



University of Tuscia
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Design of an IoT system for monitoring livestock behavior and welfare through low-cost technologies

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Supervisor

Prof. Riccardo Valentini

PhD

Francesco Renzi

PhD coordinator

Prof. Andrea Vannini

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ABSTRACT

In recent years, concerns regarding animal health and food traceability have increased, along with the number of animals per farm. To address this issue, the concept of precision livestock farming (PLF) has been introduced, which consists of the use of technologies in farms to help farmers monitor their animals effectively and react in a timely manner to possible issues, thereby enhancing productivity and animal welfare. Several IoT sensors are already commercially available to monitor livestock behavior; they usually focus on a specific parameter and provide information about the status of the animal to the farmer. A network of sensors can provide a more comprehensive understanding of animal status; however, IoT sensors on the market are usually manufacturer-specific, owing to market strategies. This study, conducted with the support of Nature 4.0 S.r.l., focuses on the development of a network of sensors, encompassing the entire process, from conceptualization to testing and data management. The goal is to test devices for the collection of data on the welfare of cows and sheep, animals' subcutaneous temperature, air quality, and greenhouse gas emissions in shelters and transmit them in near-real time to a central server for their storage and visualization. A collar was designed to collect geographical coordinates, air temperature and relative humidity around the animal, average acceleration and standard deviation over three axes, heart rate, and cutaneous temperature. Moreover, an IoT RFID reader was designed to read RFID subcutaneous temperature tags in chickens. Finally, a customizable IoT gas analyzer was designed featuring NH₃, CH₄, H₂S, CO₂, PM1, PM2.5, PM10, air temperature, and air humidity as standard configurations to monitor animal and human health in shelters as well as GHG emissions. A server for the collection, storage, and visualization of the collected data was also designed and tested using FAIR-compliant standards and open-source software. The central server collects data from different protocols, such as MQTT and HTTP, and saves them in a PostgreSQL database exposed by the OGC SensorThings API. The data can also be visualized using the Grafana dashboard. In the opening chapter, this thesis delves into the subject of precision livestock farming and the significant advancements made in this area in recent years. Additionally, the text explores the role of IoT technologies in contemporary society and science, offering a brief description and explanation of the main technologies and protocols while simultaneously highlighting their strengths and limitations. The second chapter outlines the framework within which the thesis was formulated along with the technologies and software utilized in the design of the sensors. Subsequently, the following three chapters delve into each sensor in detail and present illustrative examples of the collected data. Finally, the discussion turns to the server structure.

Keywords—precision livestock farming (PLF), animal health, animal behavior, Internet of Things (IoT), GNSS positioning, animal movements, THI, animal heart rate, RFID subcutaneous temperature, shelter air quality, GHG emissions, OGC SensorThings API, One Health

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1 INTRODUCTION

In the recent past, the overall interest around the emergence of Precision Livestock Farming (PLF) increased^{1,2}. This field has been largely influenced by the Internet of Things (IoT), which has proven to be a game changer in livestock management³. The purpose of this chapter is to delve into the core aspects of PLF, starting with the fundamental tenets of IoT. As we progress through various technologies and communication protocols that facilitate seamless connectivity, we explore the critical processes of data collection and sharing. Together, these innovations pave the way for a future in which data-driven decisions can enhance the efficiency, sustainability, and welfare of animal farming operations.

1.1 PRECISION LIVESTOCK FARMING

The trend of increasing animal numbers per farm has been well documented in recent literature, indicating a significant shift in livestock production dynamics⁴. This trend is characterized by a shift from small-scale farming to larger and more concentrated operations. At the same time, an increase in livestock health diseases, partly attributable to climate change, has been registered^{5,6}, which in turn has economic implications⁷. Moreover, globalization of the food supply chain has led to heightened interest in food traceability, both among institutions and the general public^{8,9}. The implementation of IoT technology in livestock farming offers a solution to several emerging challenges by enabling continuous and timely monitoring of animals, regardless of the herd size, and assisting farmers in executing and optimizing their daily tasks^{10,11} (see Figure 1).

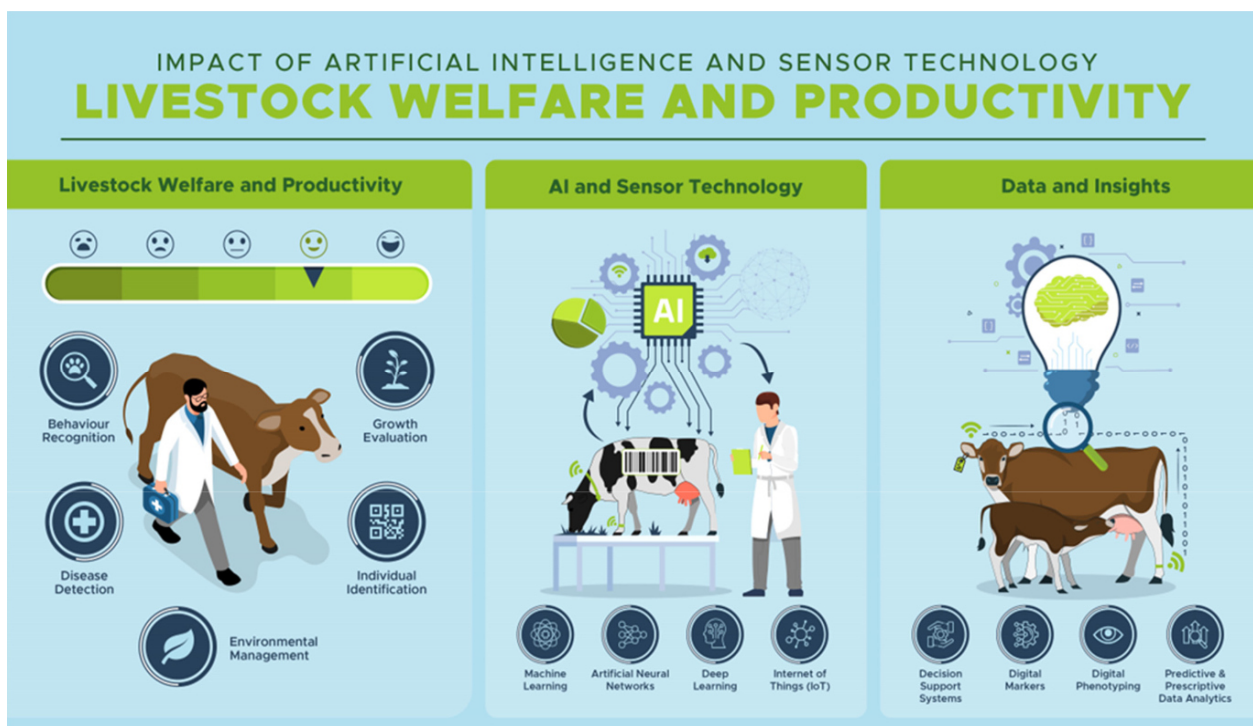


Figure 1 Advantages of the application of PLF¹²

Precision livestock farming constitutes a transformative approach within the agricultural sector that leverages advanced technologies to enhance animal welfare, productivity, and sustainability. The integration of digital technologies and real-time monitoring systems enables farmers to make informed decisions based on data-driven insights, thereby optimizing livestock management practices¹³. This paradigm shift extends beyond mere automation, encompassing a comprehensive perspective of animal husbandry that places the well-being of animals at the forefront while concurrently promoting financial sustainability for farmers^{14,15}. At the core of

PLF is continuous monitoring, which allows farmers to promptly detect changes in the behavior and health status of their animals. Technologies such as accelerometers, RFID tags, and advanced imaging systems are employed to gather data on a multitude of parameters, including movement patterns, feeding behavior, and physiological responses^{16,17}. The collection of real-time data facilitates the early identification of health issues, allowing for timely interventions that can prevent disease outbreaks and improve the overall health of herds¹⁸. For example, automated systems can alert farmers to deviations from normal behavior, prompting immediate investigation and care¹⁹. The adoption of PLF has significant economic implications. By streamlining operations and reducing labor costs, farmers can achieve higher productivity levels with fewer resources. One example is the use of automated milking systems and real-time milk analysis technologies to optimize dairy farming practices, resulting in improved milk quality and yield²⁰. Additionally, the integration of artificial intelligence (AI) in livestock management enhances decision-making processes, enabling farmers to efficiently analyze vast amounts of data and implement best practices tailored to their specific operational contexts¹². Moreover, PLF contributes to sustainability in livestock farming by promoting efficient resource use and minimizing environmental impacts. Continuous monitoring of animal welfare and productivity allows the development of management strategies that balance economic goals with ecological considerations¹⁵. For instance, precision feeding techniques can reduce waste and improve feed conversion ratios, thereby lowering the greenhouse gas emissions associated with livestock production²¹. The application of various technologies (see Figure 2) has been assessed through research studies over the years to determine their effectiveness in real-world scenarios and in different species of animals. These studies include technologies such as accelerometers, Radio Frequency Identification (RFID), cameras, thermal cameras, infrared sensors, microphones, GNSS receivers, temperature sensors, weight scales, flow meters, boluses, unmanned aerial vehicles (UAV), automatic milking systems and environmental sensors^{22,23}.

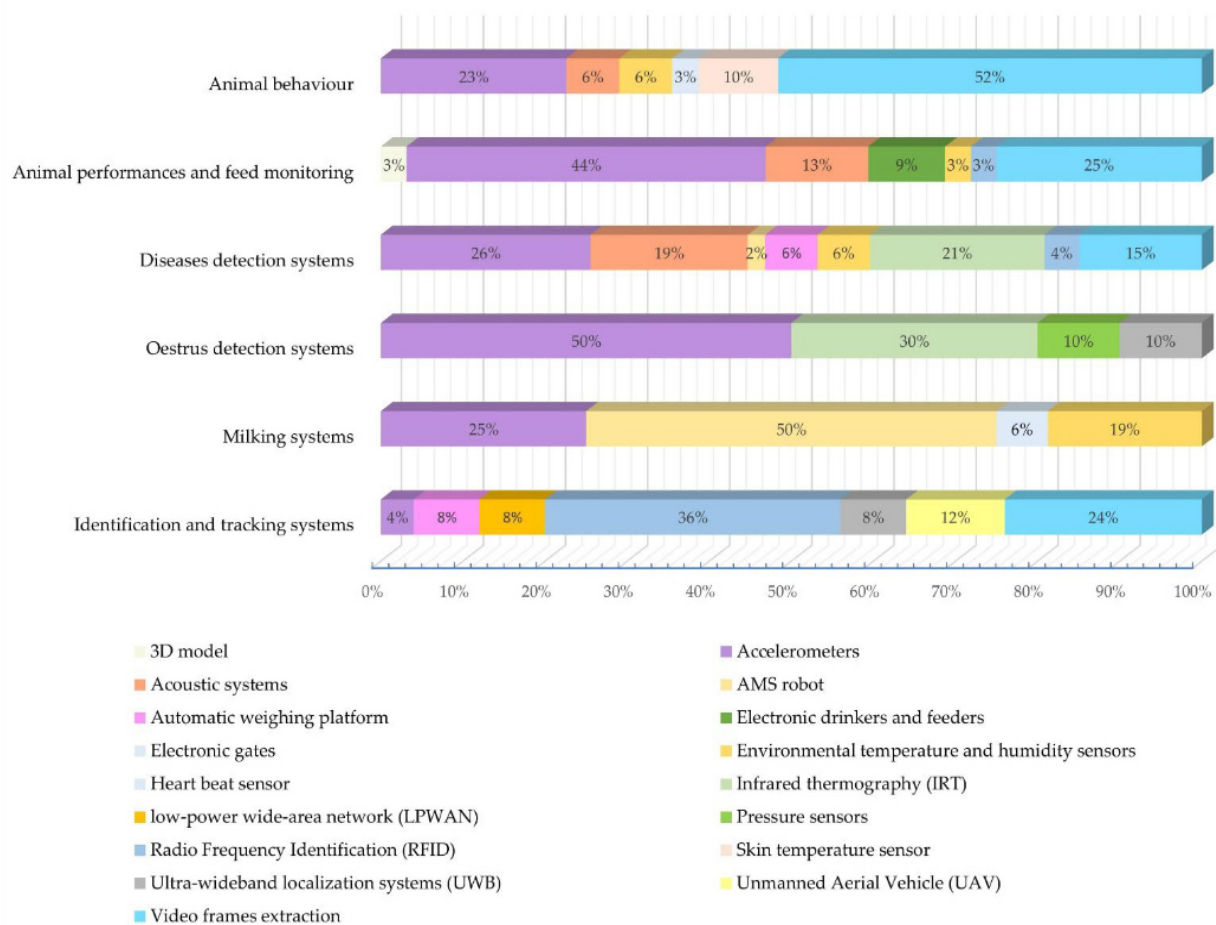


Figure 2 Most used sensors in precision livestock farming³

However, not all tested technologies are applied commercially, and the data collected are often not combined because each manufacturer provides its own application to access the data. The datasets collected during training and in the field are utilized in the PLF model to create behavioral patterns that are compared with the animals' behaviors to detect potential abnormalities. The model should also be adapted to the individual animal's "normal" state. The detection of abnormal behavior can trigger alarms for the farmer or activate countermeasures if possible. In this scenario, animal datasets for training algorithms represent a valuable resource for all stakeholders involved in the PLF field. The application rate of precision livestock farming technologies also varies depending on the species, with bovine being the main species in which PLF solutions are applied³. The acceptance rate depends also on the value the farmers recognize for these technologies. According to a survey conducted online among Italian daily farms, primarily located in Lombardy, devices with the highest adoption rate are related to the activity of cows and their milk production. The study reveals that farmers primarily concentrate on the productivity of individual animals, with a focus on estrus²⁴ estimated by activity and milk production. Among all commercial solutions applied, an even smaller number has been externally validated²⁵. Accelerometers are the most used sensors to measure activity, estrus, and feeding, while RFID ear tags, load cells, boluses, and automatic milking machines are also widely deployed.

