Automated Granary Monitoring And Controlling System Suitable For The Sub-Saharan Region

Temesgen Belay Tedla, Joe Joe L. Bovas, Yonas Berhane, Maxim Nikolaevich Davydkin, Shaji James P.

Abstract : In the Sub-Saharan region, a large amount of the harvested grain is lost during storage. The inability to precisely monitor and control the internal conditions of a storage house is one of the major factors leading to this loss. Timely, relevant and accurate information regarding the internal status of the granary helps in maintaining the quality of the grains as well as in storage loss reduction. This paper presents an automation system for grain storage houses found in the Sub Saharan region. The automation system was built on the paradigm of the Wireless Sensor Network, where spatially distributed sensor nodes seamlessly communicate with a Linux based Raspberry Pi computer. The communication between them is achieved through a lightweight and reliable machine-to-machine communication protocol. Each node is equipped with sensors for monitoring the climatic and environmental conditions of the grain storage house. Based on the incoming data from the sensors the system executes a number of tasks to help the grains to be safely stored for a long period of time – with minimum losses. Additionally, an easily accessible and secure web interface has been developed allowing the owner to graphically visualize the status of store, in real-time. If any risk factor is confirmed to exist inside the store, the owner is automatically informed through SMS.

Keywords : Aeration, Arduino, Granary, Grain loss, MQTT, Microcontroller, NodeMCU, Node-RED, Raspberry Pi, Sensor, WSN

1 INTRODUCTION

The global population is growing and is expected to reach 9.1 billion by the year 2050. Meeting the food demand of this growing population is a challenge that we have to face. We need to produce nearly 70% more to meet this demand [1] [2] [3]. To reduce the pressure of increasing production, minimizing the post-harvest losses must be considered. This must be taken care of, especially by developing countries. Thus, the pressure on natural resources and thereby improving the farmers' livelihood can be achieved [4]. Almost 70% of the people in the sub-Saharan African region, directly or indirectly depend on agriculture for their food and income [5]. But low productivity and post-harvest losses are a matter of main concern [6]. Before reaching the final customer, products of the farm have to undergo processes such as harvesting, threshing, winnowing, drying, bagging, storage, and transportation [5].The losses at each stage cannot be avoided but can be minimized. The losses during the postharvest operations are considered to be more than one-third of the harvest [4] [7]. In Africa, it is estimated to be in the range between 20% to 40% [6]. This increased loss is mainly due to inappropriate handling, storage, and processing techniques - in addition to these - lack of storage infrastructure and market facilities add to the problem [6].

Globally the food loss in storage is estimated to be 30% on cereals, 20% on oilseeds and 40-50% on fruits, vegetables and root crops [8]. In the African countries, these losses are found to be in the ranging between 20% to 40%. The significance of these values comes to play when the fact of lower production in this region is considered [5]. Storage plays a vital role in food security [9] [10]. Unscientific design of indigenous storage structures cannot guarantee the protection against pests for a long time [11] . Considering West Africa, most of the farmers traditionally store their produce on open fields, jute or polypropylene bags, raised platforms, clay structures and baskets [5]. These methods can increase the losses and cost small scale farmers a lot. The main cause of losses during storage is due to the lack of proper infrastructure [4]. The people of sub-Saharan countries mainly depend on grains and the lack of efficient storage facilities contributes to the food insecurity in the region [4]. The total losses in this region are estimated to be 4 billion US dollars per year [6], out of which storage accounts for 35% [12]. It should also be considered that grain losses can contribute to global warming [4]. Studies show that they contribute 4.4 Gigatons of CO2 [13]. Ambient temperature, relative humidity, moisture, O2 level, bacterial and fungal infection, rodents, birds and pests, are the important factors to be considered to reduce grain storage losses [14]. The quality of the grain to be stored is another important aspect worth considering [4]. The implementation of locally adaptable modern storage technologies contributes to minimizing grain loss as well as help in preserving grain quality [15].

1.1 Similar Works

The application of the recent advances in electronic and information technology and affordably atomizing grain storage facilities can improve grain storage and reduce losses [16]. Various attempts have been made in this regard. Arduino microcontrollers along with sensors were effectively applied to control the internal climatic status of the silo by [17]. Automated warehouse management and data transmission system using Arduino microcontroller, temperature and humidity sensors, and a GSM module was successfully attempted by [18]. A similar wireless communication concept, for grain storage, was proposed by [19]. A storage house automation prototype, equipped with a WiFi module, was developed by [20]. This system has three Arduino Due microcontrollers each connected with a temperature sensor, humidity sensor, and ammonia gas sensor. The microcontrollers send the data harvested from the sensors to the server by using the standard WiFi protocol and decision is made on the server-side based on

- *Temesgen Belay Tedla is currently pursuing his master's degree in electrical engineering in National University of Science and Technology NUST, MISIS, Moscow, Russia. E-mail: teme.tedla@edu.misis.ru*
- *Joe Joe L. Bovas is currently pursuing Ph.D. program in Agricultural Machinery in Gandhigram Rural Institute (Deemed to be University), Tamilnadu, India. E-mail: jojojainkerala@gmail.com*
- *Yonas Berhane , has graduated from Hamelmalo Agricultural College, Departement of Agrcultural Engineering, Keren , Eritrea*
- *Maxim Nikolaevich Davydkin, Ph.D., is currently assistant professor in National University of Science and Technology NUST, MISIS, Moscow, Russia. E-mail: davydkimn@misis.ru*
- *Shaji James P., Ph.D., is currently professor in Kerala Agricultural University, Thrissur, India. . E-mail: shajijamesp@gmail.com*

the received data. Thus, if any of the sensors register a value well beyond the preset values, an alarm is triggered alerting the store administrator. Similarly, another project was done emphasizing on the importance of monitoring the CO_2 level of the stored grain and applying a machine learning algorithm for the analysis of the data, obtained from the sensors - which were inserted into the storage bin [21]. Implementation of a Wireless Sensor Network (WSN) technology inside a model grain storage facility, using Xbee radio transceivers was successfully done by [22]. The Xbee modules transmit data from the sensors inserted inside the granary to a Sink Node and which in turn routes the data to a GPRS shield or a personal computer. When we consider all the above studies, they lack a basic and easily accessible interface for monitoring the status of the grain storage facility. Additionally, there is no mention of real-time rodent detection mechanism in all the studies. Rodents are one of the major factors responsible for stored grain loses [12]. Thus, the present paper proposes an affordable microcontroller-based grain storage control and monitoring system which is suitable for the Sub-Saharan scenario. The main objectives of this paper are: 1) To develop and implement a Wireless Sensor Network (WSN) model for Controlling and monitoring factors such as temperature, humidity, CO_2 level and presence of intruders inside a grain storage facility. 2) To create a simple and secure Graphical User Interface (GUI) for visualizing (or controlling) the aforementioned factors in real-time while making it easily accessible to the store owner. 3) To set up an automated communication link that provides the owner with some critical updates from the granary through SMS.

