IoT Livestock Monitoring

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1 Introduction

The US currently has around 2.1 million farms with almost half of those containing over 164 million livestock animals [1]. Each of these farms own upwards of hundreds of farm animals, and many of these farms need an easy and efficient way to monitor the health of their livestock animals. Because of this, the use of livestock monitoring systems has become increasingly popular. These livestock monitoring systems have various different usages and capabilities depending on the animal and the desires of the users; however, the abilities of the systems range from health monitoring, location tracking, early disease detection and diagnosing, behavior tracking, and more.

The Internet of Things (IoT) is a tool for improving more traditional systems into more intelligent, capable systems that can provide data or actionable information. These systems provide a bridge between the physical world or "things" and the digital world or the "internet" [2]. What makes IoT unique from other embedded technology systems is the wired or wireless connectivity that it provides between objects [3]. Recent technologies have enabled IoT to become more prevalent including low-power processors, RFID, phones, and cloud/fog computing [3]. IoT has had significant impact on many different fields including embedded computing, healthcare, energy, and agriculture. Medical care has proven to be a good use for IoT technology specifically in remote health monitoring, chronic diseases, and elderly care [4]. These same principles are also applied to livestock monitoring and health tracking. Similar ideas are applied to areas in agriculture like precision farming and greenhouse management [5].

In this report, we will be focusing on health monitoring systems specifically for dairy cows. There are around 9.1 to 9.4 million dairy cows in the U.S. alone, and having a system that allows farmers to monitor and track the health and behavior of their dairy cows would improve the efficiency and profitability of dairy farms. IoT systems with these capabilities already exist and are in use, so this report will first cover the architecture of IoT systems as well as communication and security protocols relevant to cow health monitoring. Three cow health monitoring systems implementing a few of these IoT system components and their use cases will be reviewed. The conclusion of this paper will consist of a final evaluation of all three systems with the consideration of any ethical concerns surrounding livestock monitoring, and will include potential improvements that could be made to the existing systems.

2 System Architecture of IoT Systems

2.1 Livestock Monitoring IoT System Architecture

This section will cover the general architecture of IoT systems, IoT components used in existing cow-monitoring health systems, and security protocols used in IoT systems that could affect livestock monitoring.

2.1.1 General IoT System Components

All IoT systems have four general components [5]:

- Things: These are the physical objects in the IoT system that can communicate with the rest of the system. In the case of a livestock monitoring system, this includes the sensors that the animals wear and any surrounding sensors that record situational information.

- Gateways: These are the methods by which the information from the things makes its way to be processed. For example, the encryption of data would happen at this stage. In a livestock monitoring system, this could include any access points positioned across the farm.

- Communication Technologies: These are the technologies that are used to take information from the gateways and pass it along to be processed and used for future decision making. In a livestock monitoring system, this could be the WiFi technology used to transmit live video feed.

- Cloud Infrastructure: This is the computing infrastructure that takes all of the filtered and encrypted data from the Things and either stores it for future processing or makes immediate decisions without storing. In a livestock monitoring system, one potential cloud infrastructure could be using Machine Learning (ML) or Artificial Intelligence (AI) to predict real time events like individual cow health or make decisions to prevent disease.

2.1.2 Protocols Used For Livestock Monitoring

IoT networks have similar layers to the regular Open Systems Interconnection (OSI) model. The traditional OSI model has the following order: (1) Physical Layer, (2) Data Link Layer, (3) Network Layer, (4) Transport Layer, (5) Session Layer, (6) Presentation Layer, and (7) Application Layer. This model transfers to the livestock monitoring IoT system directly.

Physical Layer and Data Link Layer: This includes the sensors and the hardware associated with the livestock monitoring. There are several protocols that are commonly used at this layer.

- IEEE 802.15.4: This standard is used in the Media Access Control (MAC) layer and is good for low-rate wireless devices. This protocol has low complexity, low power consumption, and is low cost [5].

