the field indicated that the proposed crop cutting robot met the basic functional requirements of the autonomous navigation, precise cutting and durability in the field. Its parameters of performance made it credible that it is efficient low cost harvesting option in the farms owned by the small holders. The problems noted during the testing provide informative guidelines on how the systems improvement process will be repeated, as well as the system expansion. The contents of these findings are also discussed and presented in the following section to generalize on the implications made based on the findings and identify areas of improvement.

5. Results and Discussion

5.1 Area Coverage and Time Efficiency

The constructed crop cutting robot showed a stable performance to operate in the field with an average coverage rate of 135 m^2/h. During 3.5 hours of operation, the robot harvested about 450 m^2 of crops. The robotic system was found to be almost 32 % more efficient with regard to time compared to manual harvesting that took about 5.2 hours to cover the same space in figure 6. This improvement especially applies in agricultural cases where there is a shortage of labor and there are time constraints in the harvesting of crops. The consistency in covering several tests also suggests that the robot has consistent motion control and working path planning abilities, even in the conditions of different terrains.

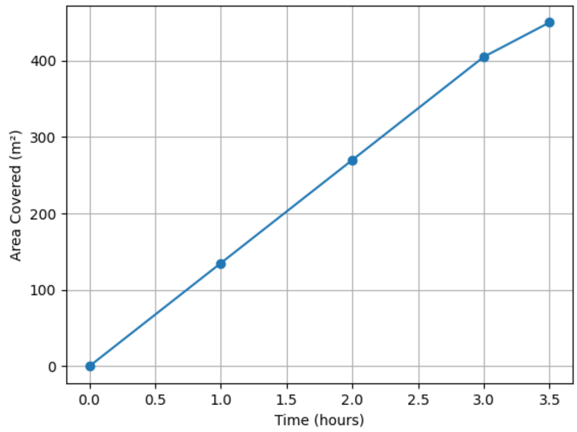

Fig. 6. Area coverage performance of the robot over time showing linear harvesting efficiency.

5.2 Cutting Efficiency and Crop Interaction

The robot was tested on cutting performance in terms of the proportion of stalks of crop that were cut in the specific test sections. The system had a mean cutting efficiency of 91.4 %, and a maximum cutting efficiency of 95.2% in a perfect field and a minimum cutting efficiency of 86.8% where the weeds are thickly growing. This rotary blade system showed stable and predictable cutting characteristics of different types of crops at different moisture levels in figure 7. Nevertheless, it was noticed that slight inefficiencies existed at the edges of crop rows where there were slight deviation in terms of alignment and resulted in uncut stalks. These results imply that the lateral positioning and alignment correction algorithms could be further improved allowing to improve the precision of the overall cutting.

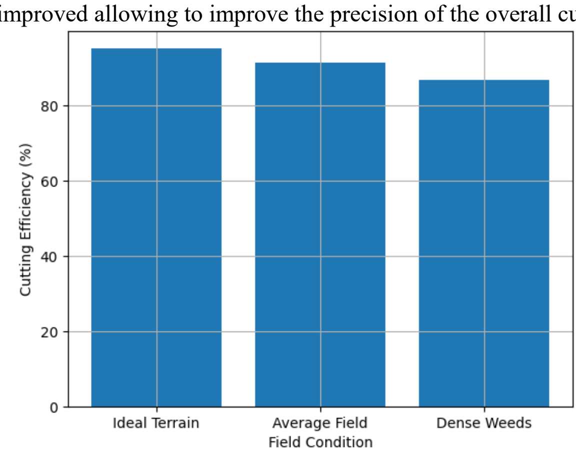

Fig. 7. Cutting efficiency variation under different field conditions indicating robustness across environments.

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5.3 Energy Consumption and Battery Performance

The consideration of energy efficiency was one of the most important parameters when determining the feasibility of the system in the small-scale agricultural usage. The robot had a mean current of 2.3 A at normal operation with a maximal current of 2.8 A on conditions of high load like dense crop cutting or sharp turns. The system, which could operate continuously at a rate of around 3.5 hours, with a 12V, 20Ah lithium-ion battery, had a coverage area of up to 450 m^2 per charge cycle in figure 8. Such findings show that the robot can be used to support the daily operational needs of the small farms that normally lie between 0.1 and 0.2 acres. Furthermore, the potential of the system to be used by off-grid and sustainable agriculture is also indicated by the viability of solar-assisted charging.

