Design and Prototyping of a Remote Livestock Monitoring Device for Low-Resource Settings

Mwango M. Makumba
Dept. of Electrical and Electronic Engineering
University of Zambia
Lusaka, Zambia
mwangomakumba@outlook.com

Joseph C. Moya
Dept. of Electrical and Electronic Engineering
University of Zambia
Lusaka, Zambia
josephcmoya670@gmail.com

Daliso Banda
Dept. of Electrical and Electronic Engineering
University of Zambia
Lusaka, Zambia
daliso.banda@unza.zm

Kangwa E. Mukuka
Dept. of Computing and Informatics
University of Zambia
Lusaka, Zambia
kangwa1mukuka@cs.unza.zm

Abstract*—The agricultural sector is one of the beneficiaries of technological advancements. Innovative solutions help address challenges and improve efficiency. Some of the challenges include too much time spent on physical monitoring, nutrient depletion due to grazing on specific patches of land, and the loss or theft of livestock. One solution is the implementation of real-time location and health monitoring of livestock. This paper explores the development of a low-cost functional GPS-based tracking device facilitated by in-house PCB manufacturing. The device was designed to integrate an ESP32-S3-WROOM-1 microcontroller, a Quectel LC86G GNSS module, and an MPU-6050 accelerometer. The microcontroller chosen enabled efficient, low-power, peer-to-peer communication in a network, eliminating the need for cellular infrastructure. The PCB was designed using KiCad and developed using the Dry Film Photoresist Method. Field testing demonstrated a reliable communication range of approximately 210 meters between two sensor nodes, thus validating the system's ability to track animal movements and patterns. This prototype demonstrated the potential of locally built, cost-effective IoT solutions in promoting Precision Livestock Farming, thus enhancing livestock welfare. It demonstrated the capacity to produce a Minimum Viable Product specifically tailored to the needs of rural and underserved communities, thus promoting inclusion in the technology revolution.

Keywords*—Printed Circuit Board (PCB), Global Positioning System (GPS), Internet of Things (IoT), Precision Agriculture (PA), KiCad.

I. Introduction

Many communities in the world, and particularly in Africa, have agriculture as a backbone for survival. Livestock production plays a very important role, and over 70% of Africa's agricultural land is dedicated to grazing [1]. However, this practice doesn't go without challenges. One way to address the challenges faced is through the integration of smart solutions into livestock management systems, and in our case, described in this paper, leveraging GPS technology and PCB manufacturing to enable remote livestock management.

Through research, it has been highlighted that the inefficiencies and challenges faced by farmers in monitoring their livestock lead to wasted time, reduced productivity, and decreased overall efficiency [2]. There are several limitations with the current physical monitoring approach which include limited visibility, nutrient depletion, animal loss or theft, seasonal challenges and being a time-consuming process. With these challenges in place, it becomes more difficult to have time for alternative agricultural activities.

Another aspect addressed within this project is an attempt to bridge the technological gap that exists with local innovation. By bringing the manufacturing of electronic devices within Zambia, this would promote the development of skills and build capacity within the local populace. This translates to the creation of job opportunities, thus empowering local communities. The majority of already existing electronic products have many functionalities, which make them expensive. Nonetheless, a minimum number of features may be needed in some cases to still produce good results. In order not to leave behind poorer communities in technological advancements, this project aims to build a minimum viable product that can work well and, once mass-produced, overcome overhead costs.

Livestock industries in developing countries lack the technology that can directly impact meat and dairy products, where human resources are a major factor [3]. The project has the potential to realize some of the Sustainable Development Goals (SDGs), with a focus on ending poverty and hunger by providing an inclusive solution for all communities and by promoting sustainable agriculture. Additionally, by promoting sustainable industrialization and fostering innovation through the building of resilient infrastructure [16].

II. Literature Review

The monitoring of livestock can broadly be categorised into two main sub-units, namely, non-electronic and electronic identification. This study will primarily focus on the electronic aspect of livestock monitoring [4]. Previous work showcases the design and implementation of individual devices, while others follow a hybrid system that comprises the integration of two devices: GPS collars connected to an LPWA network and low-cost Bluetooth low energy (BLE) tags connected to those collars [5, 6].