In conclusion, precision livestock farming is reshaping the landscape of animal agriculture by integrating advanced technologies that enhance productivity, animal welfare, and sustainability. The continuous monitoring capabilities provided by PLF systems empower farmers to make informed decisions that positively impact both their operations and animal welfare. As the agricultural sector continues to progress, it is crucial to carefully consider the ethical implications of these technologies to ensure that the benefits of PLF are realized without compromising livestock dignity and welfare.

1.2 IoT CONCEPT, DEVELOPMENT AND APPLICATION

The importance of data and its management is continuously brought to everyone's attention in everyday life as an internet user. Modern software and algorithms are often based on massive datasets (**big data**) that allow extrapolation of information and complex correlations between phenomena, resulting in technologies such as large language models (e.g. ChatGPT) or personal advertising. To apply these algorithms to the physical world instead of the virtual world, devices that can register what is happening in the actual world and/or interact with it are required. Thus, sensors and actuators that can interact with each other through the Internet and embed more advanced algorithms have been developed; their network constitutes the **Internet of Things**. The term was coined in 1999 by Kevin Ashton, referring to RFID sensors for supply tracking. By 2008, the number of connected devices exceeded the number of people on the planet²⁶ and since then, the number of devices connected to the Internet has been increasing in consumers' lives, enterprises, and public spaces, ranging from phones to smart houses and even traffic lights. Its integration into industrial processes, along with other complementary technologies such as cloud computing, machine learning and robotics, gave birth to the concept of **Industry 4.0**^{3,27}, a data-driven management aimed at increasing efficiency and productivity and improving decision-making processing, making use of strategies applicable only by the availability of real-time data (e.g. predictive maintenance). In summary, Industry 4.0 transforms real-time data collected by sensors into in-depth and granular knowledge of its internal processes and uses this knowledge to improve its processes. To achieve maximum efficiency, a key role is played by timely assessment of future issues. The availability of massive amounts of data on every possible aspect of a chain has made it possible to simulate a physical system in a virtual environment for testing, monitoring, and maintenance at a lower cost. A **digital twin** is a digital replica of a physical object, system or process. It mirrors the physical counterpart in real time using data collected from sensors and other sources as input to simulate and analyze the behavior and performance of the physical entity. Its application can not only help in the early detection of failures due to divergences between the behaviors of the two objects but also simulate different scenarios and changes to spot issues or increase performances. The use of digital twins also reduces the costs of maintenance and design, increases the depth

of knowledge about the object and provides a low-cost testing ground compared to physical tests^{14,28,29}. Collecting a larger amount of data, however, is not an advantage by itself if the studied phenomenon is too complex and it is not possible to find reasonable correlations between the collected data and the phenomenon itself^{14,30}. The growing amount of data available along with the increased complexity of the subjects has led to the development of different types of algorithms that can extrapolate information from large amounts of data, find patterns between provided inputs and outputs, or pursue given tasks when the systems are too complex or depend on too many variables to be programmed in a standard manner. **Machine learning** algorithms are now being integrated into all aspects of human life to make machines suitable for performing complex tasks. Most of the data needed by all models and applications in the real world are collected by IoT sensors that require suitable technologies and communication protocols to connect to the Internet. Some principal solutions are briefly described in the following sections.

1.2.1 Technologies for IoT communication

The introduction of IoT networks has significantly increased the number of devices connected to the Internet and the volume of exchanged data^{31–33}. However, IoT sensors do not usually require a large bandwidth consisting of devices that send a small amount of data at fixed intervals or in response to certain events. Therefore, suitable technologies and protocols have been developed to support these devices; a comparison among different communication technologies on the market is shown in Figure 3.

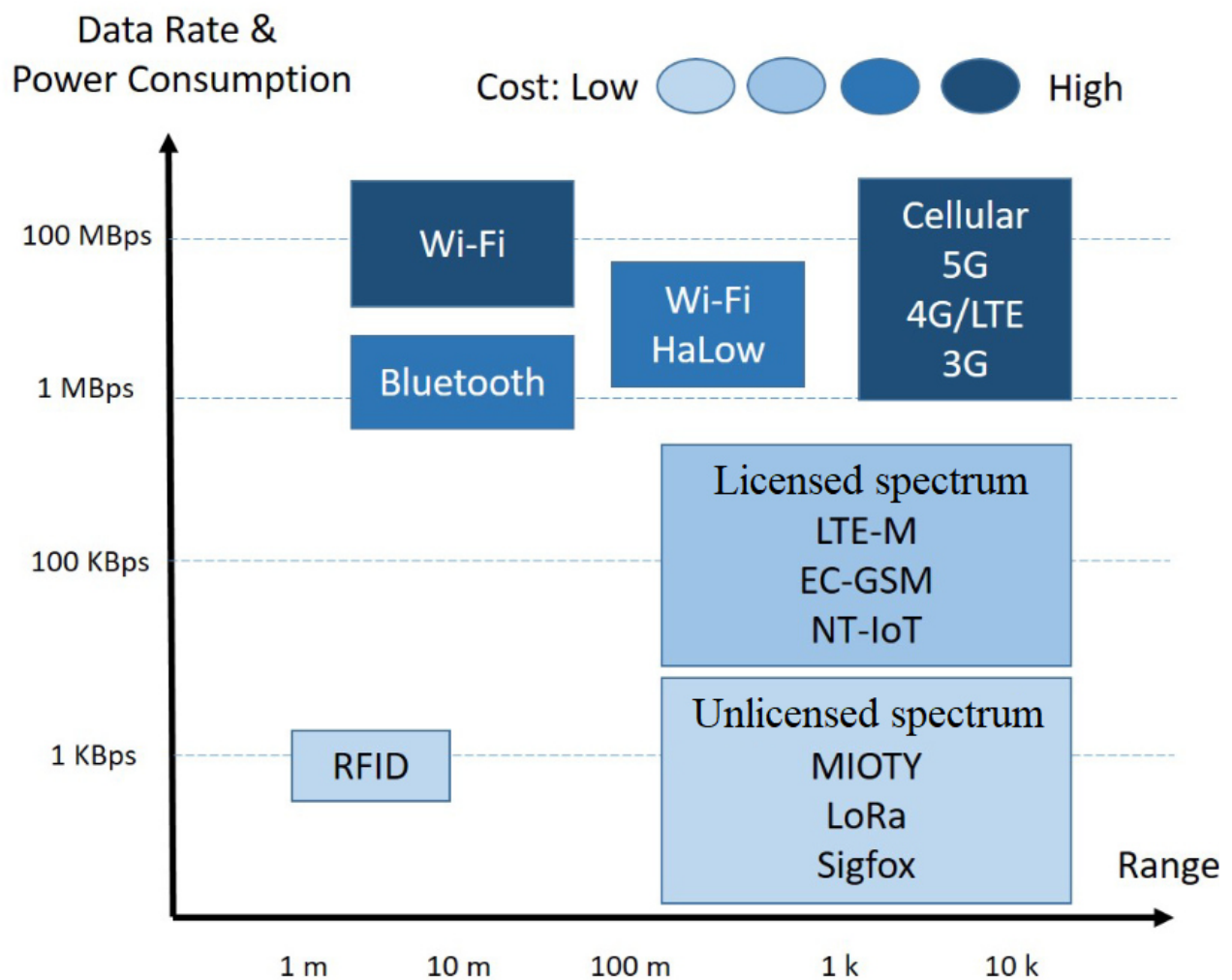


Figure 3 Comparison among different communication technologies³⁴

A Low Power Wide Area Network (LPWAN) is a set of wireless communication technologies designed to connect many battery-powered devices over long distances. Therefore, they are optimized for low power consumption and low data rates. The main LPWANs technologies include LoRa, Sigfox, NB-IoT, and LTE-M. Here, I describe the most important technologies currently available for IoT deployment: LoRaWAN, Sigfox, and NB-IoT. In my research, I mainly used LoRaWAN and NB-IoT technologies for data communication.

1.2.1.1 *LoRa*

Lora^{35,36} stands for Long Range and is a technology developed in 2009 and held by Cycleo in 2010. In 2012, Cycleo was acquired by Semtech, which improved its technology and designed the chips required for its use. In 2015, the LoRa networking protocol (LoRaWAN) was established and the LoRa alliance³⁷, an organization that promotes the adoption of the standard, was founded. A LoRa network is usually composed of multiple devices that need to send small data packets and one or more gateways that forward received data packets to a central server. The gateways also deliver messages sent by the server to the devices, making this technology bidirectional. The star configuration is the most used, but it can also work in a mesh configuration or point-to-point to exchange messages between two devices. The advantage of LoRa technology, other than its being low cost, low power and long range, is the possibility of deploying a LoRa network with the installation of at least one gateway in the area. The gateway itself should be connected to the Internet to make the data available online; however, each device can be installed in an area without connection and still be able to make its data accessible remotely. Another possibility is to connect the central gateway directly to a data logger to collect data from every sensor in the area. This application is particularly meaningful when paired with **edge computing** functionalities. Unlike centralized data servers, edge computing relocates resources to bring computation and data storage closer to the location where they are required, typically near the source of data generation. The advantages of this solution are: **latency reduction** due to the physical shorter distances the information travel, **bandwidth optimization** being the data elaborated locally and sent to a central server only if required and after their pre-elaboration, **enhanced privacy and security** being the data elaborated locally and **increased reliability** of the system. In fact, even if the Internet connection is severed, the local gateway can maintain some of the functionalities of the system; in particular, if actuators or responses to external factors are expected, they can be handled locally regardless of the Internet connection (e.g. smart irrigation). Therefore, the creation of local LoRa networks, in which the gateway is also an edge device capable of elaborating the received data, presents great potential. LoRa is a technology based on the Chirp Spread Spectrum (CSS) technique and it transmits information using symbols. A symbol can be defined as a piece of information; effective communication is based on different symbols that can carry more or less information with them. An example could be to pass an information changing the frequency of a signal with each frequency representing one value, if two frequencies are used, 1 bit can be transmitted for each symbol (one frequency will represent one while the other will represent zero) but if 128 different frequencies are available, each frequency can carry 2^7 **bits or chips** (one frequency will represent one value between 0000000 and 1111111). Of course, increasing the number of symbols increases the difficulty of interpreting the received signal. LoRa is a technology that changes the frequency of the signal linearly along the entire bandwidth (one symbol is transmitted when a cycle of frequencies is completed), as shown in Figure 4; one complete cycle is called **chirp**. The zero value starts at the lower frequency of the bandwidth and ends at the higher one, whereas for the other chirps, the starting point is at a different frequency between the f_{low} and f_{high} . This modulation causes a discontinuity when the end of the bandwidth is reached, which depends on the symbol transmitted.

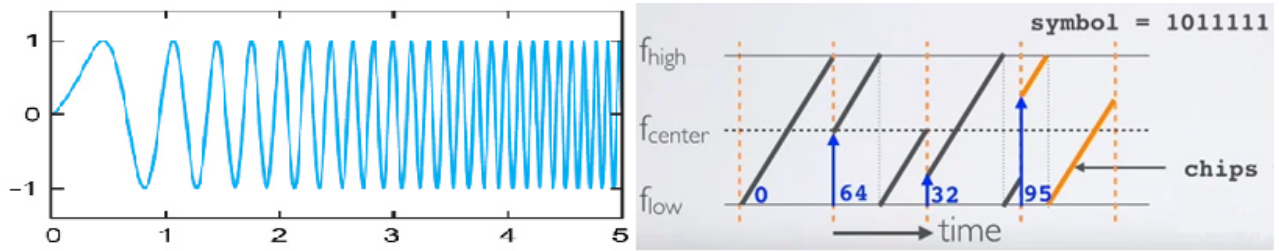


Figure 4 On the right example of changing frequency over time³⁶, on the left an example of Chirp Spread Spectrum transmission³⁸. Each diagonal line represents a frequency sweep while each vertical section corresponds to one symbol (chirps). The last frequency sweep, in orange, represents a value of 95 (1011111).

A LoRa packet starts with the repetition of the zero symbol multiple times and a different number is read as repeated if there is a packet misalignment on the receiver. Misalignment in the preamble provides information regarding the misalignment of the entire message. The signal is then analyzed, and the information is extrapolated using simple math³⁹, making LoRa signal demodulation extremely easy and fast. The time required to transmit one symbol is called spreading factor (SF) and it can be seen as the time required to complete a frequency cycle. The information encoded in a symbol is 2^{SF} and the minimum piece of information is called a chip and can be seen as a bit. A symbol transmitted at a higher spreading factor requires more time to be modulated (see Figure 5) but makes the signal more detectable when the SNR (Signal-to-Noise-Ratio) is lower (in environments where noise can be several times higher than the signal), so it can be transmitted for longer distances.

