AN IOT BASED AUTONOMOUS ROBOT SYSTEM FOR MAIZE PRECISION AGRICULTURE OPERATIONS IN SUB-SAHARAN AFRICA

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Abstract

The importance of agriculture to the economic growth in sub-Saharan Africa suffers from several challenges. One major problem faced by the sector is the lack of suitable technology to optimise yield and profit to reduce the reliance of farmers on manual techniques of farming which is accompanied by drudgery, wastage, and low yields. Precision Agriculture has been applied to maximise agricultural outputs while minimising inputs. This study presents the design of an Internet of Things (IoT) based autonomous robot system that can be used for precision agricultural operations in maize crop production. The robot consists of a camera for remotely monitoring of the environment and a tank incorporated with a liquid level sensor which can be used for irrigation and herbicide application. The real-time feed from the camera as well as the output from the liquid level sensor is accessed from a cloud database via a web application. This system can be adopted for improved crop production which in turn will increase crop yield, profit, and revenue generated from agriculture.

Keywords: Artificial Intelligence, Fuzzy Logic, Image Processing, Internet of Things, Precision Agriculture, Robot Navigation.

5.1 Introduction

a. Background of the Study

In the 21st century, there has been a rapid growth in the Information and Communication Technology (ICT) sector. This development has influenced human operations and industrial services. One of the most important developments in the ICT sector is the introduction of the internet [1]. Internet of Things (IoT) is a system of interconnecting computing devices that are interrelated. These devices can transfer data over a network with the absence of human involvement [2]. The IoT is a network of physical devices, objects, buildings, people, animals, and other items that are embedded with sensors, software, electronic devices, and network connectivity that supports communication, collection, and exchange of data. This technology allow devices to be remotely controlled and sensed using network infrastructure. This process allows the integration between the physical world and computer systems which in turn, results in improved economic benefits, efficiency, effectiveness, and accuracy [3]. The IoT has a wide range of applications in various sectors including agriculture.

The Food and Agriculture Organization (FAO) estimated a 70% increase in global food production by the year 2050 [4]. Also, the population of the African continent is projected to reach 2 billion by 2050 [4]. Feeding this population would be quite challenging with limited farming methods. Currently, farmers in sub-Saharan Africa cultivate less area of land and harvest less due to lack of technological development in the agricultural sector. Besides, traditional farming techniques predominantly used in the region results in low crop yield compared to mechanised farming methods. Africa has 25% of the world's arable land, yet it contributes only 10% of the global agricultural output [4].

Nigeria is West Africa's largest economy, and second largest in sub-Saharan Africa. The country is vast with approximately 68 million hectares of arable land, 12.6 million hectares of freshwater supplies, and an ecological diversity that provides the supplies required to produce and grow a wide variety of crops [5]. Agriculture makes approximately a quarter of Nigeria's overall nominal Gross Domestic Product (GDP).

In Nigeria, maize has evolved from a backyard crop to the third most important crop in terms of output and the area cultivated. Nigeria is the leading producer of maize in West Africa and the tenth-largest producer in the world. The 2008 FAO statistics reported that about 7.5 million tons of maize with an average yield of 1.9 metric tons per hectare produced in the country [6]. The crop is recognised as a major source of food and cash income among Nigerian farmers. Although the production of maize significantly increased in Nigeria between 1990 and 2011, an increase in population which leads to an increase in demand results in the need for improved maize production in the region [6].

Precision Agriculture (PA) highlights the fact that an understanding of variability within a crop field will achieve increased agricultural production. The goal is not to obtain the same outputs or yields all over the farm, but to evaluate the environment and distribute different site-specific inputs. This method can optimize agricultural benefits and produce a strong return on investment [7]. In PA, the gap between mechanized farming and ICT is bridged by collecting farmland information and applying data analysis based inputs. Farm operations such as application of herbicides, fertilizers and irrigation can be done smartly, enabling farmers to achieve high yields, exact inputs use, reduce wastage and maximize income [8].

The implementation of PA and IoT technologies has the potential to revolutionise the agricultural sector in sub-Saharan Africa. This study presents the conceptual design of an IoT-based autonomous robot system for maize production under precision agricultural operations. This system uses IoT, Control, and AI technology to incorporate a smart, intelligent robotic device for precision maize farming. This system is expected to improve agricultural yield and profit, as well as bring a high return on investment for the region.

The remainder of the chapter is organized into four sections. Section 2 presents a review of existing literature including identified research gaps. The research implementation strategy and methodology is presented in Section 3. The expected results of the research are presented in Section 4 while the conclusion is given in Section 5.

b. IoT Advancements in Sub-Saharan Africa

The IoT development in the sub-Saharan African region has improved over the years as many African countries have already taken advantage of the technology. This stride can be seen in healthcare which track the health of their patients remotely, to utility companies that monitor the usage of their resources for analytics purposes. However, despite the advancement in some sectors, the lack of suitable infrastructure makes it difficult for the region to make significant growth in areas that other developed nations find relatively easy [9]. West Africa has recently experienced rapid economic development with 90% of the population having access to mobile phones. With this trend, IoT has the potential of contributing immensely to various sectors [10].

Several factors can lead to massive IoT deployment in numerous sectors. These include cost reduction for the majority of the products and services associated with IoT systems [9]. Other factors include:

i. Cheaper cost of bandwidth and sensors
ii. Cheaper processing costs
iii. Introduction and use of Big Data analytics
iv. Widespread use of smartphones
v. Cheaper and more accessible Wireless Networks.
vi. Alternative energy and low power technologies.

Despite the lag of IoT development in the sub-Saharan African region, there have been implementations of this technology in several areas across the region. These applications include vehicle tracking, air quality monitoring, railway tracks, and disease diagnosis in countries such as Kenya, Rwanda, South Africa, Nigeria, and Congo [11].

The implementation of IoT systems in sub-Saharan Africa has been negatively affected by several factors which include low power supply, high poverty rate, network capacity constraint, illiteracy, absence of local content, low internet penetration, security challenges, cost of hardware and services, low ranges for rural access, dependency on proprietary infrastructure, and difficulty in deployment [9], [10].

c. Problems of IoT Technology in Nigeria

In Africa currently, the rate of adoption of IoT technologies is slow when compared to other continents. Nigeria, being the most populous country on the continent, has a large mobile market and thus, numerous prospects in IoT implementation. Considering the benefits of IoT deployment, its implementation can lead to improved national and regional economic development and improve the standard of living of the populace [11].

