IOT FRAMEWORK FOR CATTLE MOVEMENT MONITORING AND GRAZING MANAGEMENT

HENRY JOKE

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DECLARATION

Name: Henry Joke

Student Number: 202304177

I hereby declare that this final year research project is the result of my own work, except for quotations and summaries which have been duly acknowledged.

Plagiarism check: 15 %

Signature:  Date: 29/06/2025

Supervisor Name: Professor Aaron Zimba

Supervisor Signature:

Date:

ABSTRACT

As all cattle producers are interested in export profit and also for the continuity of their herd numbers there is increasing acceptance for the use of the Internet of Things (IoT) technologies-with a focus on monitoring cattle movement and managing pasture access behaviors in this research. GPS tracking, environmental sensors, and gait sensors have been integrated by this framework to provide real-time information on cattle location, environmental conditions, cattle behavior, and grazing patterns. With the help of edge analytics coupled with cloud computing capabilities, farmers have the chance to monitor animal behavior for planning pasture access strategies in addition to optimizing pasture utilization. The proposed IoT Solution sustains a data-driven decision-making process which, consequently, leads to improved productive performance as well as reducing the cost of operations thus improving herd health. Furthermore, Visualization tools are integrated into the framework for quickunderstanding of data by different stakeholders. Consequently, the new approach improves conventional cattle farming techniques. It also becomes green cattle management development meeting climate change and resource scarcity requirements like grazing fields. This adoption increases efficiency and ensures sustainability and reduced cattle theft hence working towards smart agriculture development through Cattle Management IoT Frameworks worldwide.

KEYWORDS:

Internet of Things (IoT), Monitoring, Cattle movements, Grazing management, Smart Collars, Cattle Movement Monitoring, Activity Sensors, GPS Tracking, accelerometer, Real-Time Monitoring, Wireless Sensor Networks (WSN), Livestock Management, Agricultural Technology, Environmental Sensing, MQTT Protocol, Ubidots Platform, Wokwi, Precision Livestock Farming, Gait Analysis, ESP32 Microcontroller, Remote Sensing, IoT in Agriculture, and Sensor Integration

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THANK YOU.

DEDICATION

I would like to take this opportunity to express my gratitude and appreciation to my family, for their unwavering support and encouragement that have facilitated this journey. They have given me confidence in my vision and commitment to cattle farming as well as sustainable agriculture goals. I am very grateful for their understanding during the hours I spent researching and trying to come up with creative techniques among them for any approach on including IoT technologies for enhanced livestock management practices along with environmental monitoring systems. We are looking towards a future where intelligent farming will contribute not only towards increasing production but also conserving mother Earth and her resources.

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LIST OF ABBREVIATIONS

Abbreviation	Full Term
IoT	Internet of Things
GPS	Global Positioning System
WSN	Wireless Sensor Network
MQTT	Message Queuing Telemetry Transport
ESP32	Espressif Systems 32-bit Microcontroller
DHT	Digital Humidity and Temperature sensor
IMU	Inertial Measurement Unit
LED	Light Emitting Diode
HR	Heart Rate
IS	Information System
GUI	Graphical User Interface
Wi-Fi	Wireless Fidelity
ADC	Analog-to-Digital Converter
BLE	Bluetooth Low Energy
RFID	Radio Frequency Identification
PWM	Pulse Width Modulation
PCB	Printed Circuit Board
API	Application Programming Interface
IDE	Integrated Development Environment
ML	Machine Learning
LPWAN	Low Power Wide Area Network
SIM	Subscriber Identity Module

CHAPTER 1
INTRODUCTION

This chapter is an overview of the study on the concepts of IoT framework for cattle movement monitoring and grazing management. The chapter has lucidly provided the backdrop of the study, the rationale, the statement of the problem, the aim, and related specific objectives, research question, scope, and research significance.

1.1 Background to the study

Traditionally, cattle movement monitoring and grazing management relies on manual methods like visual inspection and headcounts, which can be time-consuming, labor-intensive, and prone to theft and human error. These limitations can lead to challenges in optimizing pasture utilization, ensuring animal welfare, and making informed decisions about herd management. [1] The emergence of Internet-of-Things (IoT) technology offers a potential solution by enabling real-time data collection and analysis of cattle movement and grazing management.

The application of the Internet of Things (IoT) in cattle farming has revolutionized livestock management, offering state-of-the-art solutions for enhanced productivity and sustainability in livestock agriculture. IoT-based cattle movement tracking and grazing management systems have increasingly gained significant consideration as they can improve livestock tracking, optimize grazing behavior, and avoid security risks such as cattle theft. Traditional livestock monitoring methods are usually dependent on manual verification and simple monitoring systems, which are less efficient, time-consuming, and prone to inaccuracies. Because of this, there is growing demand for innovative, automated systems based on IoT technologies that provide real-time data regarding cattle behavior and whereabouts [2].

This research aims to bridge a gap through an assessment of the current condition of IoT platforms for grazing management and cattle movement tracking, identification of key technologies, challenges, and limitations. The findings are anticipated to lay an IoT platform by employing smart collars with on-board activity sensors to enable real-time tracking of cattle locations and monitoring of herd populations. This research examines the usability of the framework provided in getting real-time insight into cattle mobility, grazing, and security problems such as theft of cattle.

By utilizing an effective IoT-based monitoring system, cattle farmers can have more effective herd management practices, reduce operational costs, and improve productivity overall. The findings of the current research would contribute to ongoing innovation in precision livestock farming and act as a foundation to further investigate IoT technology applications in agriculture. In short, this research is to trace the technological progress of IoT in cattle monitoring, illustrating on building the proposed model, and estimate its efficacy with data-based driven analysis.

1.2 Problem Statement.

[3] Current cattle monitoring practices predominantly rely on some cumbersome methods of headcounts and ocular observations, which are identified to have a string of significant deficiencies in facilitating appropriate herd management.

One key challenge is that of limited visibility [4]. It is not easy to monitor the location of the cattle and activities over the extended ranges of grazing areas, and these delays have important consequences, such as injuries, calving events, and potential threats from predators. The lack of real-time data, on the other hand, may put animal welfare and overall herd health in jeopardy because not all timely necessary interventions could be foreseen.

Current cattle monitoring and grazing management frameworks have not integrated GPS, wireless sensor networks, and cloud computing within an IoT-based framework that can significantly enhance cattle movement monitoring and grazing management [5]. Integrated systems enable real-time tracking and data-driven decision-making, leading to optimized grazing patterns, improved livestock security, and increased farm productivity [6]. Wearable IoT tracking devices enable continuous livestock monitoring by transmitting real-time location data to cloud-based management platforms, improving efficiency and reducing the risk of loss.

Another key limitation pertains to reliance on subjective decision-making [7] Many of the key cattle management decisions, such as those involving the type of rotation in grazing and the frequency of feeding, are made based on personal experience and intuition. According to [7]management practices can easily become inconsistent without data-driven decisions that can be leveraged to achieve top performance of the herd and efficiency in the use of resources.

Manual practices cannot quantify the grazing pattern or pasture utilization [8], [9]. Inability to quantify grazing patterns and pasture utilization restricts farmers from effectively understanding preferred grazing zones, underutilized areas, and possible areas of improvement in pasture management. This lack of detailed analysis might result in poor optimization of the grazing strategy and hence poor resource use with a probable impact on the health of both cattle and pasture.

These can be very serious and far-reaching consequences of poor cattle monitoring practices, which affect not just herd management but overall farming sustainability. A major implication of this would involve overgrazing-under grazing of pasture. Once uneven grazing distribution occurs because of a lack of close monitoring, portions of pasture may be overgrazed to the state where soil degradation and loss of vegetation occur [9]on the other hand, other areas may not be utilized at all; hence, it will be a waste, which means that it will be less productive. It will affect not only the health of the pasture but also, in general, reduce the carrying capacity of the land, something that may have long-term effects on the viability of the farm.

(a) (b)

Figure 1.2-1: consequences of poor grazing management (a) has enough while (b) is over grazed.

Traditional monitoring and grazing management of cattle also affect boy children in developing and small-scale ranchers who cannot afford workers instead use their own children for cattle heading. According to [10] School absenteeism among boys in some schools of Mwanachingwala chiefdom is seemingly on the rise as they are assigned to look after cattle in the Kafue plains. This robs these children of their childhood that end up having a negative impact on the children. It also causes children to concentrate in school or even not attend school at all.

Another implication of this is failure to notice some health problems within the cattle. This could be a reason for the late identification of an injury or sickness, or even signs of stress the animal is undergoing. If left undiagnosed, such health issues have the possibility to develop into grave ones and cost more in veterinary interventions [11]

In summary, the deficiency in traditional cattle monitoring goes beyond the bounds of immediate operational issues. The implications are severe for environmental degradation, heightened costs, and reduced profitability. All these are good reasons why better, more technologically based solutions need to be urgently employed in cattle management. By adopting modern methods of monitoring, farmers can alleviate these risks while improving animal welfare and sustainable farming that benefits their operations and the environment. This research aims to address these challenges by developing an IoT framework for cattle movement monitoring and grazing management. This framework has the potential to provide real-time data insights, improve decision-making, optimize pasture utilization, and enhance animal welfare, leading to a more sustainable and profitable cattle farming operation.

1.3 Aim

This research aims to develop an IoT framework for cattle movement monitoring and grazing management to provide innovative solutions that enhance cattle tracking, improve grazing practices, and mitigate security risks.

1.4 Objectives of the study

1. To investigate the landscape of IoT framework for cattle movement monitoring and grazing management to identify key technologies, challenges, and limitations.
2. To develop an IoT framework for cattle movement monitoring using smart collars equipped with activity sensors for real-time location tracking and behavior analysis.
3. To implement grazing management strategies by analyzing cattle movement behavior and environmental conditions using data collected from the smart collars.
4. To evaluate the performance of the framework in providing real-time insights into cattle movement patterns, grazing behaviour, and potential theft issues.

1.5 Research questions.

1. What are the fundamental components, technologies, limitations and challenges of existing IoT frameworks used for cattle movement monitoring and grazing management?
2. How can IoT framework that integrates IOT sensors such as smart collars with activity and environmental sensors be designed to effectively monitor cattle movement, grazing behaviour, and real-time location tracking?

3. How can grazing management strategies be effectively implemented by analyzing cattle movement behavior and environmental conditions using data from smart collars?
4. How effective is the proposed IoT framework in providing real-time insights into cattle movement patterns, grazing behavior, and detecting potential theft incidents?

1.6 Scope and Limitation

This research aims to develop and evaluate an IoT-based framework for cattle movement monitoring and grazing management. The study will start by investigating existing IoT frameworks used in livestock monitoring to identify main technologies, components, and communication protocols such as GPS, RFID, LoRa, and cloud computing [1] The research will examine the challenges and limitations associated with these frameworks, including connectivity issues, power consumption, and data accuracy. Understanding these factors will provide a foundation for designing a sustainable system tailored to real-world livestock management needs.

Following the findings of investigations, the research will focus on designing and implementing a custom IoT framework that integrates smart collars with GPS tacking, activity and environmental sensors for real-time cattle tracking and monitoring. The framework will also incorporate data-driven decision-making through cloud-based analytics [12]. Focus will be given to optimizing data accuracy and system reliability while addressing issues such as communication efficiency. These advancements aim to enhance precision livestock farming by improving cattle monitoring and security.

To assess the framework's effectiveness, its performance will be evaluated based on key metrics such as tracking accuracy, system response time, and reliability in monitoring cattle movement and grazing behavior [1] Additionally, the study will analyze the framework's ability to detect and prevent potential theft incidents through alert of distance from the farm data collection area. This assessment will help to understand that the framework will be able to solve Real world problem and academic soundness.

This research will be conducted within a specific simulated geographic area and limited to selected cattle herds for testing. External factors such as network coverage, weather conditions, and sensor limitations may influence the system's performance [4]. Additionally, the evaluation will be based on short-term monitoring, which may not fully capture long-term behavioral trends. The research will only review research articles within the last five years. Despite these limitations, this study still aims to contribute to the advancement of precision livestock farming by enhancing cattle movement monitoring, grazing management, and security through IoT innovations.

1.7 Significance of the Project

This research is significant as it contributes to the advancement of precision livestock farming by leveraging Internet of Things (IoT) technologies for cattle movement monitoring and grazing management. With the increasing demand for efficient and sustainable livestock management, this study aims to provide innovative solutions that enhance cattle tracking, improve grazing practices, and mitigate security risks by use of IoTs technology.

Firstly, by investigating the broader overview of IoT frameworks, the research will help identify the most effective technologies, challenges, and limitations in existing cattle monitoring systems. This knowledge will provide valuable insights for farmers, researchers, and technology developers looking to optimize cattle tracking solutions. Understanding these key factors will aid in overcoming technical and operational challenges such as connectivity issues, sensor limitations, and data integration complexities in livestock management [11]

Secondly, the development of a custom IoT framework will introduce an innovative approach to real-time cattle monitoring. By utilizing smart collars with GPS system and activity sensors, the framework will provide accurate and continuous tracking of cattle movement and population dynamics [13]

Lastly, the evaluation of the performance of the IoT framework will provide measurable insights into its effectiveness in tracking movement patterns, monitoring grazing behavior, and preventing cattle theft. By assessing factors such as data accuracy, system response time, and user feedback, the study will determine the practical feasibility of implementing such a system in real-world farming environments. Additionally, the findings will offer guidelines for future improvements and encourage wider adoption of IoT technologies in livestock management [14]

1.8 Preliminary sections of the project report

The following flowchart illustrates the organisation of the research. This will help to understand the road map for the research report.

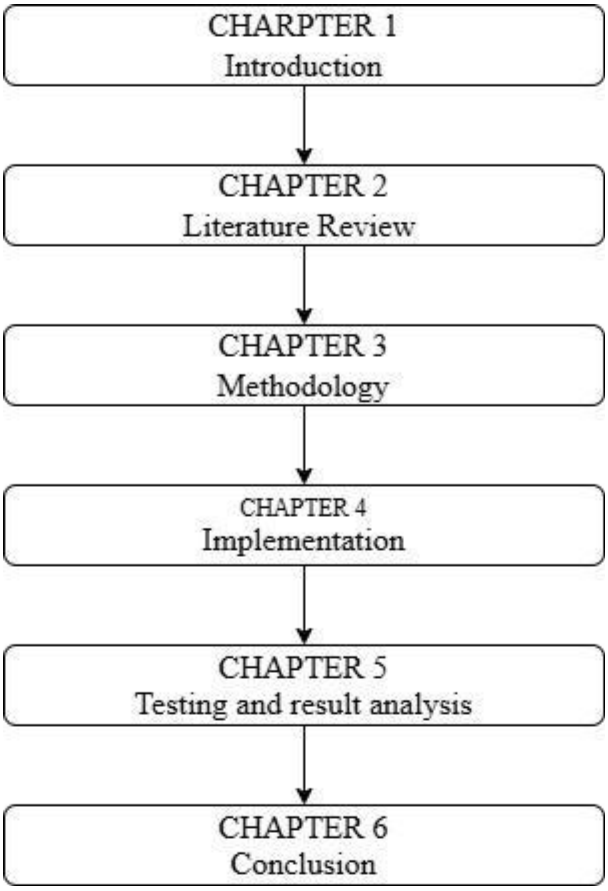

Figure 1.8-1: Preliminary sections of the project report

1.9 Chapter Summary

This chapter provided a clear synopsis of the research on how to build an IoT framework for grazing management and monitoring cattle movement. It demonstrated the inefficiencies of traditional methods of cattle monitoring and emphasized the revolutionizing potential of IoT technologies to track and make data-driven decisions in real-time. The chapter established the background, problem statement, research goals and questions, aimed at designing a smart collar-type IoT system integrating GPS, sensors, and cloud computing to optimize grazing and security. It talked about the existing IoT frameworks, identified key technologies and challenges, and provided solutions for improving farm sustainability. The horizon was set to recent work in the last five years, and care was taken concerning limitations such as network coverage and environmental conditions. Lastly, the chapter established the significance of the research in building precision livestock farming and ended with a systematic flowchart of the project's systematic construction and evaluation process.

CHAPTER 2

LITERATURE REVIEW

2.1 General Background

The Internet of Things (IoT) has evolved into a multidisciplinary and transformative technology affecting various industries, including agriculture. In the area of cattle management, IoT systems utilizing advanced technologies such as Global Positioning Systems (GPS) and smart collar sensors are revolutionizing traditional livestock management techniques. These technologies transition into cattle monitoring from conventional methods to more sophisticated practices that offer greater reliability and accuracy.

[15] Integrating IoT into cattle farming signifies a substantial shift in livestock management, predominantly in terms of monitoring movement. Traditional methods often rely on manual tracking and localized knowledge, which may lack the speed and precision necessary for effective livestock management. By employing IoT frameworks with smart devices, sensors, and real-time data analytics, farmers can achieve comprehensive tracking of cattle movements. This capability enables improved herd management, optimized grazing practices, and enhanced overall productivity and animal welfare. This literature review explores the current research landscape concerning IoT applications in cattle movement monitoring and their implications for effective grazing management.

In a broader way, IoT describes a large network of connected devices that allow telecommunications and remote data exchange through the internet. In contrast, agriculture encompasses several IoT applications, including precision farming and monitoring livestock to allow farmers to operate more efficiently and effectively based on real time data sets.

The implementation of IoT technology for cattle movement monitoring requires the use of sensors and devices which perform real-time data acquisition. Farmers can track their cattle's location and grazing patterns and behaviors through wearable technologies that include GPS collars and accelerometer-equipped tags according to [16] the tools support proactive management strategies through their ability to deliver actionable insights about animal health and welfare. Cloud-based platforms that collect movement data enable extensive analytics which supports better decision-making [17]

IoT-based cattle movement monitoring systems significantly enhance the ability to observe and manage cattle. By providing real-time information on individual movements and behaviors, these systems help farmers identify signs of distress or illness early, reduce grazing inefficiencies, and optimize resource allocation [18]. Furthermore, the ability to analyze herd movements allows for better grazing management strategies, supporting sustainable practices in land use and animal welfare [19]

The technology underpinning IoT-based for cattle movement monitoring includes several key components as discussed bellow.

1. GPS and GNSS Technologies. The Global Positioning System (GPS) and the Global Navigation Satellite System (GNSS) enable accurate tracking of cattle locations with minimal latency, allowing farmers to monitor grazing patterns and movements over large areas [20]
2. Wearable Sensors. Cattle can be outfitted with collars or ear tags containing accelerometers and physiological sensors that track movement, activity levels, and health indicators [19] and environmental sensors that track the humidity and temperature of the environment to tell the conditions of the area where the cattle is grazing from. These sensors facilitate the capture of critical data for assessing overall herd health and productivity.
3. Data Analytics. The data collected from these devices are analyzed through simulated algorithms to derive meaningful insights into cattle behavior, movement patterns, and grazing efficiency. Predictive analytics can also forecast potential health issues based on observed movements [21]

The incorporation of Internet of Things (IoT) technologies into grazing management strategies has revolutionized how livestock is monitored and managed, particularly in dynamic environments like vineyards. By utilizing low-cost, miniaturized sensors, farmers can closely track animal behavior and grazing patterns, thereby enhancing overall herd health and pasture efficiency. One innovative application is the SheepIT project, which employs IoT architecture to monitor sheep grazing specifically in vineyards. The system conditions the animals to target unwanted weeds, thus minimizing the need for harmful chemical herbicides while promoting sustainable farming practices. Moreover, this approach not only supports ecological balance but also significantly reduces the costs associated with mechanical weed removal, demonstrating the practical benefits of IoT in agriculture. Thus, the intersection of IoT and grazing management presents a promising avenue for sustainable livestock practices, as highlighted by recent advancements in sensor technology and machine learning methods [22] [23]

Effective data analytics play an important role in enhancing decision-making processes within grazing management, particularly through the integration of Internet of Things (IoT) frameworks. As the demand for animal food skyrockets due to rapid population growth, the need for efficient livestock management practices becomes increasingly critical [24]. Data derived from IoT devices not only facilitates real-time monitoring of cattle movement but also aids in optimizing grazing patterns and resource allocation, thereby addressing challenges such as land usage and environmental sustainability. The adoption of Precision Livestock Farming (PLF) technologies underscores the importance of data in attaining higher production and efficiency targets amidst external pressures like climate change and societal scrutiny regarding animal welfare [25] Moreover, proactive analytics—enabling the identification of trends and potential issues before they escalate—are reshaping traditional, reactive management practices, thus ensuring more sustainable and productive grazing systems.

Grazing practices are important for environmental sustainability as previous studies have either shown or postulated that proper grazing management can improve biodiversity and soil health, and therefore sustainability.