2 METHODOLOGY ADOPTED

This section describes the methodology which was adopted to achieve the objective of developing a suitable microcontroller-based monitoring system for a grain storage facility in the Sub-Saharan region. The conceptual framework of the system is described in figure 1. The system monitors, temperature, humidity, intruders and CO_2 inside the storage house and will communicate to the central control unit. The central control unit will display the values on a real-time basis on a web page generated and will produce a warning notification if there is any deviation from the optimum level. If any of the values go beyond the critical level, the control unit will send an SMS to the registered mobile number requesting immediate action. The webpage can be accessed by authorized persons around the storage house through the WiFi connectivity. The storage house can be accessed from any location by simply linking the existing network with the internet. Taking into consideration the conditions prevailing in the Sub-Saharan region, easily available software and hardware tools opted for use in this project. While selecting the electronics and the associated software tools, the following criteria were used. The microcontroller should meet the computing requirements of the system, like data processing speed, to effectively and efficiently handle multiple tasks. All the sensors and actuators should be compatible with the main controller. Sensors and actuators must have fast response time and be accurate and durable. All the components should: be in their latest version, affordable, easily available and open source. All the components should be able to properly function under the climatic conditions of the regionThe software, the development environment, and all additional libraries should be up to date and freely available. All the components and the software must have been successfully used in similar applications and well tested by researchers.

The development of the system will be explained in three phases, Hardware Design, Software Design, and Testing.

The block diagram in figure 2 illustrates the general architecture of the proposed system.

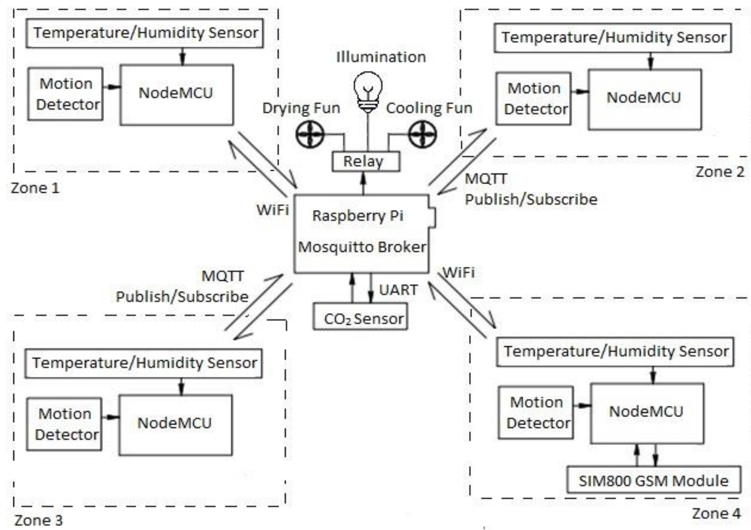

***Fig. 1**. Complete architecture of the WSN and the main controller*

The hardware needed for the system was selected by considering the fact that the majority of the grain storage facilities in the Sub-Saharan region are located in close vicinity of the farmer's house. The developed Wireless Sensor Network (WSN) consists of four nodes with each node having a climatic sensor, a motion detector, and a microcontroller unit. Taking into consideration that most of the storage structures are not very large, the grain storage facility was divided into four equal zones and each sensor node is assigned to one zone. The fourth sensor node is integrated with an additional GSM module for establishing a communication link through SMS. The fact that there are more than 456 million mobile subscribers in the Sub-Saharan region makes this arrangement more adaptable [23]. A Raspberry Pi-based sink node is responsible for controlling the data flow in the WSN. All the communication between the sensor nodes and the sink node is achieved through the implementation of the lightweight application layer protocol known as MQTT (Message Queue Telemetry Transport) protocol. An interactive webpage, showing the status of the granary in real-time, was developed and deployed on the Raspberry Pi. Thus, the owner can access the application with or without an internet connection. Automatic SMS notifications by the system are reserved for some critical situations such as the presence of an intruder or abnormal climatic conditions [24]. This system is scalable and can be adapted for use in any type of grain storage facility.

2.1 Hardware Design

The selection of the hardware part of the system is discussed in this section. Each node in the WSN consists of four basic elements: Sensor, processor, wireless communication unit and a power supply unit [25] [26]. Additionally, the system is made accessible externally through a Gateway. The Raspberry Pi computer is configured to function as a Gateway, a web server and as a sink node. A Carbon dioxide sensor and a relay module are also directly connected with the computer. The relay module is used for controlling the aeration and the illumination circuits inside the granary. A description of the major components used in the project is given below.