- Bluetooth Low Energy (BLE): BLE is a low power version of the more traditional Bluetooth technology which is great for IoT systems. This is also a low-cost system to implement thus making it an attractive option for small farms. BLE is great for location and proximity detection which is directly applicable to livestock monitoring and tracking. [6]

- X-10: X-10 is a protocol that relies on existing wiring to transmit and receive data. The communication data is modulated onto the house AC supply at 120 kHz. This protocol is not useful for livestock monitoring systems as large farms do not have this preexisting wiring set up. [7]

- IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN): This protocol is designed to work in highly constrained and unreliable environments with low-power and low-bandwidth. That is what makes this protocol so attractive for livestock monitoring systems. 6LoWPAN uses IPv6 and IEEE 802.15.4 standard. [5]

- Radio Frequency (RF): RF communication utilizes radio frequency bands to transmit information across the network. This is useful for long range information transfer. The HeatWatch® System uses RF frequency bands to transmit information over long distances for the livestock monitoring portion. [8]

Network, Transport, and Application Layers: The protocols used in these layers involve transporting data across nodes and the transmission of data to the end receiver.

- Constrained Application Protocol (CoAP): CoAP is a Machine to Machine (M2M) web transfer protocol for constrained networks. The Representational State Transfer (REST) protocol uses HTTP or CoAP to transmit information based off commands such as POST, GET, etc. CoAP uses the User Datagram Protocol (UDP) which means that a guaranteed connection is not made across the network before transmitting packets. This protocol uses the Datagram Transport Layer Security (DTLS) which is equivalent to 3072-bit RSA keys. There are security issues with using RSA and DSA which have been exposed recently, but this is still a high level of security. CoAP can be used in memory-constrained systems with only 10 KB of Random Access Memory (RAM). If the livestock monitoring system is highly memory constrained, this protocol is a great choice. [9]

- Message Queuing Telemetry Transport (MQTT): MQTT is also a M2M protocol using a publish and subscribe method of relaying information. Using brokers and clients, information is made available to those who want it. There are also multiple levels of Quality of Service (QoS) in MQTT where different levels of acknowledgments are provided to ensure delivery of a message. In this protocol, once one node gets disconnected, a message is sent out which allows the network to be repaired easily. [10]

- Advanced Message Queuing Protocol (AMQP): AMQP is an application layer protocol that works well over unreliable networks at long ranges. This aspect is particularly good for livestock monitoring systems. It also uses the publish and subscribe method to communicate information. Like MQTT, AMQP has QoS implemented to ensure the delivery of messages.

However, a high bandwidth is required for AMQP when compared with other protocols. This larger bandwidth requirement makes this less attractive for livestock monitoring systems which are largely unreliable networks with low bandwidth and connectivity issues. [11]

- Extensible Messaging and Presence Protocol (XMPP): XMPP is an application layer protocol based on Extensible Markup Language (XML). It is a very secure protocol using a decentralized client-server architecture. Secure authentication (SASL) and TLS encryption help make this more secure. Additionally, the decentralized approach to XMPP makes it harder to hack the IoT system. The publish and subscribe mechanism is used here similar to MQTT. Unlike CoAP, this protocol uses TCP which has a guaranteed connection. XMPP does not have QoS support however. [12]

- Zigbee: Zigbee follows the IEEE 802.15.4 protocol and is good for low power, low cost networks. In the Zigbee protocol, there are three different types of devices: the coordinator, the router, and the end device. The coordinator acts like a root node, while the router and end devices act similar to that in a regular WiFi system. Zigbee has a maximum range up to 100 meters with a maximum number of nodes of 65,560. For security, 128-bit AES encryption is used. Additionally, in the MAC layer, Carrier Sense Multiple Access Collision Avoidance (CSMA/CA) is implemented. Zigbee based livestock monitoring systems have been widely studied and is an attractive option [13].

- Z-Wave: Z-wave protocol is a low-energy protocol which involves a central computer, like a controller, which acts as a gateway to the internet at large from the IoT devices. This protocol uses AES-128 bit encryption. However, it isn't great for deployment over a wide area which is not ideal for livestock monitoring. [14]

- LoRa: LoRa uses low-energy bands which allows it communicate in the range of more than 10 kilometers. LoRA, unfortunately, is proprietary for the physical layer. However, Low-Power Wide-Area Network (LoRaWAN) is the protocol that is used for the MAC layer. This protocol is great for applications like livestock monitoring due to its long range capabilities. LoRaWAN has also been studied widely in livestock monitoring systems and is attractive for this purpose [15].