B. R. Stojkokska et al, present a conceptual design of the architecture for real-time wireless tracking based on the IoT. They describe the generic system architecture as three main building blocks: the sensor side (nodes organised as a Wireless Sensor Network), the server side (cloud that performs data aggregation and processing), and the client side (end users' computers or smartphones). GPS sensors are used to obtain location data that is transmitted to the base station (cloud) in real time. Not all devices in the WSN have GPS or wireless communication modules, so the data collected by the enabled nodes is propagated through the network via the nearest equipped neighbor until it reaches the cloud. RF over GSM transmission is chosen, eliminating the need for cellular infrastructure and data for SIM cards. In addition, the integration of watertight solar panels makes the device self-sustainable as it is capable of generating enough power to supply the device even after no sunshine for a week [7].

In this smart livestock monitoring system [8], the writers highlighted energy supply and network connectivity constraints. Lack of communication infrastructure in rural/farming areas brings out the need for a low-power localization and monitoring system. They implemented an IoT-based system integrating Low-Power Wide Area (LPWA) technology, cloud, and virtualisation services to provide real-time livestock location monitoring. Radio coverage of cellular communication is not guaranteed everywhere, so alternative communication is required. LoRa and LoRaWAN, low-cost, low-power technologies, were identified as the most suitable connectivity solutions.

In order to enable remote monitoring, an accelerometer can be used. These sensors have the ability to record three-dimensional movement. In a case study done by Sara C. Gurule et al, they have been used to detect parturition in sheep, as well as monitor grazing, rumination, and drinking behaviour in cattle [9].

Following the success of Arduino and RepRap 3D printers, it has been demonstrated that Open-Source Hardware can be financially viable even in highly competitive markets [10]. The Espressif Systems ESP32-S3-WROOM-1/1U modules represent a high level of microcontroller technology, well designed for the demands of Artificial Intelligence (AI) and IoT applications. These modules are built around the ESP32-S3 series of SoCs, whose features include a powerful Xtensa dual-core 32-bit LX7 microprocessor clocked at up to 240 MHz. With integrated support for 2.4GHz Wi-Fi (802.11 b/g/n) and Bluetooth 5 (LE), these modules provide a very good solution for wireless connectivity and sensor networks [11]. KiCad, the PCB software of choice, has gained traction as a replacement for proprietary software such as Eagle due to its community, continuous support, libraries, and growing ecosystem. It has a minimum system requirement and runs on Linux, Windows, and macOS [12]. Proper design of PCBs is vital to ensure compliance with industry standards [13]. However, there is a huge gap between the skills taught to students during their academic lifetime and the skills needed in industry. Kurtay [14] argues that PCB design skills are especially relevant if soon-to-be graduates are seeking hardware-related jobs. Apart from making the students attractive to potential employers, PCB design can provide a more enriching experience through the period of study.

III. Proposed Methods

A. Design Steps

At the core of the Remote Livestock Monitoring Device is the PCB that is the foundation of the IoT Sensor Node. The IoT Sensor Node was powered by a Lithium-Ion Battery, and the power supply was managed by two low-dropout regulators (LDOs). One LDO powers both the Microcontroller Unit (MCU) and the MPU-6050, while the other LDO solely powers the GPS module and can be turned on/off by the MCU via Digital I/O, as highlighted in Fig. 1. The IoT sensor node wirelessly communicates with the sensor gateway.

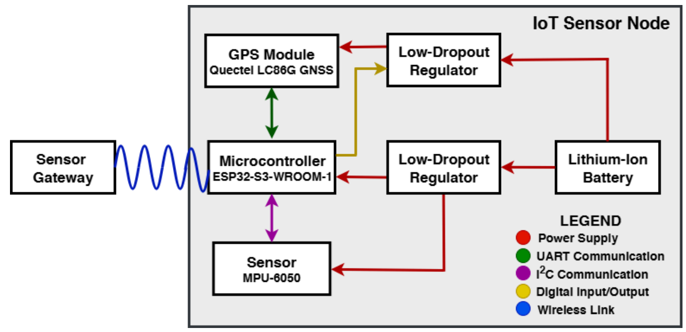

Fig. 1. System overview of the device showing Sensor Gateway and IoT Sensor Node and the various links among the sub-units within the Node.