2.1.1 Raspberry Pi

The Raspberry Pi, used in the system is, Raspberry Pi 4 Model B. It has the following specifications, Broadcom BCM2711, Quad-core Cortex-A72 (ARM v8) 64-bit SoC @ 1.5GHz, 4GB LPDDR4-3200 SDRAM, 2.4 GHz and 5.0 GHz IEEE 802.11ac wireless, Bluetooth 5.0, BLE, Gigabit Ethernet, 2 USB 3.0 ports; 2 USB 2.0 ports, standard 40 pin GPIO header 2 × micro-HDMI ports, 2-lane MIPI DSI display port, 2-lane MIPI CSI camera port, 4-pole stereo audio and composite video port, Micro-SD card slot for loading operating system and data storage, 5V DC via USB-C connector, 5V DC via GPIO header. The high-performance quad-core 64-bit ARM V8 processor, gives the device the power to execute the required tasks without any significant performance issues. This helps while serving an interactive and dynamic web page, in processing the data from the sensors and coordinating the WSN inside the granary - simultaneously. The standard 40-pin GPIO header gives the device the capability to directly connect with various peripheral devices. The Raspberry Pi operates at a range of temperatures between 0 -500C which makes it ideal for its application in the Sub-Saharan region. Raspberry pi was effectively used by [27], [28], [29], [30], [31]and [32] for home automation, Rajkumar and Prakash [33] use for automatically monitoring the student attendance, Yuvashree et al.[34], used for the automation the handloom operation, Shilpashree et al. [35] ,used for image processing and Ibrahim et al. [36] , used for monitoring infants. From the above studies, it is clear that Raspberry pi can successfully be used for various types of automation projects. All the researches sited above had a functional concept more or less similar to us and only differed on the specific application. In addition to this, Raspberry pi was selected for these projects as it was small in size, programmable, good performer, supports different programming languages, open-source, reliable, affordable and energy-efficient.

2.1.2 Node MCU

The Node MCU (Node Microcontroller Unit) has a Lua based interactive firmware that runs on the ESP8266 Wi-Fi SoC from Espressif Systems and the hardware is based on the ESP-12 module. It is an open-source firmware. The device is equipped with a built-in USB to serial converter, up to 17 GPIO ports, 802.11 b/g/n wireless transceiver, and onboard power supply. Besides, it has a 32bit built-in processor with a speed of 80 - 160 MHz. The board is designed to control electronic devices that are connected with its GPIO ports or wirelessly - through WiFi. Its compact size, cheaper price, compatibility with various components and its support of the TCP/IP protocol make it the right solution for environmental monitoring WSN applications [37] [38] [39]. Various researchers used the Node MCU to: develop a WiFi controlled robot [40], forest fire detection system [41], tomato sorting machine [42], computerized power transformer monitoring system [43], web-based automated system to control the air quality [44], automatic electricity billing system [45], LPG gas leakage detection and alert system [46] and wireless body temperature and heart rate monitoring system [47]. The successful results of the above projects indicate that Node MCU is reliable and stable hardware and thus, was selected to be used in the present system.

2.1.3 GSM module

SIM800 module was selected to be used in the system. It is a quad-band GSM/GPRS module which supports GSM frequency bands of 850/900/1800/1900MHz. The device can transmit voice, SMS, and data. Its ability to control TTL levels of 3.3/5V makes it convenient to connect it with a wide variety of microcontrollers including the Node MCU. The device can support 2G, 3G and 4G mobile networks thus making it compatible with various local operators. It was found that Jishnu et al. [48]; Trivedi et al. [49] and Muskan et al. [50], have successfully used SIM800 module on their projects and was working satisfactorily.

2.1.4 MH-Z19 CO2 gas sensor

The MH-Z19 sensor module detects the presence of carbon dioxide in the air - using the Non-Disruptive Infrared (NDIR) principle. Its built-in temperature compensation capability, ability to resist interference caused by water vapor, low power consumption, high sensitivity, and long lifespan make the device an ideal solution for measuring the CO_2 level inside the storage house. Besides, the device is developed using infrared absorbing gas technology and produces output signals through the UART (Universal Asynchronous Receiver-Transmitter) and PWM (Pulse Width Modulation) ports [51]. Some notable features of the sensor include it has an interface signal level of 3.3V, has a measuring range between 0-5000 ppm with an accuracy of ± 50 ppm, operating temperature and humidity ranges are 0-500C and 0-95% RH respectively [52]. A high level of CO_2 inside a grain storage facility is directly related to an on-going biological activity. Which means an increased fungal, mold spoilage or insect infestation [53]. The table outlined by Neethirajan [54] correlates the ppm levels of CO_2 with the intensity of infestation in grain stores. According to them, ppm levels between 380-500 indicate a normal acceptable level, 1100-3500 indicate the slight presence of infestation and 3500-5000 ppm levels indicate a high amount of infestation either by insects or microorganisms. Thus, any value above these means that the grains are severely spoiled and storage house is in a critical situation. These correlation values were used as a reference while programming the NodeMCU microcontroller which reads the data from the MH-Z19 sensor. Table1 shows how the MH-Z19 is interfaced with the GPIO pins of the Raspberry Pi 4.

TABLE 1

GPIO PIN ASSIGNMENT BETWEEN THE SENSOR AND MAIN CONTROLLER

Raspberry Pi Model 4		MH-Z19 CO2 Gas Sensor	
Pin No.	**Function**	**Pin No.**	**Function**
2	5 V Power out put	6	Vim, Input Voltage
6	Ground	7	Ground
8 (BCM 14)	TXD (Digital Transmit)	2	RXD (UART Digital Input)
10 (BCM 15)	RXD (Digital Receive)	3	RXD (UART Digital output)

2.1.5 DHT22 Humidity and Temperature Sensor

The sensor selected for this project is AM2302 digital temperature and humidity sensor (commonly referred to as DHT22) module. The DHT22 is a high-performance 8-bit microcontroller unit. This device uses a high-precision capacitive technology for measuring the ambient temperature and relative humidity [55]. Attributes such as the high-precision, strong anti-jamming capability, low power consumption, ultra-small size, and low cost make the sensor the ideal choice for this project. The device uses a Serial Data communication protocol to communicate with the peripheral microcontrollers. In this protocol 40bits of data are sent to the microcontroller with specific timing and out of which 16 bits resolution are for humidity and 16 bits resolution assigned for temperature reading. Some key features of the DHT22 sensor are operating temperature range -400C to 800C, operating humidity range 0-100%RH, accuracy for temperature ±50C and humidity ±2% RH, sensor delay 2s and operating voltage of 3.3 - 6V [55].