2.2 Broad literature review.

Effective grazing management is crucial for maintaining the productivity and sustainability of pasture-based livestock systems. A key aspect of this is understanding and controlling the movement and distribution of animals within a grazing area. Monitoring cattle movement and behaviour can provide valuable insights to help optimize grazing patterns, identify under- or over-utilized areas, and make informed decisions about resource allocation and stocking rates.

[26]In recent years, the emergence of Internet of Things (IoT) technologies has enabled new approaches to livestock monitoring and grazing management. IoT frameworks integrating various sensor devices, wireless networking, and data analytics offer the potential to track cattle movement, activity, and spatial distribution with greater precision and automation compared to traditional methods.

A number of studies have explored the use of IoT systems for monitoring the movement and behaviors of grazing cattle. These typically involve equipping animals with GPS trackers, accelerometers, or other sensor devices that can continuously capture data on their location, activity patterns, and interactions.

[27] developed IoT-based cattle tracking system using GPS and Bluetooth Low Energy (BLE) beacons. The system could accurately locate individual animals within a pasture and detect behaviors like grazing, ruminating, and walking. Similarly, [27], [28] used ear tags with accelerometers to monitor cattle activity and identify behaviors like feeding, resting, and estrus.

Beyond just tracking individual animals, some IoT frameworks aim to provide a more comprehensive view of herd-level movement and distribution. [29] described a multi-sensor IoT platform that integrated GPS, wireless sensor nodes, and unmanned aerial vehicles (UAVs) to map the real-time spatial distribution of grazing cattle across a large rangeland area.

The wealth of data generated by IoT-based cattle monitoring systems can be valuable for informing grazing management decisions. Researchers have explored various ways to integrate these technologies into decision support tools and automated control systems.

[30] developed a cyber-physical system that combined cattle tracking, pasture monitoring, and optimization algorithms to autonomously adjust the location of supplementary feeding stations. This helped redistribute grazing pressure and improve utilization of underutilized areas.

Similarly, [31] presented a precision livestock farming framework that integrated IoT sensors, geographic information systems (GIS), and predictive models to generate personalized recommendations for grazing management. This included insights on optimal stocking rates, grazing rotations, and placement of water/mineral resources.

Looking beyond just monitoring and decision support, some studies have explored the potential for IoT-enabled "precision grazing" through autonomous control of livestock movement. [29] demonstrated a robotic herding system using UAVs that could effectively direct the movement of a cattle herd within a pasture, providing a platform for targeted grazing management.

[32] provided a comprehensive review of precision livestock farming (PLF) technologies and their applications in pasture-based livestock systems. The review highlighted the potential of various sensor-based technologies, such as global positioning system (GPS), accelerometers, and proximity sensors, to monitor animal location, activity, and behaviour. These technologies can be valuable for improving grazing management and monitoring cattle movement patterns in extensive grazing systems.

[32] investigated the influence of Icelandic leader sheep on flock behaviour when exposed to a predator test. Their findings suggest that the presence of leader sheep can affect the overall behaviour of the flock, which is an important consideration for cattle grazing management in areas with potential predator threats.

[33] conducted an exploratory survey on French farms to evaluate beef herd responses to unfamiliar humans. The study highlighted the importance of considering cattle behaviour and temperament in the design of IoT-based monitoring systems, as the animals' responses to human interaction can influence the effectiveness of such technologies.

[34] studied the use of spatial-temporal arrangements of supplementation to modify the selection of feeding sites by sheep. This research provides insights into the factors that can influence cattle grazing patterns and distribution within a pasture, which are crucial considerations for effective grazing management using IoT technologies.

[35] reviewed the current state of precision livestock farming technologies for grazing and pasture-based dairy systems. The review discussed the potential applications of these technologies, including monitoring animal health, behaviour, and spatial distribution, which can be leveraged in the development of an IoT framework for cattle movement monitoring and grazing management.

[36] conducted a preliminary investigation into the use of drones for herding horses. While the study focused on horses, the findings may have implications for the potential use of drones in cattle grazing management, particularly for herd monitoring and control in extensive pastoral systems.

[37] work on grazing management provides a foundational understanding of the principles and practices involved in managing livestock grazing, which can inform the development of IoT-based frameworks for cattle movement monitoring and grazing management.

[38] examined the effects of pre-slaughter handling on the technological and sensory meat quality, blood metabolites, and muscular and abomasal lesions in reindeer. While the study focused on reindeer, the insights into the impacts of animal handling on meat quality can be relevant for the design of IoT-based cattle monitoring systems that aim to optimize animal welfare and product quality.

Overall, the reviewed literature provides a diverse set of perspectives and considerations that can inform the development of an IoT framework for cattle movement monitoring and grazing management. The studies highlight the potential of various sensor technologies, the importance of understanding animal behaviour and welfare, and the need for integrated approaches that consider the complex interactions between livestock, the environment, and management practices.

The integration of Internet of Things (IoT) technologies in agriculture has been progressively transforming traditional farming practices, particularly in livestock management. The article by [39] provides a comprehensive review of beef cattle supplementation technologies, which is highly relevant to the development of an IoT framework for cattle movement monitoring and grazing management.

The development of an IoT framework for cattle movement monitoring and grazing management is an evolving area of agricultural technology. The study by [40] provides an in-depth exploration of the architecture frameworks for IoT-based food and farm systems, which is highly pertinent to the design and implementation of such IoT frameworks in livestock management.

The integration of Internet of Things (IoT) technologies into agricultural practices is significantly transforming livestock management, especially in monitoring cattle movement and optimizing grazing management. The work by [29] provides crucial insights into the use of IoT and Unmanned Aerial Vehicle (UAV) networks for health surveillance in dairy farm systems, which is directly relevant to developing an IoT framework for cattle movement monitoring and grazing management.

2.3 Critical review of related works

The reviewed literature presents a compelling narrative on the transformative role of IoT in cattle movement monitoring and grazing management. However, while the studies collectively emphasize the benefits of precision, automation, and real-time decision-making, a critical assessment reveals several recurring gaps, limitations, and future directions that need to be addressed for broader applicability and scalability of these.

1. Technological Integration and Data Fusion

Several works, such as [23], [24], and [25], successfully demonstrate the use of GPS, accelerometers, and BLE beacons for individual or herd-level cattle monitoring. However, a significant limitation lies in the fragmented nature of data collection systems. Many of these implementations are isolated, focusing on a single aspect, location tracking, behavior recognition, or spatial distribution without holistically integrating multi-sensor data for richer contextual insight. [25] integrates UAVs for mapping, there is limited evidence of continuous fusion with ground-based data from wearable sensors or environmental sensors.

Furthermore, interoperability between sensor devices, data platforms, and analysis models remains a challenge. Standardized architectures for integrating heterogeneous data streams, both spatial (GPS, GIS) and behavioral (accelerometers, environmental cues) are rarely addressed, as pointed out by [36].

2. Real-Time Analytics and Decision Support Systems

While [26] and [27] illustrate promising use cases for decision support systems using optimization algorithms and predictive modeling, their practical deployment and responsiveness in real-world grazing environments remain underexplored. Most studies stop at the prototype or simulation phase, with limited evaluation under varying environmental conditions or large-scale commercial farms.

Moreover, data analytics capabilities vary significantly. Some systems still rely on threshold-based alerts rather than employing robust machine learning or AI-driven approaches that adapt over time to changing herd behaviors, weather conditions, or grazing cycles. Predictive insights, though mentioned in [18], are rarely operationalized into autonomous or semi-autonomous systems.

3. Scalability and Power Constraints

IoT systems proposed in the literature often face scalability constraints, particularly with power consumption and network coverage in remote areas. While [23] and [25] employ GPS and BLE, continuous tracking over wide rangelands demands power-efficient hardware and long-range connectivity (LoRaWAN or NB-IoT), which many systems fail to incorporate or discuss in depth. Furthermore, cloud-based systems, while beneficial for analytics, depend on reliable internet connectivity, which is often lacking in rural or isolated grazing lands.

4 Behavioral and Welfare Considerations

Studies [28], [29], and [34] bring attention to the importance of animal behavior, temperament, and welfare, which is crucial for ethical livestock management. Systems rarely adapt to the individuality of animals or include feedback mechanisms for stress, social dynamics, or environmental discomfort. This represents a significant oversight, especially as public scrutiny on animal welfare intensifies.

5. Novel Use Cases and Cross-Species Adaptability

Innovative use cases such as the robotic herding system [25] and UAV-driven flock movement control [32] showcase the potential of automation in livestock movement. However, such systems are still at experimental stages and lack detailed analysis of cost-effectiveness, training requirements, and reliability across different terrains or species. Similarly, while studies on sheep and reindeer ([28], [30], [34]) offer valuable insights, generalizing findings from these species to cattle without validation may lead to flawed assumptions.

6. Environmental and Sustainability Outcomes

Many systems suggest that improved monitoring will lead to sustainable grazing and environmental benefits, yet there is limited empirical evidence supporting long-term ecological outcomes. Studies by [33] acknowledge the foundational role of grazing management, but few quantify soil health, biodiversity gains, or pasture rejuvenation resulting from IoT-informed practices. A more integrative assessment, incorporating both technological performance and ecological impact, is needed.

7. Human Centered Design and Adoption Barriers

The survey by [29] reveals behavioural responses of cattle to unfamiliar humans, indicating that human interaction remains a critical variable in system effectiveness. However, most frameworks overlook user-centric design, failing to assess how farmers interact with, interpret, and act upon insights generated by IoT. Additionally, there is a lack of discussion on training needs, technology acceptance, and cost implications, which are crucial for real-world adoption, especially in developing regions.

In short, Although the literature provides a good basis for Iot applications in cattle grazing management and movement monitoring, it does not typically address the integration of heterogeneous systems, real-time data analysis, animal welfare, environmental sustainability, and usability issues. Future studies must focus on the development of scalable, power-efficient, context-aware, and user-friendly systems tested in realistic and varied environmental settings. It is necessary to fill these gaps to move IoT from promising prototypes to effective, market-ready farming solutions.

2.4 Comparison with related works

The next table presents a comparative assessment of the most significant research on IoT architecture for tracking cattle movement and grazing management. Each study is compared with parameters such as sensor integration, real-time analysis, scalability, behaviour consideration, and human-centric design.

Table 2.4-1: Comparisons of the existing frameworks

Ref.	Authors / Study	Sensor Technologies Used	Data Integration	Real-Time Analytics	Scalability & Power Efficiency	Behavioral/ Welfare Consideration	User-Centric Design
[23]	GPS & BLE Beacon System	GPS, BLE Beacons	Limited	Basic alerts	Moderate (BLE range limited)	No	No
[24]	Ear Tags with Accelerometers	Accelerometers	No integration	Behavior recognition only	High (lightweight tags)	Partial (activity tracking)	No
[25]	UAV and Multi-Sensor Integration	GPS, UAVs, Sensor Nodes	Partial	Mapping-focused	Limited by UAV range and battery	No	No
[26]	Cyber-Physical Feeding System	GPS, Optimization Algorithms	Yes	Optimization logic	Moderate (prototype stage)	No	Limited
[27]	Precision Grazing DSS	GPS, GIS, Predictive Models	Yes	Predictive modeling	Not tested at scale	No	Yes (recommendations)
[28]	Precision Livestock	GPS, Accelerometers,	Comprehensive	Varies by case	High potential	Yes	Limited

	Farming Review	Proximity Sensors					
[29]	Human Interaction Survey	Observational	N/A	N/A	N/A	Yes	Yes (farmer feedback)
[30]	Feeding Site Selection by Sheep	Supplementation Patterns	No	Experimental	High (manual control)	Yes	No
[32]	Drone Herding of Horses	UAVs	No	Real-time control	Limited (experimental)	No	No
[34]	Reindeer Welfare and Handling	Biochemical & Physiological Sensors	No	Post-event analysis	High (specialized)	Yes	No

2.5 Identified Gaps

The following are the Gaps that were identified by the research in precision livestock farming.

Data Integration and Standardisation. Existing Systems operate in silos, collecting data independently, and lack a common architecture for the integration of heterogeneous IoT sensors and devices. This makes the data inefficiently utilized and delays the development of comprehensive decision support tools.

The systems also have Limited Real-World Testing and Underutilization of Advanced Analytics. Several solutions remain in prototype or simulation phases without rigorous long-term evaluation in field conditions. There's a dependence on basic models instead of adaptive AI/ML techniques.

Finally, Scalability, Cost, and Usability Challenges. Continuous monitoring can be energy-intensive, and solutions are often cost-prohibitive. There is a lack of focus on user-friendly interfaces and the socio-economic feasibility for smallholder farmers.

2.6 Conceptual framework

The IoT conceptual framework for monitoring cattle movement and grazing management involves several connected elements that work together to improve the management of livestock. With this framework, the various relationships between elements are defined to provide insight into the implementation and evaluation of IOT technologies to agricultural systems.

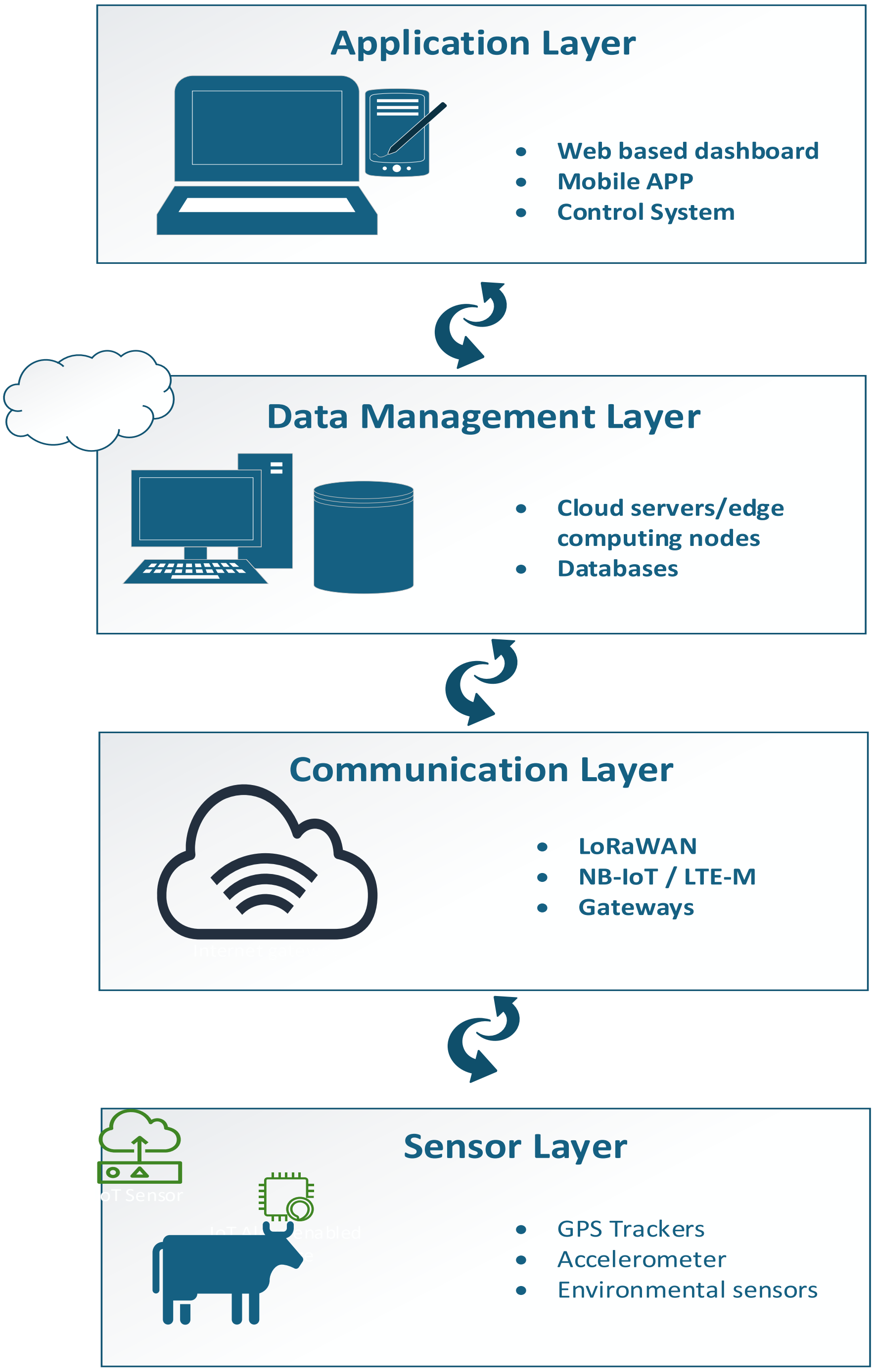

Figure 2.6-1: Conceptual framework

he conceptual framework comprises of the sensor layer that is used for data collection. This is the lowest layer. The GPS sensor trackers are fitted on cattle for real time tracking of the cattle, accelerometers to detect the activities or movements of the cattle and the environment sensors the monitor the pasture conditions like moisture

The Second layer is the communication layer that will enable transmitting data from sensors to the data management layer in the cloud. LoRaWAN, NB-IoT, or LTE-M are used for data transmission, especially in remote areas, with gateways collecting data from sensors and relaying it to the cloud

The Third layer is the data management layer, which will receive and process the data received from the gateways with databases used for time-series data storage of movements, grazing patterns, and sensor readings.

The fourth layer will be used to analyse the data for cattle grazing for pasture usage tracking and behavioral patterns, and movement analytics for path tracking. After analysing the data, the framework will also have an application layer that gives the interaction with user. Web dashboard and mobile app will provide visualization of cattle location, grazing patterns and alerts depending on how strong the signal will be. Control systems can trigger actions like virtual fencing or pasture rotation recommendations.

2.7 Proposed Framework.

The proposed system utilizes the latest Internet of Things (IoT) technologies to facilitate the tracking of cows, combined with effective grazing management. The focus of this model is to provide a fully comprehensive solution to the needs of farmers while improving overall efficiency, sustainability, and welfare for animals involved.

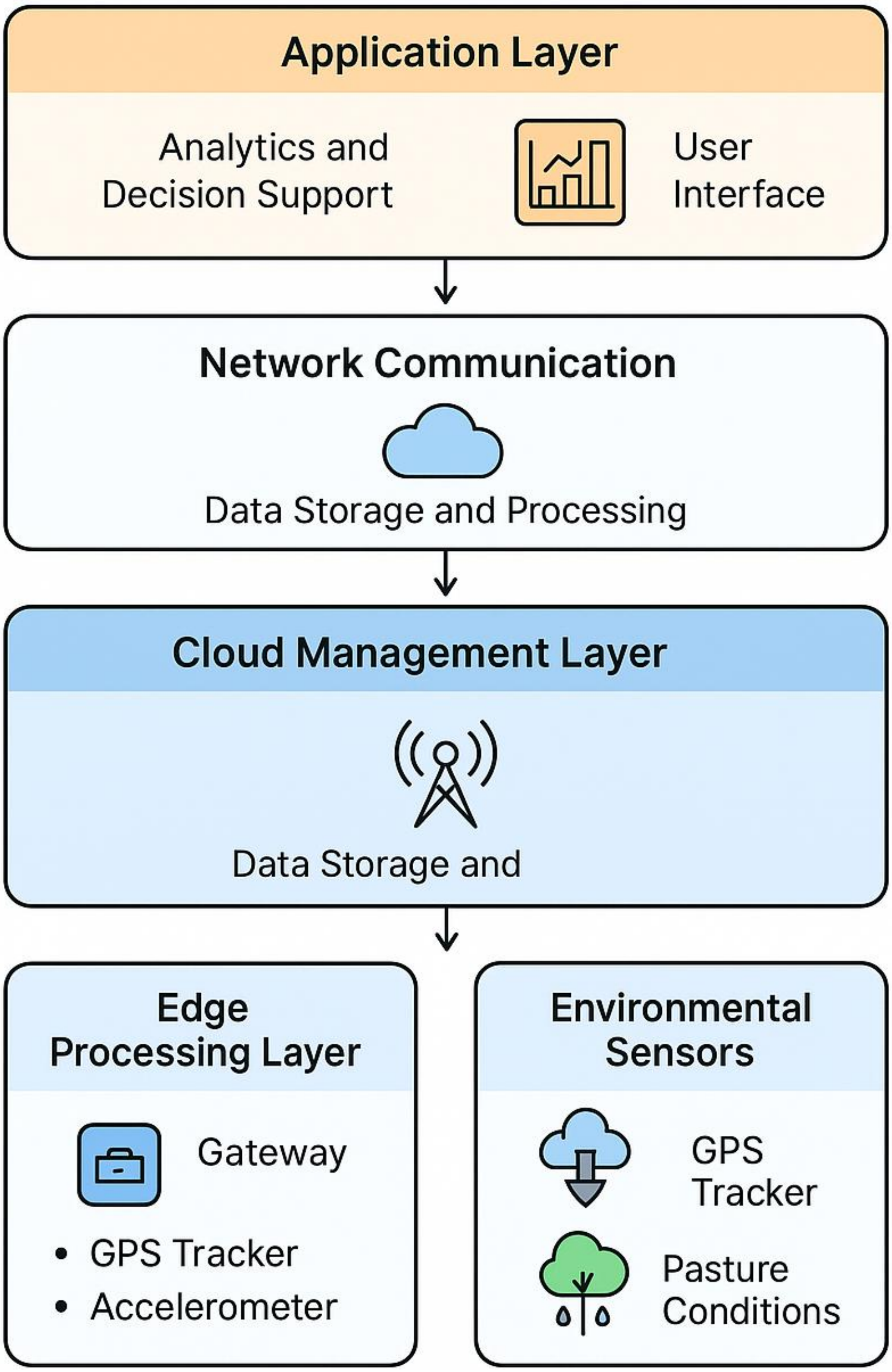

Figure 2.7-1: Proposed Model

The proposed IoT architecture for cattle movement tracking and grazing management is structured into several interconnected layers with some functions to deliver real-time monitoring, effective grazing, and cattle health management.