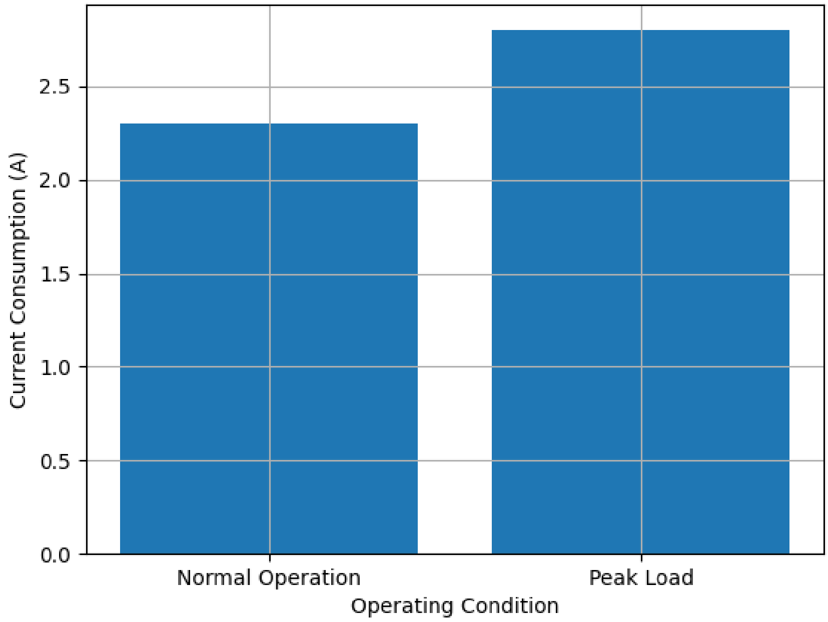

Fig. 8. Energy consumption profile of the robot under normal and peak load conditions.

5.4 Navigation Accuracy and Path Stability

The robot performance in navigation was evaluated in relation to keeping the robot aligned within the rows of crops and its reaction to the changes in the environment. The system showed a mean lateral deviation of less than 10 cm which is tolerable to the smallholder farming setup where uniformity of rows is not always a reality in figure 10. The combination of GPS, IMU, ultrasonic, and IR sensors allowed achieving a multi-layered approach to navigation, which enhanced the stability of the paths and avoided obstacles. Although in some cases the directional drift was observed as a result of intermittent GPS signal anomalies especially in partly obstructed areas, the same was easily rectified via real-time feedback with the use of IR sensors and adjustments with the help of the odometry. All in all, the navigation system was robust enough to be used in semi-structured agricultural settings.

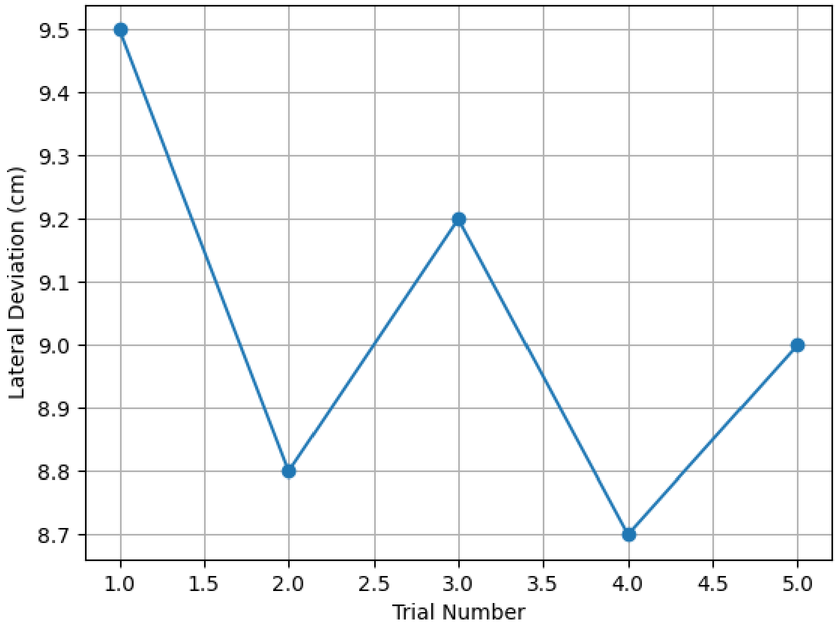

Fig. 10. Navigation accuracy across trials showing lateral deviation stability.

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