2.1.6 PIR based motion detector

Passive Infrared sensor (PIR) is a device that detects the infrared radiating from warm-blooded animals such as rodents and humans. The body temperature of rodents such as rats is around 37.5-38.50C producing enough IR to trigger the sensor during ordinary microclimatic conditions [56] [57]. Basically, the sensor is made up of two separate slots which are highly sensitive to IR and are wired to the opposite inputs of a differential amplifier. During stationary conditions, the two slots register an equal amount of IR radiating from the background. The two signals cancel each other and produce zero signal output. Such an arrangement prevents the device from giving false signals due to the event of sudden illumination or surge in ambient temperature. But when a warm-blooded creature moves by, there would be some imbalance and differential values are registered from the two slots. This triggers the sensor to send a signal indicating the detection of a movement. A Spherical shaped lens - known as Fresnel lens - is fitted on the top of the sensor. This lens focuses the incoming IR radiation and thereby, improving the detection distance up to 9m while sweeping a region around l20 degrees. It was also observed that Oyebola [58] ; Rao et al. [59]; Vijayavargiya et al. [60]; Olalekan, O.B. [61] and Iyapo et al. [62], have successfully used PIR detector in their studies.

2.1.7 Aeration

Indeed, aeration is one of the most important methods which is employed for effectively preserving the grains in the storage houses. Aeration is the forced circulation of the ambient air inside the storage facility to minimize the effects of bacterial infestation, molding and high humidity. The two aeration schemes proposed in this model are Aeration drying and Aeration cooling. Aeration drying scheme employs a high capacity fan for reduction of grain moisture. While aeration cooling uses a low capacity fan for reducing the temperature of the storage facility [63]. Relays controlled by the Raspberry pi will be used to switch on and off the fans based on the need, while the size of the fan will be decided based on the size of the storage house. Process.

3 SOFTWARE DESIGN

All of the software tools used for the development of this project are open source and are freely available. The software development process for this project was carried out with two separate approaches. They are the named as Front end and Back end development processes. The front-end process involved mainly with the development of user interfaces and human-machine communication means. During back end process all the embedded components were programmed and calibrated according to standards formulated for granaries.

3.1 Back end development

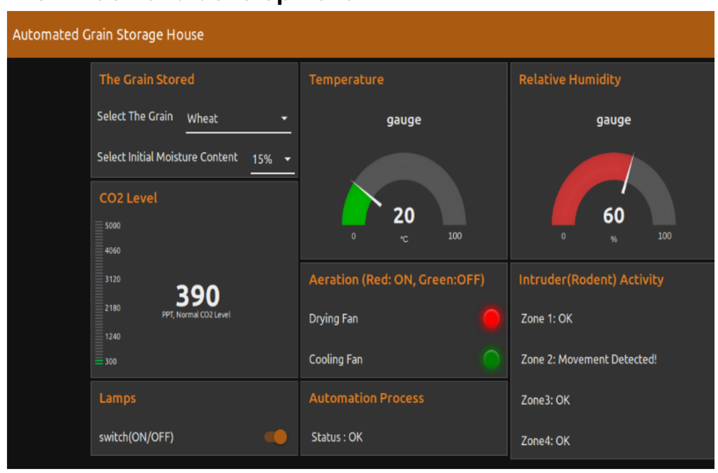

***Fig. 2**. The Designed Web Application Showing the Status of the Granary in real-time basis*

Arduno IDE is one of the most popular and freely available tools for coding embedded systems. In this project, it was used for programming all the sensor nodes in the WSN. Arduino is a flexible C++ based development environment which can be used to program different types of microcontrollers. Numerous WSN based projects have successfully used this tool for programming the microcontroller [64] [65] [66]. A package, known as Esp8266 core, was installed on the Arduino IDE to enable it to access the NodeMCU. Additional libraries, such as the Adafruit DHT - sensor - library, are used for the proper operation of the sensors connected with the microcontroller. Using the Linux based Raspbian operating system on the main controller provides the Raspberry Pi with more efficiency, speed, security and wide community support [67] [68]. Interaction among the embedded devices in the WSN is achieved through a lightweight application layer protocol known as MQTT. It is a Publish-Subscribe protocol where the client subscribes to a particular topic and get updates whenever a new message is published. The usage of this protocol in environmental monitoring WSN has been proved to be efficient through various researches [69] [70] [71]. The publisher and subscriber in the network communicate through an intermediary known as Broker [72] [73]. The broker selected for this project is Mosquitto - a lightweight broker suitable for machine to machine communications [74] [75] also acts as a bridge for integrating the WSN to the cloud if an internet connection is available. The broker was deployed on the Raspberry Pi. In our model each sensor node publishes data to the subscriber via Mosquitto. Thus, the topic Zone1/Climate is published by the DHT22 sensor, which is located in zone1, while Zone3/Motion is published by the motion sensor which is in zone3. With regard to this, the broker transfers these messages to a client which is subscribed to the topics. In this case the client is a web server which uses the data to generate charts and gauges on the web page. The client server also publishes messages with a particular topic. For instance, whenever the server publishes a message with the topic Alert/SMS, the Mosquitto broker directs the message to Zone3 as a node in that area is specifically subscribed to this topic. Thus, based on the message received the node triggers the GSM module to send an SMS message. An interactive web page was developed for visualizing the climatic parameters and controlling some events in the storage house conveniently.

3.2 Front end development

In this process, an interactive web page was designed and developed for visualizing climatic parameters and controlling some events in the storage house. The web application was programmed with a flow-based development tool known as Node-RED. It is an open source development environment with comes readily installed on the Raspbian operating system. The development of event driven web applications through the use of Node-RED has been shown to be robust, faster and easier to build [76] [77] [78]. In a Linux environment, the Node-RED is activated by typing the command sudo node-red-start, on the terminal of the Raspberry Pi [79]. The web application, developed by Node-RED, consists of gauges, a chart and a notification panel for displaying the incoming data from the sensors. The lights on the storage house can be controlled through virtual button available on the web page. It also consists of a drop-down menu which prompts the user to input data such as the variety of grain to be stored and its harvest moisture value. Based on the inputted data, the system automatically customizes its aeration algorithm to be suitable for the stored gain. The web application can be accessed through any standard browser. The IP address used for accessing the web page from a local network is 192.168.43.163:1880/ui. A username and password-based authentication portal was also configured - to prevent an unauthorized party from accessing the system. Screenshot of the webpage is shown in figure 2.