- Time Division Multiple Access (TDMA): TDMA is a protocol that divides a single channel into time slots [16]. Each time slot is used to transmit on byte or segment of data sequentially. It is good for high speed data such as compressed video or slow voice data. One system that uses TDMA is Global System for Mobile Communications (GSM) [16]. GSM divides the radio spectrum into 200 kHz bands and uses TDMA to put 8 different data transmission into one channel. The whole channel is transmitted at 270 kbits/second using Gaussian minimum shift keying (GMSK).

2.1.3 Security Protocols

In a livestock monitoring system, it is critical to ensure security of the data being transported across the network. In this case, especially with sensitive biometric data of the livestock, it is important to prevent against several types of attacks [5].

- Side-Channel Attack: These attacks take advantage of computation time of certain computer operations or take advantage of physical properties in the hardware like EM leakage.
- Misinformation Attack: By releasing false information about the state of animals into the livestock monitoring system, certain processes that could cost the farm time and money could be alerted.
- Denial of Service (DoS) Attack: DoS attacks involve sending a large amount of packets to a node which will cause a large disruption in the livestock monitoring system as a whole.
- Malware Injection Attacks: Due to large amounts of overlap in hardware across livestock monitoring systems, malware can be repurposed across systems.
- Radio Frequency (RF) Jamming Attack: If GNSS or GPS technologies are used, an attacker can jam the radio signals used to disrupt the function of the livestock IoT system.

There are several proposed methods to increase security in IoT systems including the encryption provided by the protocols that are being used. However, in order to ensure that the system as a whole is secure from attacks like those listed above, a security system should be implemented [5]. One potential way to increase security is to install an attack detection system which would then alert a reaction service. This reaction service would then filter out alerts from the detection system and alert a protection service. All livestock monitoring IoT systems should have some sort of security measure in place.

3 Livestock Monitoring Systems

There are three existing livestock monitoring systems that will be discussed in this paper: the CowMonitor system, a wireless sensor network, and the HeatWatch® system.

3.1 The CowMonitor system

The CowMonitor system is a health monitoring system for dairy cows with an emphasis on estrus, the recurring period of fertility and sexual receptivity in female mammals [17]. The primary goals of the CowMonitor system was to determine when dairy cows entered estrus and to detect and diagnose critical illnesses. In this system, every cow wore a collar, called a CowDevice, that collected behavioral data for that cow and transmitted the collected data to receiver stations, called Hubs, to be forwarded to a server. The collected data could then be used to determine whether a cow was in estrus or if a cow has fallen ill. This information could then be accessed by the user via an Android application where information about the health and well being of each cow or a group of cows could be viewed.

3.1.1 Architecture of CowMonitor System

The CowMonitor system consists of four main components: the CowDevice, the Hubs, the server, and the Android mobile application.

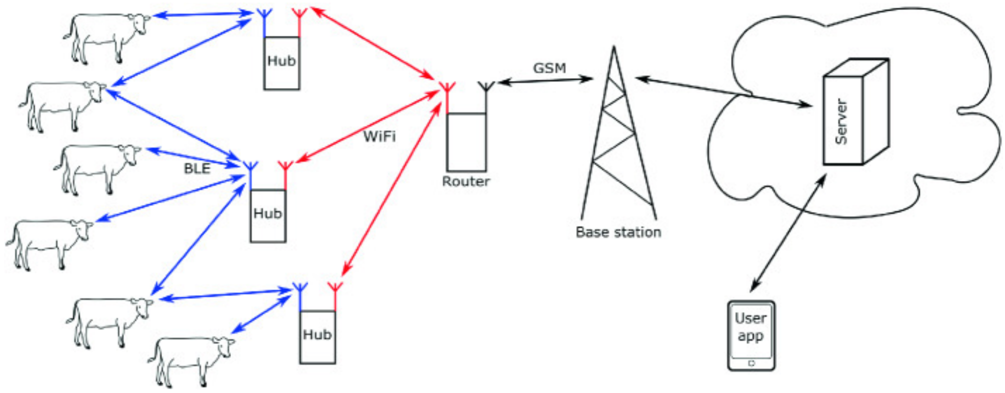

Figure 1: The Architecture of CowMonitor System. The different arrow colors denote different wireless communication technologies: BLE (blue), WiFi/Ethernet (red), GSM/Internet (black) [17].