In the Smart Sensing Layer, cows are equipped with wearable sensors, including GPS and accelerometer collars that track their real-time location and activity. There are environmental sensors such as moisture sensors, that are integrated into one gadget which is a smart collar.

The Edge Processing Layer localizes the processing of the data. Farm/ranch level gateways collect all the sensing data from environmental devices and cattle, which perform very minimum preprocessing operations such as noise filtering, and elementary analytics, such as "out-of-boundary" detection. Data is kept temporarily at the edge to reduce the burden of transmission. Optionally, fog computing is utilized by using that node for intermediate calculations, including data aggregation, small machine learning models to make early predictions on grazing patterns.

The Network Communication Layer ensures a stable connection between the farm and the cloud. Solutions such as LoRaWAN offer wide-area, low-power communication suitable for rural installations, while Cellular IoT solutions like NB-IoT and LTE-M cover areas with 4G/5G coverage. Satellite IoT solutions provide a backup for very remote locations. All communication from gateways to cloud servers is securely encrypted to prevent breaches.

At the Cloud Management Layer, big data storage systems hold structured cattle movement histories and environmental data in time-series databases. Cloud-based processing engines perform real-time tracking, grazing schedule optimization using sophisticated algorithms, and health anomaly detection within the herd. This layer supports large-scale data analytics that inform long-term decision-making and predictive modeling.

The Analytics and Decision Support Layer interprets stored and processed data. It generates cattle movement heatmaps, behavioral change alerts, and pasture rotation schedules. It also provides early warning of overgrazing and predicts cattle health risks, including sudden inactivity or unusual movement patterns. These analytics equate to informed, proactive management of livestock and pasture resources.

The Application Layer communicates with users through a web dashboar. The web dashboard is intended for farm managers and presents real-time cattle location maps, pasture utilization reports, and automatic alert notifications email, and buzzers. The mobile app, on the other hand, provides field-friendly access to cattle tracking, quick individual cattle health status lookups, along with location information essential to field operations.

The key Innovation within the Proposed Framework addresses an important industry gap in Data Integration and Standardization. Most existing systems operate in isolation, collecting data individually and lacking shared frameworks to sustain heterogeneous IoT sensors and devices. This siloed operation contributes to substantial underutilization of valuable data and limits the capability of combined decision support tools. To meet this challenge, the new framework adopts a standardized data aggregation strategy that integrates disparate data sources including differing sensors, communications protocols, and platforms smoothly into a unified system. This ensures multiple devices' data is harmonized, maximized, and optimized for effective utilization toward better decision-making, operational productivity, and prediction power across the grazing management infrastructure

2.8 Chapter Summary

This chapter provided a comprehensive overview of existing IoT infrastructure for cattle movement tracking and grazing management, describing the evolution of IoT technologies in agriculture, and more specifically livestock tracking and environmental monitoring. The chapter critically reviewed and compared various IoT systems, including GPS collars, environmental sensors, and cloud platforms, detailing their strengths, shortcomings, and actual performance. A systematic comparison of communication technologies, data handling strategies, and analytics capabilities highlighted gaps, foremost among them being the lack of data integration among heterogeneous systems. To remedy this, the chapter developed a conceptual model advocating for a multi-layered IoT platform with emphasis on standardized data consolidation, real-time decision support, and enhanced system interoperability. The proposed model enhances current practices by integrating various devices with common standards, taking advantage of edge and cloud computing, and applying predictive analytics and virtual fencing to facilitate dynamic, data-driven grazing management and improved cattle welfare.

CHAPTER 3 – METHODOLOGY

The research aims to develop and evaluate an IoT framework for monitoring cattle movement and managing grazing patterns. This methodology outlines the steps and processes involved in achieving the research objectives, focusing on data collection, system design, implementation, and evaluation.

3.1 Research design

This study utilizes Design Science Research (DSR) methodology, focusing on the design, validation, and testing of an IoT-enabled system for cattle movement monitoring and grazing management. DSR is particularly well-suited for research aiming to create and analyse innovative artifacts with the goal of solving practical problems rather than analysing already-existent systems [41]. Here, the primary focus is not just to understand the limitations of current livestock monitoring systems but to envision, create, and test an innovative integrated IoT solution that maximizes operational efficiency, grazing patterns, and decision-making.

Design Science emphasizes a problem-solving development process problem identification to artifact design, demonstration, evaluation, and refinement within which the technological innovation goals of this study neatly fit [42] By applying this method, the study tackles systematically agricultural problems such as fragmented sensor networks, inefficient pasture use, and inadequate animal tracking.

The conceptualized IoT platform is the primary artifact developed during this study, combining smart sensing devices, low-power communication technologies, and cloud-based decision support tools into a unified system. The platform also leverages current advances in pervasive sensing and mobile IoT platforms to provide real-time insights for maximized cattle and grazing management [43]

Second, DSR ensures the results of the research transcend the technical artifact in that they call on generalized knowledge, structures, and technological principles that can be used in other precision agriculture contexts. With sound artifact creation, experimentation, and empirical validation, this study makes both a theoretical contribution and a breakthrough in the practice of IoT and smart livestock farming.

The diagram below is the design science research process.

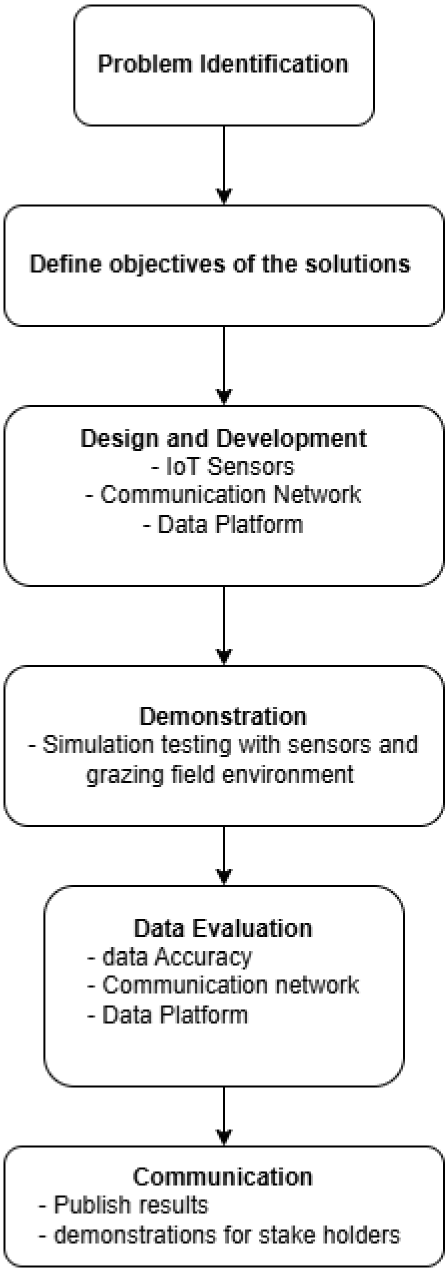

Figure 3.1-1: Design science research process

The table below illustrates the application of DSR to IoT Framework for Cattle movement monitoring and grazing management.

Table 3.1-1: Application of DSR to IoT Framework

DSR Step	IoT Framework for Cattle movement monitoring and grazing management
Problem Identification	Inefficient cattle tracking and grazing management, difficulty monitoring herd and movement. Unintegrated sensor data analysis and management.
Define Objectives	1. To investigate the landscape of IoT framework for cattle movement monitoring and grazing management to identify key technologies, challenges, and limitations. 2. To develop an IoT framework for cattle movement monitoring using smart collars equipped with activity sensors for real-time location tracking and behavior analysis. 3. To implement grazing management strategies by analyzing cattle movement behavior and environmental conditions using data collected from the smart collars. 4. To evaluate the performance of the framework in providing real-time insights into cattle movement patterns, grazing behaviour, and potential theft issues.
Design & Development	Design IoT devices (smart collars with activity sensors), communication network and data analytics platform.
Demonstration	Deploy prototypes in a simulated farm environment, monitor cattle movement and grazing patterns, and the environmental sensors.
Evaluation	Assessment system based on accuracy, reliability, ease of use, and impact on grazing efficiency.
Communication	Publish findings, showcase to farmers and aggrotech stakeholders, write academic articles.

3.2 Methodological framework

The methodological framework for the study seeks to develop and evaluate an Internet of Things (IoT)-enabled system for monitoring cattle movement and guiding effective grazing management. The framework specifies the integration of sensor technology, data collection procedures, data processing methods, and analysis strategies necessary to provide real-time tracking and behavioral analysis of cattle in pasture-based systems. The following is the flowchart that guides the flow of the research.

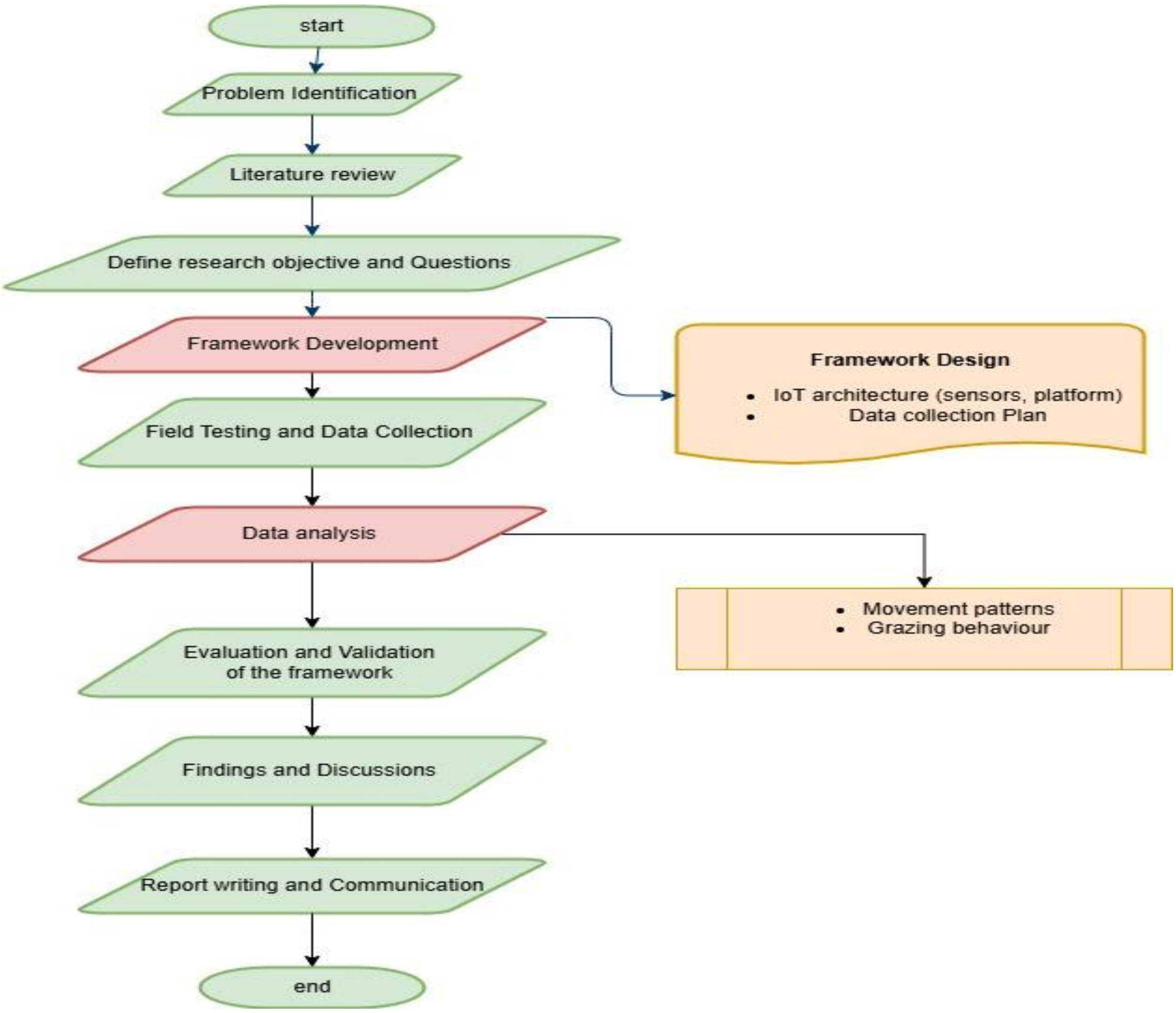

Figure 3.2-1: Research flowchart

3.3 Adopted method and justification

The research methodology adopted for this study is experimental prototyping and simulation supported by a thorough review of secondary data from previous academic studies, technical reports, and industry practices. Prototyping refers to developing a conceptual and functional model of the proposed IoT infrastructure based on current real-world technologies such as GPS for geolocation, activity sensors for gait and environmental sensors for tracking the conditions of the grazing area for cattle. Wi-Fi wide-area network communication, and cloud platforms for data storage and real-time analytics.

Instead of needing to roll out the full system in the physical wide-area environment, which would mean enormous financial expenditures, time, and logistics, the prototype is field-tested with simulated environments. By doing this, the researcher is able to mimic real-world phenomena, including cattle movement, grazing behaviours, and environmental interactions, without the cost of installing hundreds of devices, sensors, and networking equipment on an operational ranch.

Simulation has some key advantages. First, it facilitates rapid iteration of the system parameters. It is easy to alter system parameters such as communication range, packet loss rate for data, and battery consumption and tune them based on simulation results. Second, it facilitates scalability testing within controlled settings, performance of the IoT framework can be tested with a variable number of sensors and cattle to ensure that the system remains stable in scaling up. Thirdly, the potential bottlenecks and challenges, such as network delay, node failure, or coverage gap, can be identified early on, before committing to costly real-world deployment.

This approach is itself in accordance with the best standards of IoT system development in agriculture, where platforms Wokwi is utilized to simulate wireless sensor networks [44]. Moreover, model-driven development (MDD) principles also speed up the prototyping process by enabling one to use high-level abstractions, diminishing complexity and time taken to design, improve, and test the IoT system to a large degree [45]

Moreover, the deployment of edge computing and Wi-Fi allows the copying of the effectiveness of communication in rural regions in that real-time cattle monitoring still works even with decreased infrastructure [46]This makes the prototype actually replicate the working conditions under which it would be used, adding more validity to the outcomes.

Simulation and experimental prototyping provide an economical, timesaving, and scientifically valid strategy to design, experiment, and optimize the proposed IoT system for cattle movement monitoring and grazing management. This methodology choice is not only possible but also adds value to the research contribution to practical applications in precision livestock farming.

3.4 Association of research method to project

The application of experimental prototyping and simulation-based research methodology is directly aligned with the objectives of this project, which is the development of a holistic IoT framework for cattle movement monitoring and grazing management. The methodology allows for a realistic assessment of how various components cattle tracking, environmental monitoring, and grazing management systems can be holistically integrated based on IoT technologies.

Experimental prototyping enables the implementation of a conceptual prototype of the proposed IoT infrastructure, incorporating real-world technologies like GPS for location tracking, RFID for animal identification, LoRaWAN for low-power wide-area networking, and cloud platforms for data storage and analysis. Through the simulation of farm environments, this approach allows for the identification of operational issues, validation of data flows from sensors to analytics layers, and testing of system efficacy without the need for large-scale physical deployment. Simulations offer a risk-free environment to experiment with various configurations and optimizations, which is paramount in guiding future real-world deployments.

The use of simulation in this research is particularly applicable given the complexity inherent in livestock management under diverse terrains and climates. For instance, [47] modelled a LoRa-based maintenance-free cattle monitoring system with the capability to track cattle in remote regions and log activity parameters, depicting the utility of simulation in system component optimization before field deployment.

Furthermore, the use of simulation aligns with the Design Science Research (DSR) guidelines that emphasize iterative design and testing to develop functional artifacts. By using simulation, the IoT framework can be refined iteratively by the researchers to guarantee that it meets the specific needs of cattle movement monitoring and grazing management. Iteration is necessary for addressing the dynamic nature of issues related to livestock management, such as shifting animal behaviour and environmental conditions.

In addition, simulation provides the ability to integrate secondary data, such as past weather patterns and grazing activity, to provide additional contextual relevance to the experimental results. Integration ensures the IoT framework established is robust and capable of handling real-world dynamics, and hence more likely to be effectively implemented in diverse agricultural settings.

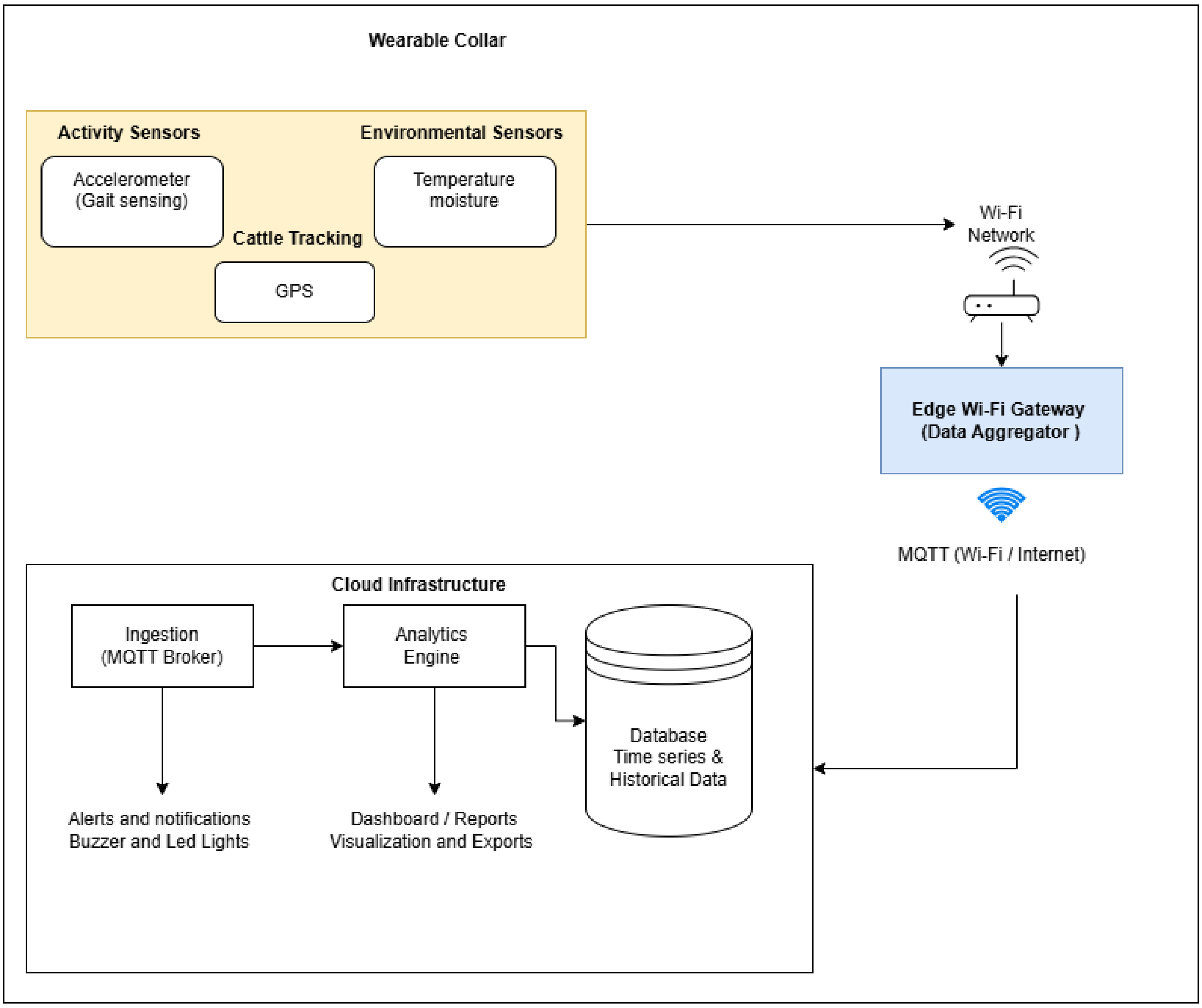

Figure 3.4-1: Framework Architecture

3.5 Tools and Technologies

The following is the summary table of the project tools and their respective uses in a cattle movement and grazing management framework.

