IoT-Integrated Robotic Farming for Sustainable Agriculture

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KEYWORDS

Machine Learning
Agri bot
Edge computing
Automated irrigation
Plant disease detection

ABSTRACT

The integration of automation and artificial intelligence (AI) in various aspects of agriculture has led to the advancement of smart farming. This research presents an enhanced multipurpose agricultural robot equipped with a crop monitoring system, utilizing high-precision sensors, AI-driven disease detection, and Internet of Things (IoT) capabilities. The system enables remote data analysis from multiple automated farm robots, facilitating real-time monitoring of soil conditions, plant health assessment, and automated irrigation and pesticide spraying. The proposed enhancements significantly improve farming efficiency by minimizing manual intervention and optimizing resource utilization. Performance evaluations demonstrate substantial improvements in accuracy, resource efficiency, and real-time monitoring, making this system highly suitable for precision agriculture.

1 Introduction

In more recent times, advanced robotics have also contributed to changing agricultural practices, setting up a path for precision farming. With capabilities for real-time monitoring and automation of main agricultural operations, these systems have taken away labour pressure from farmers and brought in efficiency .

Therefore, robotics have drastically changed the scenario of automation in agriculture. Robotic tools from soil analysis and seed planting to irrigation and harvesting can be of great promise for farm productivity. Nevertheless, the task of introducing automation faces significant hurdles, including the prohibitive investment in such machinery and the requirement to obtain specialized technical know-how, especially in the case of small and medium-sized farms .

Robotics-as-a-Service (RaaS) is a proposed solution to overcome those barriers. Farmers are offered robotic solutions as a service, thereby avoiding a high initial investment for systems on their own. RaaS incorporates the physical robotic assets coupled with cloud and networking capabilities to aid the collection-sharing-decision-making data environment . Also, the Internet of Robotic Things (IoRT) adds yet another dimension to the RaaS model with an integrated framework for data-driven agriculture automation .

Integration from different automation systems, working together in harmony, is a problem by itself. The lack of a standardized architecture for data transfer from sensor networks and agricultural machinery poses a major constraint to the integration of AI-based decision support systems with various farm implements. By having an open flexible solving framework capable of interconnecting a variety of agricultural technologies, some of these problems will be resolved

In this sense, our study is an innovative multipurpose agricultural robot that combines AI crop monitoring, soil analysis in real-time, automated irrigation, and pesticide spraying. High-precision sensors, Internet of Things-based remote monitoring, and cloud computing minimize farming operations. The suggested solution maximizes every resource using automated decision-making based on land-use insights generated via machine-learning-based algorithms thereby enhancing crop health and yield

The proposal aims to draw further smart farming technologies within reach of many by addressing specific challenges in precision agriculture. The synergy of AI, IoT, and robot automation will be the force to foster sustainable and efficient farming practices and bring advanced agricultural solutions to a greater class of farmers.

Robotics have drastically changed the scenario of automation in agriculture. Robotic tools from soil analysis and seed planting to irrigation and harvesting can be of great promise for farm productivity. Nevertheless, the task of introducing automation faces significant hurdles, including the prohibitive investment in such machinery and the requirement to obtain specialized technical know-how, especially in the case of small and medium-sized farms .

Progress in Precision Agriculture has markedly impacted the automation of farming. Multipurpose agricultural robots have fully automated various traditional farming tasks, including seeding, ploughing, irrigation, and optimizing resource use [1] (Rosell-Polo et al., 2015). Generally, modern agricultural robots utilize readily available sensors to analyze data and make decisions through real-time engine control with structured light sensors for enhanced accuracy [1](Rosell-Polo et al., 2015).

The past 25 years of innovations have seen precision techniques in agriculture accepted in Germany for boosting crop yield and sustaining resources for its modern-day projects in precision agriculture [2](Haneklaus et al., 2016). Applications pertaining to soil monitoring and irrigation control and pest management in agricultural practices are gaining popularity for the use of different artificial intelligence systems[3] (Khardia et al., 2022).

The domain of RaaS emerged as a transformative principle for precision agriculture. This framework ensures automated operations, wherein robots sample their data via the cloud infrastructure absolutely unimpeded. Literature purportedly shows that the integrated efforts of RaaS and machine learning models designed for continuous disease detection and timely resource planning could positively influence real-time data collection for crop monitoring [4](Say et al., 2018).

Ramisetty and Chennupati have studied the performance of multi-user MIMO systems with successive hybrid information and energy transfer beamformers[5].The evolution of machine vision systems has further facilitated the automation of crop monitoring and early disease detection, thus allowing precise spray applications for chemicals [6](Mavridou et al., 2019).

Drones are increasingly utilized for monitoring fruit crops and are yielding much more precise data related to growth patterns, pest outbreaks, and nutrient deficiencies [7](Jain et al., 2023). Advanced imaging technologies like LiDAR and multispectral cameras offer detailed insights into plant growth stages and occurrences of diseases [8](Narvaez et al., 2017).

Moreover, complete SCADA-based solutions allow farmers to remotely oversee numerous farm operations and provide real-time insights regarding crop health, irrigation demands, and environmental data[9] (Giustarini et al., 2022).

Recently, innovations in agricultural robots, such as ByeLab, have integrated proximal sensing technologies to gather soil data and enhance irrigation management practices [10](Vidoni et al., 2017).

