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Development of Smart Laboratory Information Management System: A Case Study of NMAIST Arusha of Tanzania

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ABSTRACT

Testing Laboratories in Higher Learning institutions of Science, Technology, and Engineering are used by institutional staff, researchers, and external stakeholders in conducting research experiments, analysis, and dissemination of results. However, there exists a challenge in the management of Laboratory operations and processing of Laboratory-based data. Operations carried out in the laboratory at Nelson Mandela African Institution of Science and Technology, in Arusha, Tanzania, where this case study was carried out, are paper-based. There is no automated way of sample registration as well as identification and researchers are prone to making errors when handling sensitive reagents. Users have to physically visit the laboratory to enquire about available equipment or reagents before borrowing or reserving. Additionally, paper-based forms have to be filled out and handed to the Laboratory Manager for approval. The outlined manual operations make it difficult to keep track of expiry dates of reagents, storage conditions such as temperature, software licenses, tools, data regarding borrowed equipment as well as stock remaining, as they lack automated notification mechanisms. This study, therefore, was carried out to investigate the Development of a Smart Laboratory Information Management System (LIMS) integrated with the Internet of Things (IoT), Wireless Sensor Network (WSN), and Radio Frequency Identification (RFID) technology for real-time monitoring of sample and reagents storage conditions, including digital sample identification and tracking respectively. A web application was developed to allow remote access to Laboratory information by users. Based on the performance test, it is concluded that Wireless Sensor Networks can be integrated with the Internet of Things to automate recurring tasks in laboratories, aid in monitoring, and eliminate paper-based record keeping.

Key Words: *Radio Frequency Identification, Wireless Sensor Networks, Internet of Things, Message Queuing Telemetry Transport, ZigBee Protocol, ThingSpeak.*

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1. INTRODUCTION

1.1 Background

Higher Learning Institutions of Science, Technology and Engineering conduct experiments in Testing Laboratories. According to the Oxford Learner’s Dictionary, a Laboratory is a building or a part of a building or any other place set aside and equipped for conducting scientific experiments or investigations, in order to develop new products. These testing Laboratories are accessible to institutional staff, researchers as well as external stakeholders. The Nelson Mandela African Institution of Science and Technology (NM-AIST), based in East Africa, in Arusha, Tanzania, has one such testing Laboratory that is subdivided into three sub-sections. Each subsection deals with a different thematic research focus area, and is led by a Head of Section. The flow of information in testing Laboratories is complex, from the sample registration, to assigning the sample to an analyst, recording the sample results for each parameter tested and relaying the results back to the client or researcher. Conventional paper-based approaches for recording all this information are not efficient. A lot of time is bound to be wasted following up paper work and crucial details might be missed or lost in the process. There is therefore need to aggregate laboratory information on a single platform that can be accessed remotely in order to guarantee real-time access of laboratory data as well as automate manual processes to increase efficiency, speed and accuracy. This study therefore proposes a web-based smart laboratory information management system integrated with wireless sensor network technology, internet of things and radio frequency identification to streamline laboratory operations and consolidate all data on a single platform for easy accessibility and tracking.

1.2 Problem Statement

There exists a challenge in management of most Testing Laboratories, in that operations are carried out manually. There is no established mechanism of sample identification and researchers are prone to make errors when handling sensitive reagents. If users require to borrow laboratory equipment, they have to physically visit the laboratory office, enquire about the availability of equipment and manually fill a paper-based form, before handing it to the Laboratory Manager for approval. Due to the manual operations, it is difficult to keep track of expiry dates of reagents, Software Licences, tools, data regarding borrowed items as well as stock remaining. It is therefore in light of the aforementioned setbacks that this study was carried out to investigate the development of a Smart Laboratory Information Management System to automate processes in the Testing Laboratories, enabling researchers to plan activities.

1.2 Objectives

The main objective of this research was to investigate the Development of a Smart Laboratory Information Management System. The specific objectives were:

i. To determine and gather requirements for the design and development of a Smart Laboratory Information Management System (LIMS).
ii. To design and develop a Smart Laboratory Information Management System.
iii. To validate the developed System.

1.3 Research Questions

i. What are the requirements for developing a Smart Laboratory Information Management System?
ii. How should the Smart Laboratory Information Management System be designed and developed?
iii. How will the study ensure the developed system met the user requirements?

1.4 Conceptual Framework

Fig.2 below represents a conceptual framework model that guided the development of the Smart Laboratory Information Management System. A web application links an Internet of Things (IoT) module and inventory module to the different user categories such as researchers and Laboratory staff.

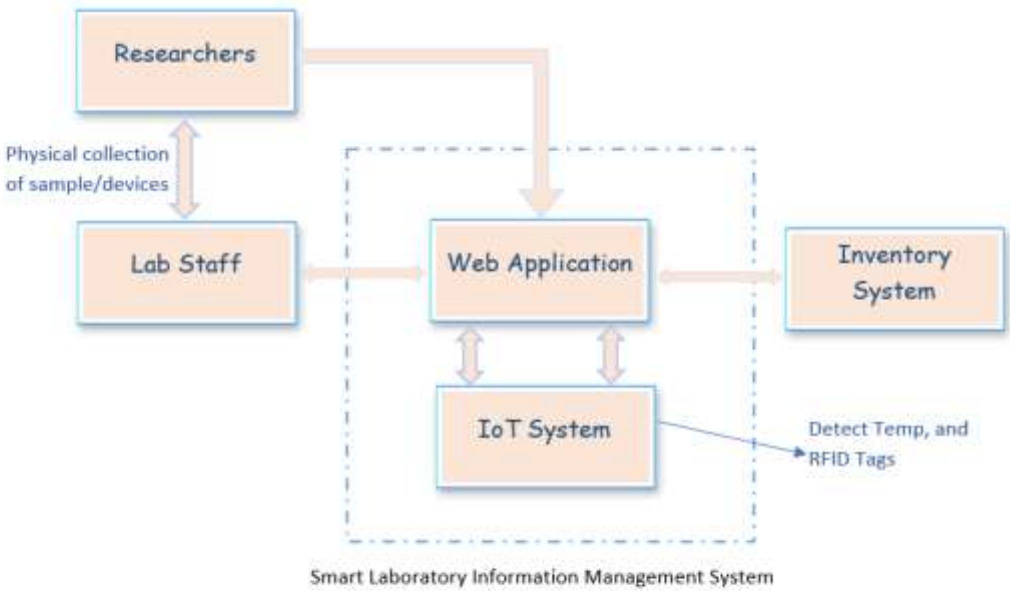

Figure 1 Conceptual Framework

1.5 Significance of the study

The implementation of the system is significant in the following outlined aspect:

- Reduction of overhead in the reporting and management processes within laboratories.
- Having a central database of all Laboratory data in order to digitize operations.