On one hand, several developed countries have adopted the use of IoT while harnessing the benefits of the technology. Yet, these developing countries have not fully utilised and adopted IoT platforms. For instance, in Nigeria, the impact of IoT is not widely conspicuous. This lack of prevalence of the technology has several causal factors ranging from illiteracy, poverty, low level of awareness, to the absence of facilitating conditions, especially in rural areas where the need is more pronounced [3].

There are a few other factors that significantly hinder IoT development in Nigeria. Low electric power supply impedes the implementation of smart technologies across the country. This lack of power supply, while being vital for industrial, technological, and economic growth, is prevalent across the nation [2]. Alternative energy sources have been explored by individuals, but the high involved in the installation of solar panels, inverters, and other power systems discourage populace from exploring these options.

Besides, the difficulty in procuring IoT devices has resulted in low IoT adoption across the country. Although the cost of sensors and processors have dropped over time, these devices are challenging to obtain especially in the Nigerian market. Developers and researchers tend to order for the required devices online from outside the country. However, the time it takes for delivery is usually large and this discourages individuals from venturing into the field [2].

With at least 48 million active internet users, Nigeria remains a large market for IoT development [12]. Agencies such as the National Information Technology Development Agency (NITDA) and the Nigerian Communications Commission (NCC) have been developing infrastructures to enhance ICT development across the country. This stride in technology can be fully utilised to provide improved production and revenue across all sectors, including the Agricultural sector.

d. IoT for Agricultural Development

In conventional farming, operations such as application of herbicide, fertilizer, and irrigation generally rely on the expertise of the farmer. While this knowledge is of the utmost value in farming, precision is not assured [13]. Considering conditions such as temperature, humidity and illumination that are difficult to quantify and regulate, it is important to incorporate a method that not only tests certain parameters but also includes a mechanism for controlling them. The application of IoT in farming has immense benefits in optimising production. Some potential areas that can be transformed by IoT in sub-Saharan Africa include pest and disease management, crop water management, food production and security, weed control, and smart greenhouses [4].

5.2 Review of Existing IoT Schemes in Agricultural Research

In the area of IoT based smart agricultural systems, there exist several related works. In [14], an intelligent monitoring device for the agricultural greenhouse was presented. The system utilises IoT infrastructure made up of nodes of a wireless sensor network to provide a monitoring feature for a greenhouse. The system monitors water level, temperature, soil moisture, humidity, and light intensity. However, it does not possess a control feature for remotely managing farm operations.

Similarly, [15] presented a smart agriculture system using IoT technology. The system makes use of a wireless sensor network to monitor power supply, soil moisture, humidity, temperature, and water levels. The system is controlled by an ARM 7 processor and transmits the data to a web server via a Wi-Fi module. This system also does not possess a feature for remotely controlling the farm operations.

Ji et al.,[16] presented an IoT and mobile cloud-based architecture for smart planting. Here, a system initiative for remote monitoring of agricultural parameters was designed. The system uses technologies such as 3G, GPRS, and RFID to implement a remote monitoring feature. The data from the sensors can also be visualised via devices such as tablets and mobile phones. Although the design presented an architecture for the platform, no specific information was given regarding the techniques and schemes used in the design.

A smart agriculture IoT with Cloud, Fog, and Edge computing techniques was presented in [17]. The proposed system utilises a machine learning edge-based IoT system for remote monitoring of agricultural parameters. The technique provides low latency and secure connectivity for IoT operations. However, the system provides no remote control techniques.

Furthermore, in [18], a remote monitoring and control system for poultry feed dispensing was presented. The system uses Global System for Mobile Communications (GSM) and Short Messaging Service (SMS) technologies to monitor and control poultry feed dispensing in a deep litter poultry farm. The system has an average response time ranging from 1.6 seconds to 3.6 seconds depending on the network operator used. The system, however, had limited coverage due to its use of SMS and has the potential of being improved upon with Wi-Fi technologies.

A review of the state of the art IoT in protected agriculture was presented in [19]. The study did a literature survey on existing technologies as well as the limitations of current schemes. Although several IoT based systems exist for agricultural operations, there also exists significant challenges in the field. These challenges include but are not limited to network issues, hardware and software challenges in terms of cost, durability, and availability, security challenges, and environmental factors.

Similarly, in [20], a review on IoT based smart agriculture is presented. The authors explored the use of unmanned aerial vehicles (UAVs), sensors, and communication techniques for the development of a smart agriculture system based on IoT. Based on the review carried out, the authors noted that the use of IoT to boost agriculture is not optional, but necessary.

Based on the aforementioned review, the following research gaps were identified:

i. The absence of a mechanism for remote control of farm operations.
ii. The use of technologies with a limited range of accessibility.
iii. The absence of automation in systems that do not provide remote control features.

iv. The lack of artificial intelligence incorporated in the decision-making process.

Based on these findings, this study presents a conceptual design of an autonomous robot system based on IoT for maize precision farming operations in sub-Sahara Africa. This system uses IoT, control, and AI technologies to implement a smart and intelligent robotic system for maize precision farming.

5.3 Proposed Solution and Research Implementation Strategy

a. System Description and Characterisation Model

The proposed system architecture is presented in Figure 5.1. The system is controlled by Raspberry Pi 3 microcontroller. This controller serves as the central processing unit of the system. The inputs to the microcontroller are the images acquired from the camera module, the level of the liquid tank, and the remote commands received via the Wi-Fi module. The outputs of the microcontroller are the position of the servo motor for navigation, the speed of the DC motor for movement, the pump action of the DC pump for spraying, and the transmitted data for the web application sent via the Wi-Fi module. The microcontroller runs a Mamdani based Fuzzy Logic control algorithm for navigation, and an image processing algorithm for determining the edges of the ridges in the farm environment. The controller also works bi-directionally with the Wi-Fi module to transmit and receive data from the web application via the IoT cloud platform.