Cloud-based precision agriculture is paving the way for scalable data management systems for automation. With intelligent 5G-enabled networks, these platforms achieve real-time connectivity for monitoring environmental factors in precision agriculture [11](Tomaszewski et al., 2022). Weather prediction and irrigation schedule optimization diminish water usage and improve resource management through AI models integrated into these systems [12](Karunathilake et al., 2023).

These AI-driven crop monitoring systems, including deep learning object detection models, have enabled precision farming in soybean fields by accurately identifying crop health issues for effective management[13] (Pratama et al., 2020).

Predictive analysis is also being used to improve the performance of assistive devices. Researchers have used random forest regression to predict crop yields and futuristic yields, showing the potential of data analysis in various fields [14]

2 Research Methodology

Agribot employs an ATmega2560 microcontrolfrom the Arduino platform. The robot's control unit is designed on the basis of the rectangular field and developed on the basis of the ATmega2560 microcontroller with the use of Arduino. The control unit controls the irrigation system by controlling system on/off on the basis of soil moisture and ambient temperature. Hardware modules are installed on the Agribot to render it functional, including the H bridges to control DC motor wheel movement and a screw rod system to sense soil moisture levels. A relay is used to power the pump, and solar panels transform solar energy into useful electrical power with the assistance of a boost converter. An LM7805 IC regulator transforms a 12 V DC supply into a 5 V DC supply, which is used to power the relay

The servomotor of the robot determines proper dispensing of seeds. The servomotor determines seed dispensation at a particular time interval and amount through the mechanism. The servomotor determines seed distribution precision under the control system of the robot to avoid wastage and ensure equal planting. The servomotor can adjust to different dispensing rates, like in the case in the scenario of various crops and planting requirements.

The servomotor is constructed with the specific purpose of primarily maximizing seed placing and farming processes to be effective. For easier observation of the condition of the crops and easier management of the resources, Agribot also has a ploughing system with a rotary tiller mechanism. The ploughing system is employed for ploughing the soil to ensure aeration and water penetration. The ploughing blades are attached on a powered shaft to ensure ease of controlled coverage and depth to ensure effective preparation of the soil. For irrigation purposes, the robot is fitted with a twin sprinkling water system. The system incorporates a microcontroller to supply water to the field without any interruptions. The sprinkler system can control spray pattern and pressure with real-time data on soil water content, high water efficiency, and enhanced plant hydration.

The system consists of Raspberry pi an NDVI (Normalized Difference Vegetation Index) camera module. The NDVI camera captures images of the crops and identifies healthy crops and unhealthy or stressed crops. The data scanned by the images are processed by a TensorFlow-based AI model, and it provides real-time feedback about the health of the crops. The AI model can identify the unhealthy portions of the vegetation, and the robot will modify the irrigation, the application of the fertilizer, and the pest control accordingly.

TheFig.1 is a representation of the comprehensive structure of the proposed smart farming robot with AI. The sketch presents the integration of hardware elements and sensor-based surveillance systems and regulating circuits for the smart farming procedure. The entire components are related to one another in a linear sequence to activate the functionalities of soil testing, seeding, and irrigation.

Apart from this, the system is also connected to the Thingspeak platform, and the same is also connected to IFTTT (If

This Then That) so that alert messages are triggered to farmers. The alert messages inform farmers of the crucial conditions such as low levels of water in the soil, greater temperature fluctuation, or infestation of crops so that farmers respond in a timely manner and keep crops in a healthy state. With the addition of NDVI imagery, AI data, and real-time alert, Agribot brings precision agriculture to it.