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- Minimizing operational costs of laboratories.
- Facilitating enforcement of Laboratory policies, rules and standard operating procedures.
- Appropriate and timely calibration of Laboratory instruments.
- Easy Monitoring of inventory for equipment, samples, supplies and reagents.

2. LITERATURE SURVEY

Laboratory Information Management System (LIMS) is a database software application used to acquire, store, analyze, manage and monitor data in a testing laboratory. The LIMS improves the laboratory logistics and productivity by managing data of the samples, reagents, laboratory equipment and stakeholders. LIMS is the single source of all laboratory information and it reduces the communication gaps between the head of laboratory, Quality Assurance Manager as well as other stakeholders [1].

Different researchers have previously attempted to address automation and digitization of laboratories. We analyzed different papers critically to identify gaps and inconsistencies.

A Radio Frequency Identification (RFID) based functioning model for managing inventory was developed by [2]. RFID is a wireless, contactless identification technology that does not require line of sight. The technology operates in both low frequency and ultra-high frequency of RFID standards. However, in their proposed model, a control unit was used to relay data between 13.56-Megahertz (MHz) Micro RFID reader and Programmable Integrated Circuit (PIC), then sending the data to a computer. The drawback of the proposed solution was lack of mechanism for remote or wireless accessibility of the system.

In another study, [3] developed an Internet of Things (IoT) based smart laboratory administrator system for intrusion and sound detection as well as monitoring temperature and controlling laboratory access. The system employed OpenCV technology to detect invasion of objects and Arduino Microcontroller with IoT sensors to collect environmental sounds and temperature. The system detected invasion, temperature and voice in real-time and sent immediate messages through an application or email. The limitation of the study however was the use of Quick Response (QR) code to manage the inventory through a mobile application. QR code requires line of sight, needs objects to be scanned one by one, they are read only and have a short scanning range.

A system to manage laboratory information and track large amounts of DNA sequence data was developed [4]. The system employed bar code technology to label the DNA sequence data and track experimental procedures. However, Sample parameters were manually fed into the system which could be prone to error and result in lack of validated data.

Another Laboratory equipment management system based on RFID technology was developed for colleges and universities [5]. The system was customized to monitor and track laboratory equipment in real time. It was based on RFID technology which is superior over other identification technologies because it is automatic, contactless, has a strong ability to adapt in demanding environments and possesses a high data storage, up to 116 bytes of data. However, RFID implementation costs more compared to barcode.

RFID is among the popular technologies that have been used for identification. A similar study was based on development of a web-based laboratory equipment monitoring system that used RFID technology. The system architecture consisted of an RFID reader, RFID tag, RS232 cable, personal computer and a Local Area Network Hub. RFID was tested to be 100% accurate in terms of real-time data capture of outbound and inbound equipment in the database. However, a passive RFID tag with an operating frequency of 125 kilohertz (kHz) was used. Its limitation is short response distance and the metal shield in the RFID tag can block and interfere with the electromagnetic field produced by RFID reader, thus preventing the tag from being read [6]

In a different study, a system to manage the maintenance of equipment was developed based on mobile 2-dimensional barcode and RFID technology. In the study, it was demonstrated that both RFID and barcode systems can be used on the same equipment. Both 2D barcode and RFID technologies store and provide information. However, RFID tags are easier and faster to read compared to 2-dimensional barcodes. In terms of cost, 2-dimensional barcodes are cheaper than RFID [7].

Another RFID system was developed to manage and track students' experiments. RFID was selected over other technologies such as magnetic cards due to being contactless, robust, high data reading speed, being user friendly and ability to read multiple tags simultaneously [8].

RFID technology has also been employed in the development of library system for automating activities related to borrowing, renewal and return of books. The system employs GSM technology to alert the users on the return due date. The system is efficient in terms of speeding up the processes of searching, borrowing and returning books. However, users cannot access the system remotely [9]

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Recent studies are focused on RFID technology due to its superior features over other identification technologies in terms of long response distance range, longer life-span, reusability and robustness. In the reviewed studies, the systems were implemented to be accessed locally when a client is in the same Local Area Network (LAN). Based on functionality, the studies focused on majorly laboratory equipment and not management of samples, reagents and research analysis.

This study therefore was carried out to bridge the gaps identified in the previous works.

3.0 MATERIALS AND METHODS

3.1 Study Area and Scope

This study was carried out in the United Republic of Tanzania, whereby the Nelson Mandela African Institution of Science and Technology (NM-AIST) was used as a case study. The scope entailed the development of a web-based Smart Laboratory Information Management System and integration with Radio Frequency Identification (RFID) for tagging samples as well as an Internet of Things (IoT) module for real-time monitoring of sample storage conditions (Humidity and Temperature).

3.2 Data Collection Method

Primary data was collected from laboratory staff, Management and researchers using group discussions, observation and face to face interviews. Secondary data was collected from policy documents, journal articles, research reports, articles, websites and white papers.

3.3 System requirements

The system requirements were categorized into Software requirements as well as Hardware requirements. The software requirements were tabulated as represented in Table 1.