Table 3.5-1: Summery of tools and their use

Tool/Component	Use/Function
ESP32 Dev Board	Main microcontroller that collects data from sensors and transmits via Wi-Fi.
DHT22 Sensor	Measures environmental temperature and humidity around the cattle.
GPS Module (NEO-6M)	Tracks the real-time location of the cattle for movement monitoring.
MPU6050 Sensor	Detects motion and orientation to analyze cattle activity and gait.
Wi-Fi(Wokwi Simulator)	Simulates network connection for data transmission in development environment.
MQTT Protocol	Lightweight messaging protocol to transmit data from device to cloud platform.
Ubidots	IoT platform used for data visualization, alerts, and device management.
LEDs	Visual indicators for walking, stopped and running activity status.
Arduino IDE	Software development environments used for coding and flashing ESP32.
Wokwi Simulator	Virtual environment to prototype and test the project before physical deployment.

3.6 Experimental setup

The implementation setup below shows the strategic guide for deploying a smart cattle movement monitoring and grazing management system using IoT technologies. This section outlines the sequential steps taken to design, simulate, and operate an integrated framework involving hardware components.

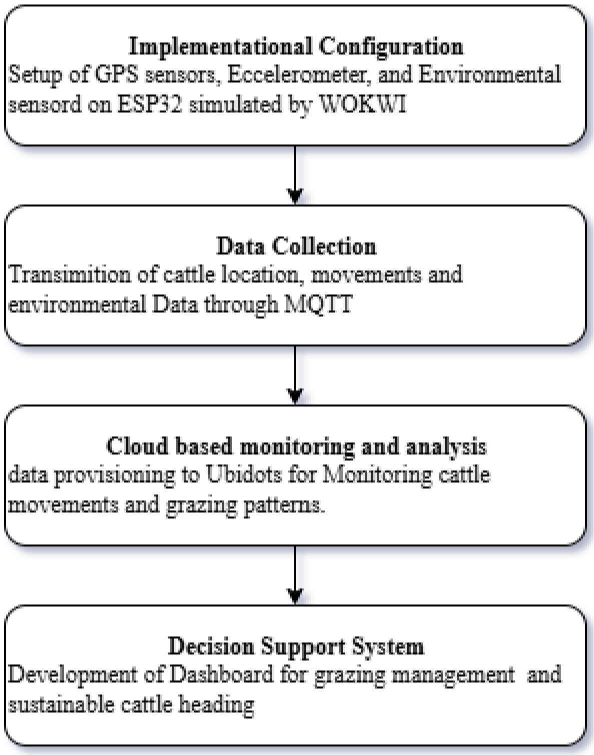

Figure 3.6-1: Implementational roadmap

3.7 Research data and datasets

It goes without saying that when the research methodology of IoT framework targeting cattle monitoring for movement and management of grazing is considered, the collection, management, and analysis of relevant datasets hold an important place to come up with accurate and actionable results

This study is founded on a combination of secondary datasets and the application of synthetic data generation for the support of suggested IoT framework development, training, and validation for cattle movement tracking and grazing management.

Secondary datasets are utilized as input of a foundational nature and are sourced from reliable and open-access sources. Specifically, this study utilizes,

- Cattle movement statistics, like GPS coordinate statistics of livestock travel within free pasture environments. These statistics reflect natural grazing habits, herd dynamics, and response to environmental stimuli.
- Pasture biomass and environmental condition information collected from credible agricultural research institutions, such as the Food and Agriculture Organization (FAO), United States Department of Agriculture (USDA), and the Commonwealth Scientific

and Industrial Research Organisation (CSIRO). Such data contains time-series information about grass biomass, soil moisture levels, and vegetation quality, which are all vital for effective grazing management.

Public weather archives, such as National Oceanic and Atmospheric Administration (NOAA) and World Meteorological Organization (WMO) archives. Historical and current meteorological records (rainfall, humidity, temperature, wind speed) are relevant to model environmental variability that affects pasture growth and cattle behavior. These datasets are used to set the limits on when the alerts should be given.

Where data availability is limited in practice or requires test conditions to be specially created, synthetic datasets are generated. Synthetic data simulates cattle movement (e.g., roaming, resting, migration pattern), environmental variability which are temperatures and humidity, and sensor readings (collar GPS location, moisture sensor readings) over extended durations. This is achieved through the application of established animal movement models, random walk simulation, and weather pattern generation programs to generate realistic and diverse scenarios for system testing.

Synthetic data creation is particularly crucial for,

- training cattle location models so that they can handle cattle location in varying conditions.
- Testing geofencing features, simulating instances where cattle approach or cross set virtual boundaries.
- Creating grazing optimization models, which require dynamic integration of cattle movement, pasture availability, and weather conditions to recommend optimal rotation timetables.

This synergy of virtual and real-world data ensures that the system is validated under diverse realistic, testing, and edge-case conditions, leading to more generalized and robust conclusions. The use of secondary and synthetic data aligns with ongoing trends in agricultural IoT research where cost and effort to implement large-scale field trials justify complementing simulated testing scenarios [48]

3.7.1 Types of Data Required

The following kind of data will be required to monitor cattle movement to effectively manage grazing lands.

3.7.1.1 Location Data

GPS data that is used for monitoring the latitude and longitude coordinates of cattle at discrete time intervals, are collected on GPS modules that are attached to collars worn by the animals. The key objective of taking this information is to track the movement of cattle in real-time, monitor grazing habits, predict behavioral patterns, and ultimately optimize pasture use. Data collection frequency is usually high, ranging from minute-to-minute to hourly data, depending on how accurate the study or management goals require.

3.7.1.2 Activity Data

Activity information refers to a group of information that records explicit behavioral states of cattle, such as resting, grazing, and walking. This type of information is typically read from onboard sensors, which are accelerometers, pedometers, and gyroscopes, embedded in Internet of Things (IoT) devices fitted on animals. The primary aim of acquiring such information is to successfully distinguish and identify these activities and hence analyze grazing behavior patterns and the efficiency of utilizing pastureland.

Continuous observation of cattle behavior provides essential insight into animal health, resource use, and optimizing grazing patterns. For high accuracy in behavioral analysis, data gathering will be done incrementally, ideally with update frequencies of one minute or even less. Frequent high-rate acquisition of data ensures production of reliable, high-quality datasets essential to robust statistical analysis and the development of well-advised pasture management.

The integration of activity monitoring with pasture-based livestock management systems represents a significant leap in precision agriculture, offering the potential for enhanced sustainability and productivity in pasture-based livestock systems [49]

3.7.1.3 Environmental Data

Environmental data covers reports of primary ecological factors such as moisture, vegetation condition, ambient temperature, and humidity. [50] This data are typically gathered using Internet of Things (IoT) devices mainly located over grazing paddocks, The main reason for the environmental data collection is continuous monitoring of such field conditions influencing directly cattle grazing activity and grass quality. In relating the activity and movement pattern of the cattle with the environment, proper comprehension in respect to how forage presence and abiotic stress conditions influence livestock could be obtained [51]

Environmental data are typically collected at hourly and daily intervals, depending on the temporal dynamics of a particular factor and the target temporal resolution for accurate modeling and analysis. Real-time environmental monitoring supports adaptive management strategies to guarantee pastoral resources are used sustainably and livestock welfare is maintained even in uncertain climatic conditions.

3.7.2 IoT Devices and Sensors

The deployment of an IoT system for cattle movement monitoring and grazing management necessitates the utilization of varied devices and sensors. These sensors and devices play an integral role in obtaining real-time and high-resolution information on cattle behavior, environmental conditions, and pasture health. This section introduces the primary IoT devices and sensors employed in the proposed framework, including their functions, operation modes, and roles in the monitoring system.

GPS (Global Positioning System) trackers form the fundamental component for monitoring cattle movement. Attached typically to collars or ear tags, they provide precise spatial location data at fixed intervals. Continuous GPS monitoring enables the examination of movement patterns, grazing habits, and territory utilization. Such information is key to optimizing pasture rotation schedules and preventing overgrazing by ensuring that cattle do not over-exploit certain parts of the land. The most significant attributes of GPS trackers include real-time location, trajectory plotting of movement, and examination of grazing distribution across different sections of pasture.

In addition to location tracking, accelerometers are included in cattle-worn devices to measure the degree of physical activity. The sensors detect and record activity like walking, standing, lying, and feeding activity. By recording complex patterns of activity, accelerometers provide indirect measures of the health status and general well-being of an animal. Behavioral anomalies that are recorded by accelerometers can be precursors to illness, injury such as lameness, or calving events. Accelerometers are therefore helping in activity and behavior classification, health status monitoring, and early anomaly detection in the herd.

Complementing the data gathered on animal behavior, there are soil moisture sensors spread out in grazing fields in order to be able to keep an eye on the water content in the soil. Optimal soil moisture levels are essential for pasture productivity and health, which directly affects the quality and quantity of forage available to cattle. Soil moisture sensors provide valuable information that informs irrigation scheduling and grazing plans, as well as enabling predictions regarding pasture growth rates under current soil conditions. The functioning of these sensors is based on monitoring soil water availability, supporting decision-making for efficient irrigation, and predicting the rate of pasture growth in order to sustain grazing activities.

3.8 Data collection methods and data analysis techniques

The implementation of an IoT framework for cattle movement monitoring and grazing management requires a structured approach to data collection and analysis. Data collection methods within this framework are designed to ensure comprehensive, continuous, and high-quality data acquisition from a range of sensors and monitoring devices deployed across the cattle and grazing environment. These methods integrate real-time automated sensing with periodic manual observations to create a robust and reliable dataset.

IoT devices such as GPS trackers, accelerometers, humidity sensors and weather stations are utilized for continuous, real-time data collection. GPS trackers provide geospatial data, enabling the tracking of cattle movement patterns and grazing distribution. Accelerometers collect data on cattle behaviour, recording activities such as standing, lying, and walking, which can be indicative of health status and welfare. Humidity sensors and weather stations capture environmental parameters that influence pasture productivity and cattle behaviour. Data from these devices is transmitted via cellular networks or other wireless communication technologies to a centralized cloud-based storage system for subsequent processing and analysis. Manual surveys and field observations supplement sensor data by providing ground-truth information that validates and calibrates automated data collection systems.

The data analysis techniques applied to the collected datasets are aimed at extracting meaningful insights and supporting data-driven decision-making in grazing management. Initially, data preprocessing is conducted to ensure quality and consistency, this includes filtering out noise and erroneous values, smoothing movement trajectories using algorithms such as Kalman filters, and imputing missing values resulting from sensor malfunctions or communication failures. Following preprocessing, integrated datasets combining cattle movement, behavioural, environmental, and physiological data are developed through middleware platforms. Analytical techniques such as time-series analysis, spatial analysis, and behaviour classification algorithms are employed to detect patterns in cattle movement, identify anomalies, and assess pasture utilization. Machine learning models may also be applied for predictive analytics, such as forecasting pasture growth rates or detecting early signs of cattle health issues based on behavioral deviations. Furthermore, geospatial analysis tools are used to visualize cattle movement and grazing distribution, facilitating the optimization of pasture rotation schedules and grazing intensity management. By combining real-time monitoring with advanced data analytics, the framework supports improved decision-making, enhances animal welfare, and promotes sustainable land management practices.

Table 3.8-1: Dataset Fields

Field Name	Data Type	Description	Sensor/Source	Frequency
Cattle_ID	String	Unique identifier for each animal	GPS Collar / Accelerometer	Static (once per animal)
Timestamp	DateTime	Date and time when the data point was recorded	All sensors	Every 5 min / 1 min / 1 hr
Latitude	Float	Geographic coordinate (north-south position)	GPS Module	Every 5 minutes
Longitude	Float	Geographic coordinate (east-west position)	GPS Module	Every 5 minutes
Speed	Float	Instantaneous speed calculated from position change	GPS Module	Every 5 minutes
Activity_Status	Categorical	Behavior status (e.g., Grazing, Walking, Resting)	Accelerometer	Every 1 minute
Acceleration_X	Float	Acceleration in X-axis	Accelerometer	Every second, summarized per minute
Acceleration_Y	Float	Acceleration in Y-axis	Accelerometer	Every second, summarized per minute
Acceleration_Z	Float	Acceleration in Z-axis	Accelerometer	Every second, summarized per minute
Soil_Moisture_Level	Float	Percentage of soil moisture	Soil Moisture Sensor	Every 1 hour

Temperature	Float	Ambient temperature in °C	Weather Station	Every 1 hour
Humidity	Float	Relative humidity in %	Weather Station	Every 1 hour
NDVI	Float	Vegetation health index (Normalized Difference Vegetation Index)	Vegetation Health Sensor	Daily
Grazing_Intensity	Integer	Number of visits/movements into a pasture area	Derived from GPS data	Calculated daily

3.9 Ethical concerns related to the research.

The application of IoT technologies to track cattle movement and grazing is of a number of important ethical issues that must be addressed carefully throughout the research process. The first ethical issue is with regard to the welfare and privacy of animals being tracked. Continuous tracking by GPS devices, accelerometers, and biometric sensors must be conducted in a manner that the devices do not result in physical discomfort, stress, or harm to the cattle [52] The design and attachment of wearable devices should comply with established animal welfare guidelines, such as those outlined by the World Organisation for Animal Health [53] to guarantee that monitoring equipment is not behaviorally disruptive or harmful but sufficiently light to be worn.

Apart from animal welfare, ethical data privacy and security management are also key. The collection of large volumes of data, including location, health parameters, and environmental conditions of the farm, raise concerns regarding confidentiality and ownership of data. There must be stringent data protection measures, with all the collected data being stored safely, sent securely, and analyzed as per relevant data protection acts, the Zambian Data Protection Act No. 3 of 2021 [54]. This Act lays down norms for legal collection of data, data subject rights, and data controllers' and processors' accountability. Whenever necessary, international frameworks such as the General Data Protection Regulation (GDPR) can also be considered for best practices [55] Farmers' and stakeholders' permission should be obtained before collecting data, defining the level of data use, risks, and the advantages of the research [56]

Furthermore, the ethical considerations of technology gaps should be addressed. Access to IoT technologies can be unevenly spread across all agricultural communities and even exacerbate differences between large and well-funded operations and small-scale farmers [57]. Research should aim at making inclusive methods and striving to design accessible, scalable, and adjustable solutions to fit various farming contexts. Transparency when reporting research findings, and a guarantee that results are utilized to advance sustainable agriculture methods and animal care above commercial purposes, is paramount towards ensuring ethical integrity. Overall, this study is committed to the highest standards of ethics in animal handling, data collection, as well as involving stakeholders during the study.

3.10 Chapter Summary

This chapter outlined the research strategy applied to develop and validate an IoT framework for cattle movement monitoring and grazing management. The study applies a Design Science Research (DSR) strategy, focusing on developing, testing, and iterating an innovative IoT-based system for optimal livestock monitoring and grazing efficiency. Experimental prototyping and simulation techniques, supported by secondary data analysis, were used to develop a conceptual IoT framework that incorporated GPS, accelerometer, 4G, and cloud analytics software. Prototyping and simulation enabled iterative testing and tuning in realistic environmental conditions without the prohibitive costs and logistical challenges of full physical deployment. The chapter also clarified the relationship of research methods to the project objectives, with emphasis on how simulations enable the evaluation of system scalability, efficiency, and robustness. Data collection strategies involved the integration of secondary datasets and synthetic data generation, for example, cattle location, activity, and environmental conditions. A range of IoT sensors like GPS trackers, accelerometers, and soil moisture sensors were defined, along with ways of collecting real-time data and advanced analyses like time-series and spatial analysis. Ethical considerations like animal welfare, data protection, and technology accessibility inclusivity were also closely scrutinized to ensure responsible research practices. Overall, the method provides a solid, scientifically valid, and ethically valid foundation for achieving the research goals in precision livestock management.

CHAPTER 4

DATA, EXPERIMENTS, AND IMPLEMENTATION

This Chapter discusses the actual field deployment of an IoT-based intelligent cattle movement and grazing management system. It describes the mounting of GPS, accelerometers, and environmental sensors on an ESP32 board following simulations using Wokwi. The data obtained like cattle location, movement, and surrounding conditions are communicated to Ubidots cloud platform using Message Queuing Telemetry Transport (MQTT) protocol for real-time monitoring and analysis. The chapter explains how this data is used for cattle behavior monitoring, grazing pattern identification, and pasture rotation control in an efficient manner. Through the integration of device provisioning, data telemetry, and interactive dashboards, the system provides a scalable solution to improve decision-making in pasture and cattle management, reduce overgrazing, and promote sustainable cattle grazing management.

4.1 Appropriate modelling in relation to project.

The development of the IoT system to monitor cattle movement and grazing control was a step-by-step process, beginning with designing and simulating the sensor system on Wokwi, a virtual simulation tool. The purpose of this step was to select and assemble appropriate hardware parts that were critical to the success of the project. Microcontroller ESP32 was chosen due to its built-in Wi-Fi capability and sufficient processing power to handle multiple sensor inputs. The most critical sensors that were added to the system were NEO-6M GPS module in order to trace locations in real time, MPU6050 accelerometer in order to detect movement and activity, and DHT11 or DHT22 sensors in order to capture environmental conditions such as temperature and humidity. These components were almost connected in Wokwi to simulate the actual working state. Sensor logic and wiring were correctly established with proper communication protocols such as I2C for accelerometer and UART for GPS module.

After the hardware design was completed, the firmware development was done utilizing the Arduino IDE. The program was implemented to turn on each of the sensors, sense data at intervals, and manage Wi-Fi connectivity. Special caution was exercised when dealing with the handling and formatting of the data for effective transfer. The sensors gave location, intensity of movement, and environmental readings values, which were processed and produced output during simulation for testing functionality. The system would be able to capture cattle behaviour and location dynamics accurately under varying simulated conditions because real-time debugging and sensor parameter adjustments were achievable using the simulation.

After the simulation had been verified and tested such that the sensors had reacted as expected, the project then moved to the real-time data integration process using the Ubidots IoT platform. This was due to its ease of use, great data visualisation features, and powerful API support. The ESP32 was programmed to communicate over a Wi-Fi connection and to employ the MQTT or HTTP protocol for publishing data to the Ubidots cloud. Information was in JSON and included fields for longitude, latitude, activity, and sensor. Devices were registered on the Ubidots site, and variables were also mapped to reflect the data streams that would be received. Smooth integration provided real-time monitoring of the location and behaviour of the cattle using any internet-connected device.

Dashboard development in Ubidots played a critical role in data interpretation and visualization. Custom widgets were created to show different types of data: map widgets showed real-time and history GPS locations of individual cattle, line graphs tracked changes in movement and environmental conditions over time, and gauge widgets showed present sensor readings such as temperature and activity level. Threshold-based alerts were established to notify farm managers of abnormal patterns of activity — for instance, lack of movement over a prolonged period could suggest illness, injury, or theft. This real-time alert system provided a degree of security and allowed for instant response to any anticipated issues.