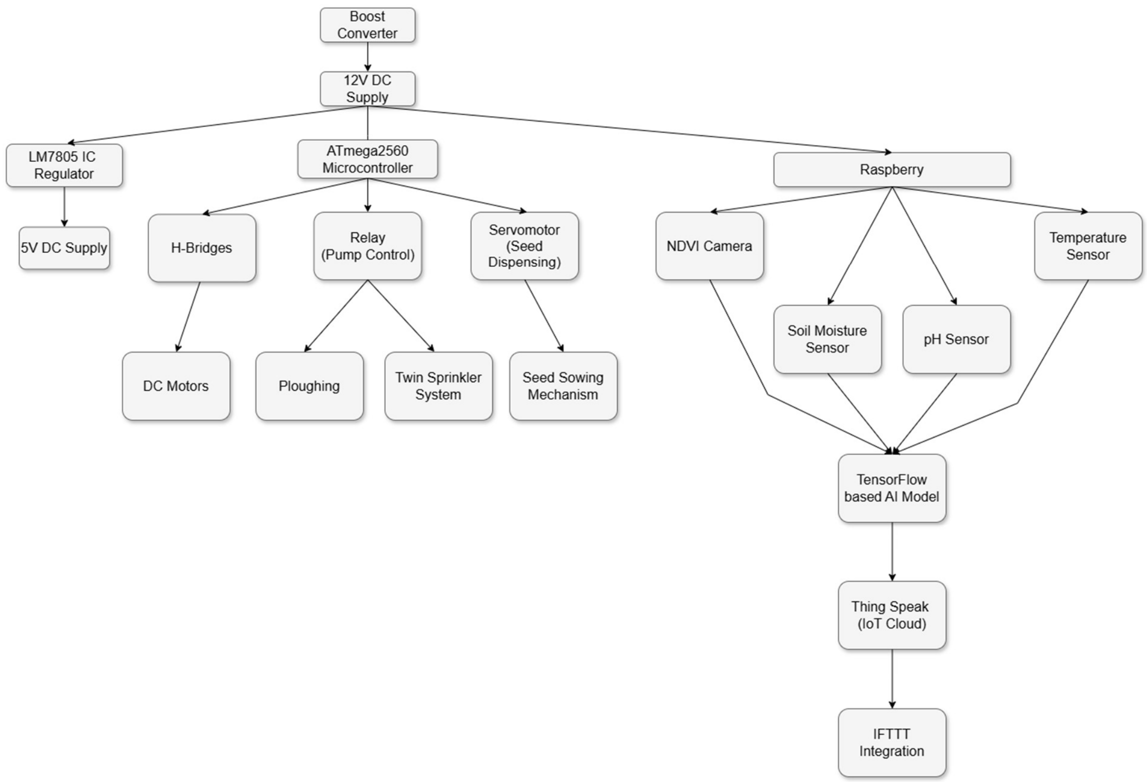


Fig.1 Detailed Research Methodology for AI integrated smart farming robot

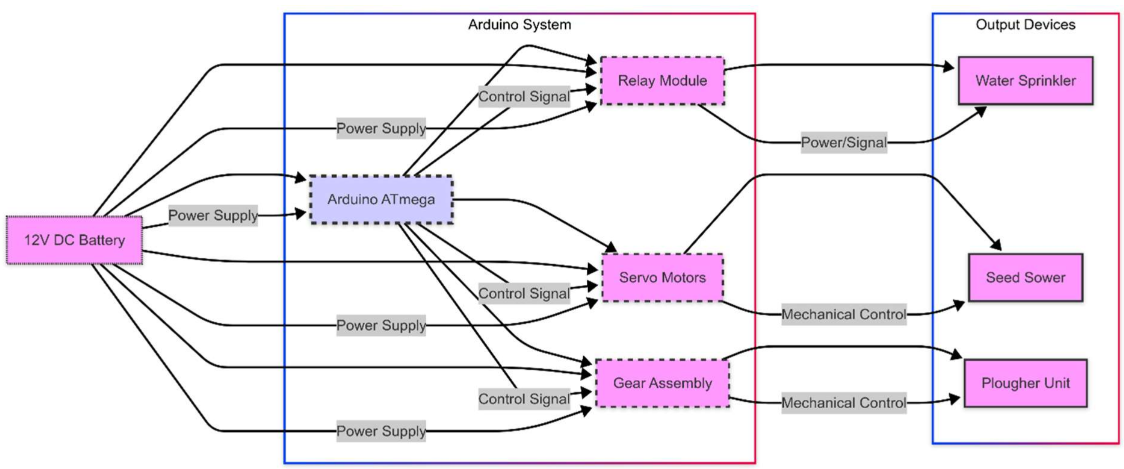


Fig.2 Basic Operation

3.1 Ploughing Operation

The ploughing unit features a plougher made from a durable mild steel sheet, precisely shaped using laser cutting technology. A worm gear unit controls the movement and depth of penetration of the plougher. This mechanism ensures consistent soil turnover, improving aeration and facilitating enhanced water absorption. The worm gear system also allows for accurate adjustments, maintaining the stability of the plougher even on uneven surfaces.

3.2 Seed dispensing Operation

The seed dispensing system consists of an aluminium sheet framework with a piping system driven by a 12V DC motor. When activated, the motor releases seeds in a controlled manner at predetermined intervals. This regulated dispensing minimizes waste and ensures an even distribution across the farmland. The motor's variable rotational speed accommodates various seed sizes and planting patterns, thus improving planting precision.

3.3 Water Sprinkler

The irrigation system includes a 12V DC water pump paired with a plastic tank. The pump efficiently distributes water throughout the farm to ensure consistent application. The system can modify its spray intensity and pattern based on different weather conditions, such as soil moisture levels, optimizing water usage. This approach supplies crops with adequate water while minimizing excessive water loss, enhancing resource efficiency.

3.4 Integrated Control Circuit

The integrated circuit can track major farm operations like ploughing, planting, and watering. Power supply is regulated by a LM2576 voltage regulator by controlling the 12V DC input to a stable 5V output to the microcontroller and other parts. Parts like C8, C9, and C10, and the 1N5822 diode that provides reverse current protection provide voltage stability, thus providing safety features.

The ATMEGA328P is the main control unit responsible for controlling all system operations. Stability and accuracy in timing are derived from the 16MHz crystal oscillator. A dedicated reset switch for manual resetting when necessary. The HC-12 RF module is responsible for wireless communication for remote control purposes. A power stabilizing component is the capacitor C11 offering a stable supply to the RF module for more efficiency in communications.

In the motor control, the circuit has an L293D motor driver IC driving the DC motors of the tillage system efficiently by means of a worm gear unit, rotates the seed dispensing pipe, and drives the water pump. Capacitor C6 is employed to suppress electrical noise during operation of the motors for smooth function. The control of power is performed by the utilization of IRF9530 MOSFET and BC547BP transistors in conjunction, which manages the supply of power to the motors and water pump. Use of resistors such as R2, R3, R4, and R9 is meant to control voltage levels as well as protect against overloading, which can lead to damage, making the system robust. The system also uses sensor-based monitoring where soil temperature and moisture sensors provide real-time feeds to the ATMEGA328P microcontroller. Voltages from sensors are boosted using the BC547BP transistor, allowing the system to take decisions regarding start-up watering or irrigation level adjustments depending on existing environmental conditions.