Table 1: Software requirements

Software	Purpose
STM32CubeProgrammer	Flashing Boot-loader application on STM32F103C8T6 Microcontroller
Digi XCTU Software	For Configuring the XBee S2C radio Modules.
Draw.io	Modeling the UML diagrams for the system.
Visual Paradigm 16.3	Modeling the entity relationship.
KiCad 5	Printed Circuit Design and simulation.
Visual Studio Source Code editor	Writing PHP, HTML, CSS and JavaScript code.
Arduino IDE	Writing sketches for the ESP32 Microcontroller.
MySQL	Database design and queries.
Apache	Http server.
ThingSpeak	Cloud for aggregating and visualizing sensor data from Internet of Things hardware devices.
Twilio	Communication API platform for sending SMS notifications.

Hardware requirements on the other hand were captured as represented in Table 2. XBee S2C modules were selected due to their range of more than 60 metres when indoors and up to 1200 metres when outdoors, with a data rate of up to 250,000 bits per second. They operate using IEEE 802.15.4 wireless protocol within the Industrial Scientific and Medical frequency band (2.4 Gigahertz-2.5 Gigahertz). Communication peripherals include Serial Peripheral Interface (SPI) and Universal Asynchronous Receiver-Transmitter (UART) interfaces [10].

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Table 2: Hardware requirements

Hardware	Model
Programmer	ST Link V2 Mini Programmer
ZigBee Wireless Module	XBee 6.3mW wire Antenna Series 2C (ZigBee Mesh)
XBee Adapter	Funduino XBee USB adapter
Microcontroller Boards	ESP32, STM32F103C8T6
RFID Reader and Tags	RC522 13.56 MHz S50 Mifare one
Liquid Crystal Display	1602 LCD Display
I2C Display interface adapter	PCF8574
Temperature Sensor	AM2302 Wired DHT22 Temperature Humidity Sensor
Buzzer	Piezzo Buzzer
LED	Standard 5mm LEDs
Prototyping Boards	PCB Copper Vero Boards
Power Supply	3.7V Lithium rechargeable batteries
Step Down converters	DC-DC Buck converters LM2596
Toggle Switch (Two Pin)	117S 125V / 6A

The study's proposed ZigBee topology is as illustrated in Fig.2, consisting of router nodes and a coordinator node.

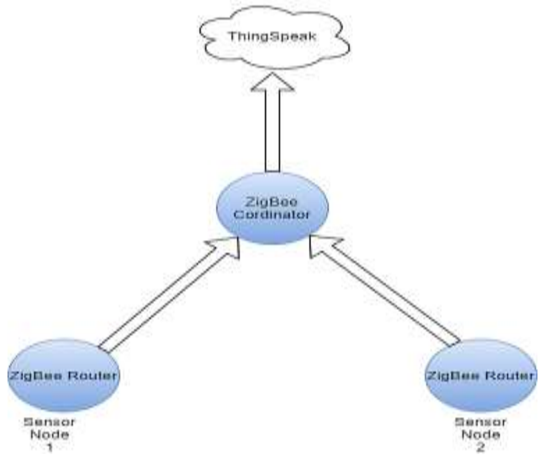

Figure 2. ZigBee network topology

3.3 System Development Approach

Agile Software development methodology was adopted in the development phase of this study due to the short development cycles in terms of iterations as well as integrated testing throughout the entire lifecycle of the project. Extreme Programming (XP) was particularly used due to its ability to speed up development within the limited time-frame of three months and its emphasis on producing high quality software ensuring the small team has a high quality of life.

3.4 System Design

The design framework consisted of a web-based application integrated with an Internet of Things Module, made up of a wireless sensor network and ThingSpeak Cloud as well as Radio-Frequency Identification module. The wireless sensor network was responsible for collection of data regarding sample and reagents storage conditions mainly temperature and humidity. The overall system architectural design is represented in Fig.3. XBee S2C modules were integrated with STM32F103C8T6 microcontroller boards and AM2303 temperature humidity sensor to form sensor nodes. Each sensor was configured to transmit both temperature and humidity values as bytes to a coordinator XBee module connected to an ESP32 microcontroller. The ESP32 Microcontroller was configured to convert the temperature and humidity from bytes to float values and then transmit to ThingSpeak cloud using Wi-Fi. The Smart Laboratory Information Management System Web application was configured to fetch the temperature and humidity graphs for each node from the cloud using an application programmable interface provided by ThingSpeak cloud.

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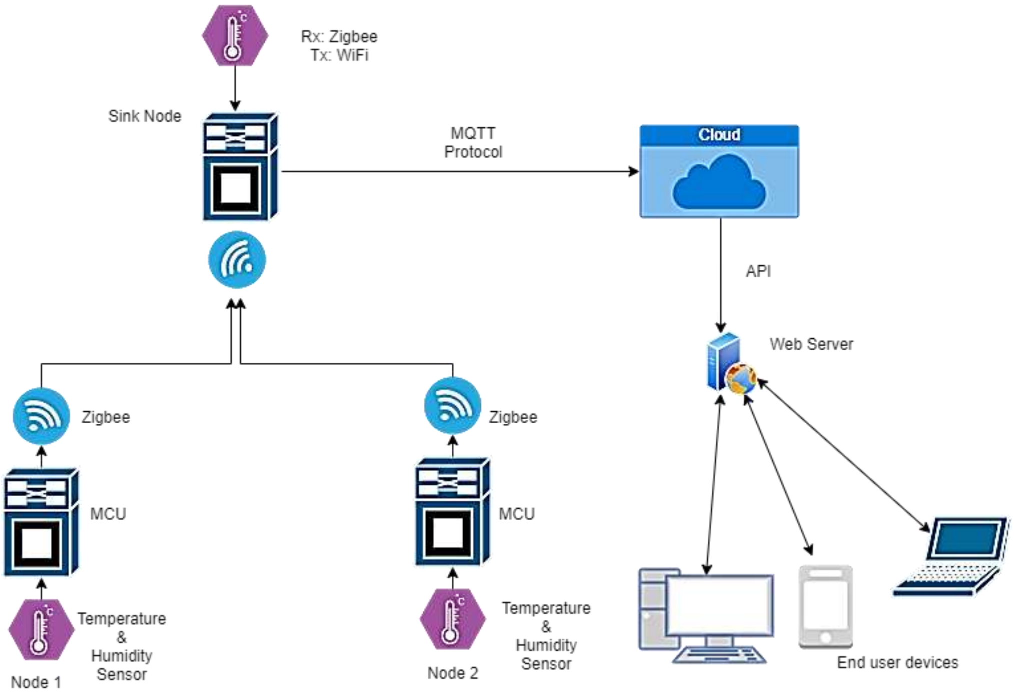

Figure 3. System Architecture

Requirements were modelled using Unified Modelling Language. Initially, the gathered requirements were modelled into a use-case diagram, with the main actors being the Laboratory Manager, Quality Assurance Officer, Laboratory staff categorized as Heads of Sections, Laboratory Engineers as well as Laboratory Scientists. Fig.4 represents the modelled use-case diagram.