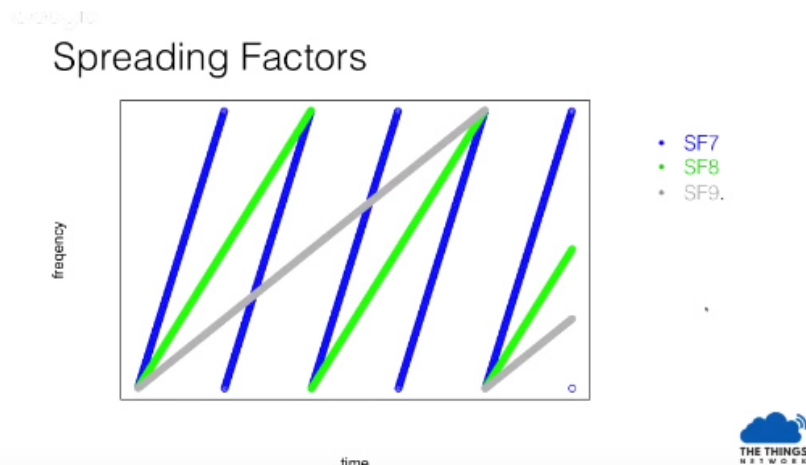


Figure 5 Representation of spreading factor with the time on x axis and the frequency band on y axis⁴⁰

On the other hand, more time (lower data rate) and thus more energy are required to send the same data packet with a higher spreading factor. The possible spreading factors for LoRa range between 7 and 12. The record for the maximum distance travelled by a data packet is 1336 km⁴¹ while the typical range goes from 12 km using SF12 to 2 km using SF7. The transmission speed in Europe is between 980 bps using SF12 and 21.9 kbps using SF7, with a bandwidth of 500 kHz. LoRa runs under unlicensed spectra that are free to use but the specific frequency depends on the region considered (for example, EU863-870, WU433, US902-928, CN470-510, AU915-928). ITU (International Telecommunication Union) regions are reported in Figure 6.

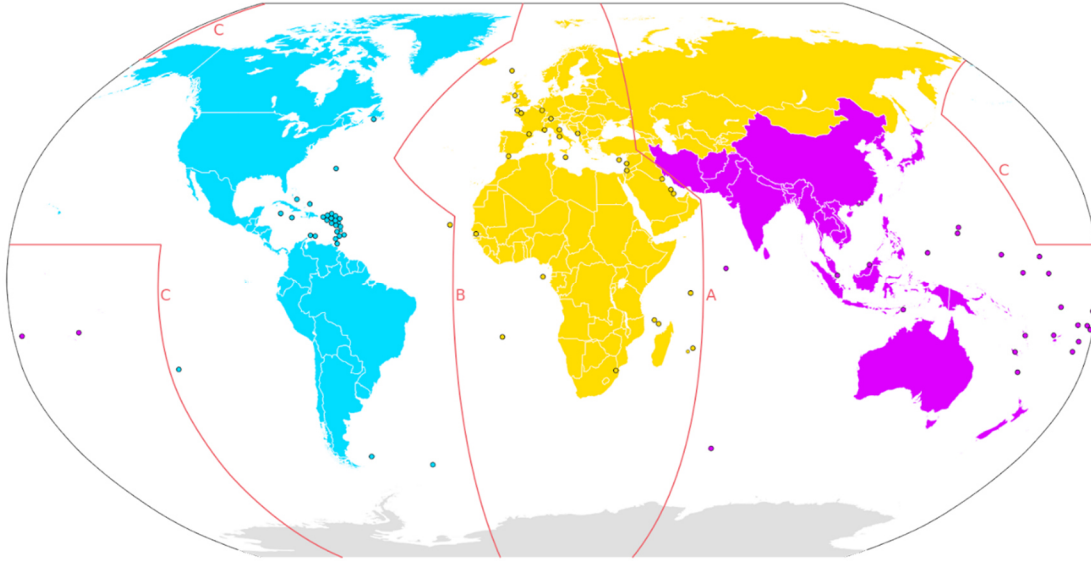


Figure 6 Representation of ITU regions, areas created to simplify the management of global radio spectrum⁴².

The use of an unlicensed spectrum is regulated by law to ensure the fair use of resources. The duty cycle is defined as the fraction of one period during which the device is active. In the LoRa case, it is the time the devices are in transmission mode over the time between one transmission and the following one. The law regulates the maximum power that can be used for transmission in the unlicensed spectrum as well as the maximum duty cycle allowed. For example, in Europe, the matter is regulated by the European Telecommunications Standards Institute (ETSI), which provides information on the actual amount of data that can be sent using LoRa per subband. The ETSI limitations for LoRa subbands are reported in Table 1.

Sub-band	Frequencies [MHz]	Duty cycle	Maximum power [mW ERP]
K	863 - 865	0.1%	25
L	865 - 868	1%	25
M	868 - 868.6	1%	25
N	868.7 - 869.2	0.1%	25
P	869.4 - 869.65	10%	500
Q	869.7 - 870	1%	25

Table 1 European LoRa sub-bands with assigned duty cycle and maximum emission power⁴³

1.2.1.2 Sigfox

Sigfox⁴⁴ is a LPWAN technology owned by UnaBiz born in 2009 that uses BPSK (Binary Phase Shifting Key) modulation to encode data. BPSK modulation transmits zeroes and ones changing the phase of the carrier signal. It works on the 868 MHz unlicensed spectrum in Europe as LoRa does, so it is bound to the same regulation and can reach 15 – 20 km transmission distance. Additionally, both technologies are based on distributed sensors that send small amounts of data to

a central device that forwards it. However, the business models differ. UnaBiz entrusted local network operators (see Figure 7) with access points to its network and made it possible for every producer to design its own hardware to reduce device costs (open market while LoRa hardware is produced by Semtech).

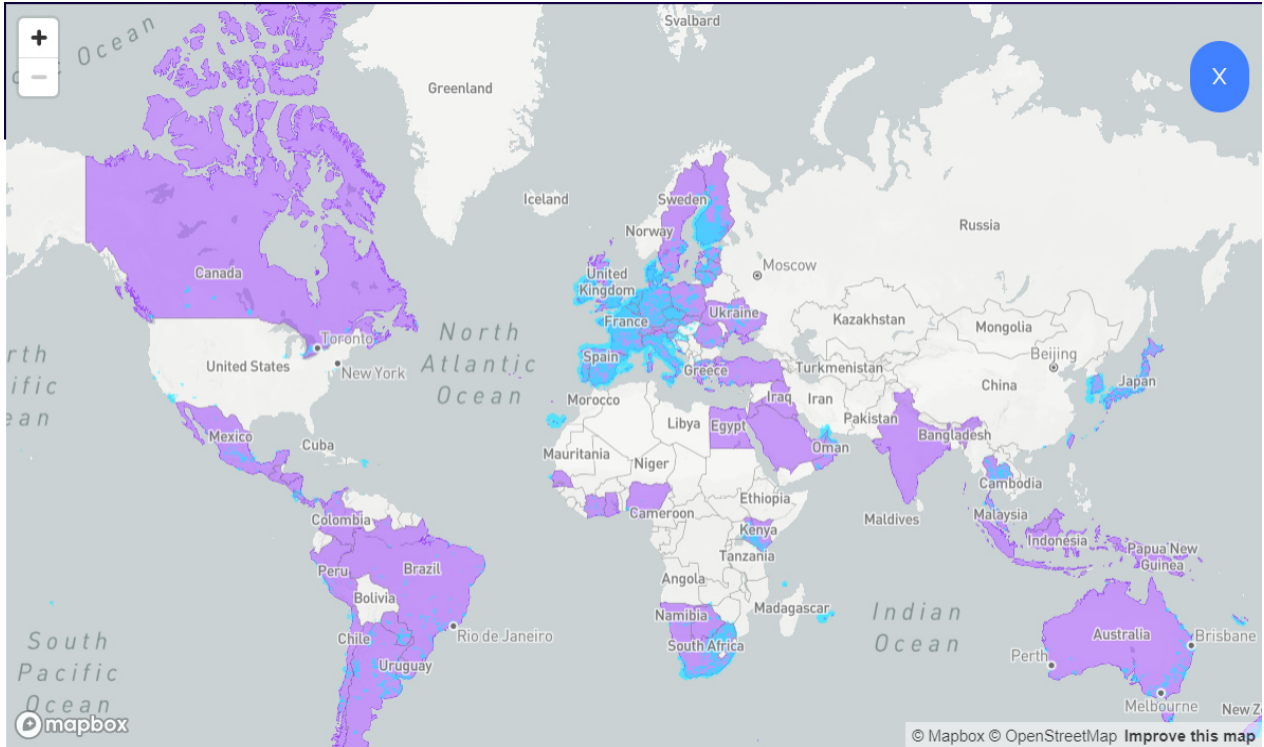


Figure 7 Sigfox network global coverage⁴⁵, in green is the current coverage is reported while in purple the are reported the countries under roll-out

In contrast, Sigfox sells software/network as a service. A user must pay ~15 €/(year*device) to access the Sigfox network everywhere in the world and have access to Sigfox Cloud, the central server that manages all Sigfox devices and makes data available to the user. Different data plans can be subscribed from two daily uplink messages/4 monthly downlink messages to 140 daily uplink messages/4 daily downlink messages. The uplink messages can transmit up to 12 bytes (a total of 24 bytes, where 12 bytes are used for the device ID and other protocol-related information), whereas the downlink messages can be 8 bytes long. While the technology is bidirectional, it is usually used to send messages from the sensors to the Internet owing to the asymmetry in transmission and reception because the base stations are more advanced than the modules and have higher sensitivity, making the reception of the data packet easier than transmission to the sensors. To reduce collisions, each data packet is transmitted at three different frequencies (semi-random hopping technique) and can be received by every base station in the area; thus, there is a high chance that at least one packet is received by at least one base station, avoiding possible collisions. Sigfox networks are particularly useful in applications where the simplicity of the implementation is important because network management is entrusted to the operator and where the devices move frequently and for long distances or are scattered in areas covered by the providers.

1.2.1.3 NB-IoT/LTE-M

The Narrowband Internet of Things⁴⁶ (NB-IoT) has been introduced as part of the 3rd Generation Partnership Project⁴⁷. The partnership unites several telecommunication standard development organizations to ensure the interoperability of mobile networks and devices worldwide. While 4G Long-Term Evolution (LTE) and NB-IoT are both wireless communication technologies that make use of existing cellular networks, there are some

major differences between the two. 4G LTE is optimized for high-speed, high-bandwidth mobile broadband communication to exchange a massive amount of information in a small amount of time, such as streaming, regardless of the power consumption required, number of devices that can connect at the same time or the coverage in challenging environments. In contrast, NB-IoT has been designed to manage a massive number of devices with low traffic requirements, possibly even in remote areas or indoors. It implements different power-saving strategies, shown in Figure 8, which the user can select to conserve energy:

1. Extended Discontinuous Reception (eDRX): eDRX allows the device to increase the time between consecutive paging operations (confirmation of its persistence in the network, retrieval of pending messages, etc.) to remain in idle mode longer and thus spare energy. The eDRX cycle time ranges from approximately 10 to 3 h. A longer cycle increases the battery duration at the cost of reachability. When the device is active, it asks the network for the presence of pending messages, thereby reducing the connection time if no messages are queued.
2. Power saving mode (PSM): In the power saving mode, the device aims to stay in deep sleep mode, thus unreachable, for the longest time possible. It periodically wakes up, sends messages, waits for messages from the network and then returns to sleep mode. Reachability and sleep intervals are regulated by two timers: T3324 (active time) and T3412 Tracking Area Update (TAU). The T3324 timer regulates the time the device monitors paging after a connection and before entering power saving mode, whereas T3412 is the time the device stays in power saving mode before the next connection. The device can request certain values of timers from the network, however the intervals are provided by the network and it can even negate the PSM if it is not supported. In general, PSM requires a longer time to reconnect to the network than eDRX; it is preferred for longer sleep periods, particularly when the device is required to exclusively send messages.

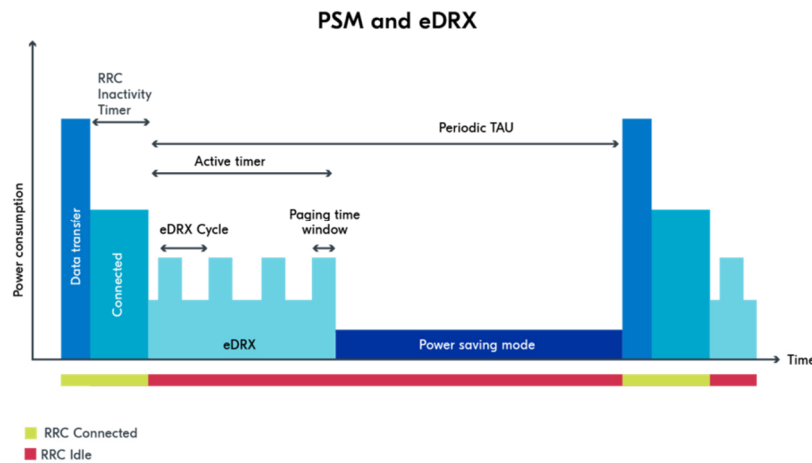


Figure 8 Power Saving Mode and Extended Discontinuous Reception cycles⁴⁸

Described power saving technique can be combined. Both PSM and eDRX maintain the device registered in the network (connection information is retained). With no limits on the exchanged data volume, if real time is not required for the application, the best strategy is to send as much data as possible per wake up. There are

also other features to spare energy during communication, such as adaptive transmission that adjusts the transmission power depending on the signal strength. The described mechanisms aim to obtain an effective schedule connection time and a better allocation of available resources, maximizing the number of devices connected in the same area compared to LTE networks. The frequency bands assigned by the 3GPP for every country were chosen to enhance the penetration and distance over the data transmission rate. In Europe, NB-IoT uses B3 (1800), B8 (900) and B20 (800). Lower frequencies can penetrate more easily through obstacles as well as travel farther, while the use of narrowband communication allows a further increase in the distance owing to the reduced susceptibility to interference⁴⁹. Two different versions of NB-IoT were defined: LTE Cat NB1 was standardized in 3GPP Release 13 and can reach an uplink data rate of 62 kbps, whereas LTE Cat NB2 released in 3GPP Release 14 increased power, improved the reconnection protocol and brought the data rate to 127 kbps uplink. LTE-M (Long-Term Evolution Machine) is similar to NB-IoT for concept and usage, but it features a higher data rate (up to 4 Mbps in Release 14), seamless radio cell changes (useful for moving objects) and supports VoLTE (Voice over LTE) but it can travel for shorter distances and has an higher consumption thus lower than 4G LTE.