The first component, the CowDevice, is a battery-powered microcontroller device with an accelerometer, magnetometer, and wireless communication capabilities. It uses an integrated ARM Cortex 4F processor and a Bluetooth Low Energy (BLE) v.5 compatible radio transceiver. The device records accelerometer and magnetometer at a frequency of 20 Hz. In the early versions of the collar, the data collected from the device was stored on a SD card and downloaded every week to be analyzed offline. However, now the collar uses its BLE capabilities to transmit the data to the Hubs in near real time. The devices are also able to exact and transmit only the essential data, around 20 bytes every 10 seconds, using a data aggregation algorithm that was created from previously collected data. The data is transmitted in a payload of BLE advertising messages which are short messages broadcasted periodically in connectionless communication mode to keep average power consumption low (below 300 microAmps). In order to ensure correct reception of the advertisements, the advertisements are transmitted every 250 ms for 10 seconds until the new aggregate values are ready to be sent out. This improves reliability of transmission with the trade-off being higher energy consumption and increased communication channel congestion. Despite this higher energy consumption, the transmission of the data is still relatively efficient and energy saving allowing the CowDevice to have a lifespan of around 5 years.

The second component, the Hub, is a gateway device that receives BLE packets and forwards them to the server in the cloud using either WiFi or Ethernet connectivity via WiFi access points and routers. The Hub consists of a Raspberry Pi Zero W that has both BLE and WiFi connectivity. There are multiple Hubs and each one receives advertisements broadcasted by the CowDevices. The Hub can eliminate duplicate measurements received by checking the sequence number included in the payload of the BLE packets, thus ensuring only unique measurements are recorded. The Hubs also record the MAC addresses of the transmitters and compare them to a list of allowed MAC addresses to ensure only packets from CowDevices are being processed and received. The Hubs also ensure reliable transmission of the measurements to the server by using an application-level protocol with retransmissions. This allows for effective data transmission, even if serial communication (e.g. GSM) is used or the central server is temporarily unavailable. The server can then remove duplicates, verify the correctness of the information, and perform backups of older data to an external server.

The third component, the server, acts as the central processing and management unit in the system. The databases in the server contain information about the cows, CowDevices, Hubs, farmers, cowsheds, sensor data, and warning alarms. The server communicates with the Hubs over the Internet using either GSM or a cable. The received data is transmitted in compressed files using REST communication methods. The server then unpacks, stores, and analyzes the received data. It also removes duplicate data received from different Hubs. The server also runs the algorithms used to calculate and evaluate whether a cow is in estrus and determine its general well being. Based on these calculations, alarms will be generated to warn the farmers about potential critical events such as illness or entering estrus. Finally, the server is also used to facilitate the REST communication between both the hubs and the server and the Android application.

The final component of the system is the Android application. The purpose of this application is to allow farmers or other users to monitor the health and status of their cows. In the application, the farmers have access to full herd data that can be seen in a large overview type format or can be seen in more detailed information for each cow. The alarms and alerts raised by the server will appear on this application. These alarms include when a cow reaches estrus, any health abnormality, or device malfunction. Finally, the application can be used to manage the cows and CowDevices. New cows and CowDevices can be linked together and connected to the server via the REST communication with the server and the BLE for the device set up.

3.2 A Wireless Sensor Network

The wireless sensor network system uses multiple components to study, monitor, and manage cattle in grazing systems. By using multiple different sensors and components in this network, more comprehensive information can be obtained about the cattle to enhance the scientific understanding of free-range cattle. [18]

The sensor network can include a range of sensors such as live-weight (LW) stations to remotely measure weight, sensors to ascertain body conditions from 3D data, monitoring collars to measure cattle location and behavior, infrared thermal cameras to measure body temperature, pasture stations to measure quantity and quality of surrounding foliage, soil sensors to measure temperature and humidity, and weather stations to check different climatic variables. The major sensors that will be covered are LW stations, LiDAR sensors, and the collars on the cows.

LW stations are used to track health and body weight of the cattle that pass through the weighing stations. The cattle can be grouped and graze certain area paddocks in a rotation to have the cows move around while also ensuring that the cows pass through the LW stations.