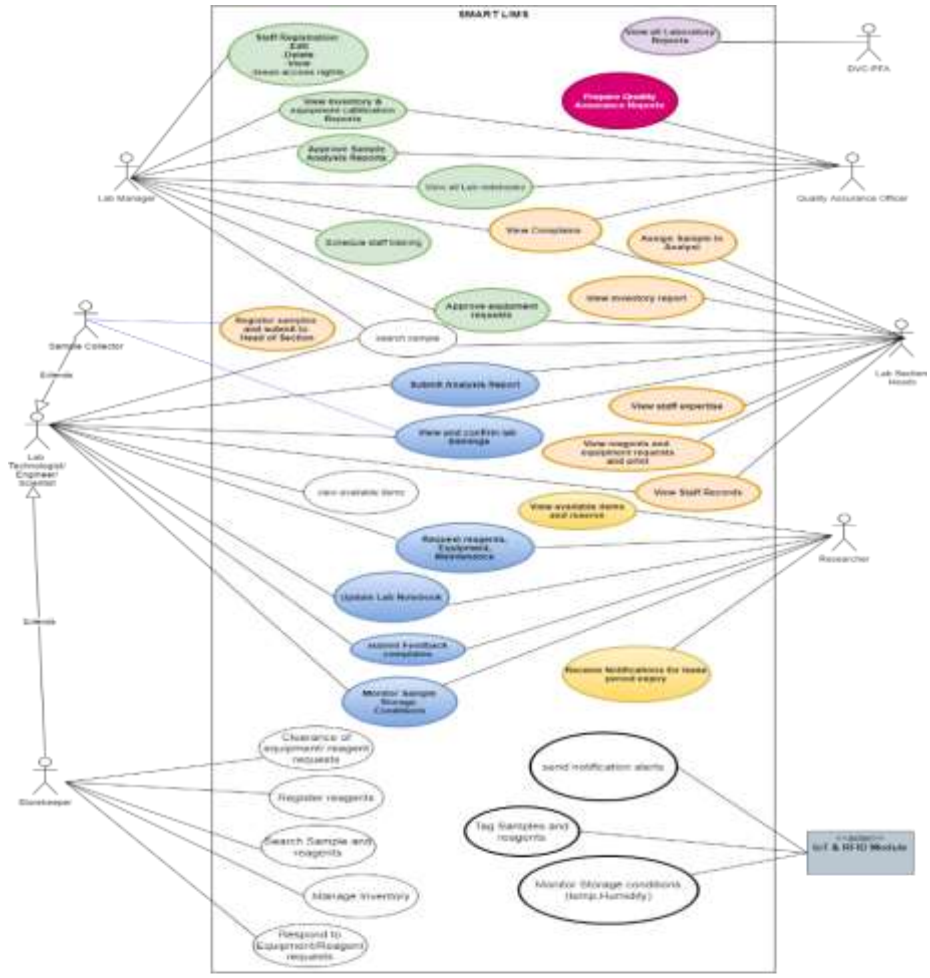

Figure 4. Model Use-Case diagram of the System

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Activity diagrams were modelled to represent the different activities within the system. Fig.5 represents the sequence of activities involved in user log in.

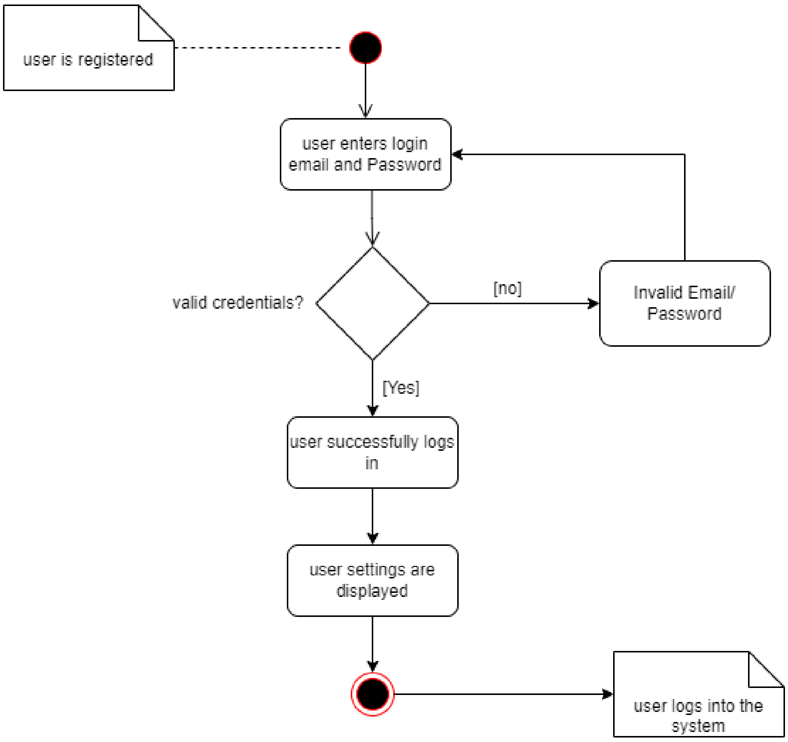

Figure 5. User Log in activity Diagram

After successful log in, there are different activities a user can perform depending on the level of access. Fig.6 represents the activity diagram for requesting reagents.