4 TESTING THE MAJOR EVENTS

In the proposed grain storage house automation system quite a number of triggers cause a subsequent event to happen. For instance, an increase of the ambient temperature triggers the cooling fan to start and the starting on the fun will bring a change on the notification panel of the web page. The algorithm developed for the automation system was tested by simulating triggers and the resulting events were outlined in a flow chart. Figure 3 shows these major processes. From the flow chart it is evident that whenever a movement is detected inside the granary, the system locks on the target area and starts counting and posts this information on the web page. The information consists of the location in which motion is detected. In the meantime, if the counting value reaches a level which worth notifying the concerned body, an SMS is automatically sent alerting the owner of the prevailing situation. A snapshot of an SMS sent by the WSN is shown in Figure 4.

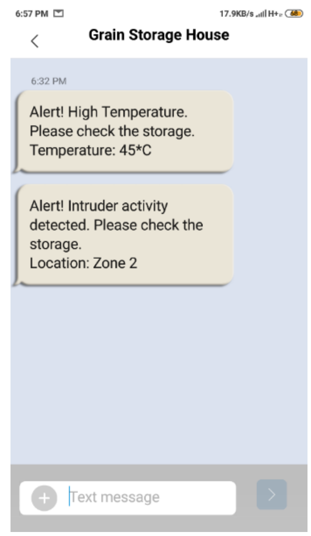

***Fig. 3**. Flow Chart highlighting the major events in the automation system*

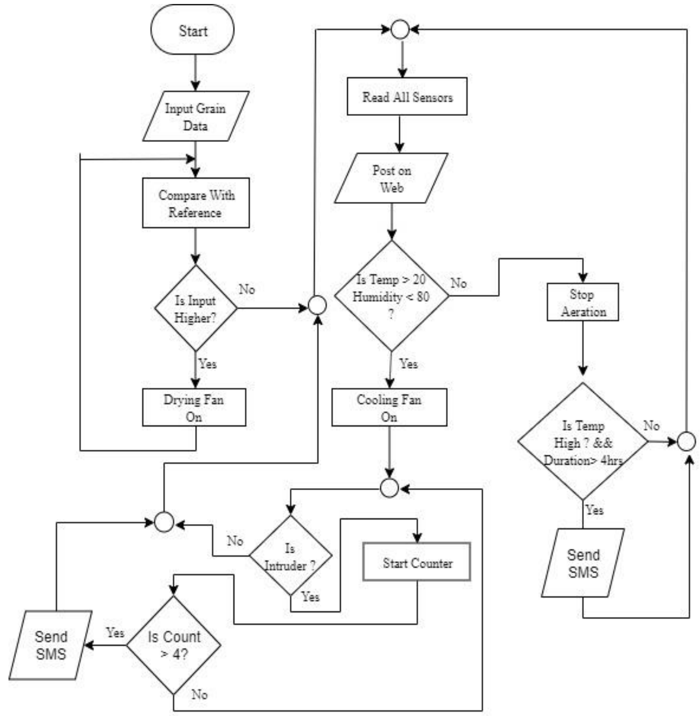

Fig. 4. *An SMS message sample sent by the Automation System*

4.1 Test of the aeration algorithm

The automated aeration system operates based on the data fed from the user and the sensors located at various points. Here, different grain moisture values and grain varieties were randomly fed to the system and the simulated response, according to the underlying algorithm, were recorded as shown in Table 2. The aeration algorithm was developed by including an array of data to serve as reference points in the automation process. One of such data is the safe moisture content value of grains recommended for long term storage. According to the data tabulated by Sadaka, the safe moisture content value for long term storage of Corn, Sorghum, Rough Rice, and Wheat is 12% while for Soybean it is about 11% [80].

TABLE 2

RESULT OF THE TEST CONDUCTED ON THE AERATION ALGORITHM

Input Data by The User		Response of the Automation System	
Grain	**Initial Moisture Content**	**Aeration Scheme**	**Aeration Operation Criteria**
Wheat	15%	Drying Fan ON for 40hrs.	Relative Humidity must be less than 80%
Sorghum	12%	Drying Fan OFF, Cooling Fan ON	Temperature greater than 20 and Relative Humidity less than 80
Soybean	17%	Drying Fan ON for 60hrs	Relative Humidity must be less than 80%
Corn	16%	Drying Fan ON for 50hrs	Relative Humidity must be less than 80%
Sorghum	18%	Drying Fan ON for 70hrs	Relative Humidity must be less than 80%
Wheat	12.5%	Drying Fan OFF, Cooling Fan ON	Relative Humidity must be less than 80%

From the table it can be summarized that, the higher the initial moisture content of the gain the longer the Aeration system keeps on running to reduce the moisture and maintain the quality. If the initial grain moisture level is less than or equal to the recommended storage value, then only the cooling fan operates to minimize the development of insects inside the granary. Besides, it was observed that the aeration mechanism was disabled, when the relative humidity level was above 80%. Such an interruption process protects the stored grain from the consequences of condensation. Because running the fans during such conditions, allow condensation to be created and the grains to be wet - consequently causing molding and spoilage.

5 CONCLUSION

This paper has demonstrated the development of an automation system for granaries located in the Sub-Saharan region. The system was built by taking into consideration of the current climatic and socioeconomic conditions of the region. Thus, the selection of the hardware and software tools were made based on this notion. The developed system provides round the clock monitoring of the grain storage house while at the same time generating live data updates on a web page. The web application was designed to be easily accessible and secure. The aeration system was designed to effectively regulate the microclimatic state of the granary. Furthermore, the automation algorithm adjusts itself based on the input from the user through the web application. The automation process was tested with simulated triggers and satisfactory responses were observed. The proposed system is scalable and can easily be adapted for use in most grain storage facilities in the Sub-Sharan region. And finally, additional research, such as the application of machine learning algorithms in the existing framework, needs to be conducted to make the system smarter and fully autonomous.

REFERENCES

[1] H. Godfray, J. Beddington, I. Crute, L. Haddad, D. Lawrence, J. Muir, J. Pretty, S. Robinson, S. Thomas and C. Toulmin, "Food Security: The Challenge of Feeding 9 Billion People," SCIENCE, pp. 812-818, 12 Feb 2010.