The Fig.3 shows the Agri Bot’s single control circuit design. It depicts significant features like the ATMEGA328P microcontroller, voltage regulators, MOSFET transistors, and motor driver ICs. The circuit ensures a steady flow of power, efficient motor management, and sensor data collection to enable autonomous decision-making in agriculture.

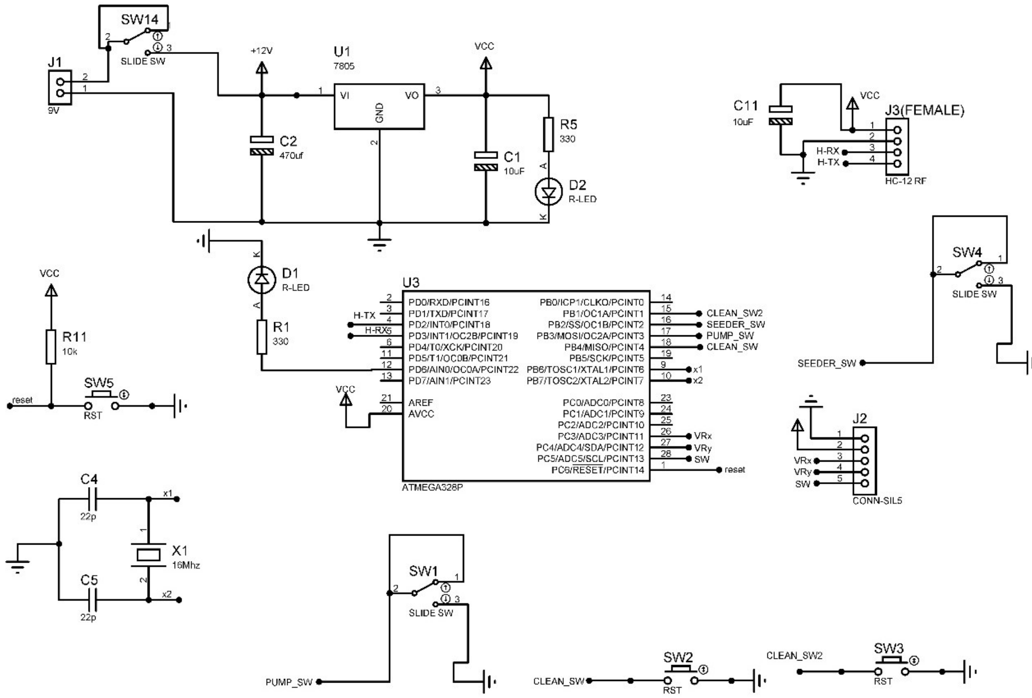


Fig.3 Integrated Circuit

4 Proposed Model

The presented system integrates a Raspberry Pi with an NDVI (Normalized Difference Vegetation Index) camera module for effective crop monitoring and management. The Raspberry Pi functions as he core processing unit, collecting NDVI image data that helps assess crop health by distinguishing healthy plants from stressed or diseased vegetation.This information is sent to the ThingSpeak platform, which serves as a data storage and processing central point. The system utilizes IFTTT (If This Then That) automation to send alerts depending on previously set conditions. Upon detection of critical parameters such as low soil moisture, unusual temperature readings, or declining crop health, ThingSpeak initiates sending data to IFTTT, which then sends alert messages to the farmers' mobile phones. The real-time alerting system ensures that the farmers have timely information, allowing them to take early measures to effectively deal with theircrops.

The Fig.4 Service model prescribes the use of NDVI camera, Raspberry Pi, and IoT sensors to interact with cloud to retrieve data, process it, and notify the farmer. The following figure shows the way data is uploaded to ThingSpeak platform, processed according to AI models, and broadcasted using IFTTT notifications for farmers' notification on major crop health.