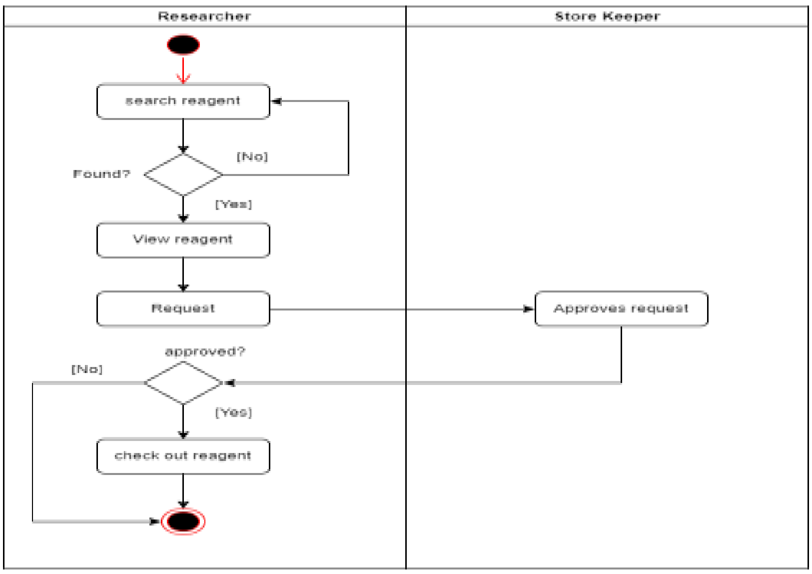

Figure 6. Reagents Request Activity Diagram

3.4.1 Simulation

The hardware prototype design was first simulated using software, mainly Fritzing and KiCad. The simulation results enabled the actual hardware implementation to minimize risk of errors as well as hardware fault which bears cost implications. Fig.7 represents the design of the sensor node as captured using fritzing software.

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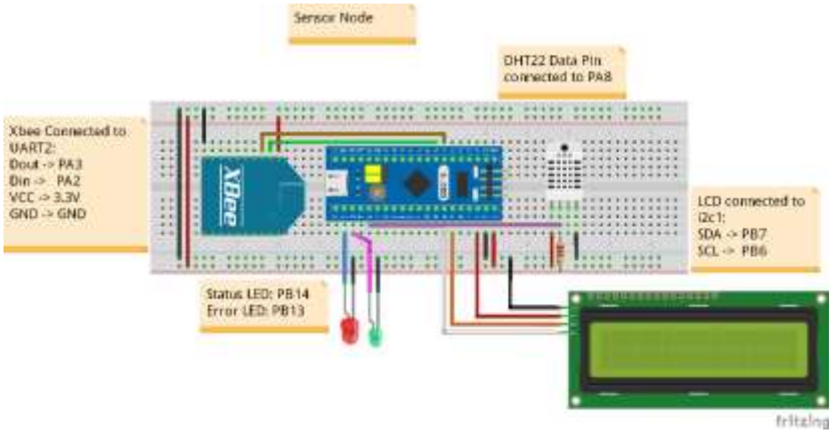

Figure 7. Senor node design using Fritzing

The sensor node design as represented in Fig.7 was replicated to produce two sensor nodes. Additionally, the coordinator node using ESP32 microcontroller was designed as captured in Fig.8.

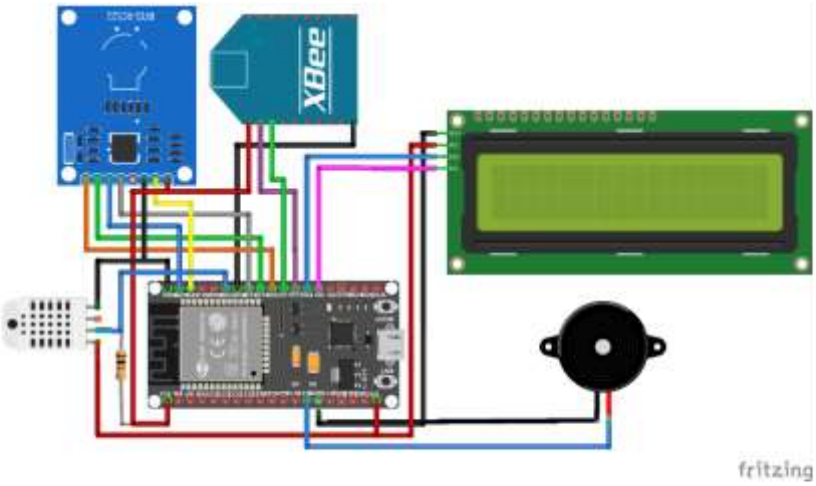

Figure 8. Coordinator Node design using Fritzing

After experimental set-up was tested using breadboards as presented by fritzing diagrams in Fig.7 and Fig.8, the circuit schematic design and Printed circuit Board were designed using KiCad software version 5. KiCad was selected because it is open source and has all the full features of a professional computer aided design tool, ranging from schematic capture, printed circuit board (PCB) layout to 3-dimensional modelling and visualization of the mechanical version of the circuit board, all free to use, and supports multiple operating systems platforms, whether windows or Linux. Fig. 9 illustrates 3-dimensional model of the final printed circuit board for the sensor nodes.