[2] R. Hodges, J. Buzby and B. Bennett, " Postharvest losses and waste in developed and less developed countries: Opportunities to improve resource use," The Journal of Agricultural Science, vol 149 no. S1 , p. 37–45., 2011.

[3] J. Parfitt, M. Barthel and S. Macnaughton, "Food waste within food supply chains: Quantification and potential for change to 2050.," Philos. Trans. R. Soc. B Biol. Sci. , 365, p. 3065–3081., 2010.

[4] D. a. K. P. Kumar, "Reducing Postharvest Losses during Storage of Grain Crops to Strengthen Food Security in Developing Countries," Foods , vol. 6(1):8, pp. 1-20, Jan, 2017.

[5] A. Abass, G. Ndunguru, P. Mamiro, B. Alenkhe and N. a. B. M. Iingi, "Post harvest food losses in a maize-based farming system of semi-arid savannah area of Tanzania," Journal of Stored Products Research, vol. Vol. 57, pp. 49-57, 2014.

[6] World-Bank, FAO and NRI, "Missing Food: the Case of Post-harvest Grain Losses in Sub-Saharan Africa," The International Bank for Reconstruction and Development / The World Bank, Washington, DC, 2011.

[7] J. Gustavsson, C. Cederberg, U. Sonesson, R. van Otterdijk and A. Meybeck, " Global Food Losses and Food Waste," Food and Agriculture Organization of the United Nations, Rome, Italy, 2011.

[8] FAO, " Global Initiative on Food Losses and Waste Reduction," Food and Agriculture Organization of United Nations, Rome, Italy, 2014.

[9] J. Aulakh, A. Regmi, J. Fulton and C. Alexander, "Estimating post-harvest food losses: Developing a consistent global estimation framework," in Agricultural & Applied Economics Association's 2013 AAEA & CAES Joint Annual Meeting, Washington D.C, 2013.

[10] B. Bala, M. Haque, M. Hossain and S. Majumdar, " Food security through increasing technical efficiency and reducing postharvest losses of rice production systems in Bangladesh," Food Sec, vol. 8, pp. 361-374, 2016.

[11] S. J. Costa, "Reducing Food Losses in Sub-Saharan Africa (improving Post-Harvest Management and Storage Technologies of Smallholder Farmers.)," UN World Food Programme, Kampala, Uganda, August 2013 – April 2014.

[12] A. Manandhar, P. Milindi and A. Shah, "An Overview of the Post-Harvest Grain Storage Practices of Smallholder Farmers in Developing Countries," Agriculture, Vols. 8(4), 57, 2018.

[13] FAO, "Food wastage footprint & Climate Change," UN, FAO, Rome, 2015.

[14] M. Z. Abedin, M. Z. Rahman, M. I. A. Mia and K. M. M. and Rahman, "In-store losses of rice and ways of reducing such losses at farmers'level: An assessment in selected regions of Bangladesh," J. Bangladesh Agril. Univ, vol. 10(1), p. 133–144, 2012 .

[15] M. Sheahan and C. B. Barrett, "Review: Food loss and waste in Sub-Saharan Africa," Food Policy, vol. 70, pp. 1-12, July 2017.

[16] C. B. Singh and J. M. Fielke, "Recent Developments in Stored Grain Sensors, Monitoring and Management Technology," IEEE Instrumentation & Measurement Magazine , pp. 32-55, June 2017.

[17] A. M. Antunes, I. A. Devilla, A. Neto, B. Alves and G. Santos, "Development of an automated system of aeration for grain storage," African Journal of Agricultural Research , vol. 11(43), pp. 4293-4303, October, 2016 .

[18] J. S. Shilpa and G. M. Sheeba, "Automated Real Time Monitoring for Food Grain Storage," International Journal of Pure and Applied Mathematics , vol. 118 No. 24 , pp. 1314-3395 , 2018.

[19] A. Bazhenov, N. Grivennaya, S. Malygin and A. Knyaginin, "Distributed System of Remote Control and Management of Technological Processes of Granary," in 17th International Scientific Conference Engineering for Rural Development, 2018.

[20] A. Akila and P. Shalini, "Food grain storage management system," International Journal of Engineering & Technology , vol. 7(2.31), pp. 170-173, 2018.

[21] R. Kaushik and J. Singhai, "An Approach for the Development of a Sensing System to Monitor Contamination in Stored Grain," in 6th International Conference on Signal Processing and Integrated Networks (SPIN) , Noida, 2019.

[22] M. O. Onibonoje, N. I. Nwulu and P. N. Bokoro, "A wireless sensor network system for monitoring environmental factors affecting bulk grains storability," Food Process Engineering, vol. e13256, pp. 1-13, 2019.

[23] GSMA, "The Mobile Economy Sub-Saharan Africa 2019," GSM Association, London, 2019.

[24] L. J. Bovas, B. T. Temesgen, A. Asrat, T. Gebreslasie and J. P. Shaji, "Development of Microcontroller Based Drip-Irrigation Control System in Eritrea," Trends in Biosciences , vol. 12(3), pp. 261-264, 2019.

[25] J. M. Dilhac and V. Boitier, "Wireless Sensor Networks," in Energy Autonomy of Batteryless and Wireless Embedded Systems, Elsevier, 2016, pp. 1-11.

[26] V. Vujović and M. Maksimović, "Raspberry Pi as a Wireless Sensor Node: Performances and Constraints," in 37th International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO), Opatija, 2014.

[27] K. S. Sankar, G. J. Rao, B. Ravi, B. Alekhya, P. Sampathkumar, D. K. Ganesh and E. Rakesh, "Wireless Health Monitoring System using IOT," IJSRSET, vol. 6(2), pp. 268-273, 2019.

[28] Ayushkhare, J. Goel, N. Bhatt and N. Kumar, " Raspberry Pi Home Automation System Using Mobile App To Control Devices," International Journal Of Innovative Research In Science, Engineering And Technology, vol. 6 (5), pp. 7997-8003, 2017.