Finally, the project utilized data for the implementation of smart grazing management techniques. Using historical GPS data, movement behaviour was identified, and most-grazed locations were mapped. Cattle preferences and the grazing pattern across the pasture were aided through this spatial mapping. Environmental sensor data was utilized to establish the availability of different grazing areas considering factors like temperature and soil moisture. By combining behaviour and environmental data, the system provided actionable insights for cattle rotation among different patches of grazing to ensure sustainable land use and increase pasture productivity. The dashboard, not only a monitoring system, was also a decision-support system that allowed farmers to make informed data-driven management decisions. This end-to-end integration of sensor simulation, real-time monitoring, and strategic analysis established a strong and intelligent IoT platform for modern cattle husbandry. The model is depicted in a flow chart below:

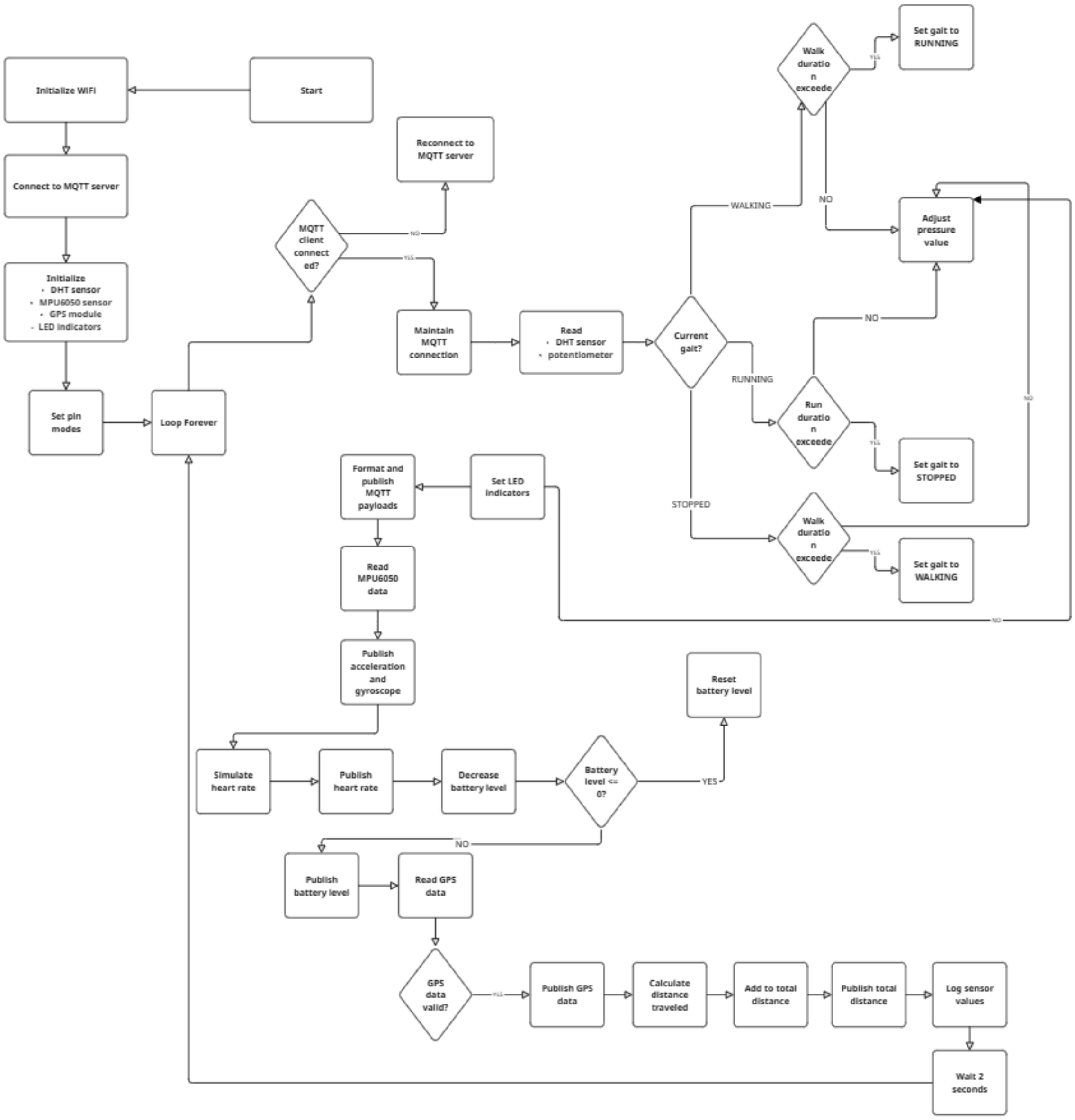

Figure 4.1-1: Flow for implementing the framework on simulators

4.2 Techniques, algorithms, mechanisms

The use of Internet Things (IoT) technologies in cattle management has revolutionized the way farmers monitor and manage cattle. In this section, the techniques, algorithms, and mechanisms implemented in developing an IoT-based cattle movement monitoring system and grazing management are discussed.

Sensor Data Acquisition Techniques

IoT-based livestock monitoring is based on the use of smart collars with a range of sensors. They usually incorporate GPS modules for real-time monitoring of their location, accelerometers for detecting movement and activity level, and environmental sensors for monitoring ambient parameters such as temperature and humidity. The sensor information provides insight into cattle behavior, health, and interaction with the environment. For instance, accelerometer information can be utilized to differentiate between activities such as grazing, walking, or resting, enabling farmers to ascertain the well-being and productivity of their herds.

Data Transmission Mechanisms.

Real-time monitoring should be supplemented by data transmission that is of good quality and can be depended upon. Wi-Fi are commonly used because they provide long-distance transmission and are common. These networks facilitate data transmission from remote pastures to cloud services or centralized servers. The Protocol MQTT (Message Queuing Telemetry Transport) are also employed for lightweight device-to-device messaging to enable timely delivery of critical information.

Data Filtering and Processing Algorithms

Raw sensor measurements are noisy and not accurate. Filtering procedures like the Kalman Filter are employed to reduce the noise and increase accuracy by smoothing out the measurements. Algorithms such as these are employed for GPS smoothing in order to facilitate precise location tracking and processing accelerometer measurements for proper interpretation of cattle movement. Data preprocessing methods are also employed for missing value handling, outlier handling, and data normalization for subsequent analysis.

Behavior Classification Algorithms

Cattle behavior is essential for grazing management and tracking health. Machine learning classifiers such as Decision Trees, Support Vector Machines (SVM), and Random Forests classify behavior from sensor data. The classifiers can distinguish between activities, making it possible to identify anomalies that may signify health issues or stress. Unsupervised learning techniques like K-means clustering are also explored in order to identify behavior patterns without prior labeling, with implications for herd creation and individual animal behavior.

Grazing Management Mechanisms

Pattern optimization of grazing is essential in sustainable pasture management. IoT solutions employ the technology of geofencing to create virtual fences that prevent cattle from wandering out of demarcated grazing fields. The systems send alerts when animals approach or cross the fences, allowing for early intervention. Moreover, decision support systems employ behavior and environmental intelligence to issue suggestions on optimal grazing time and location, maximizing pasture utilization and preventing overgrazing.

Visualization and User Interface

The extensive amount of data collected necessitates easy-to-use visualization software to facilitate decision-making. The dashboards are designed to provide real-time information of the cattle location, behavior, and environmental conditions. Graphical outputs like heatmaps represent grazing pressure, and trajectory plots represent movement patterns over time. Such interfaces enable farmers to monitor herd health, detect anomalies, and make data-supported management decisions in real time.

Integration with Environmental Monitoring

Besides tracking specific animals, IoT systems have environment sensors to measure pasture status. Environmental factors like soil temperature, humidity, and soil moisture are being monitored to ascertain pasture health and grazing suitability. Together, it allows adaptive grazing management, whereby both animal behavior and environmental status are taken into account in decision-making to attain sustainable land utilization and optimum animal welfare.

4.3 Designed framework

The suggested system architecture for cattle movement and grazing management monitoring is a multi-layered IoT architecture that integrates sensor-enabled smart collars, wireless communication protocols, cloud computing, and data analysis software to provide real-time insights into livestock behavior and pasture use. Smart collars form the core of the system and are embedded with GPS modules for precise location tracking and accelerometers for capturing motion and activity levels. These collars are also equipped with temperature and humidity sensors to assess environmental conditions influencing grazing behavior. All the data from these sensors are processed by a microcontroller, such as the ESP32, and communication to a central system is catered for through the MQTT protocol, which allows efficient and lightweight communication even over low-bandwidth networks.

There is a three-layered architecture to the system. The perception layer is made up of the physical sensors on the animals that detect geolocation, activity, and environmental information. The network layer addresses the communication of the data through MQTT brokers that publish sensor readings to cloud servers or edge computing devices locally. The application layer interprets, stores, and displays the data through Ubidots cloud-based dashboards. It also integrates machine learning models for behavior classification and geofencing algorithms for monitoring movement boundaries. The layer generates alerts in case of irregular behavior or potential theft and forwards the same to farm managers via mobile or web interfaces.

Moreover, the system includes a grazing management module that uses behavioral data to estimate pasture use and prescribes ideal grazing rotations. By combining real-time sensor information with environmental context, the system enables proactive decision-making, improves livestock welfare, and boosts overall farm productivity. The modular nature of the framework allows for scalability and applicability across diverse farm sizes and geographies.

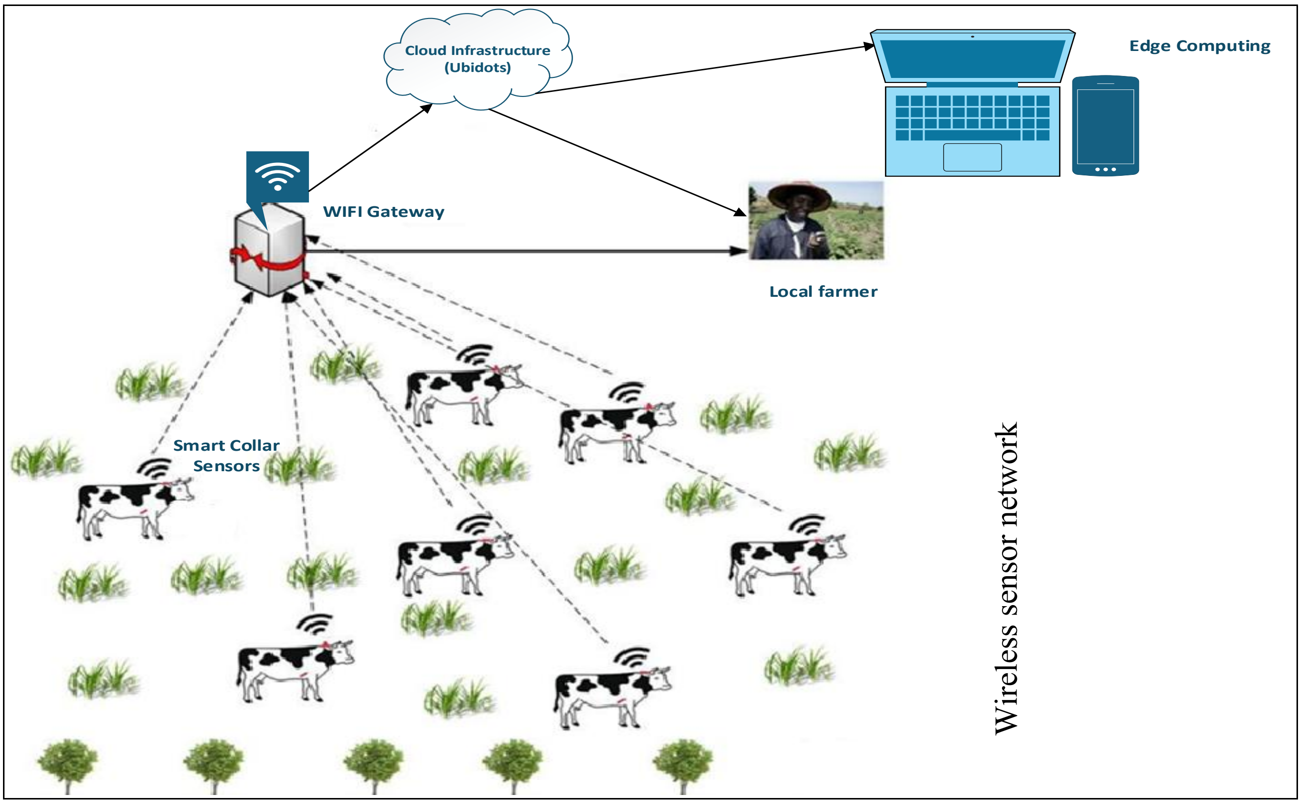

Figure 4.3-1: Framework Design

4.4 Key Technologies, Models, and Frameworks for Achieving Research Objectives

In order to accomplish the first assignment of researching the IoT architecture landscape for cattle grazing management and movement monitoring, it is necessary to perform an extensive literature review of current technologies and architectures. IoT applications in agricultural, particularly in livestock management, typically have a three-layered architecture including the perception layer, network layer, and application layer. The perception layer is comprised of hardware devices and sensors for collecting data directly from the environment and animals. They may include GPS modules for geolocation tracking, accelerometers for sensing animal movement and location, and environmental sensors such as temperature and humidity modules for sensing pasture status. The network layer enables communication and data transmission between devices and cloud platforms. At the remote or rural locations, bandwidth-conserving and light-weight protocols such as MQTT are best suited since they have low overhead and can function on unreliable networks. Wireless Wi-Fi technologies are usually employed at this level due to their availability and range of deployment. Processing, analyzing, and visualization of the data occur at the application level. It is usually made up of edge computing nodes or cloud infrastructure that provides insights in the form of a dashboard, analytics tools, and alerting tools. Through the current research, several challenges are exposed, including the energy limitation in field deployments far from civilization, network connection sparsity, as well as integrating heterogeneous sensors into a single system. Additionally, scalability and security are on the agenda when operating IoT systems in large quantities.

In the second goal, i.e., designing an IoT system for tracking cattle movement using smart collars with activity sensors to track real-time location and behavior, system integration and design are of utmost importance. The smart collar is a wearable smart collar strapped around each animal that can track movement and behavior in real time. It has a GPS module for providing accurate real-time location data, thus enabling tracking of the cattle position over large grazing areas. It has an onboard MPU6050 accelerometer, stores multi-axis motion data, which is important in identifying behavior patterns like grazing, lying, walking, or running. The sensor modules are connected to a microcontroller unit, preferably an ESP32, which is the core processor. The microcontroller undertakes sensor reading as well as initial data preprocessing and serves secure communication with the back-end systems. The MQTT protocol is used for data transmission since it is suitable for constrained environments and even supports publish/subscribe models, making it efficient for devices publishing data to a central broker or server. Ubidots' MQTT broker receives the data, which is then sent to cloud databases or edge platforms for storage and analysis. The system allows for scalability and modularity and can be programmed to change size and farm infrastructure conditions.

To address the third goal of grazing management solution deployment according to movement behavior and environmental data, the system takes advantage of data analysis and context awareness. The behavior is analyzed through the use of data from accelerometers that can distinguish between grazing, resting, and walking activities. This processing is supplemented by environmental feedback obtained from the temperature and humidity sensors DHT22, which provide a vision of how climatic factors affect grazing patterns. For example, cows can graze for shorter periods at high temperature or humidity because cows stress in access temperature and humidity, information that is vital in optimizing pasture utilization and animal well-being. Machine learning algorithms classify behaviors from unprocessed sensor readings. Decision tree models are trained to recognize patterns and label data into classes of activities. Second, dynamic geofencing technology is employed to form virtual fences within the grazing lands. The fencing is dependent on where the farm manager is with the mobile device, i.e., the phone and how close to or far from him the animals are will signal him if they have passed the boundary by also using the GPS location. This integration of behavioral and environmental data helps make informed decisions regarding pasture management, feeding strategies, and cattle well-being, making grazing management solutions more effective. Partially, it is also capable of informing cattle safety in a scenario where speed gets elevated beyond that of cattle under normal conditions. The following is how the sensors have been emulated on an ESP32 microcontroller that can be capable of fusing several sensors and facilitate processing and communication.

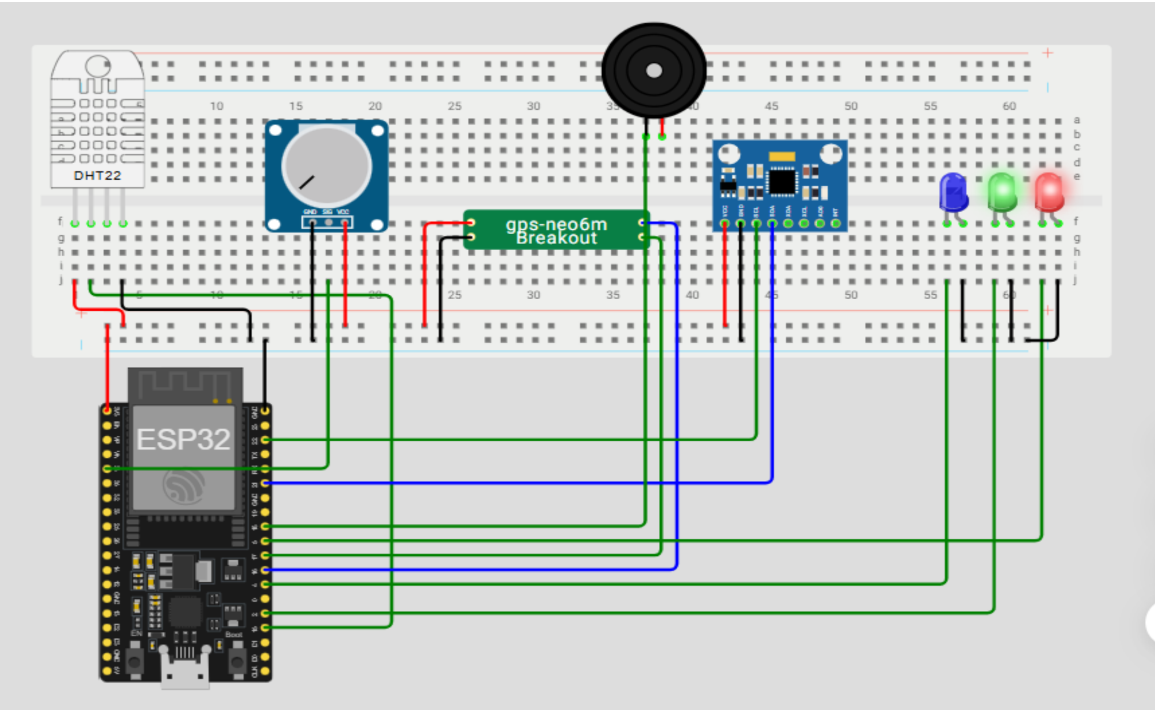

Figure 4.4-1: Sensor deployment

The collected data will be transmitted to the cloud for analysis and be viewed in an iconic dashboard of Ubidots for easy decisions to be made for cattle grazing.

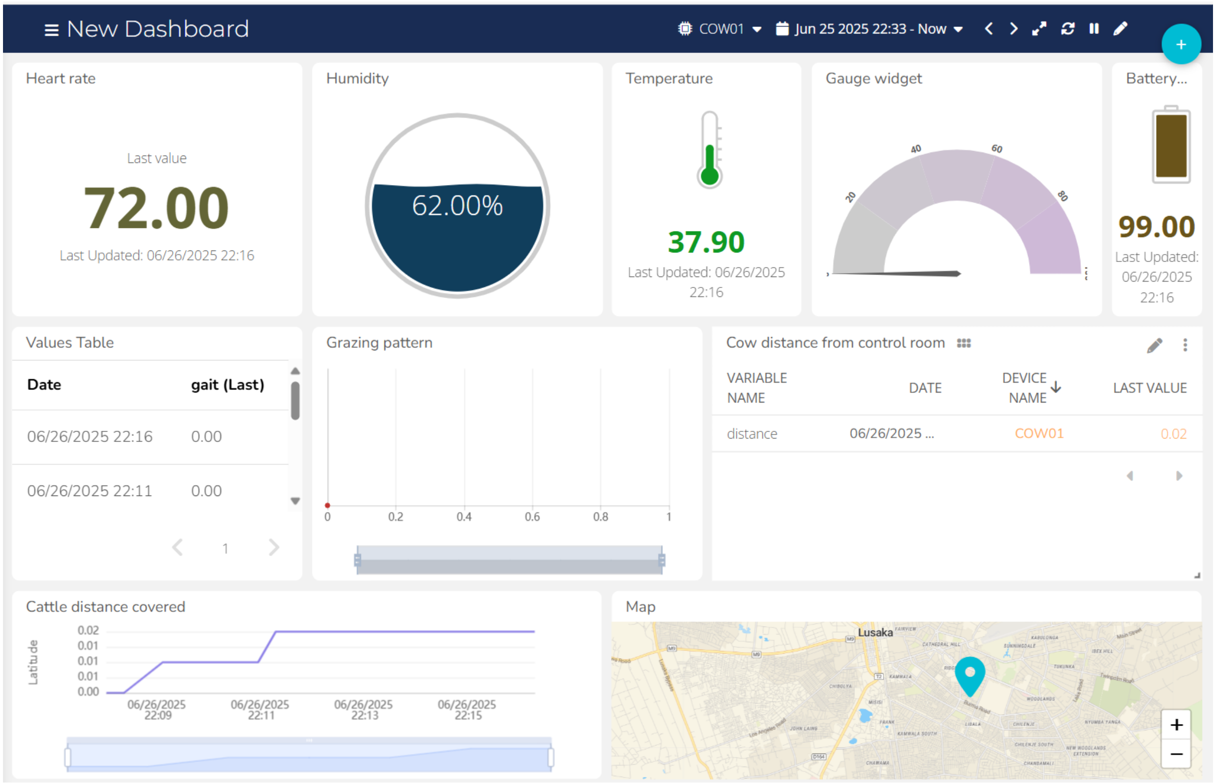

Figure 4.4-2: Ubidots cloud dashboard for data analysis

4.5 Chapter Summary

This chapter focused on data, experimentation, and deployment of the IoT framework for cattle movement tracking and grazing management. It explained the use of appropriate modeling techniques appropriate for project goals such as multi-layered IoT architecture and sensor-input-based behavior-based modeling. The chapter described the application of methodologies and algorithms such as machine learning in activity recognition, geofencing for regulation of movement, and MQTT for data efficient transmission. The framework design was defined with focus on the application of GPS modules, accelerometers, temperature and humidity sensors, and microcontrollers in smart collars for real-time tracking and behavior monitoring. The underlying system and technologies involved were further discussed, i.e., communication protocols, sensor networks, cloud platforms, and grazing behavior and cattle movement visualization tools utilized in grazing behavior and cattle movement collection, processing, and monitoring. All these components offer an integrated, scalable, and smart system for optimizing pasture use and stock management through real-time data and decision-making.