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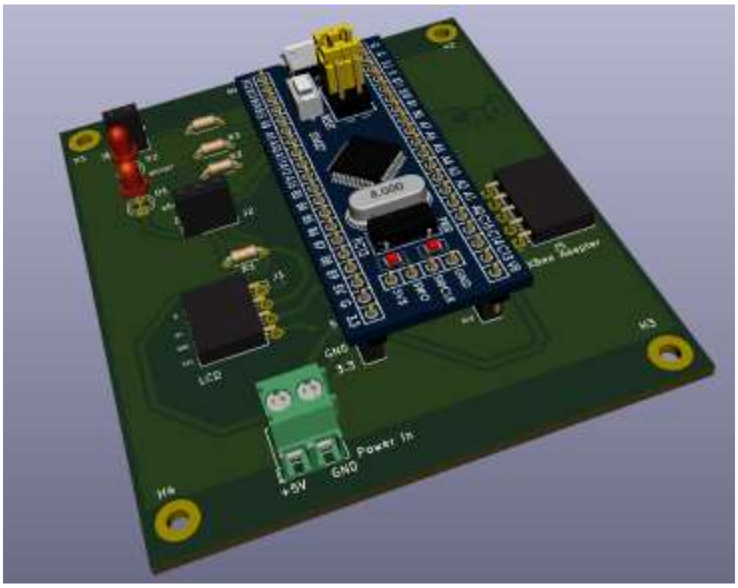

Figure 9. 3-dimensional model of the sensor node circuit

4. RESULTS AND DISCUSSIONS

A web application integrated with hardware for storage conditions monitoring as well as sample registration and tracking was developed.

4.1 Web Application

The Web application consisted of a log in page where users first log in. However, the admin is required to add users and give them specific privileges and access levels within the system. The log in page as illustrated in Fig.10, requires a registered user email address and a password in order to grant access.

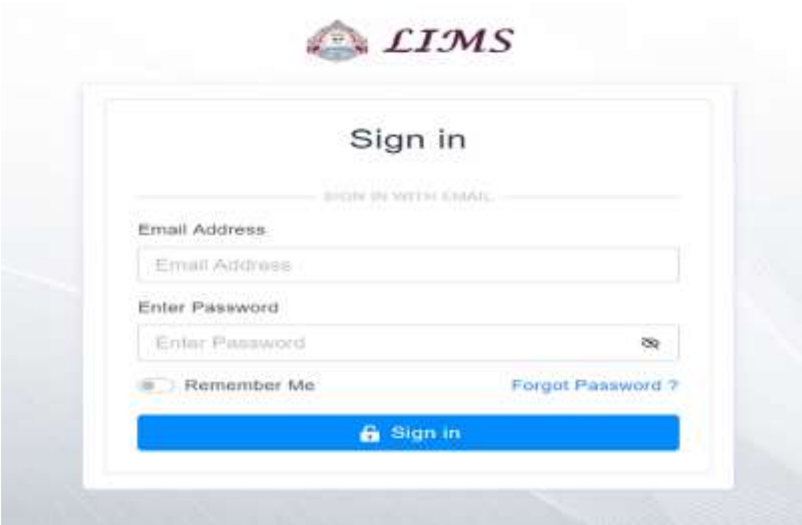

Figure 10. User Log in Page

In addition to the Log in page, a dashboard was added as illustrated in Fig. 11, where an authorized user can see an overview of the total number of samples analyzed and even revenue collected.

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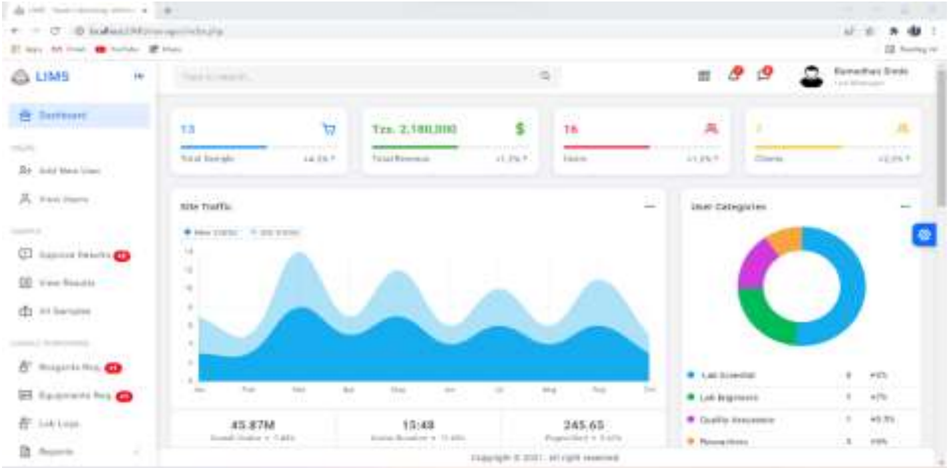

Figure 11. Analytics Dashboard view

A sample registration page was also added as shown on Fig. 12, where sample parameters are recorded and attached with an RFID tag with a unique identifier, after scanning. Details of the sample can later be retrieved by simply placing the sample close to the RFID reader. Each sample is tagged to a particular storage unit that has an identifier in the system.

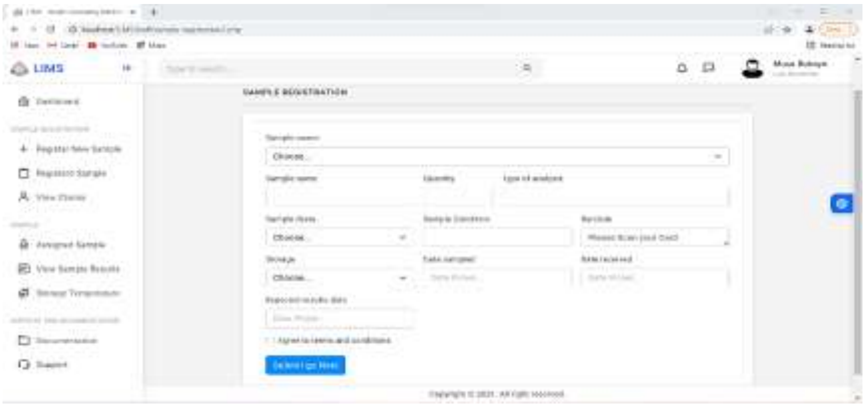

Figure 12. Sample registration page

The storage units are constantly monitored by a wireless sensor node for each storage unit. The parameters monitored are Temperature and Humidity. This information was made available to a user using real-time graphs as illustrated in Fig. 13, generated from the data sent by the wireless sensor nodes.