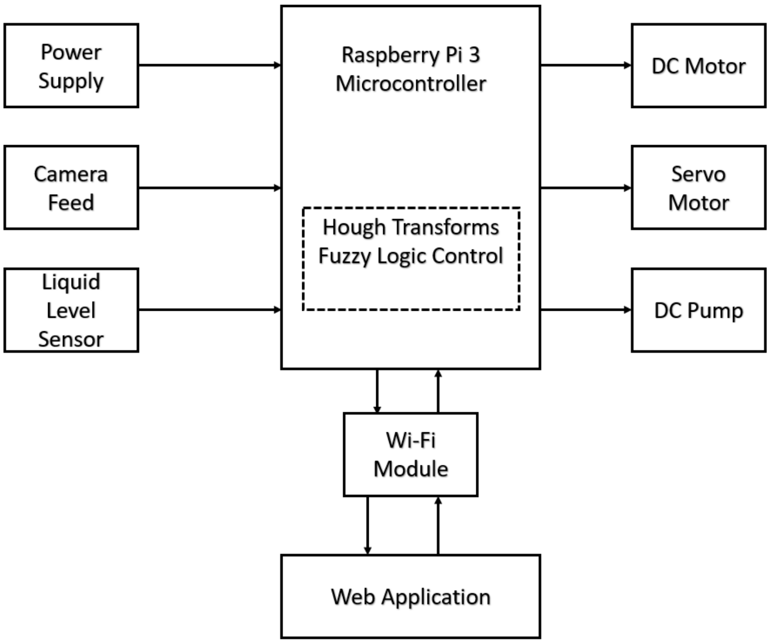

Figure 5.1: Proposed System Architecture

Figure 5.2 shows the steps of operation of the robotic system. Table 5.1 shows the technical information of the hardware design considerations. These major components are used in the design of the system. The table highlights the hardware considerations as well the component ratings.

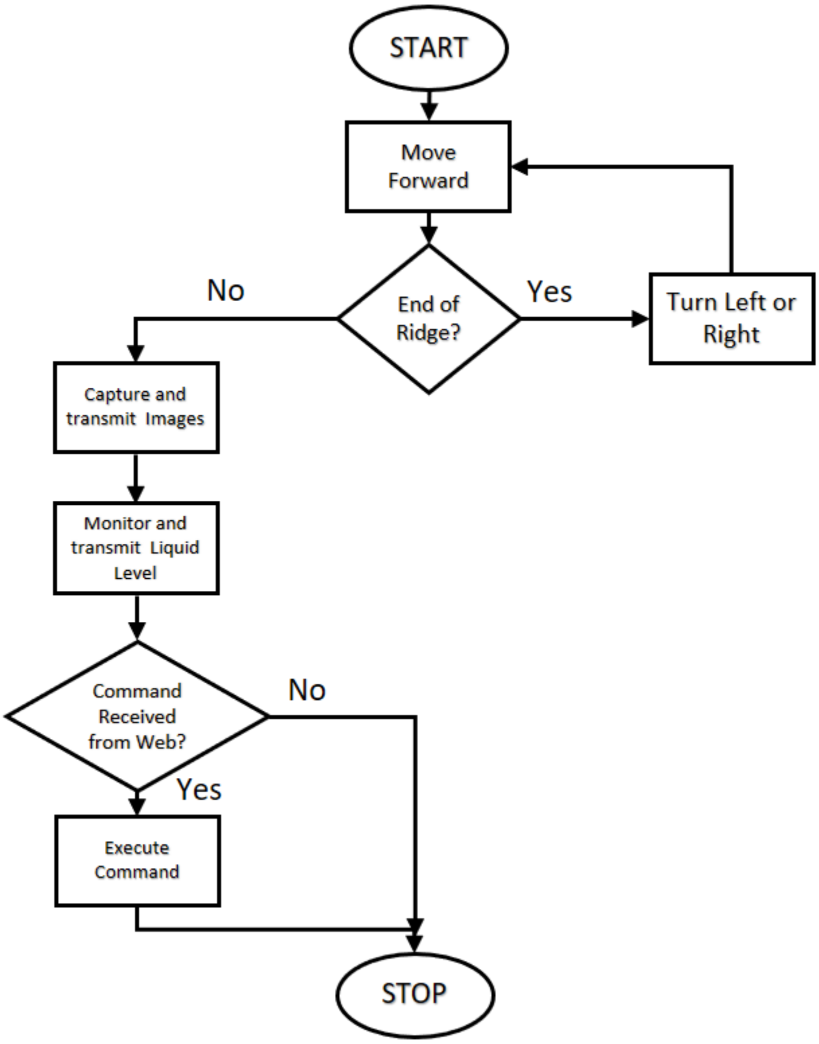

Figure 5.2: Steps of Operation of the Robotic System

Table 5.1: Hardware Technical Information

Component	**Rating**
775 DC Motor	12V, 10000 RPM, 80W
FS5115M Servo Motor	5V, 15.5 Kgcm
HQ Camera	12.3 megapixels,

Raspberry Pi 3 Microcontroller board	Model B, 1GB RAM, 1.2 GHz Quad Core
WiFi Module	802.11b/g/n
Liquid Level Sensor	CQRobot 5V

b. Autonomous Robot Navigation and Control Scheme

Hough Transforms for Ridge Detection

For the robot to move effectively between the ridges, there needs to be a technique for identification of the ridges. In this study, the technique of Hough Transforms is implemented to detect the ridges in the farm environment. This technique is selected because Hough transform is one of the most common and widely used techniques used for line detection [21], [22]. Hough transforms evaluates a unique equation at each point on an image where a possible line can be identified. Hough transforms in based on the relationship shown in equation 1.

$$\rho = x cos\theta + y sin\theta \qquad (1)$$

The variables x and y indicate the coordinates of the image pixel. These coordinates are mapped to a corresponding parameter space in terms of ρ, which is the distance between the x-axis and the fitted line, and θ, which is the angle between the x-axis and the normal line [23], [24]. Figure 5.3 shows the mapping coordinate system of the Hough transform in terms of x, y, ρ, and θ.