[29] K. Venkatesh, S. Hemaswathi, B. Rajalingam and P. Rajkumar, " Iot Based Home Automation Using Raspberry Pi," Journal of Advanced Research in Dynamical and Control Systems , vol. 10, no. 07-Special Issue, pp. 1721-1728, 2018.

[30] F. A. A. S. Oduro-Gyimah, "System Design And Implementation Of A Web-Based Raspberry Pi Home Automation," International Journal Of Technology And Entrepreneurship, vol. 1(1), pp. 84-102, 2018.

[31] C. Bepery, S. Baral and A. &. H. F. .. Khashkel, " Advanced Home Automation System Using Raspberry-Pi And Arduino," International Journal Of Computer Science And Engineering, vol. 8(2), pp. 1-10, 2019.

[32] M. Milošević, N. Četić, J. Kovačević and T. Anđelić., " Lighting Control Using Raspberry Pi And OBLO Living Home Automation System," Serbian Journal Of Electrical Engineering,, vol. 16(1), pp. 45-54, 2019.

[33] S. Rajkumar and J. Prakash., "Automated Attendance Using Raspberry Pi," International Journal Of Pharmacy & Technology, vol. 8 (3), pp. 16214-16221, 2016.

[34] S. Yuvashree, S. Sumathi and S. G. Cs., " Automation Of Hand-Powered Loom And Fault Detection Using Raspberry Pi And Monitoring Using Iot," Journal Of Advanced Research In Embedded System, vol. 5(4), pp. 1-7, 2018.

[35] K. Shilpashree, H. Lokesha and H. Shivkumar., "Implementation Of Image Processing On Raspberry Pi,," International Journal Of Advanced Research In Computer And Communication Engineering, vol. 4(5), pp. 199-202, 2015.

[36] D. Ibrahim, M. A. A. and S. A. A. S. M. Hammoudeh, " Raspberry Pi-Based Smart Infant Monitoring System," International Journal Of Engineering Research And Technology, vol. 12 (10), pp. 1723-1729, 2019.

[37] L. Shkurti, X. Bajrami, E. Canhasi, B. Limani and S. a. H. A. Krrabaj, "Development of Ambient Environmental Monitoring System ThroughWireless Sensor Network (WSN) Using NodeMCU and "WSN Monitoring"," in 6th Mediterranean Conference on Embedded Computing (MECO), Bar, 2017.

[38] X. Bajrami and I. Murturi, "An efficient approach to monitoring environmental conditions using a wireless sensor network and NodeMCU," Elektrotechnik & Informationstechnik , vol. 135, no. 3, p. 294–301 , 2018.

[39] A. Gupta, H. P. Gupta, P. Kumari, R. Mishra and S. a. D. Saraswat, "A Real-time Precision Agriculture Monitoring System using Mobile Sink in WSNs," in IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS), Indore, 2018.

[40] K. Mistri, "WiFi Control Robot Using Node MCU," International Journal of Engineering Development and Research, vol. 6(2), pp. 325- 328, 2018.

[41] M. Basu, R. Karthik, J. Mahitha and V. L. Reddy, " IoT based forest fire detection system," International Journal of Engineering & Technology, vol. 7 (2.7), pp. 124-126, 2018.

[42] A. A Istiadi, S. Sulistiyanti and H. a. H. Fitriawan., "Model Design of Tomato Sorting Machine Based on Artificial Neural Network Method Using Node MCU Version 1.0,," Journal of Physics: Conference Series, pp. 1-7, 2018.

[43] A. Mohamad, Y. Mezaal and S. Abdulkareem, " Computerized Power Transformer Monitoring based on Internet of Things," International Journal of Engineering & Technology, vol. 7 (4), pp. 2773-2778, 2018.

[44] D. Aziz, "Webserver Based Smart Monitoring System Using ESP8266 Node MCU Module," International Journal Of Scientific & Engineering Research, vol. 9 (6), pp. 801-807, 2018.

[45] D. Ananth, G. Rao, C. Satish, J. Shyam, K. Santosh, U. Prasad and K. Ramya, "Smart Electricity Billing Using Node-MCU," IJSRSET, vol. 6, no. 2, pp. 287-292, 2019.

[46] M. Shahadat, A. Mallik and M. Islam, "Development Of An Automated Gas-Leakage Monitoring System With Feedback And Feedforward Control By Utilizing IoT," FACTA UNIVERSITATIS, Series: Electronics and Energetics, vol. 32, no. 4, pp. 615-631, 2019.

[47] K. Sankar, J. Rao, B. Ravi, B. Alekhya, P. Sampathkumar, D. K. Ganesh and R. E., " Wireless Health Monitoring System using IOT," IJSRSET,, vol. 6(2), pp. 268-273, 2019.

[48] J. S, R. AP, S. UK, V. D. Nair and S. M., " Wireless Notice Board Using Arduino & GSM," International Journal Of Innovative Research In Management, Engineering And Technology, vol. 1(4), pp. 1-7, 2016.

[49] T. Trivedi, A. Narad, S. Verma, N. Purohit and D. Shrivastava, " Audio System using GSM Module for Announcement," International Research Journal of Engineering and Technology, vol. 5 (5), pp. 2816-2818., 2018.

[50] Muskan, T. Khandelwal, M. Khandelwal and P. Pandey, "Women Safety Device Designed Using IoT and Machine Learning," in IEEE SmartWorld, Ubiquitous Intelligence & Computing, Advanced & Trusted Computing, Scalable Computing & Communications, Cloud & Big Data Computing, Internet of People and Smart City Innovation (SmartWorld/SCALCOM/UIC/ATC/CBDCom/IOP/SCI), Guangzhou, 2018.

[51] G. Marque and R. Pitarma, "IAQ Evaluation Using an IoT CO2 Monitoring System for Enhanced Living Environments," in Advances in Intelligent Systems and Computing, Springer, Cham, 2018, pp. 1169-1177.

[52] Zhengzhou Winsen, "Intelligent Infrared CO2 Module (Model: MH-Z19B) , User Manual," Zhengzhou Winsen Electronics Technology Co., Ltd, 2016.

[53] K. Ileleji, D. Maier, C. Bhat and C. Woloshuk, "Detection of a developing hot spot in stored corn with a CO2 sensor," American Society of Agricultural and Biological Engineers , vol. 22(2), pp. 275-289, 2006.