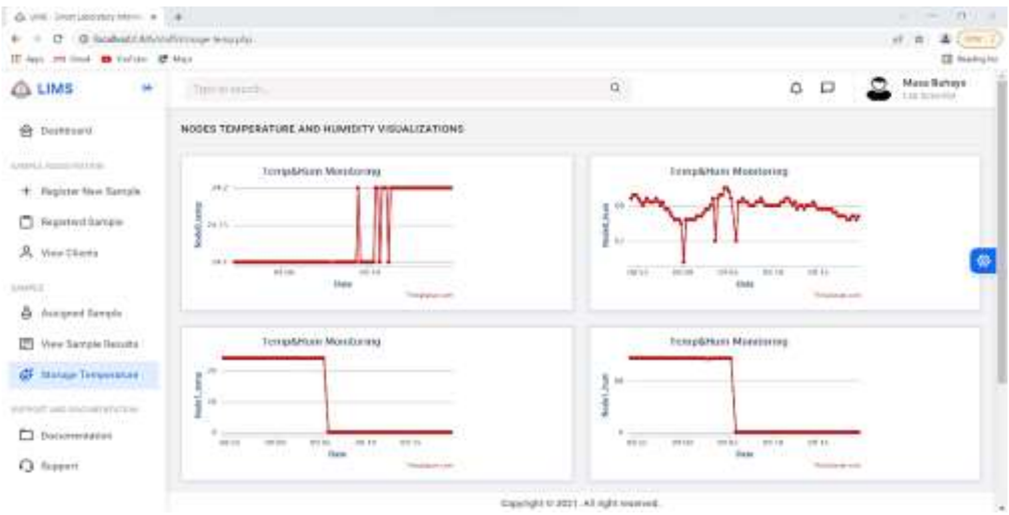

Figure 13. Storage conditions monitoring page

Twilio Software was integrated with the system to provide message alerts when temperature or humidity thresholds of the storage conditions are exceeded. Fig.14 shows a sample message alert as received on a staff's mobile phone.

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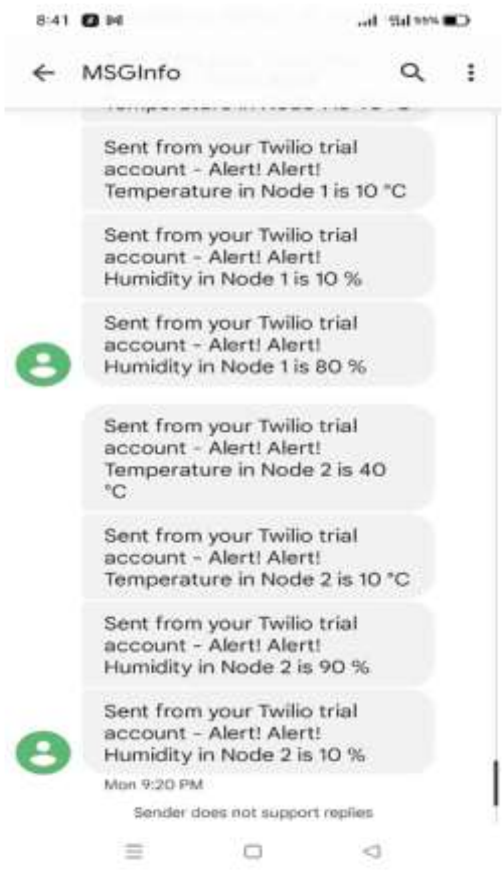

Figure 14. Twilio Message alert on a mobile phone

4.2 Hardware Subsystem

The hardware part of the system consisted of two main sections. The first section was a coordinator node as illustrated on Fig.15 and Fig.16, consisting of an ESP32 Wi-Fi based microcontroller, XBee coordinator module and an RFID reader. This module was responsible for receiving temperature and humidity data of the storage units and transmitting to the cloud. The RFID reader was responsible for tagging samples with a unique RFID identifier to simplify sample registration and tracking.

Figure 15. Coordinator Node external view

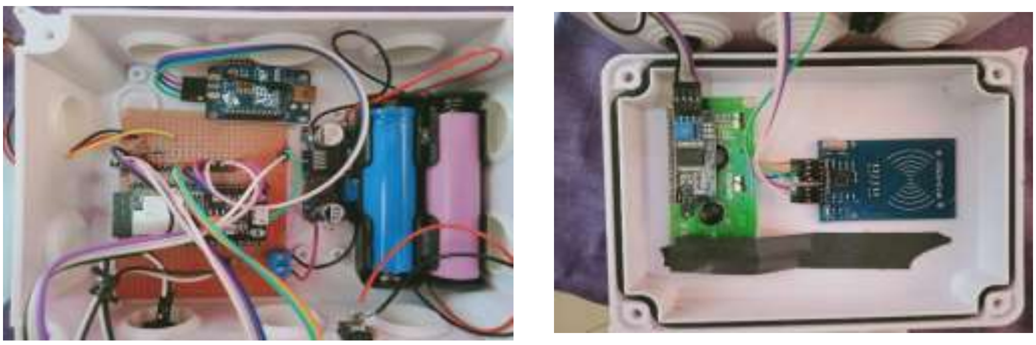

Figure 15. Coordinator module internal view with RFID reader (right)

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The second hardware section consisted of the sensor nodes as illustrated by Fig.17, developed by integrating STM32F103C8T6 Microcontroller ("Blue-pill") with XBee router modules, Liquid Crystal Display module, AM2303 Temperature Humidity sensor, Lithium Polymer rechargeable battery cells and DC-DC buck converter module for stepping down the 7.4 Volts (V) from the batteries to 5 Volts (V) required by the microcontroller board and sensors.