The schematic in Fig. 2 highlights the design of the power conditioning, GPS, MCU, and Basic Peripherals, and a provision for the Accelerometer to be added to the closest GPIO pins.

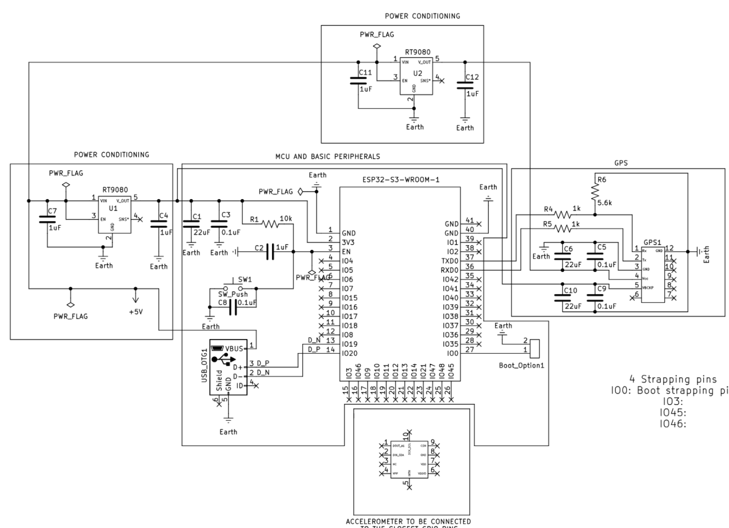

Fig. 2. Complete schematic design of the Printed Circuit Board.

Additionally, the PCB layout was designed outlining the different layers that comprise the sensor node. The red lines and blue lines symbolize layers 1 and 2, respectively.

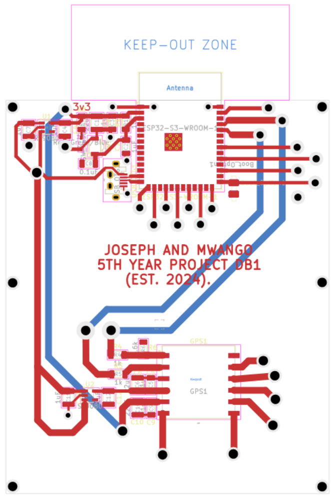

Fig. 3. PCB layout of device designed with KiCad.

B. Component Selection

To develop a low-cost, low-power, and efficient device, we focused on components that were in line with these targets. We made sure that the chosen components were suitable for our desired feature before adding them to the design. Table I lists some of the components purchased from Mouser Electronics.

TABLE I. Bill of Materials (BOM)

No.	Component Name	Qty	Unit Price
1.	ESP32 MCU (ESP32-S3-WROOM-1)	1	$3.35
2.	GPS Module (LC86GLAMD)	1	$12.13
3.	Accelerometer (MPU6050)	1	$1.49
4.	Voltage-Regulator (RT9080)	1	$0.65
5.	LG Li-ion Cells (INR21700)	1	$6.00
6.	Auxiliary Components (Bulk Purchase)	-	$10.00
	TOTAL		$33.62

The ESP32-S3-WROOM-1/1U modules possess robust processing capabilities and boast impressive memory resources, including up to 16MB of flash memory and 8MB of PSRAM. This abundance of memory facilitates the execution of complex AI algorithms and the storage of large datasets. Furthermore, with 36 General Purpose Input/Output (GPIO) pins and a wide range of peripherals such as UART, SPI, I^2C, and I^2S, these modules offer extensive flexibility for interfacing with external devices and sensors [11].

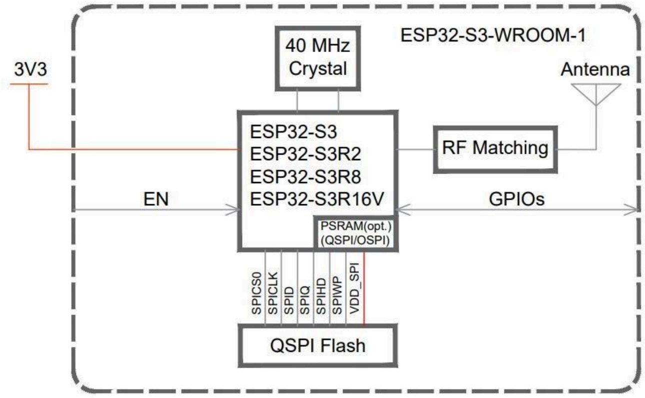

Fig. 4. Block Diagram of ESP32-S3-WROOM-1 [11].