1.2.2 Communication protocols

In the previous section, four LPWAN technologies were described. However, sending collected data to a server requires suitable protocols. A protocol can be defined as “a set of technical rules that control the exchange of information between different computers or computer networks⁵⁰”. The use of common protocols improves the compatibility between networks and data integration. Although many protocols exist depending on the application, three are briefly described in the following paragraphs: HTTP, MQTT, and LoRaWAN.

1.2.2.1 HTTP

The Hyper Text Transfer Protocol was introduced in the 1990s to facilitate the exchange of hypertext documents on the World Wide Web, and it is still used. The protocol has been updated over the years with new features and has currently reached version 3. It provides a framework for communication between clients, typically web browsers, and servers hosting content. HTTP protocol is stateless that makes every request from a client to a server independent from the previous one because all the required information to fulfil the request are contained in the request itself. Each resource is univocally identified by an Uniform Resource Locator (URL), regardless of its type (image, video, API, etc.). HTTP allows to perform a set of operations (request method) on the resources:

- GET: retrieves data from the specified URL
- POST: submits data to be processed by the resource
- PUT: replace the resource or creates one if not present
- DELETE: removes the resource at the specified URL
- PATCH: modifies the resource
- HEAD: retrieves only the headers of a resource
- OPTIONS: specifies the communication options for the target resource
- TRACE: performs a message loop-back test along the path to the target resource
- CONNECT: establishes a tunnel to the server identified by the target

HTTP works as a request-response protocol, where a client send a request to a server and the server responds with the requested data or an error. Communication is text based, with requests and responses formatted as headers, followed by an optional message body. The headers convey essential metadata, including information regarding content types, caching directives, and authentication details. HTTP operates over the Transmission Control Protocol (TCP), utilizing a connection-oriented approach. The recently developed HTTP/3 introduced the use of the User Datagram Protocol (UDP) for faster and more efficient data transfer. Although it is a reliable and versatile protocol, the required metadata and the use of text make it relatively heavy.

1.2.2.2 MQTT

The MQTT protocol was developed in 1999 (IBM) to be a lightweight protocol that could work with limited bandwidth and energy to monitor oil pipelines via satellite. In 2013, MQTT 3.1 became an Organization for the Advancement of Structured Information Standards (OASIS) standard⁵¹ and its fifth version was released in 2019. It operates on three main components: MQTT clients, MQTT brokers, and topics. Clients are entities that communicate with each other and are divided into publishers and subscribers. The broker is a central server that receives messages from the publisher and forwards them to subscribers. The topic is the address the messages are sent to and the subscribers should subscribe to if they want to receive the messages sent to that topic. In this manner, one message can be received by multiple clients subscribed to the same topic. A single device can be both a publisher and a subscriber, allowing bidirectional communication. An example of MQTT communication is reported in Figure 9.

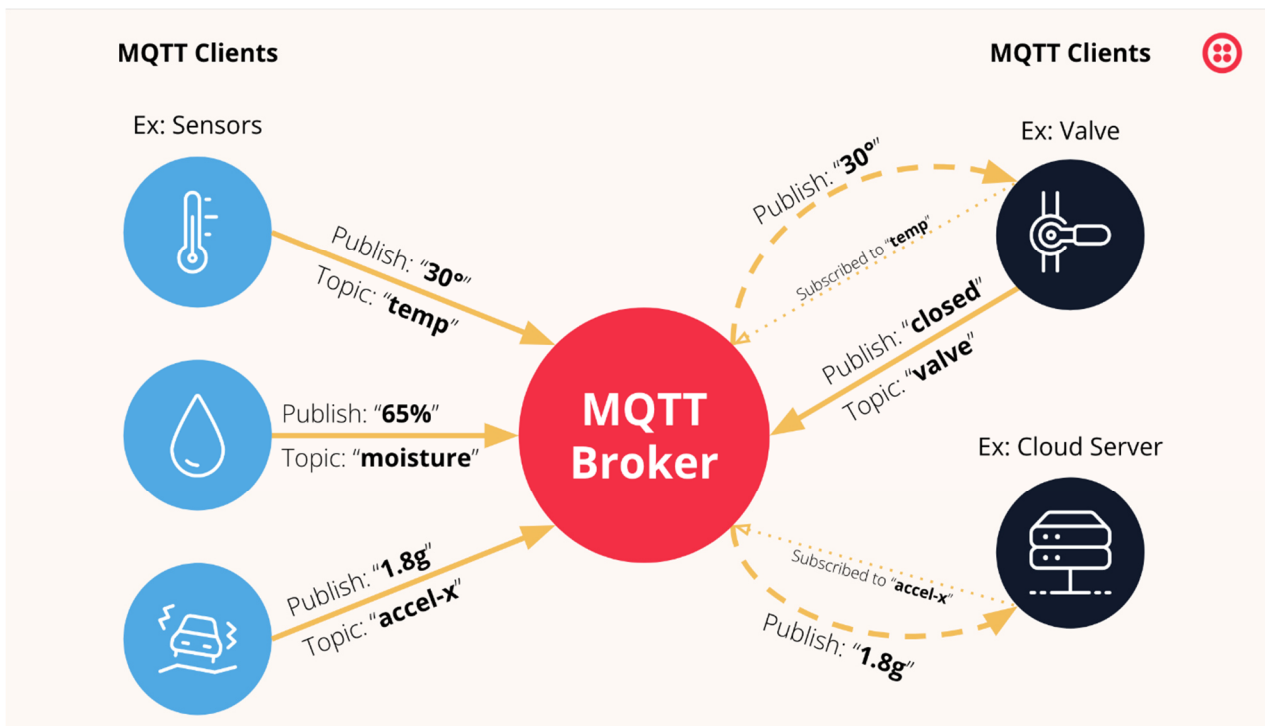


Figure 9 MQTT protocol example with sensors as publishers on the left side that send data and subscribers on the right side that receive them. The valve is an actuator and plays the role of a publisher or subscriber depending on the situation⁵².

This protocol has several features that make it suitable for IoT devices:

- It is a **lightweight** protocol with minimal overhead, making it ideal for devices with strong constraints on battery power, memory and bandwidth.
- It allows **bidirectional communication** by decoupling publishers and subscribers and allows one-to-many messages.
- It is **scalable** and can simultaneously serve many devices at the same time.
- It is an **open standard**, so it is free and allows interoperability among different types of devices.
- It supports **reliable** message delivery through QoS (Quality of Service), even for devices that are offline during message transmission.

MQTT is usually used to deliver messages in real time, with the messages delivered to subscribers as soon as they reach the broker. However, the MQTT protocol offers three QoS levels depending on the reliability required by the application:

0. **QoS 0** stays for “At most once”, messages are sent to the broker with no confirmation or retransmission mechanism and no confirmation on the delivery is required. Some messages can be lost.
1. **QoS 1** stays for “At least once”, the publisher expects an acknowledgment by the subscriber. If an acknowledgment is not received, the message is sent again.
2. **QoS 2** stays for “Exactly once”, it assigns an ID to each packet and works on four levels of confirmation between the broker and the publisher.

A higher Quality of Service (QoS) is associated with increased overhead; however, it enhances the dependability of the system. Moreover, a higher QoS enables the queuing of messages and their subsequent delivery to subscribers that are offline when the message is sent. Finally, the last message can be retained and sent to every device that submits to the topic at a later moment. The protocol characteristics listed above make MQTT a great choice for IoT devices; two well-known alternatives are AMQP (Advanced Message Queuing Protocol) that is a high performance, scalable protocol with more option than MQTT but a higher overhead due to its complexity and CoAP (Constrained Application Protocol), a RESTful protocol used for device-server communication that is simpler and more lightweight than MQTT but with fewer options, suitable for highly resource-constrained devices.

1.2.2.3 *LoRaWAN*

The LoRaWAN protocol³⁶ is a MAC protocol (Media Access Control) that regulates the way data packets are transmitted between a gateway and LoRa devices. LoRa devices can transmit data following a customized protocol; however, the use of the LoRaWAN standard makes them compatible with every LoRaWAN gateway, allowing the use of devices from different manufacturers within the same network and the seamless integration of new devices into existing networks. The first version of this protocol was released by the LoRa Alliance in 2015. The LoRaWAN network architecture uses a star-of-stars topology in which gateways forward messages from the end devices to the server, converting RF packets to IP packets (<https://loro-alliance.org/about-lorawan/>). The server manages all devices, makes data available to the final user and is the “brain” of networks based on LoRaWAN. One message can be received by multiple gateways and is identified by an ID; therefore, repeated messages are discarded on the server side. Therefore, the reliability of the network increases as the number of gateways in the same area increases. The protocol also supports bidirectional communication and mass distribution of messages. The protocol supports three different classes, depending on the required features:

- **Class A** is the default class that must be supported by any device; communication is always initiated by the end device and is asynchronous. An uplink transmission can be started at any time and is followed by two downlink windows.
- **Class B** adds to class A features some planned downlink “ping slots” at scheduled times to make the device reachable by the gateway. It increases the power consumption compared to Class A.
- **Class C** devices always listen when not sending data packets, but the power consumption is much higher than that of the remaining two classes.

The protocol also includes an Adaptive Data Rate (ADR) algorithm to set the best trade-off between battery duration, data rate and transmission power, optimizing them depending on the gateway’s distance and position from the end device. Owing to the spread spectrum technology, different combinations of data rates and frequencies do not interfere with each other, thereby increasing the number of devices that a single gateway can handle.

LoRaWAN messages are also encrypted using a 128 AES algorithm. Every device is identified by its unique ID called DevEUI, which must be provided to the server to generate two session keys: NwkSkey (Network Session Key) and AppSkey (Application Session Key). To successfully encrypt the messages and

communicate with the server the device must know the two keys. NwkSKey is used for data integrity checks and encryption, while AppSKey is an optional security layer used for encryption and decryption. The keys generation procedure is shown in Figure 10.

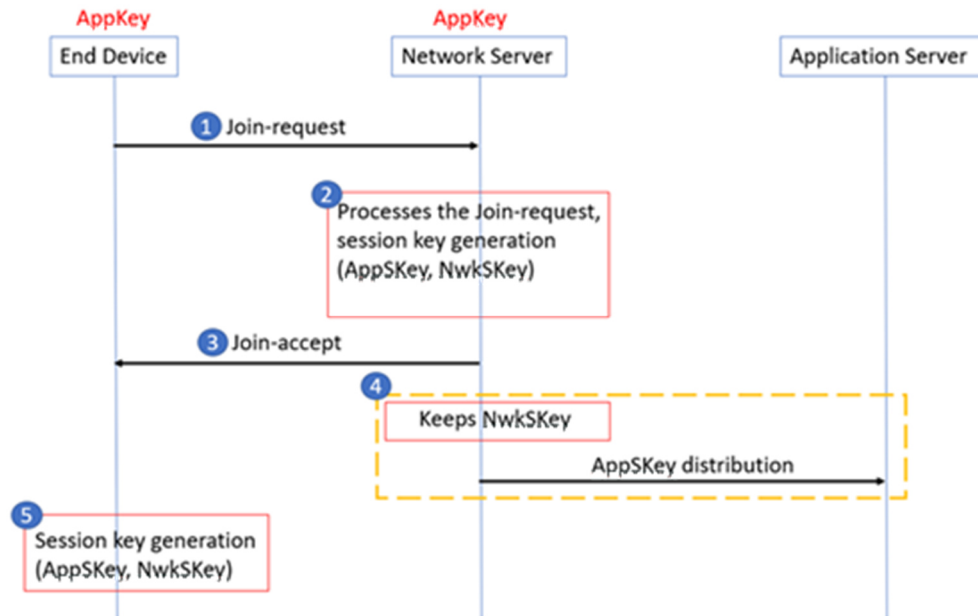


Figure 10 LoRaWAN keys generation procedure⁵³

The devices have two ways to obtain the keys corresponding to two different activation procedures: Over-The-Air Activation (OTAA) and Activation By Personalization (ABP). In the OTAA mode, a device has a DevEUI and an optional AppKey (key used for the encryption of activation and join messages) for secure communication; when the device joins the network, it receives AppSKey and NwkSKey. ABP communication, on the other hand, requires saving the AppSKey and the NwkSKey on the device before activation. ABP does not require a joining procedure, making the connection faster, but it is more difficult to change the network to which the devices are connected (the keys are always generated on the network side) and is less secure. After the joining procedure, the device is registered as active and can exchange messages with the application server. A frame counter is assigned to each message in the form of a progressive number. The server and devices do not accept messages with frame counters lower than those assigned to the last message received. This information allows the server to discard subsequent instances of the same message received by multiple gateways and to be resilient to replay attacks. Another function of a LoRaWAN server is to register gateways belonging to the network and separate devices into applications. An application is a collection of devices that share the same characteristics and can be managed in the same manner; for example, a group of devices with the same owner, the same data structure, the same functionality or whose messages should be sent to the same final user. All gateways belonging to the same network can receive messages from the registered devices. The server manager can share access to a particular application of the network with others, broadcast a message to the entire application, or make all traffic in the application available through a specific protocol (e.g., MQTT or HTTP). Some of the most famous LoRaWAN network servers are ChirpStack (open-source) and The Thing Stack (LoRa Alliance).