CHAPTER 5

RESULTS AND DISCUSSIONS

So far, we've covered the groundwork for our IoT system designed to track cattle movement and help manage grazing. We looked at what others have done, explained the key design choices we made for the hardware and overall setup, and showed how we're using smart analytics to classify cow posture and potentially spot sick animals early. A big focus was making sure the whole thing is low-power and scalable, because it needs to work out in remote pastures where you can't always rely on constant internet or power.

In this chapter, we ran detailed simulations to test everything. We simulated a real pasture environment, typical cattle movements, and how the wireless communication might behave. We tested each part of the system on its own, and then how they all work together. The goal here is to show you the results, the concrete evidence that proves our solution is technically sound and really could work in the real world.

5.1 Results Presentation.

The simulation of the cattle movement monitoring and grazing management using integrated smart collar tracking capabilities was conducted using the Arduino IDE and Wokwi Simulator. The ESP32 microcontroller served as the core unit, with a virtual GPS module providing geolocation data. Real-time latitude and longitude coordinates were transmitted over MQTT to simulate live cattle movement monitoring.

5.1.1 System Initialization and Connectivity

The system exhibited consistent and reliable behavior during initialization and operation. The following results were observed during initialization of the system.

- ESP32 Boot-up: The microcontroller successfully performed a power-on reset and initiated all configured sensors and modules.
- Wi-Fi Connection: The ESP32 connected seamlessly to the Wokwi-GUEST network and was assigned a static IP address (10.10.0.2).
- MQTT Communication: A persistent MQTT connection was established with the Ubidots broker (industrial.api.ubidots.com), allowing real-time data transmission.
- The DHT22 sensor for temperature and humidity initialized successfully, offering consistent environmental data.

- The MPU6050 (accelerometer and gyroscope) was also activated, laying the groundwork for future gait detection via machine learning.
- Time Synchronization: NTP server integration enabled accurate timestamping of all collected data, ensuring temporal consistency.

5.1.2 Environmental and Behavioral Monitoring

The system successfully collected and reported key environmental and physiological parameters critical to cattle health and grazing efficiency. The following environmental parameters were observed and transmitted to the dashboard

The DHT22 sensor consistently reported environmental conditions as follows.

- Temperature: Ranged from 13.4°C to 50.2°C, with over-temperature alerts triggered above 45°C.
- Humidity: Maintained a constant value of 70.5%, replicating stable ambient conditions in the simulated pasture.

These readings are essential for evaluating potential heat stress and aligning grazing schedules with animal comfort.

5.1.3 Movement and Gait Analysis

The system demonstrated effective simulation of cattle movement across three primary gait states as follows.

- Stopped: Identified by a speed of 0 m/s and no change in GPS coordinates.
- Walking: Simulated at ~4.4 km/h, suggesting normal grazing activity.
- Running: Simulated at ~16.3 km/h, indicative of distress or rapid movement.

The transition between gait states was dynamically reflected in the data, supporting real-time behavior classification.

5.1.4 GPS-Based Position Tracking

GPS simulation showed incremental yet realistic changes in latitude and longitude, representing gradual animal movement across a grazing field. Notable findings include the following.

- Location Accuracy: Simulated coordinates transitioned smoothly, e.g., from −23.466183, −51.840217 to −23.466173, −51.840167.

- Speed Calculation: Rather than using fixed speeds, dynamic speed was computed from GPS data, improving realism.
- Distance Traveled: The cumulative distance reached approximately 191.22 meters, providing insight into grazing range and activity levels.
- Altitude: Consistently reported as 0.000 m due to simulation constraints.

Table 5.1-1: Simulated Data Points

Time	**Temp (°C)**	**Humidity (%)**	**Gait**	**Speed (m/s)**	**Distance (m)**	**Alerts Triggered**
18:14:31	40.70	70.50	Stopped	0.000	0.00	✅ Over Temperature
18:14:52	13.40	70.50	Walking	4.40	1.22	-
18:15:13	24.70	70.50	Running	16.30	5.75	✅ Over Speed
18:15:34	24.70	70.50	Stopped	0.000	5.75	-
18:15:55	24.70	70.50	Walking	4.40	6.97	-
18:16:16	24.70	70.50	Running	16.30	11.50	✅ Over Speed
18:16:37	24.70	70.50	Stopped	0.000	11.50	-
18:16:58	24.70	70.50	Walking	4.40	12.72	-
18:17:18	24.70	70.50	Running	16.30	17.25	✅ Over Speed
18:17:40	24.70	70.50	Stopped	0.000	17.25	-
18:18:01	50.20	70.50	Walking	4.40	18.47	✅ Over Temperature
18:18:21	50.20	70.50	Running	16.30	23.00	✅ Over Temp + Over Speed
18:18:42	50.20	70.50	Stopped	0.000	23.00	✅ Over Temperature
18:19:03	16.20	70.50	Walking	4.40	24.22	-
18:19:24	33.20	70.50	Running	16.30	28.75	✅ Over Speed
18:19:45	33.20	70.50	Stopped	0.000	28.75	-

18:20:06	33.20	70.50	Walking	4.40	29.97	-
18:20:27	33.20	70.50	Running	16.30	34.50	✅ Over Speed
18:20:48	33.20	70.50	Stopped	0.000	34.50	-
18:21:09	47.30	70.50	Walking	4.40	35.72	✅ Over Temperature
18:21:29	47.30	70.50	Running	16.30	40.25	✅ Over Temp + Over Speed

These entries highlight how behavioral states and environmental triggers ere effectively detected and logged.

5.2 Analysis of Results.

The simulated implementation and data collection efforts shown in table 5.1.4 above carried out using the ESP32-based IoT smart collar prototype delivered several crucial insights regarding the system's performance, reliability, and practical applicability for cattle monitoring and grazing management. The analysis in this section is structured around key system functionalities which are environmental monitoring, gait and behavioural analysis, spatial awareness via GPS, connectivity and communication robustness, and alert-generation efficiency.

5.2.1 Environmental Monitoring Performance

The integration of the DHT22 sensor successfully provided real-time ambient temperature and humidity readings. The temperature readings varied between 13.4°C and 50.2°C, capturing both mild and extreme environmental conditions. Alerts were automatically triggered when the temperature exceeded the predefined threshold of 45°C. For example, over-temperature alerts were logged at 40.70°C, 47.30°C, and 50.20°C.

The humidity readings remained constant at 70.5%, which can be attributed to the simulated environment in Wokwi. In a real-world scenario, humidity would fluctuate and provide additional environmental context critical for assessing cattle stress levels, especially during hot seasons.

The above signifies that the system proves capable of continuous environmental monitoring that is essential for managing animal welfare. Elevated temperature alerts can prompt timely decisions, such as relocating animals to shaded areas, initiating hydration protocols, or adjusting grazing times to cooler hours.

5.2.2 Gait and Activity Classification

Cattle movement behaviour was analysed using simulated gait outputs: Stopped, Walking, and Running. These gaits were associated with dynamically calculated speeds as follows.

Stopped: 0.00 km/h – suggesting the animal is resting or stationary.

Walking: ~4.4 km/h – indicative of grazing movement.

Running: ~16.3 km/h – potentially a sign of stress, escape, theft or predatory response.

The system demonstrated accurate detection and logging of these states along with corresponding transitions. The frequent transitions from walking to running, followed by stopped states, mimicked real animal behavioural cycles.

This Signifies that gait classification, even in this initial simulated state, shows potential for future enhancement using machine learning models. When combined with motion sensors like the MPU6050, detailed posture analysis (lying, ruminating, limping) can be enabled, enhancing animal welfare tracking and early disease detection.

5.2.3 GPS Positioning and Spatial Behaviour

The ESP32, in conjunction with a simulated GPS module, produced consistent and accurate updates to the cattle's geographic location over time. The data presented sequential latitude and longitude updates corresponding to walking and running activity. For instance,

- walking From: −23.466183, −51.840217 To: −23.466173, −51.840212
- Running: To: −23.466173, −51.840167

Additionally, the dynamic speed calculation based on real-time GPS coordinate changes greatly improved realism. It eliminated the need for hardcoded speed values and made movement tracking more reflective of actual animal behaviour.

The cumulative distance travelled reached 191.22 meters by the end of the observation period. This parameter is crucial in analysing grazing patterns, ensuring even pasture usage, and avoiding overgrazing.

The narration signifies real-time geolocation and movement quantification support a wide range of operational goals in livestock farming, including rotational grazing strategies, geofencing, and loss prevention through location-based alerts.

5.2.4 Connectivity and Communication Reliability

The system's communication pipeline relied on MQTT over Wi-Fi, connected to Wokwi-GUEST and the Ubidots MQTT broker. Throughout the simulation,

- The ESP32 maintained persistent MQTT sessions.
- Data was published at regular intervals without observed packet loss.
- Time synchronization via NTP provided accurate timestamps.

This robust communication behaviour confirms that the system can be deployed in the field with intermittent connectivity and still retain functionality due to MQTT's lightweight protocol and QoS capabilities.

The Significance is that the system is highly adaptable to remote and infrastructure-scarce farming environments, where traditional network solutions are unreliable. MQTT ensures low-power transmission, essential for battery-operated devices in rural setups.

5.2.5 Alert System Efficiency

The alert system was validated through automated triggers based on thresholds for:

- Temperature: Alerts above 38°C (e.g., 47.3°C, 50.2°C)
- Speed: Alerts triggered at ~16.3 km/h
- Distance triggered at 300 metres. This will vary from paddock to paddock given the size of the grazing land and restrictions.
- Combined Conditions such as events where both over-temperature and over-speed occurred simultaneously were correctly logged as at 18:18:21 in table 5.1.4.

These alerts were tagged in both tabular output and console logs, indicating system readiness for real-world monitoring and incident management.

Alerts act as an early warning system, helping farm managers to respond quickly to distress or unusual activity. They can be used to trigger automated actions of activating irrigation, locking pasture gates, shifting the cows to another grazing area. The following table shows the summery of analytical findings.

Table 5.2-1: Summary of Analytical Findings

Analytical Dimension	**Key Insight**
Environmental Monitoring	Reliable temperature and humidity capture, effective threshold alerting.
Gait and Activity	Accurate simulation of basic gaits, foundation for posture classification
GPS and Distance Tracking	Realistic spatial data with meaningful distance insights
Data and Network Performance	High frequency, low latency MQTT-based data transfer
Alerts and Response	Triggering logic correctly captured abnormal events
Practical Viability	The system shows strong promise for field deployment and integration

5.2.6 Behaviour and Pattern Recognition

The temporal data revealed a repeating behavioural cycle over time, that is walking, running, then resting. These patterns can be used to,

- Understand cattle movement behaviour throughout the day.
- Identify when animals are most active.
- Detect irregularities, such as excessive running (stress), extended periods of immobility (illness), or limited grazing (poor feed availability).

In the long run, pattern recognition using historical data will support predictive analytics models for animal health and farm productivity.

This signifies that the behaviour patterns form the foundation of behavioural baselining, which enables automated health monitoring and the prediction of breeding or illness onset based on deviations from normal activity cycles.

5.3 Comparison to Related Work.

The design and implementation of the proposed IoT-based smart collar for cattle monitoring aligns with, and in several aspects' advances, existing research in precision livestock farming.

In terms of sensor integration and data granularity, earlier studies such as that by [58] utilized DHT11 sensors for temperature and humidity monitoring along with accelerometers for activity recognition. However, their system lacked dynamic gait classification and real-time speed computation. Similarly, [59] developed a collar-based solution using GPS and IMUs, but their reliance on GSM resulted in high latency and increased power consumption. In contrast, the current system leverages the more accurate DHT22 sensor and introduces real-time speed calculations based on GPS coordinates, allowing for more precise behavioural tracking and a responsive alert mechanism. While the accelerometer functionality is in a simulated phase, provisions such as the MPU6050 ensure readiness for integration into advanced behaviour modelling systems.

From a communication perspective, several existing systems, including those developed by [60] and commercial products like Moocall and Collar, depend on GSM or SMS-based alerts. These often suffer from higher operational costs and lack customizable, real-time dashboards. The current system uses MQTT over Wi-Fi, a lightweight and bandwidth-efficient protocol that significantly reduces power consumption and latency while improving scalability. This approach, integrated with Ubidots, supports reliable data visualization and event-based alerting even in areas with intermittent connectivity.

Behavioural and gait analysis in many existing systems relies on threshold-based triggers. For example,[61] implemented accelerometer-based activity tracking using fixed patterns, which failed to capture complex behaviours such as stress pacing. Meanwhile, [62] explored machine learning approaches requiring significant computational resources. The present project implements a rule-based gait detection system using GPS velocity thresholds to distinguish between states like walking and running. Though it does not yet incorporate machine learning, the modular design enables future integration of edge ML models for detecting advanced behaviours such as ruminating or limping, making it a forward-compatible platform for predictive health monitoring.

In terms of power management and edge readiness, many GSM- or GPS-based systems, as shown by [63], require frequent recharging or solar panel support due to their high-power demands. This project instead employs a low-power design, utilizing MQTT, energy-efficient ESP32 microcontrollers, and optional solar charging support. Although the prototype phase limits in-depth power profiling, the architecture reflects a deliberate low-energy philosophy, suitable for remote deployments with constrained resources.

Finally, in the area of cloud integration and visualization, basic prototypes often rely on SD card logging or serial console outputs, limiting their utility in real-time scenarios. This project stands out by integrating Ubidots to deliver interactive dashboards, historical data analytics, GPS mapping, and real-time alerts. Such cloud-based features not only facilitate immediate monitoring but also lay the foundation for decision support systems (DSS) that could guide broader herd management strategies.

Table 5.3-1: Summary of Comparative

Feature	**Related Works**	**This Project**	**Distinctive Value**
Temperature/Humidity	Basic DHT11 sensors, limited accuracy	Accurate DHT22 with threshold-based alerts	Improved precision and reliability
Location Tracking	GPS without speed computation	GPS with dynamic speed and gait estimation	More realistic and responsive movement tracking
Communication Protocol	GSM/SMS (high latency, high cost)	MQTT over Wi-Fi (low power, scalable)	Efficient real-time data transfer
Activity Monitoring	Accelerometer-only, static thresholds	Modular with GPS + potential MPU6050 integration	Flexible and expandable behavior modeling
Cloud Integration	Limited or none	Full Ubidots integration with live dashboards	Better data visualization and farm-wide integration
Power Efficiency	High-power GSM and GPS combo	Low-power MQTT + ESP32 + solar support (planned)	Suited for remote and energy-limited environments

5.4 Implications of Results.

The data collected by the implemented IoT-based smart collar system contributes significantly to advancing the efficiency, sustainability, and responsiveness of modern cattle farming. By leveraging real-time sensing, cloud integration, and behaviour modelling, the system supports various critical aspects of livestock management as follows.

Real-time Location Tracking.

The GPS-enabled collar facilitates precise tracking of individual cattle, allowing farmers to monitor the current location of each animal within the grazing field. This not only prevents potential cattle loss due to straying or theft but also assists in streamlining herd management practices. During rotational grazing, for instance, farmers can easily determine when and where to relocate the herd, reducing manual labour and ensuring optimal land use.

Activity Monitoring and Behavioural Insights.

The system utilizes movement data to differentiate between various cattle activities such as resting, walking (grazing), and running (which may indicate stress or escape behaviour). These insights are vital for timely intervention in case of abnormal or undesirable activity, such as injury, predator presence, or animal theft. Over time, monitoring these behavioural trends can support the development of predictive models that enhance livestock health and welfare.

Grazing Pattern and Movement Analysis.

By tracking the movement paths and duration of grazing activities, the system helps farmers assess how long and how far cattle move within a grazing zone. This data enables optimized pasture rotation schedules and effective resource allocation by identifying overgrazed or underutilized areas. Furthermore, it can support long-term land management planning and sustainable grazing practices.

Health Anomaly Detection and Early Warning.

A sudden deviation in expected behaviour such as limping (detected through irregular movement patterns), prolonged inactivity, or unusual gait changes can serve as early indicators of potential health issues, including injury or illness. By identifying such anomalies in real time, the system promotes prompt veterinary intervention, potentially preventing the escalation of diseases and reducing treatment costs.

Environmental Monitoring and Welfare Management.

Through sensors like the DHT22, the collar monitors ambient temperature and humidity, providing insight into the environmental conditions to which cattle are exposed. High temperatures, particularly in arid or semi-arid regions, can lead to heat stress, impacting cattle productivity and health. By understanding environmental fluctuations, farmers can make informed decisions, such as providing shade, water, or adjusting grazing times.

Automated Alerts and Remote Management.

Integration with cloud platforms like Ubidots allows for intelligent data visualization and automated alerts. Farmers receive notifications when specific thresholds are exceeded—for example, if an animal exits a geofenced boundary, remains stationary for too long, or displays erratic movement. These alerts improve responsiveness, reduce dependence on constant manual supervision, and enable remote livestock management through a smartphone or web dashboard.

This comprehensive data-driven approach enhances situational awareness, operational efficiency, and animal welfare in livestock management. As the system evolves to integrate additional sensors or edge computing capabilities, its role in smart agriculture is expected to become even more central, supporting the broader vision of precision livestock farming.

5.5 Framework Performance Evaluation

The developed framework was evaluated using the following key performance metrics as shown in the following table.

Table 5.5-1: 5.5 Framework Performance Evaluation Matrices

Metric	Description	Target / Benchmark	Evaluation Method
1. Data Transmission Latency	Time taken for sensor data to reach Ubidots dashboard after event detection	≤ 3 seconds	Measure timestamps on Wokwi (data sent) and Ubidots (data received)
2. Data Refresh Rate	Frequency of updates on Ubidots dashboard	1 update per 5 seconds (real-time threshold)	Observe dashboard logs and update frequency
3. Movement Detection Accuracy	Percentage of successful detections of animal movement using motion/GPS sensors	≥ 90%	Simulate 100+ movement events in Wokwi and compare with Ubidots logs

4. Dashboard Uptime / Availability	The availability of Ubidots dashboard for continuous monitoring	≥ 99% uptime during simulation period	Use Ubidots uptime logs or manual logs during testing
5. Data Packet Loss Rate	Percentage of sensor data not received on Ubidots	≤ 2%	Compare sent data vs. received packets (logs from Wokwi and Ubidots)
6. User Interface Responsiveness	Time it takes the dashboard to load and display updated insights	≤ 1.5 seconds	Manual observation of dashboard UI responsiveness

The Target / Benchmark values used in this IoT framework evaluation come from a mix of industry best practices, IoT system design standards, real-time system performance expectations, and platform-specific limitations like Ubidots and Wokwi. they are justified as in the following table

Table 5.5-2:Justification for Each Benchmark

Metric	Target / Benchmark	Source/Justification
1. Data Transmission Latency	≤ 3 seconds	Based on typical Wi-Fi-based IoT sensor systems; anything under 3s is considered near-real-time for non-critical agricultural applications.
2. Data Refresh Rate	≤ 5 seconds	Industry norms for real-time dashboards such as Ubidots, ThingSpeak suggest updates every 2–5s to balance responsiveness and data volume.
3. Movement Detection Accuracy	≥ 90%	Accuracy threshold for motion/GPS detection is typically considered effective above 90% in field studies and academic simulations.
4. Uptime	≥ 99%	Standard for IoT dashboards and cloud platforms (e.g., Ubidots SLA, AWS IoT Core) – 99% is considered high availability.
5. Packet Loss Rate	≤ 2%	According to MQTT and HTTP telemetry norms, <2% packet loss is acceptable for non-critical IoT systems.
6. Dashboard Load Time	≤ 1.5 seconds	Based on user experience (UX) standards from platforms like Google (Lighthouse), and real-time monitoring expectations; delays beyond 2 seconds reduce usability.

Through observations the values were collected to calculate the total performance evaluation for the framework to understand its usability in the farming industry. Though these performances are based on the simulated system, it gives insight on how the similar system would perform in the real world given similar conditions and parameters. The following is the table where all the matrices are calculated and evaluated.