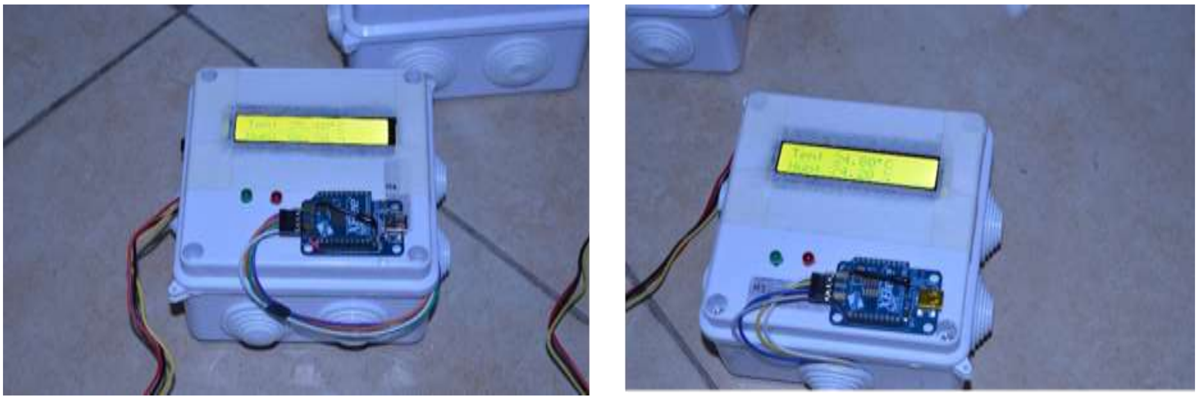

Figure 16. Wireless Sensor Nodes

4.3 Discussion

The system was validated by issuing a user acceptance survey of which six participants from the laboratory department answered. The six participants found the system useful in the streamlining of laboratory information and aggregation of laboratory data on a single platform. On average, when asked to rate the system on a scale of five, all participants rated the system with more than four out of a possible five as presented in Fig.18. With anticipated growth in research capacity in East Africa and the world at large, there is need for Testing Laboratories to digitize their operations and automate tasks as much as possible to increase efficiency and save on operational cost and time. In this advent of Internet of Things, there is room for automating nearly all activities by employing the sophisticated technologies that are advancing every day.

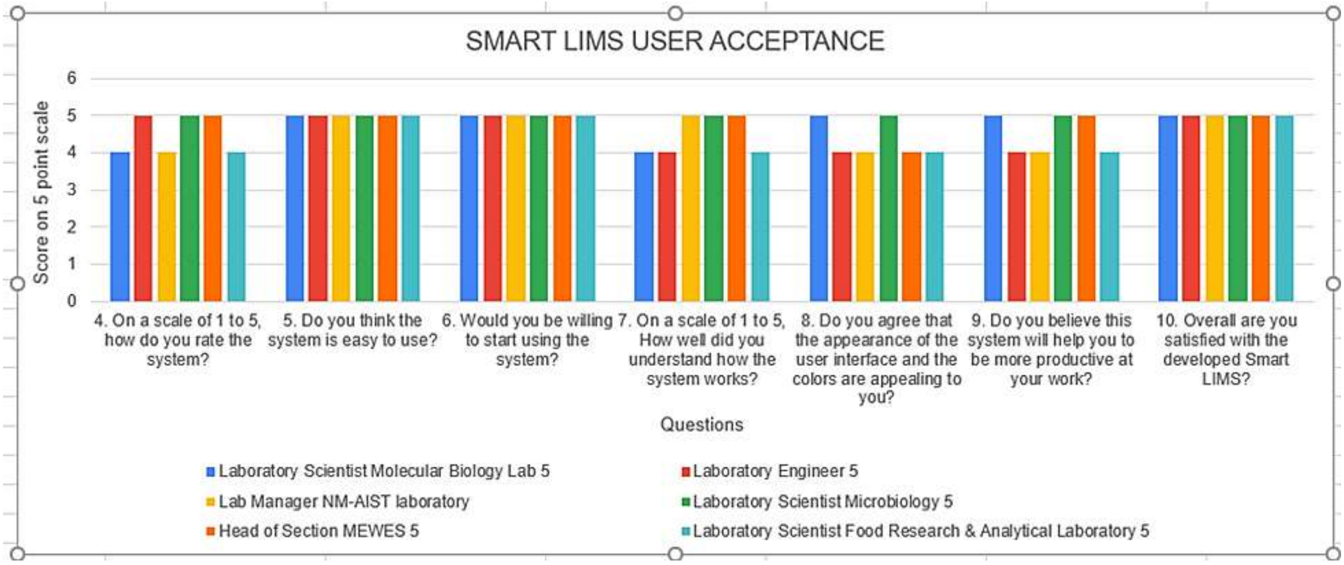

Figure 17. Summary results from the user acceptance survey

5. CONCLUSION AND RECOMMENDATION

The main objective of this study was to investigate the development of Smart Laboratory Information Management System, by integrating RFID technology with Internet of Things and a Wireless Sensor Network. A web-based application was developed and integrated with a hardware module consisting of the Wireless Sensor Network and an RFID module. The system was configured to provide real-time notifications regarding sample storage conditions. Customization was done to enable remote accessibility to the system. The developed system was tested with Laboratory staff at the Nelson Mandela African Institution of Science and Technology. The option for generating reports was included to enable the Laboratory manager to view, generate, print and sign result reports after first level approval by junior staff. Based on the performance test, it is concluded that, Wireless Sensor Networks can be integrated with Internet of Things to automate recurring tasks in laboratories, aid in monitoring and eliminate paper-based record keeping. Using the Smart LIMS, researchers can plan research activities.

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In future, this work can be improved by increasing the number of sensors to detect more parameters such as fire, light intensity and toxic gases. Also, a theft detection module can be integrated to monitor intrusion and outbound equipment from the laboratories. Machine learning algorithms can be used to analyze the number of experiments and sample analysis carried out periodically and even predict revenue or forecast expected number of samples for analysis. A payment module can be added to facilitate real-time processing of payments by external clients for analysis without the need for them to physically visit the offices. This work can also be extended to other Testing laboratories in other sectors such as Health, Agriculture as well as consumer industries. If the Laboratory sections are located far apart from each other, alternative low power wireless communication technologies should be considered such as Long-Range Wide Area Networking protocol (LoRAWAN), SIGFOX etc.

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