1.2.3 Data collection and sharing

In the era of IoT sensors and big data, collected data must be properly stored and handled to make them usable. Information can be stored in formats such as CSV and Excel files, but databases present many advantages. Databases are categorized by the data types they are designed to store; for example, relational databases organize data in rows and columns and can link tables through common fields, whereas NoSQL databases are

used for unstructured data with different data types. The use of a suitable database increases the data storage and retrieval efficiency. Regardless of the database chosen, they share some common features:

- They must be able to store data in an organized format, allowing effective storage, retrieval and manipulation of the data. In particular, the possibility of querying the data and reducing their volume to the bare minimum is crucial to reduce the bandwidth and computational power required by data analysis; therefore, the possibility of performing complex queries in a short time is often a key feature.
- The database manager can specify specific data to be indexed. The data to be indexed are converted into a different format by a given algorithm and are related to the row in the original database. The new format is easier to manage and query for a machine when the original conversion algorithm is known, which makes the retrieval of information much faster. For example, hash indexing converts a value into a unique number using an algorithm and stores the data in a bucket corresponding to that number. When the indexed value is searched, it is reconverted into a number and the data are retrieved from the bucket. The database manager can also specify some characteristics of indexed values, such as uniqueness.
- Databases should be able to assure data integrity (prevent data corruption) through validation rules, easy backup and restore mechanisms and possible replication across different servers to improve reliability.
- Databases should be scalable (both vertically and horizontally) and allow concurrent access to data.
- For security reasons, a database should be able to manage authentication, authorization, and data encryption.

A well-known and widely used database is the PostgreSQL database⁵⁴. It is a relational database created in 1986 as POSTGRES and made open source in 1994; Structured Query Language (SQL) support was added in 1994. SQL is a standard language used for managing data and performing queries on relational databases. PostgreSQL supports numerous types of data, is scalable and numerous plug-ins are available.

The choice of a database is not sufficient to determine the data structure; in fact, the database can have different columns, information and storage logics depending on the data manager. The increase in worldwide data volume and exchange has increased the need for data standardization to make them easily available and usable. Having different datasets with different structures and sometimes even with lacking documentation makes their use, interoperability and maintenance very challenging and time consuming; it requires to study how to properly access and retrieve data from every database and create specific software for the task, changing it whenever the database is modified. Therefore, scientific, business, and government organizations, including the European Union⁵⁵, decided to adhere to the FAIR principles published in 2016^{56,57}.

FAIR principles (Figure 11) state that data should be:

- Findable: data should be easy to find by humans and machines using persistent identifiers (unique IDs or URLs) and metadata
- Accessible: data should be available to users with appropriate permissions and restrictions
- Interoperable: data should be compatible with other data and software systems through consistent formatting and standards
- Reusable: Data should be understandable and well documented, including explanations of collection methods, processing steps and quality checks, allowing others to use them for different purposes. The collected data should be licensed with clear and permissive terms, allowing others to access, use, and potentially modify it for further research or applications.

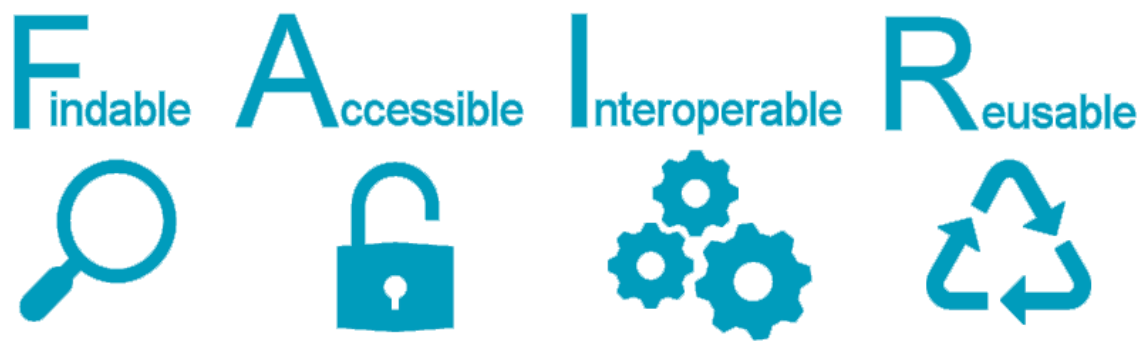


Figure 11 FAIR principles⁵⁸

The choice of a suitable standard can help comply with the FAIR principles, providing guidelines on how to store the data, what should be included in each field and how to make them accessible. The standard can explain how to organize a database or provide information on how data should be exposed. The Open Geospatial Consortium (OGC) is a nonprofit organization founded in 1994 that aims to provide royalty-free, publicly available and open geospatial standards⁵⁹. The OGC SensorThings API provides a unified way to interconnect IoT devices, data and applications through the Internet^{60,61}, in particular, it aims to provide a standardized protocol to define IoT devices and save the information they provide regardless of their purpose. Moreover, each sensor must be completely defined based on the information contained in the database.

In the OGC SensorThings API standard, an IoT device is considered a “Thing” . A thing can have a “Location”, a “Location” becomes an “HistoricalLocation” when a new one is registered. A “Thing” can also have one or more “Datastreams”, a collection of “Observations” produced by the same “Sensor” and measuring the same “ObservedProperty” (the phenomenon of an “Observation”). The “FeatureOfInterest” is the object interested by the phenomenon under observation.

The structure described in Figure 12 is the abstraction of an IoT sensor that contains all the information needed to use and analyze the stored data (such as the sensor model, accuracy and unit of measurement).

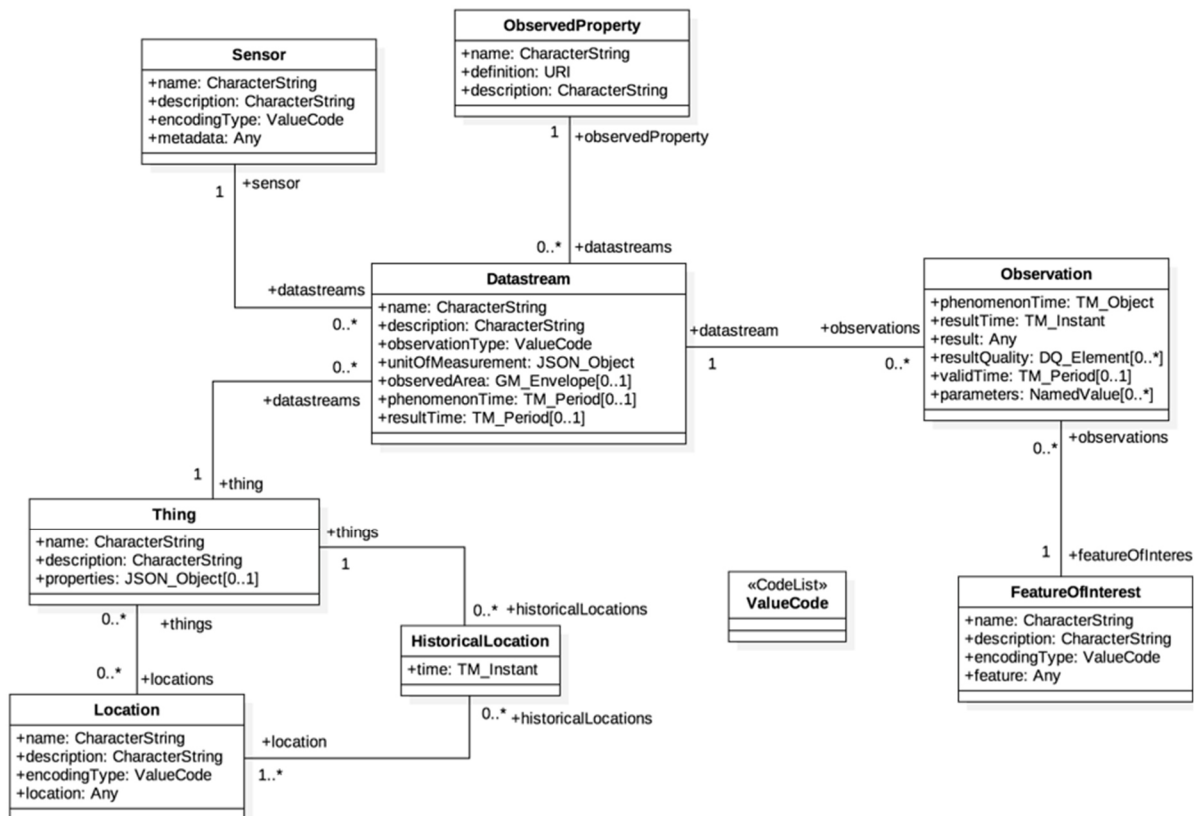


Figure 12 OGC SensorThings API structure⁶²

Each entity is composed of mandatory and optional information, such as the properties field that can contain metadata. Access to data is provided by a RESTful API: an Application Programming Interface (API) is a software intermediary that allows two applications to communicate with each other, whereas RESTful refers to its compliance with the Representational State Transfer (REST) principles. REST API are:

- **Stateless:** information about previous requests are not saved but each request contains the information needed by the server to fulfil the request.
- **Resource-oriented:** each resource has a unique identifier (URL) and can be managed using standard HTTP methods.
- **Client-server architecture:** the client application sends requests that are replied by the server.

An example of a RESTful query is to perform a get on the following URL:

[http://server.it/FROST-Server/v1.0/Things\(1\)/Datastreams](http://server.it/FROST-Server/v1.0/Things(1)/Datastreams)

It will request from a FROST database hosted by "server.it" to return all the Datastreams of Thing number 1. The results of the query are returned in the JSON format.

The SensorThings API also supports an MQTT Extension to create and retrieve data, in which case the URL is replaced by the topics. Finally, it is composed of two additional modules, one for the management of actuators (a device that can perform tasks) and the second that is an extension of the first module for managing data ownership and permissions.

2 DESCRIPTION OF THE PROJECT

Livestock management involves continuous monitoring of the animals by farmers for the early identification of diseases that could affect the rest of the herd or at least the productivity of the individual. However, farmers must implement strategies aimed at maximizing productivity by increasing the volume of the final product or the probability of pregnancy. These tasks were performed through visual assessment by farmers; however, this solution became unfeasible with the increase in the number of animals to control or for pasture farming. The utilization of IoT technologies facilitates the identification of patterns and anomalies through the comparison of historical data collected at the individual and herd levels and the analyzed trend, simultaneously reducing the resources expended on late issue detection. The collected information can also be used to improve farming and breeding methods by studying patterns of the most productive individuals. This PhD thesis focuses on the design, prototyping and testing of different types of Precision Livestock Farming (PLF) monitoring systems for real-time data collection. The term "system" encompasses not only physical devices but also data processing, storage, and visualization, as a monitoring system is efficacious only if it can be appropriately accessed to extrapolate useful information.

2.1 PROJECT GOALS

The project aimed to identify needs based on farmers' experience and European directives and create state-of-the-art prototypes to address identified issues, reaching a Technology Readiness Level (TRL) of at least four at the end of the project. The designed devices should be cost-effective and adhere to the Internet of Things (IoT) definition, equipping wireless technologies for Internet connectivity to transmit real-time data while maintaining minimal power consumption. The end point of this thesis is to design instruments for researching animal health and behavior, providing continuous data over time for the development of algorithms.

The research was divided into three different topics, each with unique challenges:

1. Animal well-being monitoring
2. Gas sensing for air quality of animal shelters and animal greenhouse gases emissions
3. Data collection and cloud computing server

The goal was to develop and test at least one IoT device or service for each topic. Following a comprehensive bibliographic review, the established objectives were:

1. An innovative wearable sensor to measure multiple individual animal physiological parameters, such as geographical coordinates, air temperature and relative humidity around the animal, average acceleration and standard deviation over three axes, heart rate and cutaneous temperature (animal well-being monitoring).
2. RFID subcutaneous temperature reader from a RFID subcutaneous microchip (animal well-being monitoring).
3. A customizable Internet of Things (IoT) gas analyzer designed to measure the atmospheric concentrations of NH_3 , CH_4 , H_2S , CO_2 , PM_{10} , $\text{PM}_{2.5}$, and PM_{10} , as well as air temperature and humidity (gas sensing for air quality assessment in animal shelters and quantification of animal greenhouse gas emissions).
4. A data server compliant with FAIR principles for the collection, storage and visualization of IoT data.