C. PCB Development

The typical workflow in KiCad consists of two main tasks: drawing a schematic and laying out a circuit board. KiCad comes with a large library of high-quality, user-contributed symbols and footprints, but it is also simple to create new symbols and footprints or modify existing symbols and footprints.

The schematic and PCB layout were done using KiCad software. The process started with designing a circuit to meet the basic operational requirements for the ESP32-S3-WROOM-1 microcontroller unit, then later on adjusted to integrate with the GPS module. Design Rule Check was used to make sure electrical standards were met. In the PCB editor, PCB dimensions and layers (2) of the board were added, components were placed, and traces were routed. Copper traces and ground planes were added, and Design Rule Check was done.

The KiCad files were saved and local manufacturing of the board using the UV Resist Dry Film Method commenced. This method included:

1. **Dry film lamination**: A dry film was laminated onto a clean copper substrate.
2. **Exposure**: The substrate was exposed to ultraviolet (UV) light through a transparent material that contained the desired pattern (PCB layout).

$$t = \frac{E}{P} \tag{1}$$

where, t is exposure time in s, E is exposure energy in mJ/cm^2 , and P is the power intensity of the UV light in mW/cm^2.
The exposure period was calculated and set to 14 seconds from an E of $35mJ/cm^2$, the device featured a power of $2.5mW/cm^2$.
3. **Developing**: The exposed resist was then developed in a Sodium carbonate solution, revealing the pattern

of interest. This had to be carefully done to avoid under/overdeveloping.

4. **Etching:** Using an etching tank, the undesired parts were removed from the board.

Component placement was also done locally under a microscope, and a reflow oven was used to solder components onto the pads. Using the Arduino IDE, the basic functionality of the developed board was tested with a simple code to blink a Light-Emitting Diode (LED).

IV. Results And Findings

The collection of data and results started from the design process. This is because a comparison had to be made between the desired (design) and the actual developed printed circuit board. This also helped us to keep a clear roadmap of the whole process from design to a working prototype.

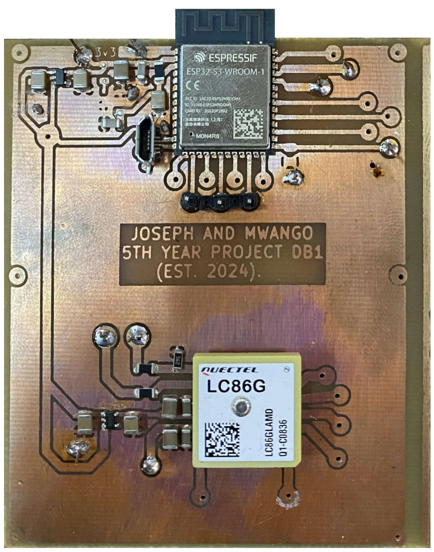

Fig. 5. IoT sensor node used in the remote monitoring device.

Once the firmware was finally developed, two students went out and tested the device's complete functionality. The tests done were initial tests on the Quectel LC86G GNSS module, tests on the communication and transmission range using ESP-NOW protocol, and tests on the accelerometer functionality. We used Quectel's QGNSS evaluation software, which provided us with a quick and simple way to interface with the Quectel LC86G GNSS module.

For the ESP-NOW communication, we conducted the tests outside the University of Zambia School of Engineering Main Building. One student stayed in a stationary position and had a module acting as a receiver while the other student moved away with the module acting as the transmitter. The student with the transmitter kept walking away until a point where the communication ceased. The distance between the two was calculated to be a communication range of 210 meters line-of-sight as shown in Fig. 6 below.