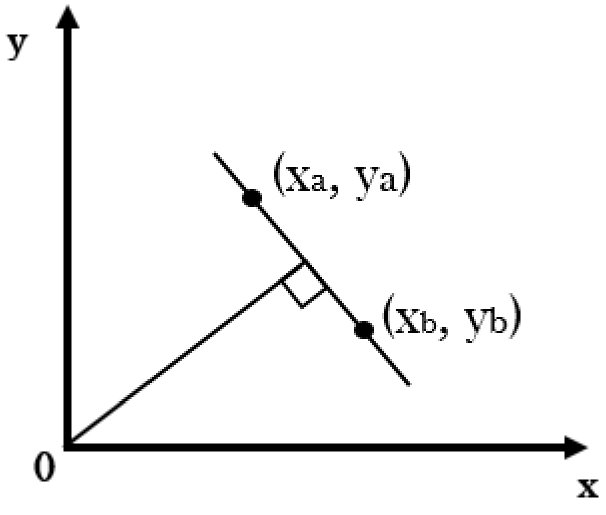

Figure 5.3: Co-ordinate Mapping of Hough Transforms [23].

The image processing steps carried out in this system are highlighted in Figure 5.4. First, the images of the farm area containing the ridges will be acquired from the camera module mounted on the front of the device. The camera will face downwards at a 45° angle. This will be done to capture the entire front view of the robot. Each video frame obtained will be processed as soon as the image is captured.

After acquiring the image, the image is pre-processed before the desired features can be extracted. This image pre-processing involves identifying the regions of interest, noise removal, and image enhancement. The region of interest of the image in the lower half of the image. This area is selected to crop out the upper region which contains unwanted features such as the sky, grass, and crops.

Deleting noise from the image further processes the image. A median filter and a 2-dimensional (2D) Finite-Impulse Response (FIR) filter are used to accomplish this noise reduction. A median filter is used afterwards in order to eliminate noise from the image while retaining the edges. This is useful for object detection since edge detection is a vital part of the algorithm. In addition, the 2D FIR filter removes noise from the image. However, it also sharpens and enhances the picture, in addition to removing noise.

The next step after pre-processing an image is the segmentation of the image. In this study, the technique of segmentation implemented is the method of edge detection. This technique highlights the image's edges. In this case, the operator Sobel is used. The Hough transform algorithm is used when detecting the edges to get the lines detected in the image. Using equation 1, this algorithm identifies the ridgelines in the image. The machine then chooses the most prominent line as the ridgeline and the nearest line to the device.

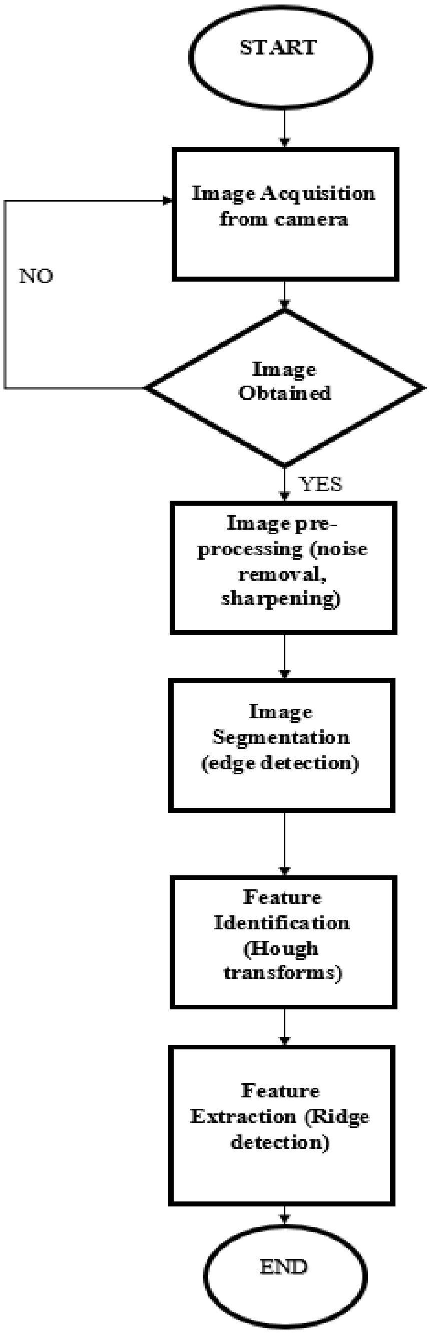

Figure 5.4: Flowchart Showing Ridge Detection Process

When the nearest line is identified, the distance between the robot and the ridgeline is evaluated. This is done by calculating the distance between the middle of the camera and the line in terms of pixels. The value is then to the Fuzzy Logic Controller for robot navigation.

Fuzzy Logic Controller for Navigation

The autonomous robot navigation scheme is carried out using a Fuzzy Logic Controller (FLC) represented in Figure 5.5. The Mamdani Fuzzy Inference System (FIS) is adopted in this study due to its intuitiveness, wide acceptance, and suitability for a wide range of activities such as robot navigation. The inputs to the FIS are the position from the left ridge (leftPosition) and position from the right ridge (rightPosition) of the farm environment. The output of the FIS is the angle of the servo motor (servoAngle).

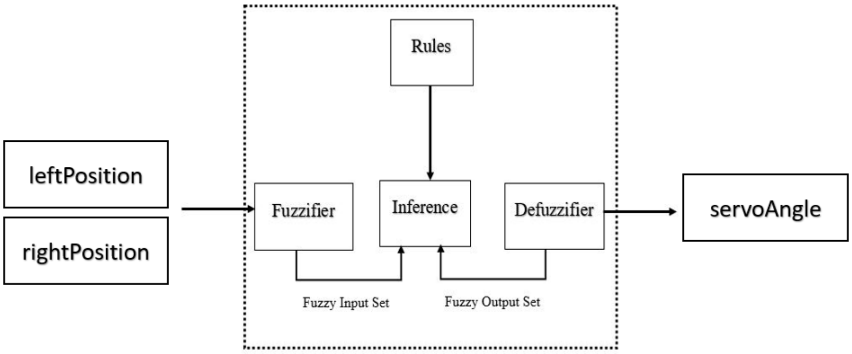

Figure 5.5: Fuzzy Logic Controller

Fuzzification is the process of converting crisp inputs to fuzzy inputs and is achieved using membership functions (MFs). These functions map the crisp inputs to a value between 0 and 1. The triangular MFs are implemented for this design. There are three MFs used for each of the input and output variables. The MFs used for each of the inputs (rightPosition and leftPosition) are high, med, and low. In the case of the output, the MFs used are left, mid, and right. The input variables have ranges between 0 and 512. This value represents the pixel dimension of the camera. The output variable (servoAngle) has a range of -90 to 90, which represents the angle (in degrees) of the servo motor. The MFs of the inputs and outputs are shown in Figures 5.6, 5.7, and 5.8.