This research has also contributed to address specific research questions which were part of three large and distinct European projects (Figure 13, Figure 14 and Figure 15), as listed below:



Figure 13 HIGHLANDER project logo⁶³

HIGHLANDER⁶³ (High performance computing to support smart land services): The objective of the Highlander project was to assess existing technologies and develop novel approaches for more efficient utilization of resources such as soil, water, livestock, and forests, with particular emphasis on the effects of climate change. Furthermore, high-performance computing was employed to facilitate accurate forecasting of climate change impacts, thereby enabling improved resource management. The acquisition of real-time data and the utilization of remote sensing technologies were of paramount importance for the HIGHLANDER project.



Figure 14 SCALA-MEDI project logo⁶⁴

SCALA-MEDI⁶⁴ (“Improving sustainability and quality of Sheep and Chicken production by leveraging the Adaptation potential of LocAl breeds in the MEDiterranean area”): SCALA-MEDI project brings together European (Italy and France) and non-European (Algeria, Tunisia and Morocco) countries to explore a common possible strategy for the mitigation of climate change impacts on livestock, in particular chickens and sheep. This research project aims to select and enhance indigenous breeds for improved adaptation to climatic conditions from a genetic perspective. The function of the technologies developed in this context is to provide phenotypic characterization of animals.



Figure 15 SEBASTIEN project logo⁶⁵

SEBASTIEN⁶⁵ (“Smarter livEstock Breeding through Advanced Services Tailoring Innovative and multi-sourceE data to users’ Needs”): The goal of the SEBASTIEN project is to provide a platform that works as a Decision Support System (DSS) for the livestock sector in Italy. It extensively utilizes Internet of Things (IoT) technologies to provide data to the platform, thereby facilitating the decision-making process.

2.2 DEVELOPED PROTOTYPES AND INVOLVED TECHNOLOGIES

The development of the prototypes was carried out from the electronics to the construction of the case to protect the sensors in challenging applications such as animal monitoring. Full control over the production line allowed a continuous improvement in every possible aspect of the sensors as well as absolute freedom in the choice of the solution to be applied. After the assessment of the basic requirements for the sensor, the process always started with a market search for existing products to understand what has been done on the topic as well as for sensors or technologies that could be applied to retrieve the desired information, possibly improving and combining different technologies to obtain the best result. After the choice of the components, the Printed Circuit Board (PCB) was designed considering the specifications of every component as well as the size and shape required by the application (an example of designed PCB is shown in Figure 16).

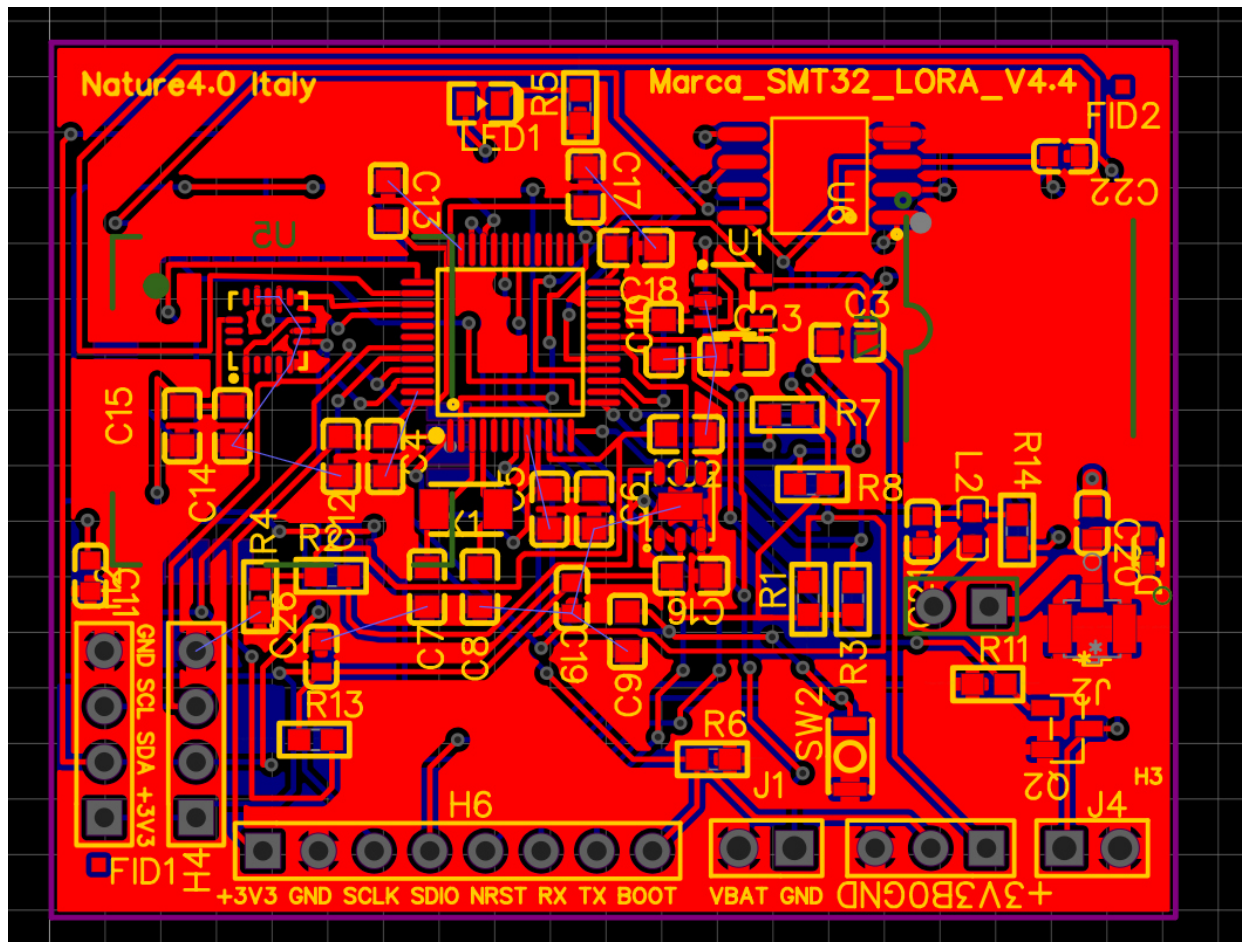


Figure 16 Animal collar Printed Circuit Board (PCB) designed in EasyEDA, upper side

The software selected for PCB design was EasyEDA⁶⁶. The received prototypes were then assembled by manually placing electrical components or using a pick-and-place machine. The functionalities of the board were then tested from an electrical point of view (power, routing, etc.) and from a functional point of view, programming the microprocessor and trying the expected features. Arduino⁶⁷ programming language, a simplified version of C++, was chosen because of its versatility and the vast number of libraries already available, as well as being open-source software. Arduino environment is broadly supported, and numerous third-party microprocessors and boards have their own implementations in the Arduino core. Working in this environment facilitates seamless portability from one microprocessor to another without substantial revision of the software, a significant feature in prototyping that enables rapid adaptation to microprocessor shortages and allows the reuse of previously written libraries in new projects. The last step consisted of finding or designing a suitable enclosure for the hardware. The choice of the enclosure is strongly dependent on the

application but some of the main driving factors are the size, sturdiness and Ingress Protection (IP) level. Commercial enclosures were chosen whenever possible but for some applications they were designed using FreeCAD⁶⁸, an open-source Computer-Aided Design (CAD) parametric software, and then 3D printed with suitable materials. The prototype was then tested, and modifications were implemented based on the obtained results and identified issues. The devices built during the PhD years include an animal collar, an RFID subcutaneous sensor along with its reader, some single-sensor devices featuring an SD card for high-frequency measurements and a gas analyzer for the measurement of multiple gas concentrations. Their individual descriptions and the preliminary results obtained are described in the following sections.

3 ANIMAL COLLAR

The animal collar (Figure 17) is a device developed for medium to large-sized animals, such as bovines and ovines. This addresses the necessity of monitoring the condition of each animal in real time to identify potential diseases or anomalies. Furthermore, it serves as an effective research instrument for collecting real-time data, identifying patterns in animal behavior, and correlating the information provided by various sensors mounted on a single device. It has been used in Sebastien project as source of real-time data from cows for the livestock dataset and in Scala-Medi project to help studying the health parameters of sheep potentially subjected to heat stress to study their phenotype and identify the most resilient individuals.



Figure 17 On the right the ovine version of the animal collar devices is shown, on the left the one for bovine. The opened box allows to see the antenna, the switched on heart rate sensor and some components such as the USB charger, the LoRaWAN module, the GNSS module and the magnetic switch. The box is filled insulant electronic gel.

3.1 SENSOR DESCRIPTION

The animal collar is placed on the neck of the animal using a collar that differs depending on the species. It can be easily installed and removed and can measure six different physiological and environmental parameters:

- geographical coordinates
- air temperature and relative humidity of the environment closed to the animal
- average acceleration and standard deviation over the three axes
- heart rate
- cutaneous temperature
- battery voltage

The selected set of parameters can be related to livestock behavior and/or health states. The activity, measured by the accelerometer, can be associated with estrus, stress and diseases^{19,69,70}. Moreover, information about the animal position can be retrieved (standing, lying, etc.) and when placed on the neck, the retrieved data can even be related to chewing and swallowing, making it one of the most used sensors for livestock monitoring⁷¹.

GNSS coordinates are particularly useful when applied to extensive breeding to identify areas where livestock eat or drink and relate them to animal health, growth and productivity⁷² and can also be used for applications such as virtual fencing⁷³.

Air temperature and humidity provide information about the environment to which animals are exposed. Collecting the data related to each animal instead of basing the evaluation on the parameters retrievable from

meteorological stations allows to consider additional variables associated with the behavior of the animal, such as the effect of the shadow⁷⁴.

Collected data are sent by the LoRa connection to a central server that saves them in csv format. Different configurations were evaluated during this thesis and four different versions were produced and tested to obtain the current one.

The components of the device were chosen to be as low-power as possible to reduce the maintenance required by the devices, which is a cost for farmers. Moreover, the need to have one device per animal to monitor makes the cost of the components another important factor.

A microprocessor from the STM32 family from STMicroelectronics, an Italian French electronics company, was chosen. **STM32L072CBT6**⁷⁵ is an ultralow-power 32-bit microprocessor that provides 128 kB of flash memory for program storage, a maximum clock frequency of 32 MHz, 20 kB of RAM, and a 12-bit Analog-to-Digital Converter (ADC). Additionally, it offers multiple sleep modes to save energy, an internal Real Time clock (RTC) for time management, an internal watchdog to reset the device in case of error, and 11 peripheral communication interfaces, all contained within a 7×7 mm package. STM32 microprocessors have their own programming language, which makes the software portable among the various STM32 microprocessors. However, it has been decided to use Arduino to write software that is portable even to microprocessors from different producers and to be able to use the libraries already available as well as to reuse functions previously written for other applications. STM32 family is supported by Arduino platform through the official repository STM32duino⁷⁶ that contains the definition of microprocessors as well as the Arduino basic library compatible with their architecture. Arduino code can also include C++ commands and structures defined by the STM32 programming language if needed. Arduino relies on STM32CubeIDE, a STM platform for the management of the microprocessors from connection to memory addresses, for interfacing with the microprocessors and program them. The choice of a microprocessor with a large memory and high clock frequency provides the possibility of future updates with more complex features and algorithms to be embedded in the chip. Having data analysis and quality control embedded in the chip itself allows to reduce the amount of information to be transmitted and correct for some possible errors directly in the field without losing data.

The accelerometer mounted on the device was also manufactured by STMicroelectronics. It is the **LIS3DHTR**⁷⁷, a three-axis linear accelerometer of 3×3 mm with a dynamically selectable full scale between ± 2 g and ± 16 g and 12-bit resolution data output. It features an ultralow power mode consumption down to 2 μ A with multiple options for possible interrupts triggered by specific events to wake up the main processor, such as the position of the sensor or instantaneous acceleration. The acquisition frequency ranges from 1 Hz to 5.3 kHz while it can be interfaced using I2C or SPI digital output interfaces. Whenever possible, the I2C interface is preferred to spare microprocessor pins. The resolution of the sensor is influenced by the selected full-scale and mode but it can attain a maximum precision of 1 mg/digit.

The choice of a suitable Global Navigation Satellite System (GNSS) depends on parameters such as supported GNSS constellations, position accuracy, Time To First Fix (TTFF) and power consumption. U-blox is a leader company in GNSS module production and offers different solutions depending on customer needs. **U-blox Max-M10S**⁷⁸ is a low-power, standard-precision GNSS receiver. It can receive 4 different GNSS constellations: GPS (USA), GLONASS (Russia), Galileo (Europe) and BeiDou (Cina). All systems provide global coverage but with different precision and availability depending on the organization that manages the system. Moreover, the support of multiple constellations allows the achievement of better precision as well as a higher probability of determining the GNSS position faster than single constellation modules. The precision offered by this module when used in the multi-constellation GNSS mode is 1.5 m. The GNSS receiver precision is calculated in combination with the Satellite-Based Augmentation System (SBAS), a network of geostationary satellites that broadcasts corrections to GNSS signals to improve the accuracy and reliability of these systems, and is defined as the Circular Error Probability (CEP), which is the radius of a circle centered

on the true value that contains 50% of the actual GNSS measurements, in this case a radius of 1.5 meters. In IoT devices, current consumption is a critical factor and is determined by the cumulative value of the current, measured in A, required by a device to operate in each mode, multiplied by the percentage of time the device spends in that mode. Different strategies can be applied in the use of GNSS depending on the acquisition frequency required by the application. They range from continuous tracking mode to on/off operation mode. Although maintaining the GNSS in an active state results in higher overall power consumption, the initial position acquisition phase exhibits the highest power consumption and can last from 30 seconds to several minutes, contingent upon satellite positioning. For this reason, if an on-off strategies is adopted, the TTFF is of great importance to determine the GNSS module power consumption. U-blox provide a useful feature for its GNSS modules called AssistNow, which utilizes previously downloaded information on the chip regarding satellite positions and orbits (almanac and ephemerides) to expedite the TTFF. The downloaded data can be stored in the internal memory of the module, which is powered by a dedicated pin, allowing the deactivation of the remaining components to conserve energy. The module itself has a size of 9.7 x 10.1 x 2.5 mm antenna excluded and can be interfaced to the microprocessor via I2C.