To get 3D data to analyze body conditions of the cows, the SOKUIKI sensor was used. This sensor is a LiDAR sensor that can construct a 3D range data map with a 2D laser range finder.

Through a USB controller, the sensor can be requested to give the 3D data and transmit it out to a centralized hub. [19]

The collar on the cattle can be used to monitor its location and behavior through the use of GPS and accelerometers to measure activity. This data can be used for behavioral classification, so as to know which cows prefer different locations or landscapes at different times. The behavioral tracking can be used to track trends such as daily activity levels, circadian patterns, eating behaviors, etc. which, over time, can be used to help with early detection of health disorders.

3.2.1 Architecture of the Wireless Sensor Network

The wireless sensor network contains 3 main components: the different sensors, a way to transport data using Zigbee, and a PC micro-controller to parse the sensor data as shown in Figure 2.[20]

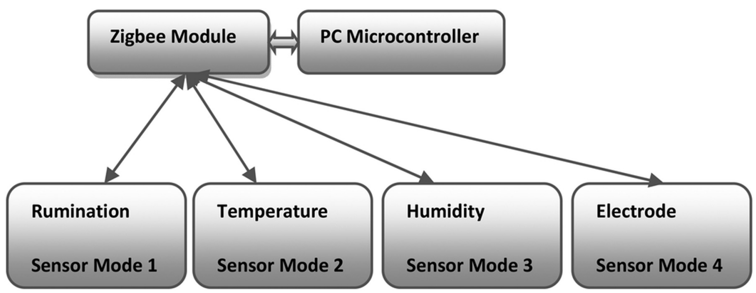

Figure 2: The Architecture of a Zigbee-based animal health monitoring system. [20]

The first component is the sensors that transmit the information. These sensors contain information on the sensor type, sensor location, measurement type, and the alerts given by the sensor for the specific occurrence that triggered it.

The second component is the communication module. In the example given in Figure 2, the Zigbee protocol was used to transmit information.

The third and final component is the PC Microcontroller. The paper does not specify the specific role of the microcontroller or which microcontroller was used and tested. However, based on previous research, the role of the microcontroller would be to run specially designed algorithms to process and analyze collected sensor data. Most microcontrollers would be capable for this processing, so we could expect to see a rather low-cost, easily accessible option such as an Arduino Uno.

3.3 The HeatWatch® System

The HeatWatch (HW) system is a pressure-sensing system for estrus detection that uses radio telemetry. The goal of the HW system is to provide a technological method to accurately tell when a female cow is on estrus compared to a method that does not use technology. The traditional method just uses a strip of paint and gauges how much paint has disappeared. However, the HW system can be used to more remotely and efficiently detect estrus in female cows and easily communicate the information to the user. [21]

3.3.1 Architecture of the HeatWatch® System

The HW system contains five main components: the pressure-sensitive transmitters, repeaters, a receiver, a buffer, and a software program to interpret information. [22]

The first component is the transmitters. These transmitters are battery-powered, pressure-sensitive, and have a 0.4 km range. The transmitter is secured in a durable nylon pouch on a 35 cm by 20 cm nylon patch. This patch is glued to the sacrum region just anterior to the tail-head with contact-type adhesive. Transmitters are activated by a continuous pressure with a duration of more than one second from the weight of a mounting female. The transmitter number is in the system along with an animal identification code and pasture number to identify the female cow. The signal from a transmitter contains the transmitter identification, date, time, and duration of sensor activation.

The second component is the repeaters. There can be two or more of them and they have a 0.8 km range. These repeaters can extend the range that is needed to transmit the data since the transmitters only have a range of 0.4 km. This way, cows that were grazing on paddocks greater than 0.4 km away can still be detected.

The third component is a signal receiver which receives the signals from the repeaters. Radio-telemetry signals sent out by the transmitters (or first sent to the repeaters) were picked up by the receiver mounted approximately six meters above the ground near the milking shed. The receiver transferred signals, that were received from the transmitters, to the buffer.

The fourth component is a buffer for receiving and storing the estrus activity data. This is where the data is stored for later use by the HW software so it can analyze and interpret the data over time.

The fifth component is the software application. The software would interpret the information contained in the radio-telemetry signals that was stored by the buffer. The estrus activity data is only stored if the number of times the female cow is being mounted exceeds three or more times based on the pressure-sensitive transmitters.