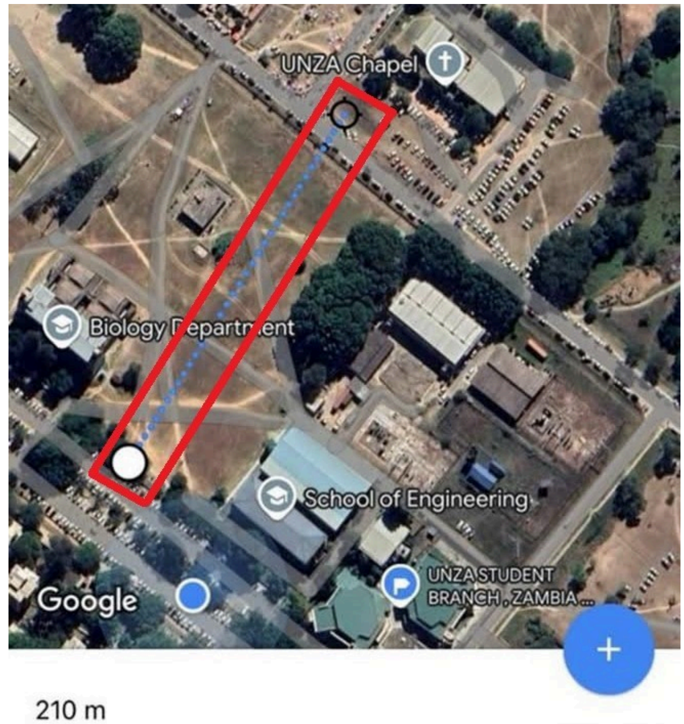

Fig. 6. Communication range line-of-sight, highlighted by the blue dashed line in the red frame, as shown in Google Maps. Source: © Google Maps, 2024. Map data ©2024 Google. Used with permission under Google Maps/Google Earth Terms of Service.

V. Discussion

The main focus of our project was to locally design and prototype a GPS-based livestock tracking device. This was aimed at enhancing livestock management tailored for specific needs, and also promoting local innovations.

In order to come up with a functional device, we had to perform electrical and design rule checks. A minimum track width of 0.2 mm was implemented. For most tracks, a track width of 0.5 mm or 0.75 mm was used. Adjacent traces had to be kept at distances of not less than 0.2 mm. Provisions for decoupling capacitors had to be placed close to the MCU, the GPS module, and the voltage regulators as we designed the PCB layout. This helped us to avoid voltage fluctuations, which can cause the MCU or GPS module to be stuck in a bootloop. Long traces, except for the power supply to the LDOs, were avoided as these could have induced inductances in the tracks, which would have led to undesired voltage drops. For the power supply from the battery, the traces had to have a bigger track width of up to 1.5 mm in order to make them suitable for relatively high current. Eventually, we successfully managed to print out our design onto a transparency film, awaiting the hardware/manufacturing process.

We made sure the design aligned with what we could achieve with the resources available. For example, traces of width less than 0.2 mm had to be avoided because they were getting washed away during etching, vias had to be at least the size of the drills we had, number of PCB layers was limited to

2, very small components that were difficult to place by hand had to be avoided if slightly bigger options were available, etc.

Functionality was first tested using a simple code to blink an LED, then a more complex code was uploaded. The MAC addresses of the prototypes played an important role in the communication using the ESP-NOW Protocol. These would eventually be used to uniquely assign tags to livestock and differentiate the source of transmitted data. In comparison to an expected 200 meters communication range outlined by the Espressif, a communication range of 210 meters (line of sight) was achieved. Environmental factors had an influence on the communication range. For example, tests conducted in places with obstacles resulted in communication ranges less than 210 m and more failed data delivery attempts between the two prototypes used.

It is worth noting that the cost can further be reduced by carefully selecting more affordable components with less specs since no complex AI algorithms or large datasets were implemented/used. Bulk purchase of components can also reduce the overall cost per unit.

VI. Conclusion And Future Work

At the ranch scale, the integration of sensor technology, including on-animal sensors, environmental monitoring equipment, and remote sensing, can shift livestock operations from a solely reactive, traditional, knowledge-based approach toward a proactive, data-driven decision-making process.

Leveraging data from sensors at the ranch scale can address logistical challenges and create efficiency in decision-making processes concerning resource management.

Future work and more recommendations include integrating additional sensors for environmental monitoring, developing AI-based algorithms for health monitoring and prediction, exploring energy harvesting for extended device lifespan, such as using the Leach protocol, and conducting large-scale field testing and validation.

Acknowledgment

This work was carried out with the aid of a grant from the UNESCO-TWAS programme, “Seed Grant for African Principal Investigators”, financed by the German Federal Ministry of Education and Research (BMBF). The views expressed herein do not necessarily represent those of UNESCO-TWAS or BMBF.