Air temperature and humidity are collected by an **SHT41**⁷⁹ sensor, which is an ultra-low power sensor that can also work in condensing environments. It measures both temperature with a resolution of 0.01 °C and an accuracy of ± 0.2 °C and relative humidity with a resolution of 0.01% and an accuracy of ± 1.8 %. It communicates with I2C. Specific PTFE membranes are commercially available, allowing the passage of air filtered from liquid and dust.

Hearth rate and surface temperature are measured using **MAX30102**⁸⁰ sensor. It is a pulse oximetry and heart rate monitor module with an embedded temperature sensor. This device is an optical sensor that operates based on the emission and measurement of two primary wavelengths: red (660 nm) and infrared (940 nm). Both red and infrared light are absorbed by blood to varying degrees. However, the key to oximetry lies in the differential absorption of these wavelengths by oxygenated and deoxygenated hemoglobin. Oxygenated hemoglobin absorbs more infrared light than red light, whereas deoxygenated hemoglobin absorbs more red light than infrared light. The reflected light intensity is measured by a photodiode and the absorbed light is therefore calculated. By measuring the ratio of red to infrared light absorbed, the oximeter can calculate the percentage of oxygenated hemoglobin in the blood, which is the SpO2 value. The amount of light absorbed depends on the amount of blood present below the skin, the heart rate is calculated from the increase or decrease of blood as the blood vessels expand or contract rhythmically during the cardiac cycle. The heart rate is a quantitative measure of blood vessel volume fluctuations, with the signal frequency being of greater significance than its absolute magnitude. The temperature sensor on MAX30102 has an accuracy of ± 1 °C and a resolution of 0.0625 °C. The sensor can be interfaced with a microprocessor by using an I2C connection.

A 16 MB flash memory was also added to locally save the collected data. This component increases the reliability of the system and provides the possibility to resend the data in case of packet loss, as well as to retrieve the data if malfunctioning occurs. External non-volatile memory also stores information about the device, such as its serial number. The chosen memory was **W25Q128JV**⁸¹. It uses SPI to communicate with the microprocessor and is divided into 4096 erasable sectors of 4096 bytes, which means that the information can be erased only in multiples of 4096 bytes. It has a data retention period of more than 20 years and each sector can be overwritten at least 100000 times. A data transfer rate of 66MB/s is sufficient for the application.

The last onboard component is the **RAK3172 module**⁸². It is a low-power transceiver module based on the STM32WLE5CC microchip used to develop LoRa and LoRaWAN applications. Its firmware is based on RUI3 (RAKwireless Unified Interface V3) that is defined as “modular IoT platform based on Arduino SDK”. This API allows access to connectivity features by using a higher level of abstraction. It is worth mentioning that it allows running custom firmware programmable by the Arduino IDE, performing the role of a microprocessor while supporting the LoRaWAN protocol accessible through the API. However, it can also be used through

the UART interface as a LoRaWAN modem commanded by an external microprocessor using AT commands. It supports classes A, B, and C of the LoRaWAN 1.0.3 specification but can also be used as a LoRa point-to-point. During the intervals between commands, it automatically enters sleep mode, reaching a power consumption of 1.69 μ A. A significant advantage of utilizing a LoRaWAN-compliant module is that the LoRaWAN protocol is previously uploaded to the module itself, eliminating the need for microprocessor memory allocation. Furthermore, the protocol is readily accessible through straightforward AT commands.

The board is powered by a 2000 mAh LiPo battery at 3.7 V. It is connected to a charger that protects the battery from overvoltage and undervoltage conditions and includes a USB-C connector for recharging. The output of the battery charger is connected to the board through a magnetic normally closed switch. The current can pass through the magnetic switch until the magnet is moved close; then, the switch is opened, and the device is switched off. The utilization of a magnetic switch enables its incorporation into the device without external exposure, thereby mitigating the risks of water ingress and unintentional shutdown due to animal movement. The power line is then connected to a 3.3 V LDO to stabilize the voltage and power all the components. Two flat passive antennas are used for the LoRaWAN and GNSS signals to keep the size of the device as small as possible and to reduce the cost of the device.

The size of the first prototype was 115 mm $\times$ 115 mm $\times$ 55 mm and it was mounted inside a commercial box using two 5000 mAh batteries as power source. For the last prototype version, following the improvement of the power management, resulting in a reduction in the battery size, and the improvement of the board design, it was not possible to find a suitable commercial enclosure that minimized the size of the device. The dimensions of the device are critical in this type of application, as livestock such as sheep or cattle may impact the headlock during feeding or attempting to insert their heads between the bars, potentially causing damage to the device. Moreover, animals can actively try to remove it, so the device should be as flat as possible. In addition, while the neck of a cow is massive (135 cm of circumference or higher), to use the same device on sheep (less than 35 cm of circumference), the device should be as small as possible. A 3D printed enclosure shown in Figure 18 was designed and printed to obtain the smallest form factor.

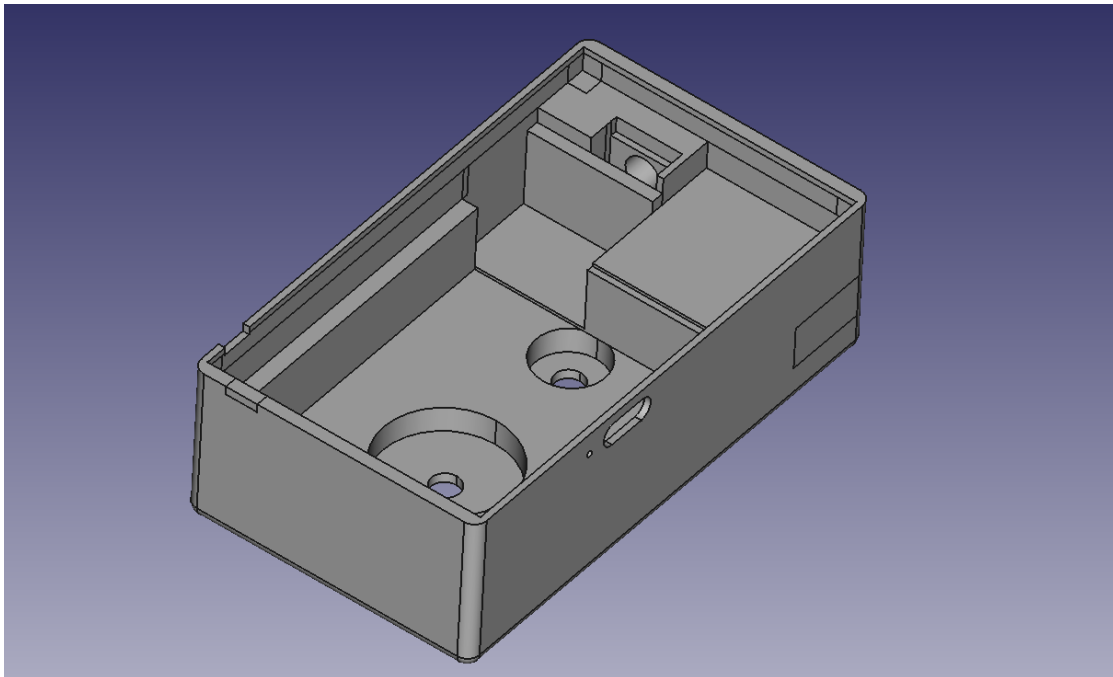


Figure 18 3D model of the animal collar enclosure designed in FreeCAD

The size of the printed box is 80 $\times$ 45 $\times$ 26 mm, with a volume reduction of 77% compared to the first design. The enclosure is secured on the collar using two rivets placed on two washers. To avoid unwanted thickness

inside the box owing to the rivets, two places for washers and rivets were designed on the bottom of the box while maintaining a suitable thickness to avoid breakage. Subsequently, the 2000 mAh battery is positioned in the rectangular space atop the aforementioned structure, and the PCB board is placed over it, with the female header of the PCB board interlocking between the battery and the box, thereby securing both components in place. The magnetic switch is fixed on the upper right corner of the box, while the temperature and humidity sensor is placed in contact with the external air through a round hole placed on the upper-left side of the enclosure and with the PTFE membrane protecting it from water ingress. The USB charger is exposed by a hole on the side of the box and is protected by a rubber lid to avoid water ingress. Finally, the heart rate sensor is fixed at the bottom of the box using a suitable glue to be in contact with the animal skin and connected to the board through a ribbon cable. The cable should adhere to the box to avoid providing a possible hooking point, which could result in device breakage. When all the components are placed inside the box, an insulant electronic gel is poured into the box to protect it from water ingress. Finally, the lid of the box is glued to complete the device, and the magnet is placed on a metal plate at the bottom of the enclosure to switch it off. The collars differ depending on the animal on which they should be placed, as clearly visible in Figure 19. A nylon collar is used for cows, excessive movements and sensor detachment are limited by a weight of 500 g, which regulates the collar orientation. The weight is too heavy for a sheep; therefore, an elastic bend with anti-slip rubber traces is used instead to maintain the sensor in position.



Figure 19 Test of the first animal collar on sheep and final version mounted on a cow

Data are sent by the collar every hour but are collected at different frequencies. A moving average is performed on the accelerometer measurements, air temperature, air humidity and surface temperature for 5 s every 5 min for a total of one minute every hour. This distribution allows to obtain an average value and standard deviation more representative of the whole hour compared to the collection of one minute every hour. The device is in low power mode for the rest of the time to spare energy. Every hour, the sending cycle is triggered, and the heart rate is calculated on average over 30 s, while the GNSS position is taken when its precision reaches a certain level. Due to LoRaWAN and battery constraints, only the hourly average is sent with as confirmed payload to “The Things Stack” server. The LoRaWAN spreading factor is fixed at 12 because the animal is a moving object, and thus, the Adaptive Data Rate (ADR) algorithm is not a suitable solution for such application because it is better to always send the message as far away as possible instead of optimizing the signal for the current position. The device current consumption measured in the laboratory was 30 mA during the

measurement period and 0.7 mA during the sleep phase when all sensors were switched off. Under the hypothesis that the GNSS position is fixed after 30 s, the current consumption of the device is 1.45 mA so the expected duration is 58 d with a 2000 mAh battery. However, external factors such as the temperature, position of satellites and subsequent FTTF, particularly when positioned under the roof of a barn, as well as the reachability of the gateway, can affect the real duration of the battery. For example, if the GNSS module FTTF is five minutes (the maximum time set for GNSS fixing), the power consumption rise to 3.7 mA and the expected duration drops to 22 days. A Python program has been developed to subscribe to the topic provided by The Things Stack broker to receive published messages. An example of a received message is reported below:

```
{'end_device_ids': {'device_id': '11245009', 'application_ids': {'application_id': ...}, 'dev_eui': ..., 'join_eui': ..., 'dev_addr': '27034AF4'},
'correlation_ids': ['gs:uplink:01J3DXZFA0DT59ZKVZCKZ18VBX'], 'received_at': '2024-07-22T19:16:31.888713540Z', 'uplink_message':
{'session_key_id': 'AZDVXIDSZaxulggD1h4L4Q==', 'f_port': 2, 'f_cnt': 32, 'frm_payload':
'CVAKExUHQAAGwSwGOa8PwjoMgEAq9vCC3sdhhGx3HgKgwsUGQAAAADGGTwFheULBA==', 'rx_metadata': [{'gateway_ids':
{'gateway_id': ..., 'eui': ...}, 'time': '2024-07-22T19:16:31.549333095Z', 'timestamp': 1568512564, 'rssi': -99, 'channel_rssi': -99, 'snr': 4, 'uplink_token':
'ChsKGQoNc2ViYXN0aWVuLTAwNBllrB8J//4QqtsQtLT26wUaDAiP4Pq0BhDF3dHEAiCgtomV06cC', 'received_at': '2024-07-
22T19:16:31.540715008Z'}], 'settings': {'data_rate': {'loras': {'bandwidth': 125000, 'spreading_factor': 12, 'coding_rate': '4/5'}}, 'frequency': '868500000',
'timestamp': 1568512564, 'time': '2024-07-22T19:16:31.549333095Z', 'received_at': '2024-07-22T19:16:31.681671406Z', 'confirmed': True,
'consumed_airtime': '2.793472s', 'network_ids': {'net_id': '000013', 'ns_id': 'EC656E0000101FC0', 'tenant_id': 'nat4-lorawan-network', 'cluster_id': 'eu1',
'cluster_address': 'eu1.cloud.thethings.industries', 'tenant_address': 'nat4-lorawan-network.eu1.cloud.thethings.industries'}}}
```