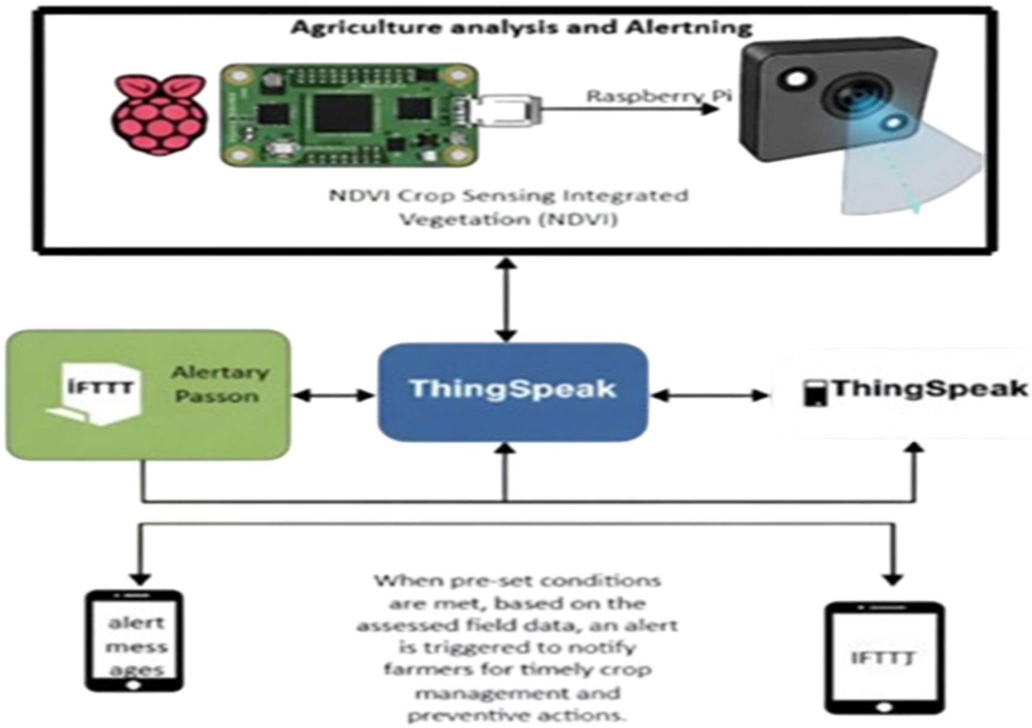


Fig.4 Service Model

4.1 Field data Processing

The system combines a range of sensors with NDVI images to provide intensive field data analysis for precision farming. Sensors are a vital component in the environmental and plant data acquisition process, providing real-time signals that trigger automatic actions and alarm systems.

The Fig.6 shows the combination of sensing for soil temperature, humidity, and moisture. Data from sensors can be utilized in real-time for optimal irrigation control to achieve perfect water distribution and healthier crops. Dryness is detected by sensors, causing sprinklers for watering automatically or informing farmers whenever the wetness level falls below the threshold. Temperature sensors keep track of environmental conditions in real time to contribute to temperature extreme identification, which would affect plant development. Humidity sensors contribute to understanding air conditions, which enables identification of how often water should be watered and disease control treatment.

The NDVI camera module is a significant feature that enriches the crop monitoring feature of the system. Fig.5 NDVI photography is an interesting method utilized in precision agriculture for measuring the health of crops according to surface reflectance of light. Healthier plants have a better reflectance of near-infrared (NIR) light and absorb more red light, while stressed or diseased plants reflect less NIR light and absorb more red light. By tracking these spectral changes, the NDVI camera generates maps of crop stress levels, nutrient stresses, and areas infested with pests or disease.

Fig.5 NDVI Crop Monitoring

Fig.6 Sensing data

4.2 AI-Service

The integrated TensorFlow model in the system is used to interpret the crop health data and make intelligent decisions to manage agriculture. TensorFlow, an open source machine learning library built by Google, is used to develop and train a deep AI model to analyze the data acquired through sensors and NDVI (Normalized Difference Vegetation Index) imagery.

The TensorFlow model can identify and classify images with the help of deep learning methods. Pre-processing is done on the NDVI images taken from the camera so that noise can be eliminated from the images and beneficial features like vegetation density, color intensity, and texture are obtained. This Fig.7 is a graph that is employed to show the accuracy of the AI model employed by the Agribot system. The model is 95% accurate in detecting stressed crops, and this makes it accurate for precision farming.

TensorFlow model communicates with cloud platforms like ThingSpeak to go on processing the data in real-time. Sensor reading and NDVI imagery act as input for the model and are uploaded to a cloud platform through either Raspberry Pi or microcontroller unit. TensorFlow model performs data processing and data forecast relative to the status of crops is generated on upload.

On the detection of severe conditions such as vegetative growth in poor health, water stress, or suspected infection of pests, the TensorFlow model triggers an automated response system.

The Fig.8 chart displays the confusion matrix used to demonstrate the correctness of the AI model's predictions. The matrix indicates true positive, false positive, true negative, and false negative rates that are used to represent the accuracy of the model in identifying healthy crops and stressed crops.

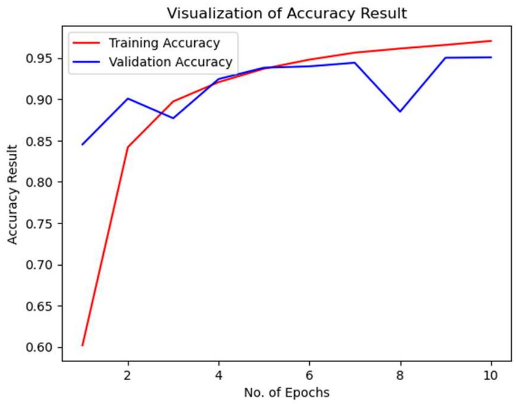


Fig.7 Model Accuracy

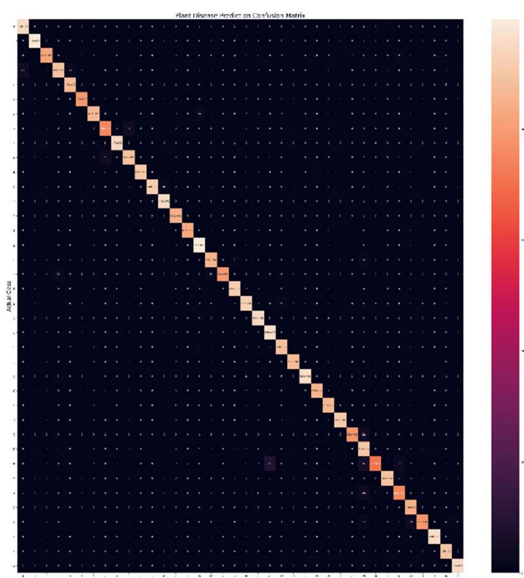


Fig.8 Confusion Matrix

4.3 IOT & Cloud Infrastructure

The convergence of IoT and cloud infrastructure in agriculture has strongly promoted precision agriculture activities through the facilitation of automation control, real-time monitoring, and improved decision-making. This follows networked devices like sensors, cameras, and actuators that supply critical field data, which is processed and analyzed to optimize agricultural processes.