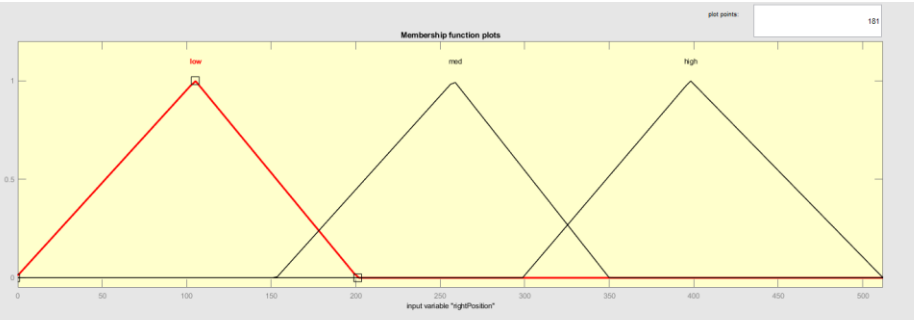

Figure 5.6: Membership Function for rightPosition

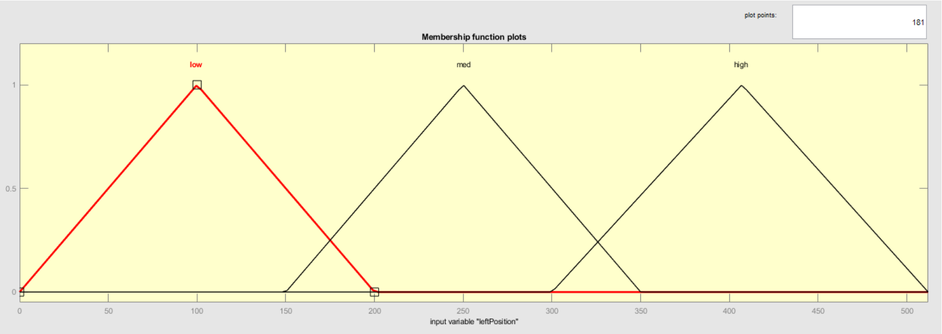

Figure 5.7: Membership Function for leftPosition

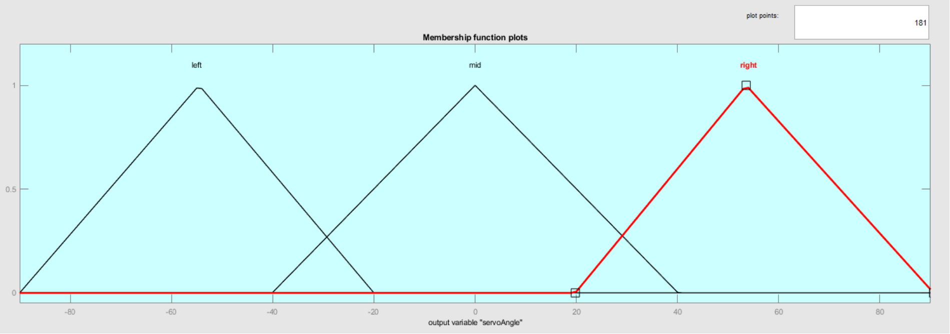

Figure 5.8: Membership Function for servoAngle

After fuzzification is achieved. The inputs are converted to outputs via a set of fuzzy rules. These rules are in the form of equation 2.

$$\textit{If } x \textit{ is } A, \textit{ then } y \textit{ is } B \qquad (2)$$

Where A and B are linguistic variables. These type of variable are not numeric but are defined by fuzzy sets. The rules defined for this study are highlighted in Table 5.2.

Table 5.2: Fuzzy Rules

	leftPosition			
rightPosition		**low**	**med**	**high**
	low	mid	right	right
	med	left	mid	right
	high	left	left	mid

After the rules are evaluated, the outputs are defuzzified to be converted from fuzzy outputs to crisp outputs. The defuzzification technique used for this design is the centroid technique. The crisp outputs will be passed to the microcontroller ports for actuator action.

c. IoT Platform Development

The IoT development platform is implemented with the Node-RED development tool developed by IBM. This choice is informed due to the platforms ability to easily integrate with a web application using APIs and JavaScript. The Node-RED runtime is built on node.js and the flows created are stored using JSON. Node-RED supports IoT development and in this case, it is used together with the IBM cloud platform for the implementation of the remote monitoring and control features of the system.

The Node-RED implementation is done on the raspberry Pi microcontroller. The controller is also connected to a 4G Wi-Fi shield for enhanced communication and internet connectivity. The architecture of the IoT platform is shown in Figure 5.9. The microcontroller together with the Wi-Fi shield is the central hub of the platform. These interconnect with the sensors on the robot (liquid level sensor and camera module) to obtain data from the farm. The data is then transmitted through the W-Fi shield to the IBM cloud database. The web application interfaces with the cloud to obtain the data and display it on the user interface.