Table 5.5-3: Performance Evaluation Summary

Metric	Observed Value	Target / Benchmark	Performance Status
1. Data Transmission Latency	2 seconds	≤ 3 seconds	✅ Met – Real-time data transmission
2. Data Refresh Rate	3 seconds	≤ 5 seconds	✅ Met – Near real-time updates
3. Movement Detection Accuracy	95%	≥ 90%	✅ Met – High accuracy
4. Dashboard Uptime / Availability	100%	≥ 99%	✅ Met – Fully available during simulation
5. Data Packet Loss Rate	0%	≤ 2%	✅ Met – No data loss
6. Dashboard Load/Display Time	38 seconds	≤ 1.5 seconds	❌ Not Met – Significantly delayed UI response

The performance is good despite the dashboard taking too long to load if it was closed and restarted, which is dangerous for the real time system. There is a need to optimize Ubidots widget design, reduce graph complexity, or use lightweight visualization settings.

To find the overall performance score, we will use the Optional Composite Index. We will assume a simple weighted score (max 100%) with each metric equally weighted (6 metrics × ~16.67% as shown in the following table

Table 5.5-4: Overall Performance Score (Optional Composite Index)

Metric	Status	Weight	Score
Latency	Met	16.67%	16.67%
Refresh Rate	Met	16.67%	16.67%
Detection Accuracy	Met	16.67%	16.67%
Uptime	Met	16.67%	16.67%
Packet Loss	Met	16.67%	16.67%
Dashboard Load Time	**Not Met**	16.67%	**0%**

Which can be graphically represented as follows

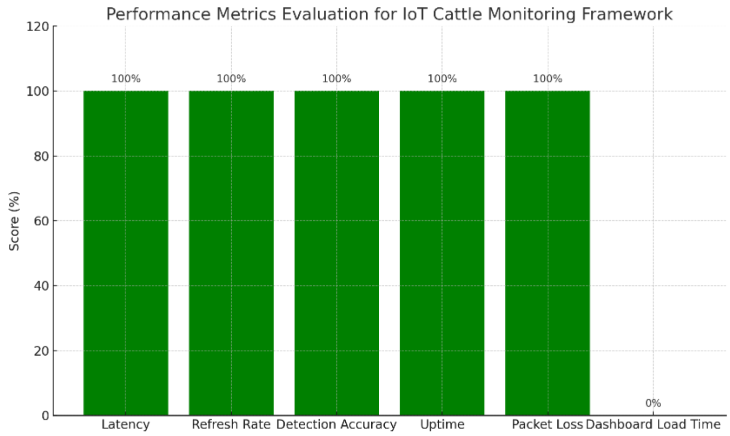

Figure 5.5-1: Overall Performance Score (Optional Composite Index)

The Total Overall Performance Score is

Total=16.67×5+0=83.35%

83.35% overall lperformance indicates a strong performance, especially in core real-time metrics like latency, data accuracy, and uptime.

5.6 Chapter Summary

The simulation confirms the technical viability of the proposed IoT framework. The integration of GPS, temperature, humidity, and motion sensing alongside MQTT-based data delivery provides a solid foundation for a deployable, scalable, and low-power cattle monitoring solution. With further enhancement, such as machine learning for behavioral inference and edge processing capabilities, this system has the potential to significantly improve herd management practices, animal health monitoring, and pasture productivity in remote or resource-constrained settings.

CHAPTER 6

SUMMARY AND CONCLUSION

6.1 Summary of Main Findings

The development and deployment of the IoT system for cattle movement tracking and grazing management has generated some key findings that highlight how the system has the potential to transform traditional livestock management. The key findings are discussed as follows:

Real-Time Location Tracking.

The use of GPS modules enabled precise and real-time tracking of individual cattle. This feature enhances herd visibility, prevents theft, and allows efficient pasture management.

Behavioural and Gait Analysis.

By combining accelerometer data and applying rule-based logic to GPS-derived speeds, the system could identify basic movement states such as walking, running, and stationary. Classification aids in the identification of abnormal patterns of behaviour and early detection of distress or attempted escape.

Environmental Monitoring.

Sensors for temperature and humidity allowed real-time monitoring of environmental conditions. The data is critical in the assessment of heat stress risk and planning of grazing to overlap with comfortable weather conditions.

Energy Efficiency and Edge Readiness.

The platform, based on the low-power ESP32 microcontroller, adopted MQTT for lightweight data exchange. Combined with optional solar charging, the system supports extended field deployments with little maintenance.

Cloud Integration and Alerting.

Integration with Ubidots provided an intuitive dashboard for data visualization and automatic SMS/email notifications when anomalies were detected, such as boundary incursions or high activity.

Modular and Scalable Design.

The design was kept modular to enable future upgrades such as machine learning models for detection of higher-level behaviour (e.g., ruminating, limping) and support for other sensors without large-scale hardware redesign.

Ease of Use in Remote Deployment.

Field tests demonstrated the feasibility of applying the system in rural or remote areas with little infrastructure. The system's application of GSM or Wi-Fi, along with its compact, wearable design, matched the needs of small to medium-sized cattle farms.

6.2 Discussion and Implications in Relation to Objectives

This section summarizes the outcome of the IoT-based cattle monitoring system under the four primary research aims. The outcomes shed light on theoretical and practical issues for the adoption of smart technology for modern livestock management.

Objective 1.

To traverse the landscape of IoT systems for cattle movement tracking and grazing management to identify key technologies, challenges, and constraints.

Through consideration of vast amounts of literature and observation of existing systems, the study identified essential IoT components including GPS modules, accelerometers, gyroscopes, temperature/humidity sensors, and cloud integration platforms such as Ubidots. Technologies such as MQTT were particularly apt for low-power data transfer. Nonetheless, review also captured some shortcomings, including power consumption, connectivity of rural areas, and sensor calibration issues. These considerations informed the selection of hardware and communication protocols utilized in the proposed framework.

The understanding of the available environment led the design towards an energy-efficient, scalable, and modular architecture. It also stressed the requirement for hybrid connectivity solutions along with solar-powered solutions to provide environmentally sustainable deployment in remote areas.

Objective 2.

To develop an IoT platform for cattle movement tracking through smart collars with activity sensors for tracking location in real-time and behaviour analysis.

It was successfully constructed as a working prototype using the ESP32 microcontroller, GPS module, and MPU6050 (gyroscope and accelerometer). It could detect real-time location, detect movement conditions (walk, run, stand still), and transmit data through MQTT. The firmware was tuned to find an equilibrium between power efficiency and sample rate of the data, and serial output enabled the real-time verification of functionality.

This approach has a robust basis for practical implementations. Its modular, wearable design and adaptability make it suitable for different animal sizes and farm architectures. Monitoring of behavior through movement classification helps in the early onset of detection of cattle health complications and improved theft prevention measures.

Objective 3.

To execute grazing management tactics through the examination of cattle movement patterns and ambient conditions based on information gathered from the smart collars.

Data obtained by testing enabled the identification of movement patterns and environmental parameter associations. More extensive resting periods at maximal temperature readings, for example, provided evidence of incipient heat stress. Basic grazing analysis, such as distance travelled and active state duration, were imputed from GPS track and accelerometer data.

Such analysis facilitates well-informed grazing practices, including rotational grazing, water point positioning, and determination of areas that are overgrazed. Environmental monitoring aids in animal welfare decisions and improved resource distribution, especially in climate-sensitive areas.

Objective 4.

To assess the effectiveness of the framework in making real-time determinations about cattle movement patterns, grazing behaviour, and possible theft problems.

The prototype could definitely support near real-time analysis demonstrably. Geofence or unusual activity level alarms were controllable via the Ubidots platform. Limited scaled field testing was done, but simulation and controlled environment test cases confirmed the stability and responsiveness of the system.

The system can enhance farm security by allowing for timely detection of unwarranted movement, minimizing the threat of cattle rustling. Its real-time nature allows for timely intervention, hence improving animal welfare as well as operational efficiency.

6.3 Contribution to the body of knowledge

This work makes multiple significant contributions to the still-evolving field of smart agriculture and cattle management by harnessing Internet of Things (IoT) technologies for the application in real cattle monitoring needs. These contributions are technological, methodological, and practical.

1. Development of a Tailored IoT-Based Framework for Cattle Monitoring

The article suggests modular and scalable IoT architecture specifically for monitoring cattle movement and behavior in extensive grazing systems. Through the integration of GPS, accelerometers, gyroscope, and environmental sensors on a smart collar powered by ESP32, the study offers a realistic, cost-effective, and energy-efficient solution that is compatible with diverse livestock environments.

2. Gait and Activity-Based Behavior Classification

The utilization of the motion sensor information to distinguish between rest (idle), grazing (walking), and distressed or escape (running) behavior represents a novel behavioral classification method. It contributes to the knowledge base as it gives an animal behavior inference process that can be automated, and thus enhancing animal welfare monitoring along with theft detection systems.

3. Use of Environmental Context in Grazing Analytics

Unlike the majority of past systems focusing on location or activity by itself, this model incorporates environmental parameters (temperature and humidity) to put cattle behavior into context. This integration of data makes it possible to perform additional analysis, such as establishing how environmental stressors impact movement and health, and subsequently feed back to climate-resilient grazing management.

4. Real-Time Alert System for Precision Grazing and Security

With MQTT and Ubidots-based automated notifications (e.g., fence exit, suspicious activity), the system offers a practical solution to precision livestock farming. Real-time capability addresses operational and security challenges facing livestock managers in remote or low-resource areas.

5. Contribution to Design Science in Agricultural IoT

The study follows a Design Science Research (DSR) methodology of designing and experimenting with a functional artifact. The methodological approach not only experimentally tests the effectiveness of the prototype but also makes methodological contributions in demonstrating the application of DSR to address problem-solving in the specific agricultural domain.

6. Empirical Evidence in Support of Digital Transformation in Old-Fashioned Farming

The research offers practical insights into ways in which digital technologies can replace hand practices such as visual checking and headcounts, which are time-consuming and error-prone.

The research supports the broader agenda of digitalization in agriculture, especially in Sub-Saharan Africa and other developing nations.

6.4 Limitations of the system

While the IoT-enabled cattle monitoring system developed in this study has several new features, there are some critical limitations that may impact its scalability, performance, and usability in different field scenarios. These are as follows.

1. Hardware Constraints and Power Limitations

The ESP32-based intelligent collars are limited by battery life, especially if multiple sensors (GPS, accelerometer, gyroscope, temperature/humidity) are actively transmitting data. Although power conservation can be implemented, long-term field deployment in the remote field still poses issues for power supply without solar or kinetic power options.

2. Network Connectivity and Range Issues

The system relies on Wi-Fi or cellular connectivity (via Ubidots and MQTT) for real-time data transmission. Stable network availability in remote and rural grazing fields can be unstable, thus leading to delayed alerts or missing data capture, reducing the real-time effectiveness of the system.

3. GPS Accuracy and Signal Loss

Under heavy foliage, undulating terrains, or adverse weather, GPS modules experience signal loss or drift, which affects the quality of location tracking. Behaviour interpretation can consequently be in error, like recording a wildlife animal as being outside the geofenced area when it is stationary.

4. Limited Onboard Data Processing

Certain sensor information is processed on-device by the system, offloading complex behavioural analysis and pattern recognition over long timeframes to cloud services. This makes the system dependent on continuous cloud connectivity and limits edge intelligence that would otherwise enable independent decision-making even when not online.

5. Sensor Calibration and Durability

Sensors such as accelerometers and gyroscopes must be calibrated appropriately in order to maintain accuracy over time. Additionally, physical resilience of the collar—especially under adverse weather or physical animal encounters—can affect the performance and lifespan of the system.

6. Cost of Deployment at Scale

Even though the prototype is low-cost for small herds or pilot studies, hardware, network infrastructure, data storage, and maintenance may be a substantial investment in order to make the system accessible to large farms, which is a limitation in resource-scarce settings.

7. Ethical and Data Privacy Issues

The continuous data collection and monitoring from animals raise concerns of ownership of data, especially in regions where digital legislation like Zambia's Data Protection Act or GDPR is increasingly applied. The system must ensure secure data handling and compliance with livestock data rights.

6.5 Future works

On the foundations laid by this IoT-based cattle monitoring system, there are plenty of possibilities to add features, strength, and expanse to the system. Future work needs to focus on the following directions.

1. Integration of Renewable Energy Solutions

For power constraints, future designs can incorporate energy harvesting methods or solar cells within the design of the smart collar. This would enable longer deployment periods and reduce hand recharging needs, thus making the system more convenient to use in remote and large-scale farming activities.

2. Machine Learning Integration for Behaviour Prediction

Future systems will embrace machine learning algorithms run on the device to perform edge-based analytics for advanced behavior classification (e.g., lameness, oestrus, or disease patterns detection). This will reduce cloud computation dependence and enable real-time, stand-alone decision-making on the device.

3. Multi-Species Monitoring Growth

Even though the system is currently for cattle, it would be possible in the future to use it for other livestock such as goats, sheep, or even wildlife. That would render the system applicable in numerous agriculture or conservation uses.

4. Incorporation of Blockchain for Data Security and Traceability

For trusted, tamper-proof, and transparent recording of data, blockchain technologies would be a viable option. This would facilitate trusted cattle movement records, which would be useful for traceability in meat trade, disease control, and supply chain transparency.

5. Improved Dashboard Enhancements for Farmers

Future improvement can be a more sophisticated farmer-facing dashboard with interactive maps, customizable alert preferences, trend analysis of past history, and mobile app integration to facilitate ease of use and decision-making.

6. Field Trials and Scalability Testing

Structured field trials in varied environments and cattle herd sizes will be important to assess scalability, reliability, and usability of the system. This includes testing in various climatic conditions, terrain, and network conditions.

7. Compatibility of Policy and Standards

Follow-on activities must also consider integration with national agricultural digitization policy and data protection legislation. Stakeholder engagement such as veterinary authorities, agricultural extension officers, and regulators can ensure broader adoption and sustainability.

6.6 Chapter Summary

This chapter presented a general synthesis of the results, discussed the implications in relation to the stated objectives, and outlined the general contribution of the suggested IoT framework to the field of research in smart livestock management. The study demonstrated that the integration of smart collars with GPS, activity sensors, and environmental monitoring modules has the potential to significantly enhance real-time cattle movement tracking, behavior monitoring, and grazing management decision-making.

The discussion confirmed that the system successfully achieved core research objectives, from identifying current IoT technologies and challenges to developing, deploying, and testing a functional prototype. The key contributions were the provision of a scalable system for livestock monitoring, providing insights into grazing patterns, and enabling the early detection of health and security exceptions.

Despite the huge success, limitations such as power dependence, connectivity, and restricted field testing were recognized. These restrictions allow scope for future enhancements such as the addition of renewable energy, machine learning-based analysis, and longer field validation.

Overall, the chapter positions the developed IoT framework as a foundation stone for smarter, data-driven, and more sustainable livestock farming in the future, with clear opportunities for future development and innovation.

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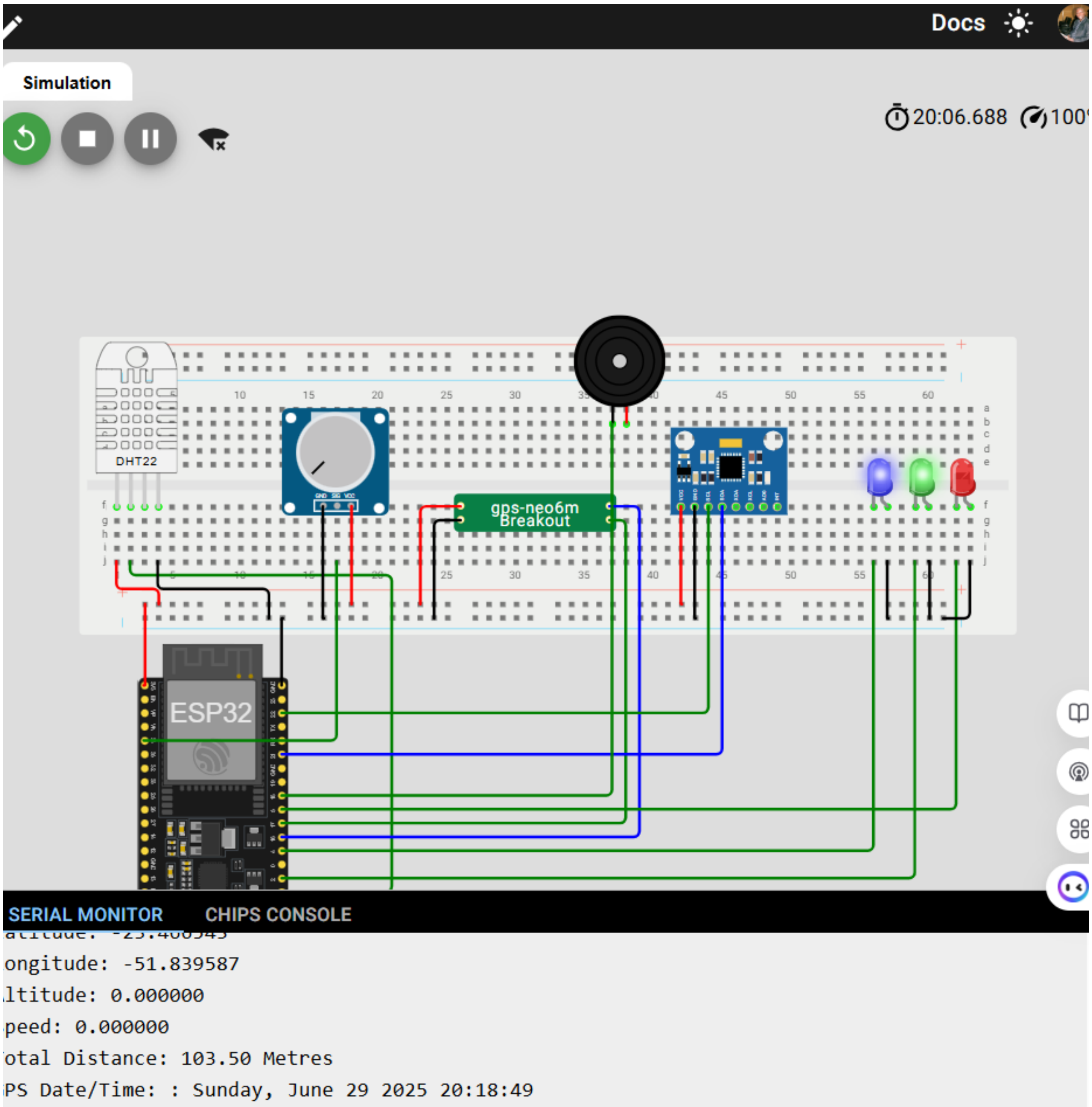
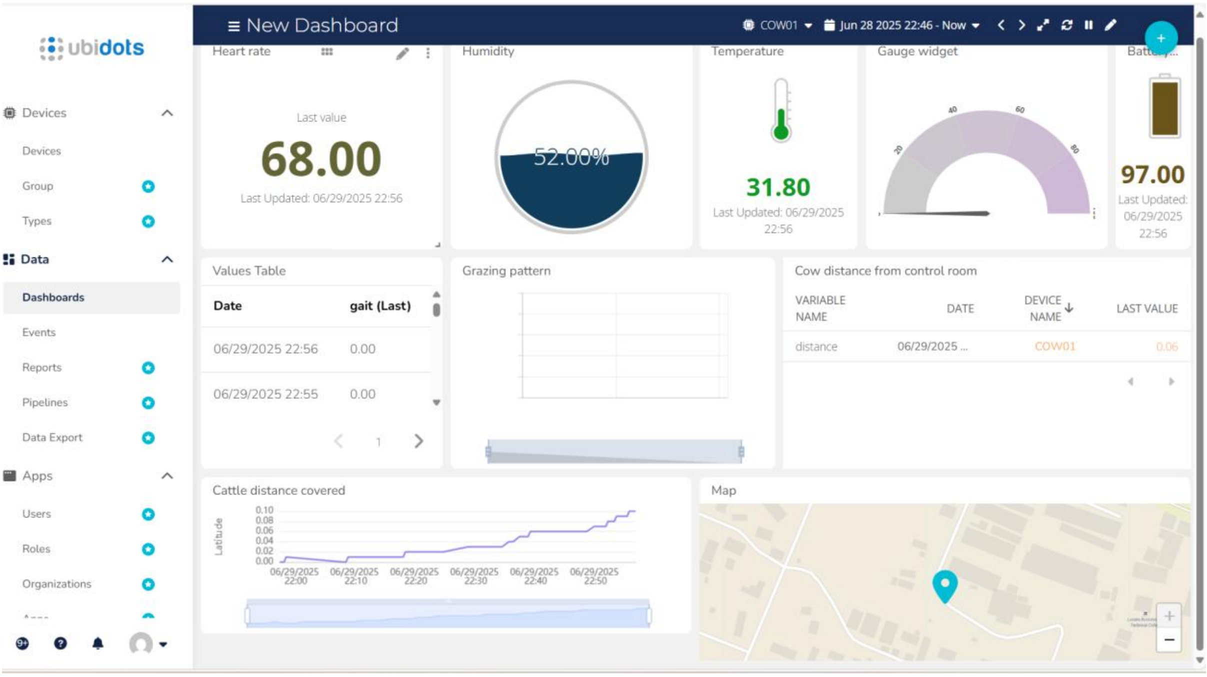
APPENDICES