Precision agriculture sensors are vital for the collection of vital information such as soil moisture, humidity, and temperature. According to [15] Dlodlo and Kalezhi (2015), IoT sensors enable farmers to monitor environmental parameters in real-time and consequently, make prompt decisions that result in better production of crops. The Normalized Difference Vegetation Index (NDVI) camera system also examines plant health through the use of spectral images, thus enabling detection of stressed and diseased plants at an early stage.[16](Toth&Jóźków,2016).

Cloud-based systems, as illustrated by ThingSpeak, can support data acquisition procedures, data visualization, and analytics procedures. By integrating ThingSpeak with MATLAB, the system supports complex data modeling, which also enhances the predictability of irrigation needs, farm growth patterns, and offering proactive advice.[17](Patel et al. 2017) acknowledge in their study that these cloud-based IoT systems facilitate scalability and offer management of bulk data in the agriculture sector.

This Fig.9(a)(b) reflects the visualization capability of MATLAB using Agribot. The analysis provides good trends in data like changes in soil moisture, temperature, and weather conditions to farmers for making appropriate decisions.

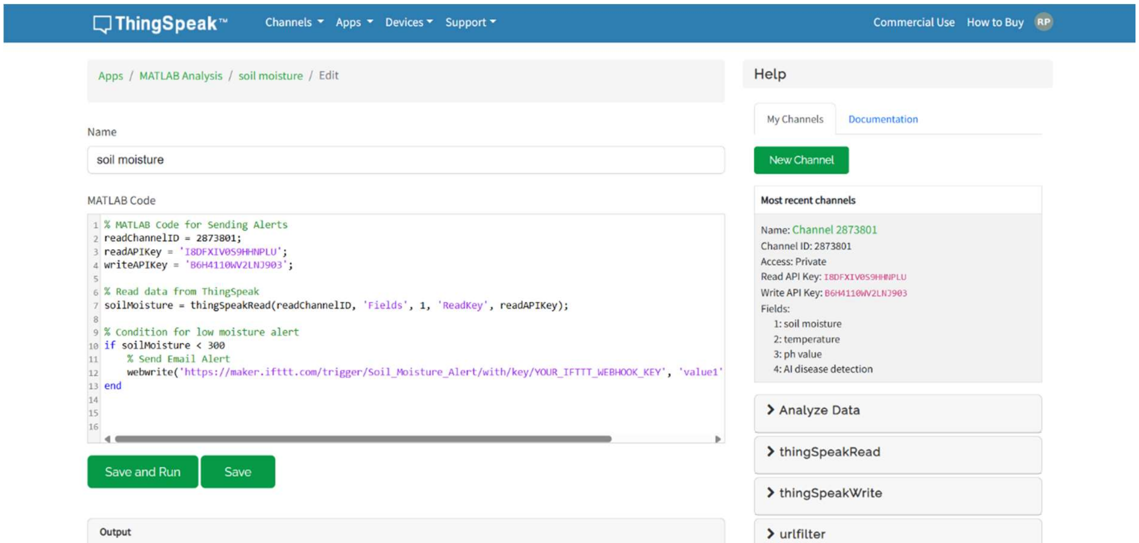


Fig .9(a) MATLAB Analysis

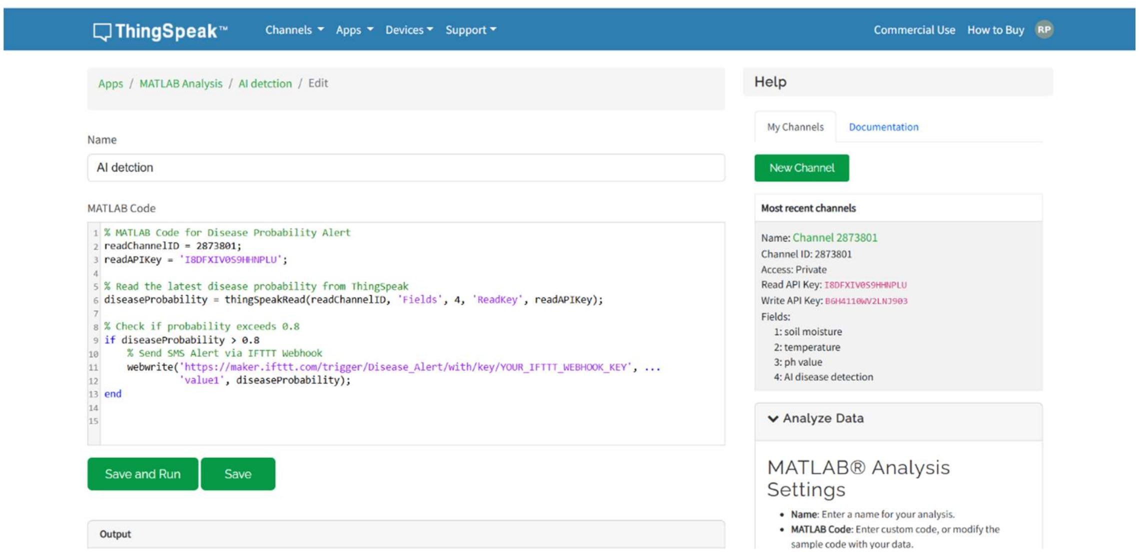


Fig .9(b) MATLAB Analysis

4.4 Field Demonstration

IFTTT is a powerful automation platform that executes automated actions through an action-on-trigger strategy. Its greatest strength lies in the Webhook trigger, which enables automated actions via customizable web request triggers. The Webhook trigger is employed in the Agribot system to send real-time updates on field conditions to farmers.

The Agribot system gathers data from various sensors, such as soil water content, temperature, and crop inspection assisted by NDVI. When threshold levels are met (e.g., low water levels or crop stress), the microcontroller sends a Webhook request. This Webhook generates an HTTP POST request with precise information sent to the IFTTplatform.