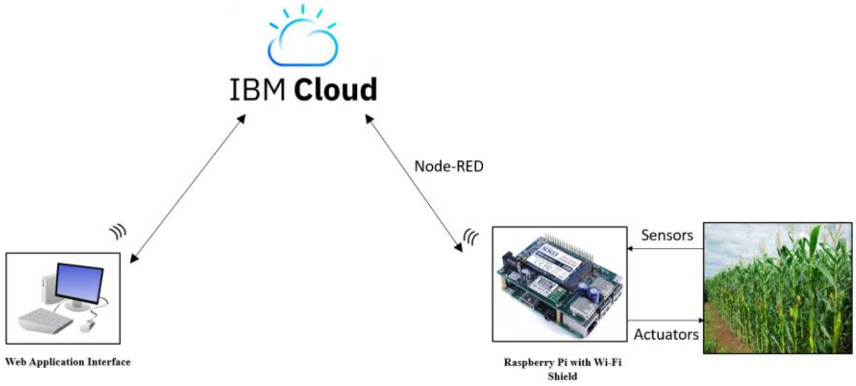

Figure 5.9: IoT Platform Architecture

In addition to obtaining and displaying data from the farm, the IoT platform is also used to send command signals to the controller. Using bidirectional connectivity, the web application is used to transmit signals to the controller through the cloud. These signals include DC pump action for spraying, servo motor position for navigation, and turning on or turning off the system. This feature enables a user to remotely control the robot's position and operations using the web application interface.

d. Web Application Design

The web application is developed to provide the user interface for remote monitoring and control. The application is developed using HTML, CSS, Javascript and PHP web scripting languages. The web application provides a graphical user interface for visualisation of farm parameters. These parameters include the liquid level of the robot tank and live feed from the camera. The application also provides an interface for remotely controlling the robot's actions. The operations that can be controlled are the robot's movement via the DC and servo motors, the robot's spray action via the DC pump, and the power status of the robot (On/Off).

5.4 Expected Results

a. Prototype Development

The circuit diagram of the system is presented in Figure 5.10. The robot is capable of moving automatically within the farm environment. The robot consists of three wheels, one in the front and two in the rear. The front wheel is powered by a servo motor which controls the direction of movement of the robot. The rear wheels are controlled by a DC motor, which is responsible for the forward motion of the robot. The camera module is mounted in the front of the robot for viewing the environment. The liquid tank incorporated with a liquid level sensor is placed at the back of the robot. The robot moves within a maize farm environment shown in Figure 5.11. The designed prototype is presented in Figure 5.12.

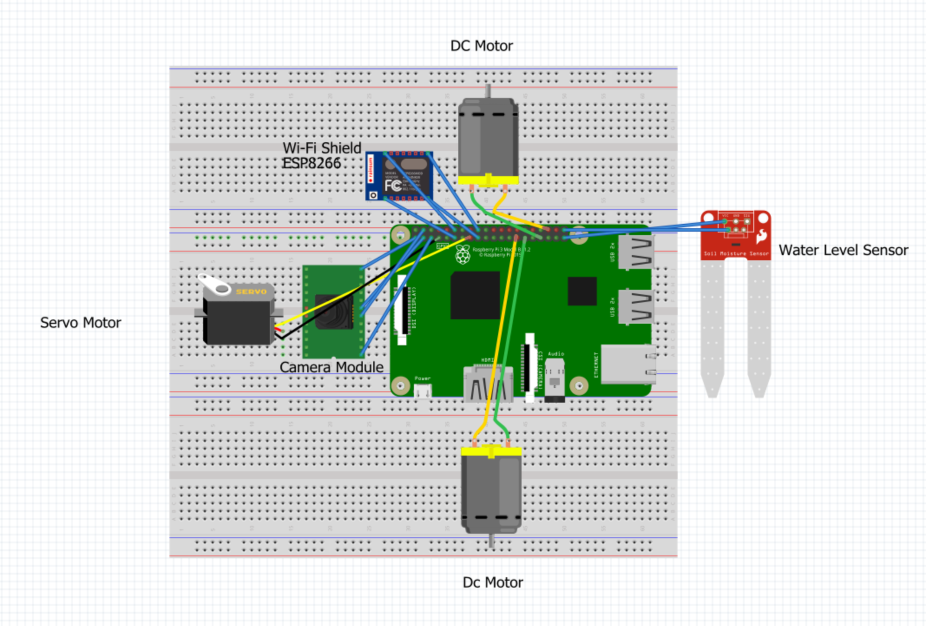

Figure 5.10: Circuit Diagram of the Robotic System

Figure 5.11: Maize Farm Environment

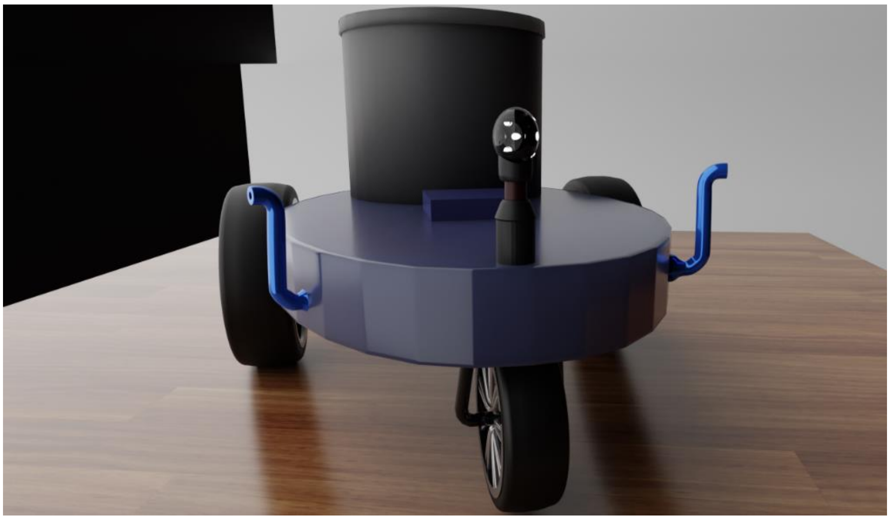

Figure 5.12 (a): Designed Robot Prototype (Front View)

Figure 5.12 (b): Designed Robot Prototype (Side View)

b. Ridge Detection, Robot Navigation and Control

The results of the image-processing algorithm are shown in Figure 5.13. In Figure 5.13(a), the original image acquired from the camera is shown. The image is pre-processed by converting to grayscale, enhancement, and noise removal. The results of the pre-processing are shown in Figure 5.13(b). Figure 5.13(c) shows the Sobel edge detection action on the image while the detected ridgelines using Hough Transforms is shown in Figure 5.13(d).