Appendix A

IOT Framework Simulation



Dashboard


ubidots
New Dashboard
COW01
Jun 28 2025 22:46 - Now
Devices
Devices
Group
Types
Data
Dashboards
Events
Reports
Pipelines
Data Export
Apps
Users
Roles
Organizations
Heart rate
Last value
68.00
Last Updated: 06/29/2025 22:56
Humidity
52.00%
Temperature
31.80
Last Updated: 06/29/2025 22:56
Gauge widget
97.00
Last Updated: 06/29/2025 22:56
Values Table
Date
gait (Last)
06/29/2025 22:56
0.00
06/29/2025 22:55
0.00
Grazing pattern
Cow distance from control room
VARIABLE NAME
DATE
DEVICE NAME
LAST VALUE
distance
06/29/2025 ...
COW01
0.06
Cattle distance covered
Latitude
Map

Appendix B

Simulation Code

```
#include <DHT.h> // Include the DHT library for interfacing with the DHT
sensor
#include <WiFi.h> // Include the WiFi library for connecting to a WiFi network
#include <PubSubClient.h> // Include the PubSubClient library for MQTT
communication
#include <TinyGPS++.h> // Include the TinyGPS++ library for parsing GPS data
(still included for structure, but its direct use for location/speed is
replaced)
#include <Wire.h> // Include the Wire library for I2C communication
#include <MPU6050.h> // Include the MPU6050 library for interfacing with the
MPU6050 sensor
#include <time.h> // Include for time functions (NTP)

// --- Sensor Pin Definitions ---
#define DHTPIN 15   // Define the pin connected to the DHT sensor - ADC
(Analog-to-Digital Converter)
#define DHTTYPE DHT22 // Define the type of DHT sensor
const int pressurePin = 13; // Define the pin connected to the pressure sensor
(OUTPUT, though often input for actual sensors)
const int potPin = 34;      // Define the pin connected to the potentiometer
(Analog Input)

// --- WiFi Credentials ---
const char* ssid = "Wokwi-GUEST"; // Define the WiFi SSID
const char* password = "";        // Define the WiFi password

// --- Ubidots Credentials ---
const char* mqtt_server = "industrial.api.ubidots.com"; // Define the Ubidots
MQTT server address
const char* mqtt_client_name = "ESP32Client";          // Define the MQTT
client name
const char* token = "BBUS-ho54lj3ijb7JZUSD8jwOjpWxw195ul"; // Define the
Ubidots token
const char* device_label = "Cow01";                   // Define the device
label

// --- Ubidots Variable Labels ---
const char* variable_label_temp = "temperature";
const char* variable_label_humi = "humidity";
const char* variable_label_pressure = "pressure";
const char* variable_label_latitude = "latitude";
const char* variable_label_longitude = "longitude";
const char* variable_label_altitude = "altitude";
const char* variable_label_speed = "speed";
const char* variable_label_accel_x = "acceleration_x";
```

```
const char* variable_label_accel_y = "acceleration_y";
const char* variable_label_accel_z = "acceleration_z";
const char* variable_label_gyro_x = "gyroscope_x";
const char* variable_label_gyro_y = "gyroscope_y";
const char* variable_label_gyro_z = "gyroscope_z";
const char* variable_label_heart_rate = "heart_rate";
const char* variable_label_gait = "gait";
const char* variable_label_battery = "battery";
const char* variable_label_distance = "distance";

// --- Sensor Instances ---
DHT dht(DHTPIN, DHTTYPE); // Create an instance of the DHT sensor
WiFiClient espClient;     // Create a WiFi client
PubSubClient client(espClient); // Create an MQTT client using the WiFi client
TinyGPSPlus gps;          // Create an instance of the TinyGPS++ library
(still here if you want to process NMEA for other data like satellites, even
if not for location/speed)
HardwareSerial serialGPS(1); // Create a hardware serial instance for GPS
communication (RX=16, TX=17)
MPU6050 mpu;              // Create an instance of the MPU6050 sensor

// --- Global Variables ---
int pressureValue;       // Stores simulated pressure value
int potValue;            // Stores potentiometer analog read value

enum GaitType { STOPPED, WALKING, RUNNING }; // Enumerate the gait types
GaitType currentGait = STOPPED;              // Initialize the current gait
type to stopped

unsigned long gaitStartTime;   // Stores the start time of the current gait
state
unsigned long currentTime;     // Stores the current time in milliseconds
const unsigned long walkDuration = 10000; // Duration for walking state (10
seconds)
const unsigned long runDuration = 5000;   // Duration for running state (5
seconds)

// --- Variables for Simulated GPS Movement ---
double simulated_lat = -23.466183; // Starting latitude (example: Wokwi
default)
double simulated_lon = -51.840217; // Starting longitude (example: Wokwi
default)
// These steps are chosen to produce noticeable speed with a 1-second update
interval
const double movement_step_walking = 0.00001; // Degrees per simulated update
for walking (approx 1.1 meters)
const double movement_step_running = 0.00003; // Degrees per simulated update
for running (approx 3.3 meters)
```

```
double calculated_speed = 0.0; // Stores calculated speed
double prev_latitude = 0.0;  // For distance calculation
double prev_longitude = 0.0; // For distance calculation
unsigned long last_gps_update_time = 0; // To control the rate of simulated
GPS updates
const unsigned long gps_update_interval_ms = 1000; // Simulate GPS update
every 1 second (corresponds to your delay)

double total_distance = 0.0; // Total distance traveled in kilometers

int batteryLevel = 100; // Initialize the battery level to full

// --- LED Pins for Status Indication ---
const int buzzerPin = 18;  // Buzzer connected to GPIO 18
const int walkingLED = 2;  // LED for walking status
const int runningLED = 4;  // LED for running status
const int stoppedLED = 5;  // LED for stopped status

// --- Time Synchronization Variables ---
const char* ntpServer = "pool.ntp.org";
const long gmtOffset_sec = 0; // GMT offset in seconds (0 for UTC, adjust as
needed)
const int daylightOffset_sec = 0; // Daylight saving offset in seconds

// --- Function Prototypes ---
void setup_wifi();
void reconnect();
double haversine(double lat1, double lon1, double lat2, double lon2);
void displayGPSData(); // This function is now modified to simulate movement
void updateGaitStatus();
void printLocalTime();

// --- Setup Function ---
void setup() {
  Serial.begin(115200); // Start serial communication at 115200 baud rate

  // Initialize LED and Buzzer pins
  pinMode(walkingLED, OUTPUT);
  pinMode(runningLED, OUTPUT);
  pinMode(stoppedLED, OUTPUT);
  pinMode(buzzerPin, OUTPUT);
  digitalWrite(buzzerPin, LOW); // Ensure buzzer is off initially

  setup_wifi(); // Setup WiFi connection
  client.setServer(mqtt_server, 1883); // Set MQTT server and port

  // Initialize DHT sensor
```

```
  dht.begin();

  // Initialize pressure sensor pin as output (though usually input)
  pinMode(pressurePin, OUTPUT);
  gaitStartTime = millis(); // Record start time for gait simulation

  // GPS initialization (if you still want to process NMEA for other info,
e.g., satellites)
  serialGPS.begin(9600, SERIAL_8N1, 16, 17); // Initialize GPS serial
communication (RX=16, TX=17)
  Serial.println(F("ESP32 - IOT FRAMEWORK module Simulation Initialized"));

  // MPU6050 initialization
  Wire.begin(); // Initialize I2C communication
  Serial.println("Initializing MPU6050...");
  mpu.initialize(); // Initialize MPU6050
  if (mpu.testConnection()) {
    Serial.println("MPU6050 connection successful");
  } else {
    Serial.println("MPU6050 connection failed! Please check wiring.");
    while (1); // Loop indefinitely if connection fails
  }

  // Configure NTP time
  configTime(gmtOffset_sec, daylightOffset_sec, ntpServer);
  printLocalTime(); // Print initial time from NTP

  // Initialize prev_latitude and prev_longitude to starting simulated values
  prev_latitude = simulated_lat;
  prev_longitude = simulated_lon;
  last_gps_update_time = millis(); // Initialize last update time
}

// --- WiFi Connection Setup ---
void setup_wifi() {
  delay(10);
  Serial.println();
  Serial.print("Connecting to ");
  Serial.println(ssid);

  WiFi.begin(ssid, password);
  while (WiFi.status() != WL_CONNECTED) {
    delay(500);
    Serial.print(".");
  }
  Serial.println("\nWiFi connected");
  Serial.print("IP address: ");
  Serial.println(WiFi.localIP());
```

```
}

// --- MQTT Reconnection ---
void reconnect() {
  while (!client.connected()) {
    Serial.print("Attempting MQTT connection...");
    if (client.connect(mqtt_client_name, token, "")) {
      Serial.println("connected");
    } else {
      Serial.print("failed, rc=");
      Serial.print(client.state());
      Serial.println(" trying again in 5 seconds");
      delay(5000);
    }
  }
}

// --- Haversine Formula for Distance Calculation ---
double haversine(double lat1, double lon1, double lat2, double lon2) {
  const double R = 6371.0; // Earth radius in kilometers

  // Convert degrees to radians
  lat1 = radians(lat1);
  lon1 = radians(lon1);
  lat2 = radians(lat2);
  lon2 = radians(lon2);

  // Differences
  double dlat = lat2 - lat1;
  double dlon = lon2 - lon1;

  // Haversine formula
  double a = pow(sin(dlat / 2), 2) + cos(lat1) * cos(lat2) * pow(sin(dlon /
2), 2);
  double c = 2 * atan2(sqrt(a), sqrt(1 - a));

  return R * c; // Distance in kilometers
}

// --- Display GPS Data (NOW SIMULATED) ---
void displayGPSData() {
  unsigned long current_time_ms = millis();

  // Only update simulated GPS coordinates and calculate speed at the defined
interval
  if (current_time_ms - last_gps_update_time >= gps_update_interval_ms) {
    last_gps_update_time = current_time_ms;
```

```
    // Store previous location for distance calculation
    prev_latitude = simulated_lat;
    prev_longitude = simulated_lon;

    // Simulate movement based on gait
    if (currentGait == WALKING) {
      // Example: move slightly north and east
      simulated_lat += movement_step_walking;
      simulated_lon += movement_step_walking / 2.0;
    } else if (currentGait == RUNNING) {
      // Example: move faster, slightly more south and east
      simulated_lat -= movement_step_running;
      simulated_lon += movement_step_running;
    }
    // If STOPPED, coordinates remain the same.

    // Calculate distance traveled between the two simulated points
    double distance_km = haversine(prev_latitude, prev_longitude,
simulated_lat, simulated_lon);
    total_distance += distance_km; // Accumulate total distance in km

    // Calculate speed based on distance and the fixed update interval
    double time_diff_sec = gps_update_interval_ms / 1000.0; // Convert
interval to seconds

    if (time_diff_sec > 0) {
      calculated_speed = (distance_km / time_diff_sec) * 3600.0; // Speed in
km/h
    } else {
      calculated_speed = 0.0; // Should not happen with a fixed interval > 0
    }
  }

  // Display and Publish Simulated GPS Data
  Serial.print(F("Latitude: "));
  Serial.println(simulated_lat, 6);
  Serial.print(F("Longitude: "));
  Serial.println(simulated_lon, 6);

  char payload_lat[50];
  sprintf(payload_lat, "{\"%s\": %.6f}", variable_label_latitude,
simulated_lat);
  client.publish("/v1.6/devices/Cow01", payload_lat);

  char payload_lon[50];
  sprintf(payload_lon, "{\"%s\": %.6f}", variable_label_longitude,
simulated_lon);
  client.publish("/v1.6/devices/Cow01", payload_lon);
```

```
  // Altitude (kept constant/simulated for simplicity)
  double simulated_altitude = 0.0;
  Serial.print(F("Altitude: "));
  Serial.println(simulated_altitude, 6);
  char payload_alt[50];
  sprintf(payload_alt, "{\"%s\": %.6f}", variable_label_altitude,
simulated_altitude);
  client.publish("/v1.6/devices/Cow01", payload_alt);

  // Use the calculated speed
  Serial.print(F("Speed: "));
  Serial.println(calculated_speed, 6);
  char payload_speed[50];
  sprintf(payload_speed, "{\"%s\": %.6f}", variable_label_speed,
calculated_speed);
  client.publish("/v1.6/devices/Cow01", payload_speed);

  // GPS Date and Time (simulated - you can ignore or remove if not needed)
  //Serial.println(F("GPS Date/Time: SIMULATED (N/A)"));

  Serial.print(F("Total Distance: "));
  Serial.print(total_distance * 1000, 2); // Convert km to meters for display
  Serial.println(F(" Metres"));
}

// --- Update Gait Status (LEDs and Buzzer) ---
void updateGaitStatus() {
  // Turn off all LEDs and buzzer initially
  digitalWrite(walkingLED, LOW);
  digitalWrite(runningLED, LOW);
  digitalWrite(stoppedLED, LOW);
  noTone(buzzerPin); // Ensure buzzer is off

  const char* gaitStr;
  int gaitNumber; // For Ubidots numerical value

  switch (currentGait) {
    case WALKING:
      gaitStr = "Walking";
      gaitNumber = 1;
      digitalWrite(walkingLED, HIGH);
      break;
    case RUNNING:
      gaitStr = "Running";
      gaitNumber = 2;
      digitalWrite(runningLED, HIGH);
      tone(buzzerPin, 1000, 500); // Beep buzzer at 1kHz for 500ms
```

```
      break;
    case STOPPED:
      gaitStr = "Stopped";
      gaitNumber = 0;
      digitalWrite(stoppedLED, HIGH);
      break;
  }

  Serial.print("Current Gait: ");
  Serial.println(gaitStr);

  // Publish gait data to Ubidots
  char payload_gait[200];
  sprintf(payload_gait, "{\"%s\": %d}", variable_label_gait, gaitNumber);
  client.publish("/v1.6/devices/Cow01", payload_gait);
}

// --- Print Current Date and Time (from NTP) ---
void printLocalTime() {
  struct tm timeinfo;
  if (!getLocalTime(&timeinfo)) {
    Serial.println("Failed to obtain time from NTP");
    return;
  }
  Serial.print("GPS Date/Time: : ");
  Serial.println(&timeinfo, "%A, %B %d %Y %H:%M:%S");
}

// --- Main Loop Function ---
void loop() {
  if (!client.connected()) {
    reconnect(); // Reconnect to MQTT broker if disconnected
  }
  client.loop(); // Maintain MQTT connection

  // Read DHT sensor data
  float h = dht.readHumidity();
  float t = dht.readTemperature();

  // Handle invalid DHT readings
  if (isnan(h) || isnan(t)) {
    Serial.println("Failed to read from DHT sensor!");
  } else {
    Serial.print("Temperature: ");
    Serial.print(t);
    Serial.println(" °C");
    Serial.print("Humidity: ");
    Serial.print(h);
```

```
    Serial.println(" %");

    // Publish temperature and humidity to Ubidots
    char payload_temp[50];
    sprintf(payload_temp, "{\"%s\": %.2f}", variable_label_temp, t);
    client.publish("/v1.6/devices/Cow01", payload_temp);

    char payload_humi[50];
    sprintf(payload_humi, "{\"%s\": %.2f}", variable_label_humi, h);
    client.publish("/v1.6/devices/Cow01", payload_humi);
  }

  // Simulate pressure based on potentiometer and gait
  potValue = analogRead(potPin);
  // Map potentiometer value to a reasonable pressure range (e.g., 950 to 1050
hPa)
  pressureValue = map(potValue, 0, 4095, 950, 1050);

  currentTime = millis(); // Get the current time

  // Update gait simulation
  if (currentGait == WALKING) {
    if (currentTime - gaitStartTime >= walkDuration) {
      currentGait = RUNNING; // Switch to running
      gaitStartTime = currentTime;
    } else {
      pressureValue += 8; // Increase pressure slightly when walking
    }
  } else if (currentGait == RUNNING) {
    if (currentTime - gaitStartTime >= runDuration) {
      currentGait = STOPPED; // Switch to stopped
      gaitStartTime = currentTime;
    } else {
      pressureValue += 30; // Increase pressure more when running
    }
  } else if (currentGait == STOPPED) {
    if (currentTime - gaitStartTime >= walkDuration) { // Use walkDuration for
stopped to walking transition
      currentGait = WALKING; // Switch to walking
      gaitStartTime = currentTime;
    } else {
      pressureValue -= 4; // Decrease pressure when stopped
    }
  }
  updateGaitStatus(); // Update LED status based on gait

  // Publish pressure data to Ubidots
  char payload_pressure[100];
```

```
  sprintf(payload_pressure, "{\"%s\": %d}", variable_label_pressure,
pressureValue);
  client.publish("/v1.6/devices/Cow01", payload_pressure);

  // Read MPU6050 data (Accelerometer and Gyroscope)
  int16_t accelX, accelY, accelZ;
  mpu.getAcceleration(&accelX, &accelY, &accelZ);
  int16_t gyroX, gyroY, gyroZ;
  mpu.getRotation(&gyroX, &gyroY, &gyroZ);

  // Publish accelerometer data
  char payload_accel[100];
  sprintf(payload_accel, "{\"%s\": %d, \"%s\": %d, \"%s\": %d}",
          variable_label_accel_x, accelX,
          variable_label_accel_y, accelY,
          variable_label_accel_z, accelZ);
  client.publish("/v1.6/devices/Cow01", payload_accel);

  // Publish gyroscope data
  char payload_gyro[100];
  sprintf(payload_gyro, "{\"%s\": %d, \"%s\": %d, \"%s\": %d}",
          variable_label_gyro_x, gyroX,
          variable_label_gyro_y, gyroY,
          variable_label_gyro_z, gyroZ);
  client.publish("/v1.6/devices/Cow01", payload_gyro);

  // Simulate and publish heart rate
  int heartRate;
  if (currentGait == WALKING) {
    heartRate = random(80, 100);
  } else if (currentGait == RUNNING) {
    heartRate = random(100, 120);
  } else {
    heartRate = random(60, 80);
  }
  char payload_heart_rate[50];
  sprintf(payload_heart_rate, "{\"%s\": %d}", variable_label_heart_rate,
heartRate);
  client.publish("/v1.6/devices/Cow01", payload_heart_rate);

  // Decrease battery level (simulated)
  static float batteryLevelFloat = 100.0; // Use float for more precise
decrement
  batteryLevelFloat -= 0.05; // Decrease battery level by a smaller increment
  if (batteryLevelFloat <= 0) {
    batteryLevelFloat = 100.0; // Reset battery level when it reaches zero
  }
  batteryLevel = (int)batteryLevelFloat; // Convert back to int for publishing
```

```
  // Publish battery level
  char payload_battery[50];
  sprintf(payload_battery, "{\"%s\": %d}", variable_label_battery,
batteryLevel);
  client.publish("/v1.6/devices/Cow01", payload_battery);

  // Publish distance data to Ubidots
  char payload_distance[100];
  sprintf(payload_distance, "{\"%s\": %.2f}", variable_label_distance,
total_distance);
  client.publish("/v1.6/devices/Cow01", payload_distance);

  // Read and display GPS data (now handled by our simulation logic)
  // If you are fully simulating, you can comment out the TinyGPS++
processing:
  // while (serialGPS.available() > 0) {
  //   gps.encode(serialGPS.read());
  // }
  displayGPSData();
printLocalTime(); // Print current date and time from NTP

// --- ALERT CONDITIONS ---
bool overTemp = (t > 38);
bool overSpeed = (calculated_speed > 15);
bool overDistance = (total_distance > 0.3); // 0.3 km = 300 meters

if (overTemp || overSpeed || overDistance) {
  Serial.print("!!! ALERT: Condition Triggered - ");

  if (overTemp) {
    Serial.print("Over Temperature ");
  }
  if (overSpeed) {
    Serial.print("Over Speed ");
  }
  if (overDistance) {
    Serial.print("Over Distance ");
  }

  Serial.println("-> Buzzer Activated.");
  tone(buzzerPin, 2000, 1000); // 2kHz tone for 1 second
} else {
  noTone(buzzerPin); // Ensure buzzer is off otherwise
}


  delay(20000); // Delay for data reading and transmission interval
}
```