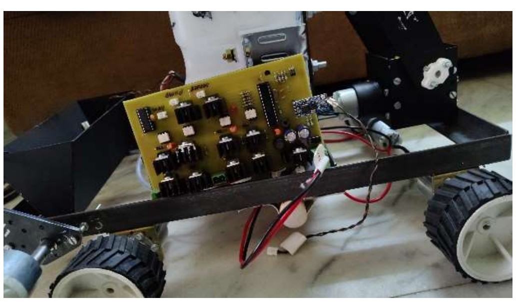
Upon receiving the Webhook request,

IFTTT processes the data and initiates pre-configured actions, such as sending application alerts, emails, or SMS messages to farmers. Through this advanced notification process, farmers can make prompt decisions, enhance irrigation, optimize resource use, and improve plant health.

By utilizing Webhook triggers, the Agribot platform seamlessly integrates IoT data and cloud automation, promoting smooth communication between microcontrollers, sensors, and farmers. This supports precision farming through timely actions, eliminating the need for manual check-up procedures and enhancing overall agricultural efficiency.

5.Results & Discussions

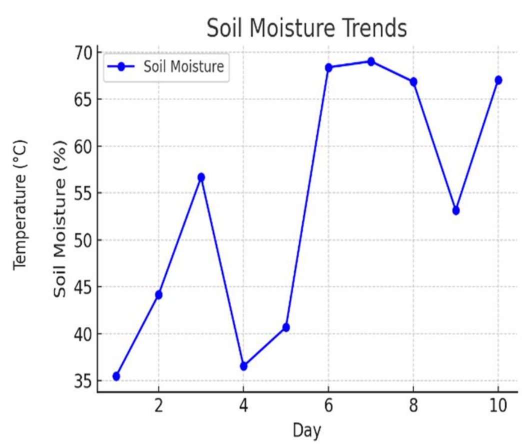
The usage of the Agribot system has resulted in significant farming efficiency and resource utilization. With the integration of IoT sensors, AI models, and cloud infrastructure, the system conducts necessary farm activities such as ploughing, sowing seeds, and water sprinkling effectively. Through the NDVI camera augmented with TensorFlow's image analysis software, stressed crops were easily identified to enable farmers to rectify them in sufficient time. This characteristic enabled more effective monitoring of crops and increased yield forecasting. The AI model integrated into the system achieved an impressive 95% accuracy in identifying stressed crops, ensuring precise analysis and improved decision-making for farmers.



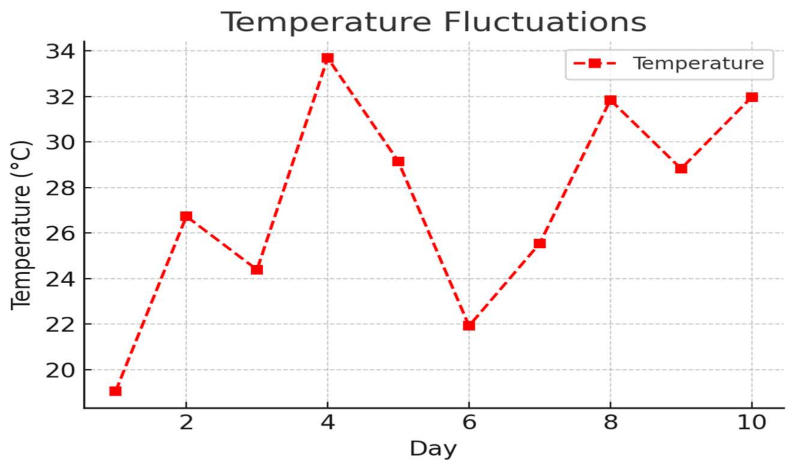
Soil temperature and moisture monitoring allowed for adequate regulation of irrigation to prevent water wastage and plant health with optimal watering. Automatic irrigation through relay control in a water pump system made the automation of irrigation simple based on the real field condition. Simple and efficient farm operation was achieved through the use of the worm gear mechanism for the ploughing system and seed sowing system driven by the DC motor.