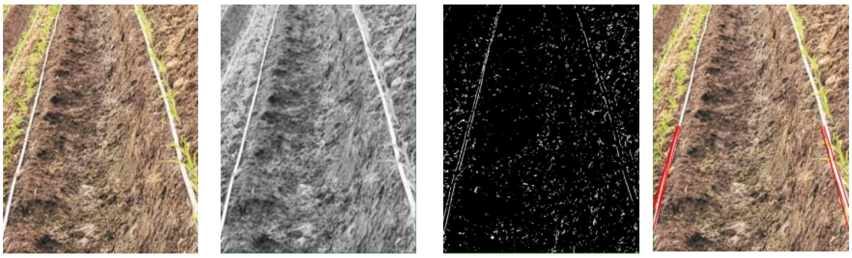

Figure 5.13: (a) Original Image (b) Pre-processed Image (c) Edge Detected Image (d) Ridge Detected Image

After the ridgelines are detected and the distance from the robot is calculated, the value is sent to the Fuzzy Logic Controller (FLC) for navigation. The expected trajectory of the algorithm is shown in Figure 5.14. The fuzzy algorithm will steer the robot to the middle of the ridges and autonomously navigate within the farm ridges.

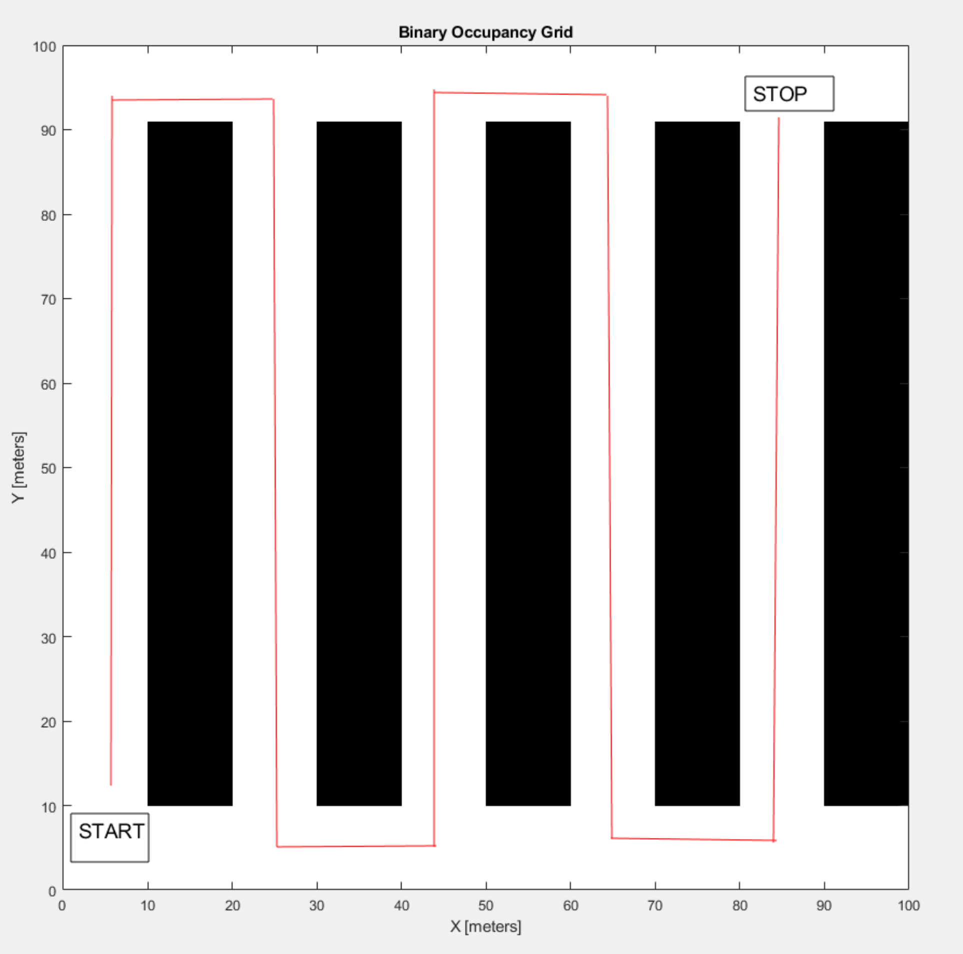

Figure 5.14: Expected Robot Trajectory

The surface view of the FLC is presented in Figure 5.15. This shows the relationship between the inputs to the FLC and the output of the controller. The relationship and mapping between the inputs and outputs provide accurate and efficient movement within the environment.

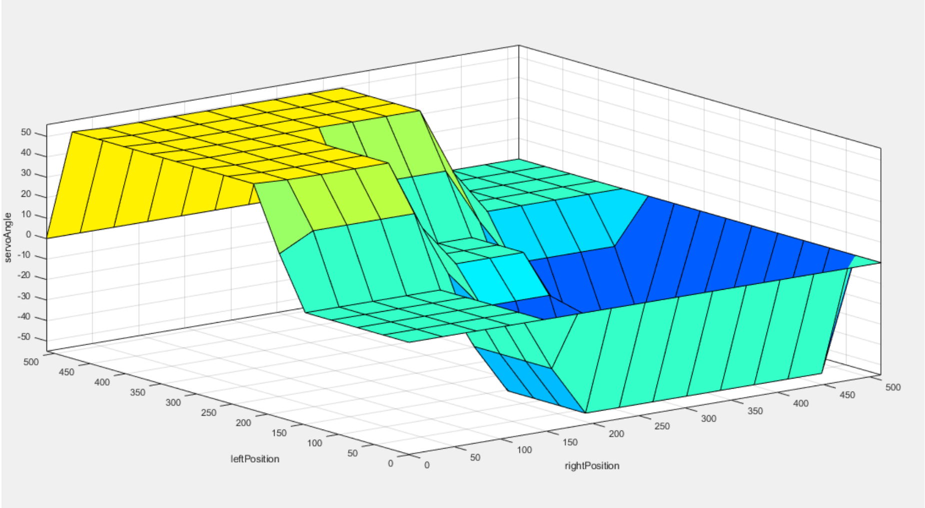

Figure 5.15: Fuzzy Surface View

c. Web Application

The layout for the web application includes the features for remote monitoring and control as shown in Figure 5.15. The application consists of a login page, as seen in Figure 5.16(a), to enable secure access and restrict unauthorised users. The dashboard, shown in Figure 5.16(b), shows a summary of the robot including liquid level, spray action, and live camera feed. The user can also go to the control section to remotely control robot operations such as movement and spraying.