[54] S. Neethirajan, M. Freund, D. Jayas, C. Shafai, D. Thomson and N. White, "Development of carbon dioxide (CO2) sensor for grain quality monitoring," Biosystems Engineering , vol. 106, no. 4, pp. 395-404, 2010.

[55] Aosong, "Temperature and humidity module AM2302 Product Manual," www.aosong.com.

[56] M. A. M. Fisol and W. M. Jubadi, "Ultrasonic and infrared repelling device for controlling the population of rat in paddy field," in IEEE Asia Pacific Conference on Circuits and Systems, Kuala Lumpur, 2010.

[57] C. Cambra, S. Sendra, L. Garcia and J. Lloret, "Low cost wireless sensor network for rodents detection," in 10th IFIP Wireless and Mobile Networking Conference (WMNC), Valencia, 2017.

[58] B. Oyebola, "Human Body Motion Triggered Lamp Indicator as an Alert with PIR Sensor for the Hearing Impaired.," International Journal of Engineering Research & Technology, vol. 4(6), pp. 52-56, 2015.

[59] K. Rao, P. Rao and B. Ravi, "PIR Sensor Based Robot With HMH Applications," International Journal of Engineering Research and Development, vol. 12, no. 5, pp. 23-28, May 2016.

[60] A. Vijayavargiya, A. Sharma, P. Kumar, M. Yadav, O. Yadav and P. Choudhary, "PIR Motion Sensor for Home Appliance," International Journal of Engineering and Management Research, vol. 6, no. 2, pp. 48-51,

March-April 2016.

[61] O. Olalekan, " Development of a Sim800l Based Reprogrammable Household Smart Security System with Recipient Phone Call Alert," International Journal of Computer Engineering In Research Trends, vol. 4, no. 1, pp. 15-20 , 2017.

[62] K. Iyapo, O. Fasunla, S. Egbuwalo, A. Akinbobola and O. T. Oni., " Design and Implementation of Motion Detection Alarm and Security System," International Journal of Applied Research, vol. 5(1), pp. 33-42, 2017.

[63] C. Warrick, "Aerating Stored Grain. Cooling or Drying for Quality Control: A Grains Industry Guide," The GRDC Grain Storage Extension Project, Kingston , June 2013.

[64] Q. A. Al-Haija, M. A. Tarayrah, H. Al-Qadeeb and A. Al-Lwaimi, "A Tiny RSA Cryptosystem Based On Arduino Microcontroller Useful For Small Scale Networks," Procedia Computer Science , vol. 34, pp. 639-646, 2014.

[65] A. Chandra, Y. Lee, B. Kim, S. Maeng, S. Park and S. Lee, "Review on Sensor Cloud and Its Integration with Arduino Based Sensor Network," in International Conference on IT Convergence and Security (ICITCS), Macao, 2013.

[66] S. Agrawal and R. Prakash, "Implementation of WSN which can simultaneously monitor temperature conditions and control robot for positional accuracy," in International Conference on Green Computing Communication and Electrical Engineering (ICGCCEE), Coimbatore, 2014.

[67] M. Maksimović, V. Vujović, N. Davidović, V. Milošević and B. Perišić, "Raspberry Pi as Internet of Things hardware: Performances and Constraints," in Proceedings of 1st International Conference on Electrical, Electronic and Computing Engineering IcETRAN , Vrnjačka Banja, 2014.

[68] J. Bermúdez-Ortega, E. Besada-Portas, J. López-Orozco, J. Bonache-Seco and J. de la Cruz, "Remote Web-based Control Laboratory for Mobile Devices based on EJsS, Raspberry Pi and Node.js," International Federation of Automatic Control, vol. 48, no. 29, pp. 158-163, 2015.

[69] R. Kazala, A. Taneva, M. Petrov and S. Penkov, "Wireless Network for Mobile Robot Applications," International Federation of Automatic Control, vol. 48, no. 24, pp. 231-236, 2015.

[70] T. Rault, A. Bouabdallah and Y. Challal, "Energy efficiency in wireless sensor networks: A top-down survey," Computer Networks, vol. 67, pp. 104-122, 2014.

[71] D. Guha Roy, B. Mahato, D. De and R. Buyya, "Application-aware end-to-end delay and message loss estimation in InternetofThings(IoT)— MQTT-SN protocols," FutureGenerationComputerSystems, vol. 89, pp. 300-316, 2018.

[72] A. C. Franco da Silva, U. Breitenbücher, K. Képes, O. Kopp and F. Leymann, "OpenTOSCA for IoT: Automating the Deployment of IoT Applications based on the Mosquitto Message Broker," in 6th International Conference on the Internet of Things (IoT'16), Stuttgart, 2016.

[73] D. Guinard and V. Trifa, "Building Networks of Things," in Building the Web of Things, New York, Manning Publications Co., 2016, pp. 109-140.

[74] R. Light, "Mosquitto: server and client implementation of the MQTT protocol," Journal of Open Source Software, vol. 2(13), p. 265, 2017.

[75] "Eclipse Mosquitto," Eclipse Foundation, [Online]. Available: http://www.mosquitto.org/. [Accessed 02 11 2019].

[76] A. Rajalakshmi and H. Shahnasser, "Internet of Things using Node-Red and Alexa," in 17th International Symposium on Communications and Information Technologies (ISCIT), San Francisco, 2017.

[77] H. Nishiyama, "Recent Enhancements of Node-RED for Rapid Development of Large Scale and Robust IoT Applications," Hitachi, Ltd., 2019.

[78] Z. Chaczko and R. Braun, "Learning data engineering: Creating IoT apps using the node-RED and the RPI technologies," in 16th International Conference on Information Technology Based Higher Education and Training (ITHET), Ohrid, 2017.

[79] M. Lekić and G. Gardašević, "IoT sensor integration to Node-RED platform," in 17th International Symposium INFOTEH-JAHORINA, 2018.

[80] S. Sadaka and R. Bautista, "Grain Drying Tools: Equilibrium Moisture Content Tables and Psychrometric Charts," University of Arkansas Cooperative Extension Service Printing Services, Arkansas, 2014.