4 Case Studies of Surveyed Systems

The Case Studies Section will explore the experiments conducted on each of the aforementioned systems and explain procedures needed to run the system for these experiments.

4.1 The CowMonitor System

The CowMonitor system was used and tested during its development from 2017 to 2019 at three different dairy farms in Poland [17]. The main data being collected and analyzed was the three-axis accelerometer measurements; this data was used to distinguish the behavior of cows. The system used a three-level architecture for processing the data. The first level, Level “0”, calculates the statistical characteristics of short-term micro-behaviors directly on the CowDevice. The second level, Level “1”, evaluates the current state of the cows. Data is pulled from the past hour and checked against data from the previous few hours. Parameterized decision trees are used to extract and pull useful cow wellbeing criteria. The third level, Level "2", builds a reference model for each cow based on their previous data.

The system was used to detect estrus and early-stage diseases. Both of these objectives were achieved. For one cow in particular, the first signs of estrus appeared and were detected around 5pm, the "Heat Alarm" was set off around 9pm, and a vet was able to confirm estrus the next morning. This led to the development of characteristic HL03 which detects estrus-specific behavior. The system also had an average disease detection efficiency of around 90%. In the case of one of the cows having mastitis, it was not only able to accurately diagnose mastitis, but also able to track and monitor the effectiveness of the mastitis treatment. The first treatment was not effective and did not end in a full recovery, so new treatments were able to be provided quickly when subsequent relapses appeared. This was due to the monitoring capabilities of the CowMonitoring system.

4.2 The Wireless Network System

The Wireless Network System was tested at the CSIRO Landown Research Station in Townsville, Queensland. This experiment contained ninety steers and one crossbred taurus would be randomly assigned into groups with 30 steers each. Each group had 15-ha paddocks to graze in a rotation. The steers were moved through the paddocks on a monthly basis. In the experiment, they had LW stations and monitoring collars. [18]

The remote LW stations were installed at the only water point for each group, so it can weigh the animals every time they accessed water. The weighing stations contatined a platform mounted on two load bars and had a radio frequency identification reader panel on it to identify the animals walking through it. The information recorded was the animal ID, date and time, and LW.

Any cattle behavior could be monitored by the collars. These collect information about the animal's location through a GPS chip as well as any body activity from accelerometers in the collar. The data could then be later collected and analyzed to identify different behavioral activities such as grazing, ruminating, resting, or travelling.

After 341 days through the experiment, 18.8% contained missing numbers and another 12.1% were outliers that recorded improbable values. Overall, there was a 64.2% success rate of weighing the animals. For the collars, they were able to correctly classify 90% of the data points. [18] Although LW was not able to be accurately predicted, the collars were able to accurately predict certain behaviors exhibited by cows. One reason why the LW could be inaccurate could be due to the fact that the animals are rotating throughout the season and can gain or lose weight depending on seasonal factors.

4.3 The HeatWatch® System

The experimental trial compared the HeatWatch® (HW) System to traditional methods such as visual observation. [22] The visual observation method would paint the tail of the cows and any disappearance or disruption of the paint strip would mean that the female cow was exhibiting estrus.

The HW system experiment was conducted in New Zealand and was approved by the Ruakura Animal Ethics Committee. [22] The HW was battery powered and contained the necessary components outlined in Section 3.3. The experiment used an IBM PS/2 personal computer with an 80287 microprocessor. In this experiment, when transmitters were activated, signals would be sent out and picked up by receivers that were approximately 6 meters above the ground near a milking shed.

The experiment was conducted in two dairy herds where one contained Friesian cows and the second herd contained Jersey cows. The cows were paired within each herd by age, date of calving, and day of estrus cycle. Within each herd, the pairs were assigned randomly to the HW group or the control group. The experiment lasted 6 weeks from the start of the breeding season. Cows in the HW group were considered to be in estrus if there were more than three mounts greater than one second in duration were recorded by the system within four hours. For cases where there were only one or two mounts within four hours, the herd owners would indicate manually whether or not the cows exhibited secondary signs of estrus. For the control group, the cows were observed in the morning and afternoon for approximately 20 minutes each. The control group also had a strip of paint applied over the cows' tailhead which would be examined during milking. If the paint strip greatly disappeared, the cow would be considered to be in estrus.