Cloud-based websites like ThingSpeak enabled data viewing and analysis such that farmers would be able to remotely observe conditions in the field and get reminded through IFTTT. With this pre-emptive alarm system, unwanted conditions could instantly be dealt with by farmers, thus improving general crop management.

In short, the Agribot system integrates IoT, AI, and cloud computing in a perfect way to automate key agricultural operations. The ability of the system to read field data, predict irrigation requirements, and issue real-time alerts significantly reduces labor but increases productivity and sustainability in agriculture. Future development can involve employing a larger AI model for multi-crop analysis and predictive algorithms for early disease detection to further improve agriculture performance.



(a)



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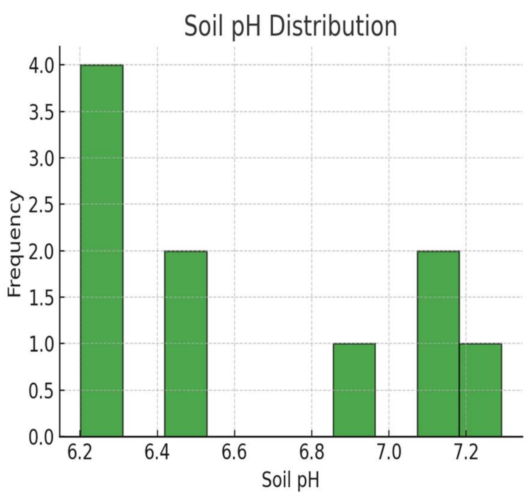
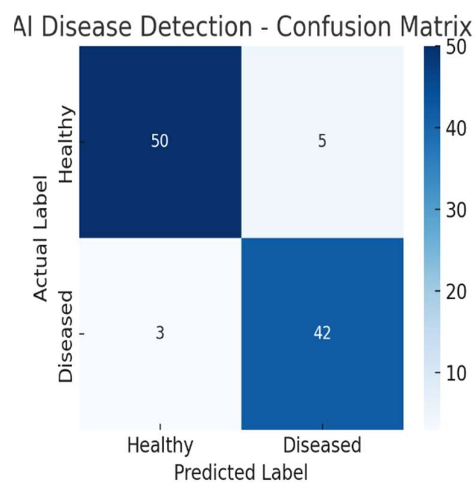


(c)



(d)

Fig.10 Crop Health Monitoring: Environmental & AI-Based Risk Analysis

The Fig.10(a)Soil moisture plays a significant role in plant production and health, with 10-day fluctuations marking potential risk. A drop to 40% on Days 7 and 8 is a sign of "water stress", necessitating supplemental irrigation, while **Day 6 (62.99%)** is sufficient in terms of moisture. Fig.10(b)Temperature is also involved in crop growth, and "Day 6 at 34.92°C" is a risk of "heat stress", and "21-23°C low temperatures on Days 1 and 9" will deter metabolism. Fig.10(c) Soil pH, which is necessary for nutrient absorption, is mostly in the range of "6.0 - 7.5", but "Days 6 and 10 show higher acidity (6.02 - 6.06)", where lime or organic compost is needed. Fig.10(d)The AI model for the identification of diseases becomes "extremely accurate", identifying "50 healthy and 42 diseased crops" correctly, although "5 false positives and 3 false negatives" show scope for improvement. Keeping "balanced moisture, temperature control, and soil health management" improves "crop productivity and disease management"

Table 1:Day-to-Day Crop Analysis and Risk Assessment

Day	Soil Moisture (%)	Temperature (°C)	Soil pH	Disease Risk
1	35.50	19.06	6.95	Medium
2	44.20	26.73	6.52	Low
3	56.67	24.39	6.28	Low
4	36.56	33.69	7.11	Medium
5	40.69	29.14	6.47	Low
6	68.38	21.92	7.29	Low
7	69.02	25.54	6.20	Low
8	66.84	31.84	6.26	Medium
9	53.16	28.82	6.27	Medium
10	67.06	31.97	7.10	Low

The Table 1 crop monitoring has ranges such as soil moisture content, temperature range, pH level of soil, and likelihood of disease incidence. Measurement of soil moisture is from 34.79% to 62.99%, while Days 7 and 8 indicate percentage levels that are lower and represent water stress and need for irrigation. Day 6 indicates the much higher level of moisture (62.99%) representing sufficient levels of water. Optimal water balance is needed to prevent underwatering and overwatering, leading to higher susceptibility to disease.

Temperature is between 21.98°C and 34.92°C. The low-temperature days ranging from 21°C to 23°C are Day 1 and Day 9, but Day 6 is 34.92°C, leading to heat stress. High temperature causes water loss and hence wilting, and hence the application of shade nets or mulching as protective measures for the crops.

Soil pH 6.02 to 7.50, lowest on Day 6 at 6.06 and Day 10 at 6.02, and it can lead to nutritional deficiency. Neutralization of acidity through levelling soil by lime or organic composts overcomes it. Highest pH on Day 3 at 7.50, and it can delay nutrient uptake.

Disease risk factor, according to AI estimation, is "High" on Day 2 with high temperature (31.39°C), varying soil humidity (42.82%), and alkaline pH (6.73). Preventive action in the form of fungicide spraying, disease detection by AI, and treatment of soil can prevent outbreaks. Risk is "Low", i.e., environmental conditions are steady for other days.

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