References

[1] J. M. Schieltz, S. Okanga, B. F. Allan and D. I. Rubenstein, “GPS tracking cattle as a monitoring tool for conservation and management,” African Journal of Range & Forage Science, pp. 173-177, 2017.

[2] S. Nyamuryekung'e, "Transforming ranching: Precision livestock management in the Internet of Things era," Rangelands, vol. 46, no. 1, pp. 13-22, 2024.

[3] J. Arshad, A. U. Rehman, M. T. B. Othman, and M. Ahmad, “Deployment of Wireless Sensor Network and IoT Platform to Implement an Intelligent Animal Monitoring System,” *Sustainability*, vol. 14, no. 10, pp. 6249, May 2022

[4] V. M. T. Aleluia, V. N. G. J. Soares, J. M. L. P. Caldeira, and A. M. Rodrigues, "Livestock Monitoring: Approaches, Challenges and Opportunities," Int. J. Eng. Adv. Technol. (IJEAT), vol. 11, no. 4, pp. —, Apr. 2022.

[5] F. Maroto-Molina, J. Navarro-García, K. Príncipe-Aguirre, I. Gómez-Maqueda, J. E. Guerrero-Ginel, A. Garrido-Varo, and D. C. Pérez-Marín, "A Low-Cost IoT-Based System to Monitor the Location of a Whole Herd," Sensors, vol. 19, no. 10, Art. no. 2269, May 2019. doi: 10.3390/s19102269.

[6] B. Patrick, T. Johnson, and E. Kanjo, "Internetless Low-Cost Sensing System for Real-time Livestock Monitoring," Smart Farming, vol. 1, no. 3, May 2023.

[7] B. R. Stojkoska, D. C. Bogatinoska, G. Scheepers, et al., “Real-Time Internet of Things Architecture for Wireless Livestock Tracking,” *Telfor Journal*, vol. 10, no. 2, pp. 145–150, 2018.

[8] M. O. Ojo, I. Viola, M. Baratta and S. Giordano, “Practical Experiences of a Smart Livestock Location Monitoring System Leveraging GNSS, LoRaWAN and Cloud Services,” *Sensors*, vol. 22, no. 1, pp. 273, Jan. 2022.

[9] C. S. Gurule, V. V. Flores, K. K. Forrest, C. A. Glifford, J. C. Wenzel, C. T. Tobin, D. W. Bailey and J. A. H. Gifford, "A Case Study Using Accelerometers to Identify Illness in Ewes following Unintentional Exposure to Mold-Contaminated Feed," Animals, vol. 12, no. 3, p. 266, 2022.

[10] J. C. Mariscal-Melgar, P. Hijma, M. Häuer, et al., “Exploring Open-Source Software Ecosystems for Hardware Development,” in *Research and Advanced Technology for Digital Libraries*, Springer, 2024, pp. 190–195

[11] E. Systems, “ESP32-S3-WROOM-1/1U Modules Datasheet,” Espressif Systems, 2023.

[12] J.Evans and G. Keeth, “Introduction|8.0|English|Documentation|KiCad,” KiCad,[Online].Available:https://docs.kicad.org/8.0/en/introduction/introduction.html. [Accessed 13 June 2024]

[13] M. Chen and G. A. Rincon-Mora, “Designing and Planning a Printed-Circuit Board (PCB) Prototype,” 2010.

[14] P. Kurtay, “Development of a Printed Circuit Board Design Laboratory

[15] Y. Verbelen, D. Belle, and J. Tiete, “Experimental Analysis of Small-Scale PCB Manufacturing Techniques for Fablabs,” *Int. J. Eng. Pedagogy (iJEP)*, vol. 3, no. S2, pp. 30–39, 2013. [Online]. Available: https://www.researchgate.net/publication/268078465_Experimental_Analysis_of_Small_Scale_PCB_Manufacturing_Techniques_for_Fablabs

[16] J. Ross, Ed., "The Sustainable Development Goals Report 2023: Special edition - Towards a Rescue Plan for People and Planet," United Nations Department of Economic and Social Affairs Statistics Division, United Nations, New York, 2023. ISBN: 978-92-1-101692-1.