With this method of experimentation, the efficiency of estrus detection was found to be 98.4% for the control method and 91.7% for the HW system. Although the HW system's accuracy is good, it did not do well compared to the control method. One such explanation for the slightly lower efficiency of the HW system could be due to the transmitters not being maintained in the proper position. For all of the missed estrus cycles from the HW system, all of them were due to the loss of transmitters. Some transmitters would come off since the early mating period would often be when cows would shed their winter hair. [22]

Even though the HW system was not as accurate as the control method, it is good for remote detection so farmers can be notified efficiently about a cow's estrus.

5 Ethical Considerations

The ethical implications of tracking cattle biometric health information has been questioned by many [23]. Animal welfare is an important factor in livestock monitoring and should be considered. Dawkins defines three factors to determine whether it is ethical:

- Is the definition of animal welfare acceptable to the public and is that definition inclusive of the animals' point of view?
- Is computer recognition of animal welfare successful enough and given a high enough priority to be ethical?
- Will smart farming actually improve animal welfare in practice?

Based on these three factors, it can be argued that cattle health tracking is in fact ethical from the animal welfare point of view. The definition of animal welfare in this context has to do with the animal's health which is acceptable to the public and does include the animal's point of view. Computer recognition of animal welfare in this context is successful and is the main priority with these IoT systems. Lastly, the livestock will be healthier in the long run from this smart farming practice. Therefore, we believe that livestock health monitoring systems are ethical and the improvement of these systems is important. One caveat to note is that public perception around animal welfare has changed significantly over time, and that this question will have to be revisited in the future as more livestock monitoring systems are created. Additionally, there is large variation in what people consider ethical with regards to animal welfare. For example, there are people who may consider collars and tags unethical on livestock. However, we believe that these systems do improve animal welfare on the whole despite potentially requiring that the animals wear restrictive items.

6 Conclusion

Based on our survey, we recommend that the cattle monitoring systems implement a reactive security system. The HeatWatch® system should implement this to avoid RF jamming which is a potentially highly disruptive attack that could cost time, money, and effort for the farm.

The CowMonitor system is vulnerable to a significantly large number of attacks due to the use of the ARM Cortex 4F processor and BLE. Known vulnerabilities in this processor leave the system open to side-channel attacks, misinformation attacks, etc. We recommend that this system also integrate a reactive security system as proposed earlier into their microprocessors. Using artificial intelligence technologies could be useful in predicting and preventing malicious behavior [24].

Out of the surveyed systems, we believe the best system is the CowMonitor system using BLE and WiFi communication. According to its use case results, it was accurate and efficient at detecting estrus in dairy cows and was highly useful in monitoring the progress of treatments for disease. The system also has a fairly long lifespan as it could last up to 5 years. Furthermore, since the system is noninvasive, there is minimal ethical concerns. The system also uses BLE which is a protocol optimized for the long-range, unreliable, and lossy network conditions. The CowMonitor system was preferred over the other two systems. The HeatWatch® system transmits via radio communications to log the cow-estrus activity. However, this system is very limited as it can only detect estrus and no other health related conditions. While the Wireless Sensor Network (WSN) has more features and sensors to monitor cow health, it is less relevant to the health of dairy cows specifically. Furthermore, it was only tested in a research station in Queensland, so it has not been tested or implemented in a real farming setting. Other viable communication protocols would be LoRaWAN, Zigbee, and 6LoWPAN and other features we would recommend implementing would be the use of cameras for live view cow monitoring. Cameras placed around the farm with a live feed accessible on the existing Android application would allow the farmers to watch and monitor the cows in real time from any location. We would also recommend implementing more Machine Learning (ML) algorithms to be able to predict when estrus will occur, detect the onset of illness, and track the spread the diseases. This would allow farmers the ability to better track and monitor the health of their herd, as well as make milk production more efficient. Finally, we recommend pursuing research into using ultra-wideband (UWB) technologies for position tracking for cattle. The current location tracking of the CowMonitor system is very general, so implementing a feature that could more accurately track and locate the cow would be useful while still incorporating all the health tracking features that are a part of the CowMonitor system.

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