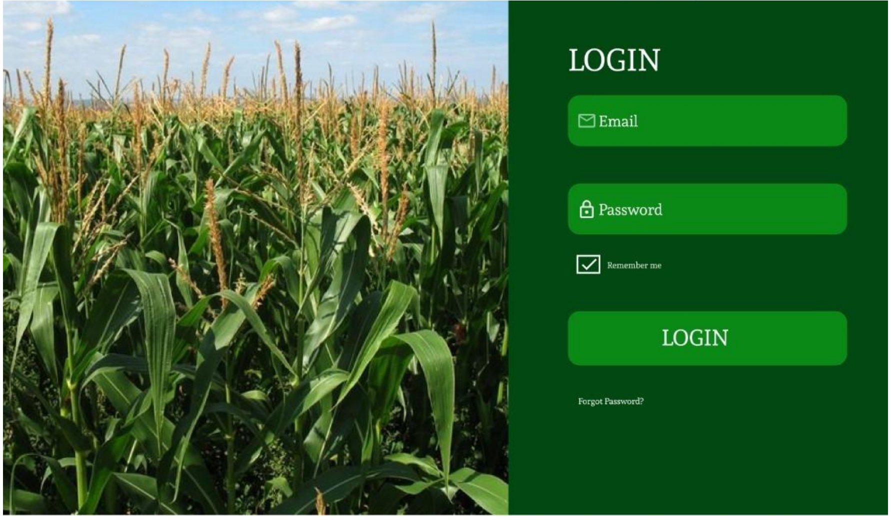

Figure 5.16(a): Web Interface Login Page

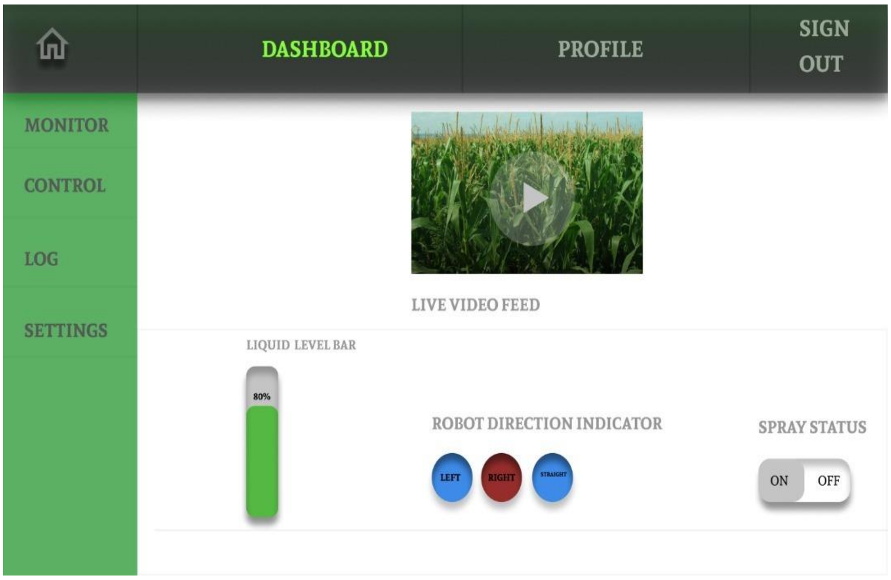

Figure 5.16 (b): Web Interface Dashboard

5.5 Conclusion

In sub-Saharan Africa, the potential of the agricultural sector can be enhanced through the adoption of precision agriculture to provide food and job security, increase income and revenues, and improve staple food crop production. Precision Agricultural practices can be implemented to reduce human involvement in farming for the positive results in terms of increased crop yield and profit. The development of robotic farming systems is becoming widespread and the application of intelligent, autonomous, and smart solutions has been explored. Implementing the Internet of Things (IoT) technology allows farmers the opportunity to be remotely present in their farms if they cannot physically be there. In this study, the conceptual design of an autonomous robot system based on IoT is presented for maize precision farming operations in a sub-Saharan Africa location.

The autonomous robotic system was designed using Node-Red, Fuzzy Logic, and Hough Transform techniques. The robot consists of a camera mounted in front of it for capturing the front view of the robot. The image-processing algorithm based on Hough Transforms processes the image to detect ridges in the farm. The distance of the robot from the ridges is fed into the Fuzzy Logic Controller (FLC). The FLC processes the inputs and based on the fuzzy rules developed, sends an output to the microcontroller for autonomous navigation. The live feed from the camera as well as the liquid level in the tank can be monitored remotely from a web application using an IoT platform. This platform is developed using Node-RED and the IBM cloud. Also, the IoT platform provides a remote control interface to control robot navigation and also control the spraying action of the pump. The system applies visual and sensory inputs to provide full functionality for farm operations.

The system will allow farmers to cover large sections of arable land while minimising human labour. Farmers will not find it necessary to hire a large workforce to cover their farmlands. This system will enable farmers to solely manage their farms. Furthermore, the system will enable remote monitoring and control of farm operations especially in areas prone to disease outbreak, insecurity, and inaccessibility resulting from natural disasters and accidents.

Upon implementation and adoption, the system is expected to increase crop yield and profit while resulting in a decrease in human involvement and labour costs. In addition, production of staple crop such as maize will be positively influenced as a result of the system's potential to encourage farming on a large scale. More revenue will be generated by the Agricultural sector thereby improving national and regional crop production.

Future areas that will be explored in this study are as follows:

i. Design Implementation and Prototype Fabrication: This involves the implementation of the designed algorithms on the microcontroller firmware, after which the performance of the implemented algorithms will be evaluated.

ii. Robot Assessment Accuracy Evaluation: this involves assessing the accuracy of the robot in terms of navigation, ridge detection, and communication with the web application.

iii. Comparative Field Evaluation: Here, the performance of the robot will be compared with the conventional weed control and herbicide application techniques to determine the more effective scheme.

To stimulate agricultural growth, stakeholders and researchers in the agricultural sector must encourage the adoption of smart and intelligent farm technologies. However, support in terms of research funding and the provision of secure communication channels to boost IoT applications will also go a long way in Precision Agriculture's technological growth. Farmers should be sensitized about the benefits of precision farming, to encourage them to adopt new technologies for improved profit and yield.

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