The device payload is contained in the 'uplink_message' key and is sent in byte format to spare bytes in the LoRaWAN message. The payload content is as follows:

1. device ID (e.g. 11243001) composed of type of device (11), year of production (24), month of production (3) and a progressive number assigned to the device during the month (1 of 999). The number of bytes used for each field is very important using LoRaWAN, this expression for the serial number uses 4 bytes to contain all the required information. The device ID is saved as a uint32_t variable but is visualized in human readable form (81243001) if it is interpreted as a hexadecimal number. This solution allows the construction month to be stored as a single digit, expressing the last months of the year as A, B or C. This code can univocally identify 999 devices every month.
2. string type: it uniquely identifies the structure of the string so that it can be easily interpreted by software
3. cycle duration (ms): 4-byte cycle duration
4. latitude ($\ast 10^{-7}$ degrees): GNSS latitude in degrees multiplied by 10^7
5. longitude ($\ast 10^{-7}$ degrees): GNSS longitude in degrees multiplied by 10^7
6. altitude (10^{-3} m): GNSS altitude in meter multiplied by 10^3
7. average acceleration component X (d.n.): hourly average of the acceleration component on the X axis in digital number at ± 2 g and high-resolution disabled
8. standard deviation acceleration component X (d.n.): hourly standard deviation of the acceleration component on the X axis in digital number at ± 2 g and high-resolution disabled
9. average acceleration component Y (d.n.): hourly average of the acceleration component on the Y axis in digital number at ± 2 g and high-resolution disabled
10. standard deviation acceleration component Y (d.n.): hourly standard deviation of the acceleration component on the Y axis in digital number at ± 2 g and high-resolution disabled
11. average acceleration component Z (d.n.): hourly average of the acceleration component on the Z axis in digital number at ± 2 g and high-resolution disabled
12. standard deviation acceleration component Z (d.n.): hourly standard deviation of the acceleration component on the Z axis in digital number at ± 2 g and high-resolution disabled
13. air temperature ($\ast 10^{-2}$ °C): air temperature in Celsius degrees multiplied by 10^2
14. air relative humidity ($\ast 10^{-2}$ %): air relative humidity in percentage multiplied by 10^2
15. heart rate (bpm): heart rate in beats per minute

16. skin temperature ($\times 10^{-2} \text{ }^{\circ}\text{C}$): skin temperature in Celsius degrees multiplied by 10^2
17. battery voltage (mV): battery voltage in millivolts
18. Position Dilution of Precision (PDOP): it is a dimensionless number that indicates the geometric strength of the satellite constellation used for GNSS positioning. The signal is better when the number is lower.
19. HDOP (Horizontal Dilution of Precision): like the PDOP but limited to the horizontal precision (latitude and longitude coordinates)
20. Position check: information about the status of the module such as a correct initialization
21. SIV (Satellites In View): It represents the number of satellites that a GNSS receiver can detect and track at a given moment.

Knowing the structure and byte size of each variable, the Python program decodes the payload from the byte format to decimal values. The resulting string is saved on a txt file in csv format. An example of a decoded string is as follows:

22-07-2024 21:02:21;11245010;12;7502;414623670;129458683;69653;11502;5139;-3327;5300;-
9930;3345;3016;5796;54;3684;3550;193;2504;11;10

It is a message sent by device 11245010. The first element of the string is the date and time in UTC when the message was received by the server.

3.2 FIELD TESTS AND COLLECTED DATA EXAMPLES

In this section, some examples of the collected data and preliminary analysis are reported and discussed. Currently, 53 devices have been installed on cows and 90 devices have been distributed for application to ovine subjects. The analysis was performed using Python⁸³.

3.2.1 Air temperature and humidity

Temperature and relative humidity can induce thermal stress in animals, affecting their welfare and productivity⁸⁴. Measuring these parameters closer to the animal instead of taking them from meteorological stations takes into account the individual situation and choices, such as seeking shade or cooling in the water. The plot in Figure 20 shows the air temperature and relative humidity patterns from 12/07/2024 to 16/08/2024 for one animal.

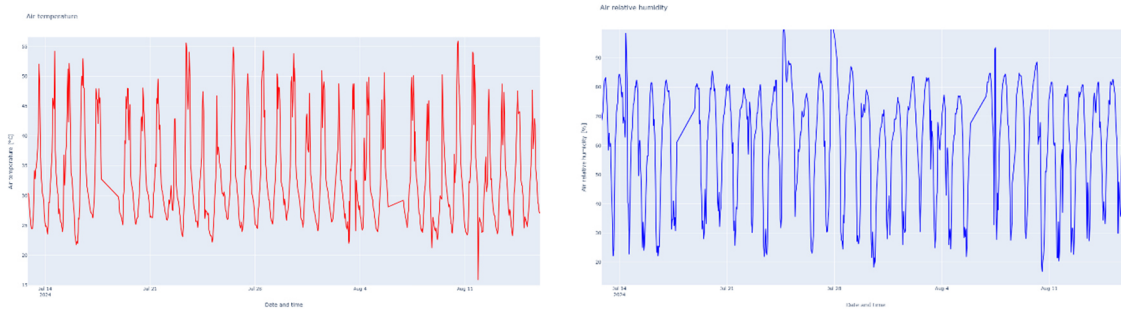


Figure 20 Air temperature and humidity plot during the period 12/07/2024 - 16/08/2024

The two parameters clearly show daily patterns with higher temperatures and lower relative humidity during the day and vice versa during the night. One of the most used indicators of thermal stress in animals is the THI (Temperature Humidity index). Different formulas exist to estimate this parameter⁸⁵, in Figure 21 the THI index is calculated using the following one:

$$THI = (1.8 Ta + 32) - (0.55 - 0.0055 * RH) * (1.8Ta - 26)$$

where Ta is the ambient temperature in degrees Celsius and RH is the relative humidity of the air.

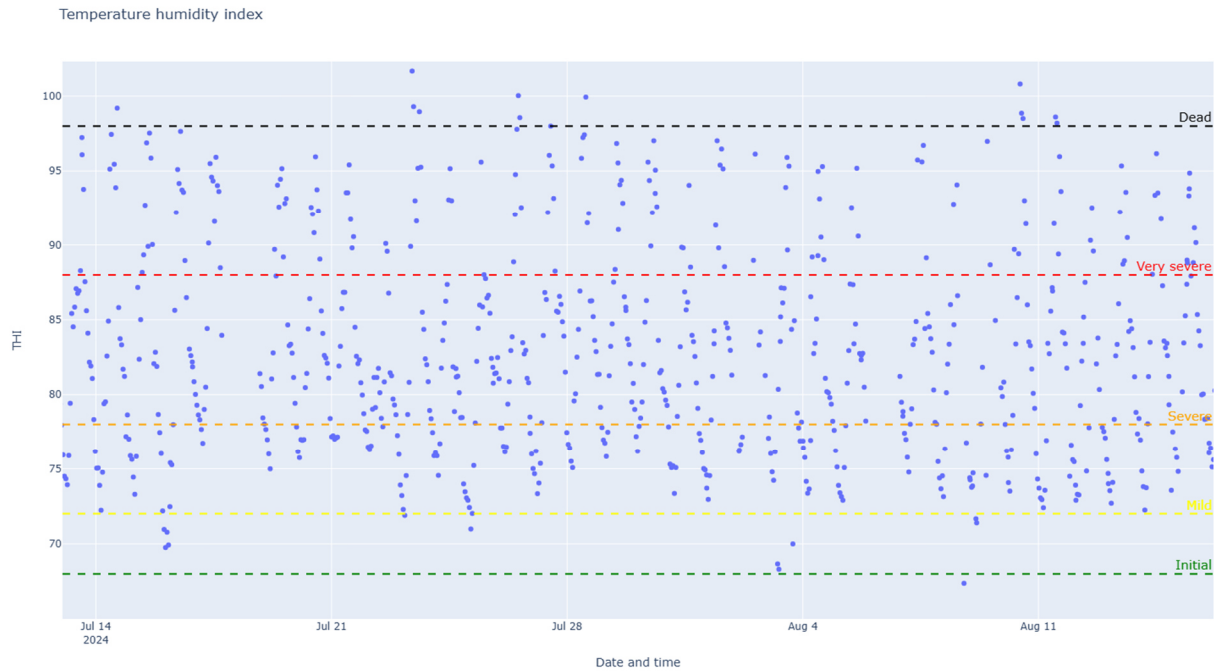


Figure 21 THI index calculation from air temperature and relative humidity data. The stress levels are reported as horizontal line and the classification is based on D. V. Armstrong article⁸⁶.

The average condition of the cow in the analyzed period was very severe thermal stress during the central hours of the day and mild thermal stress during the night. In some cases, where the humidity is very high, even during the day, conditions whose persistence could lead the animal to death were reached. The highest values are reached when high temperature is combined with high relative humidity, which hinders the proper functioning of thermoregulatory mechanisms, causing severe thermal stress in the animal. Overall, the considerable thermal stress the animal was exposed to emphasizes the importance of collecting these parameters in real time to mitigate the effects of the increase in global temperatures. However, it is worth noting that data collected near the animal are influenced by the perturbations it causes in its immediate surroundings, such as body heat, leading to higher average temperature and relative humidity values compared to a meteorological station. Additionally, when the animal is exposed to direct sunlight, the sensor is as well, resulting in even higher recorded temperatures. Since THI was originally designed to be calculated from meteorological data, applying the formula to measurements taken near the animal produces higher THI values than those from a meteorological station. To address this, a new sensor design is currently under development to minimize these effects while preserving the advantage of measuring the actual conditions the animal experiences.

3.2.2 Accelerometer

An accelerometer (Figure 22) is a sensor that measures the force applied to its components resulting from acceleration. The device is consistently subjected to gravitational force; consequently, even when stationary, it experiences constant acceleration. The output is a combination of the acceleration components on each axis resulting from movement and gravity.

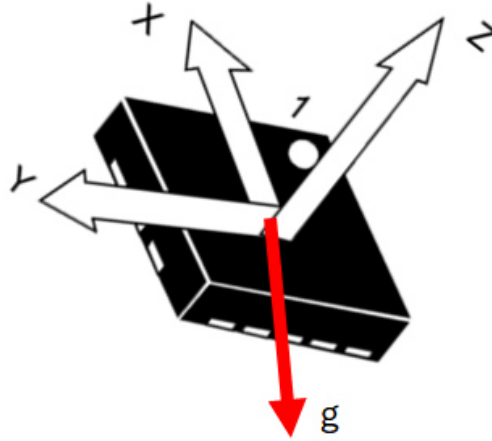


Figure 22 Accelerometer spatial orientation⁷⁷

Accelerometers are undoubtedly one of the most widely used sensors in livestock monitoring. The movements can be correlated with the behavior of the animal that provides information on its health, feeding and estrus period^{87–91}. It can be applied to different areas depending on the target information (e.g. ear, neck and leg); however, the neck was preferred because it can be related to feeding and posture as well as general movements. The collected data, for which one sample is reported in Figure 23, represent the average value of the acceleration and its standard deviation every hour for one animal.

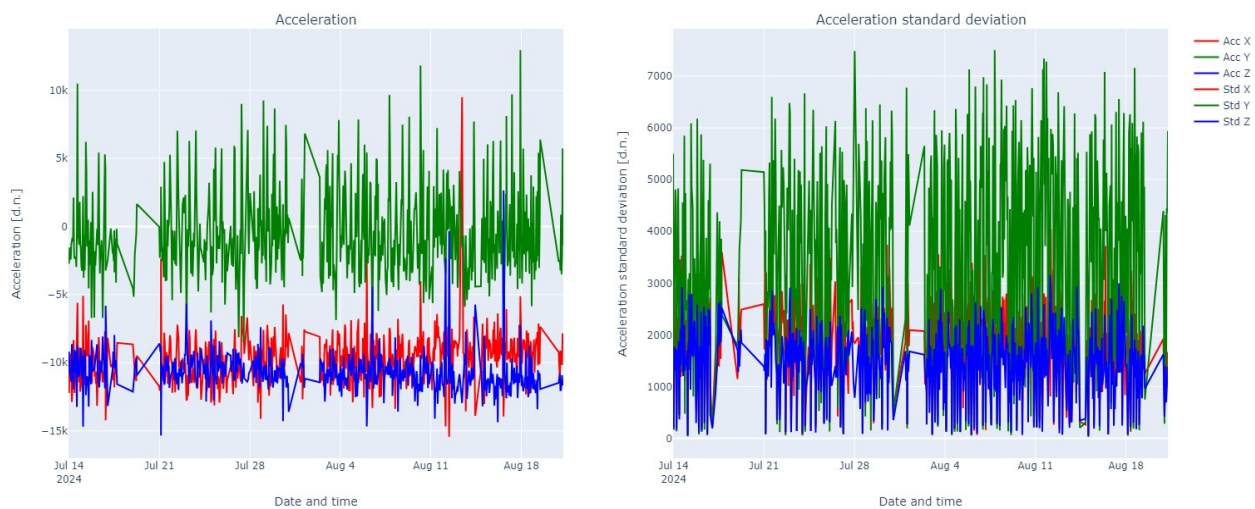


Figure 23 Accelerometric data collected from 14/07/2024 to 20/08/2024

Standard deviation is a parameter related to an animal's activity. A higher standard deviation indicates greater movement along one axis, which may correlate with a general increase in activity or a specific movement involving that axis. The average acceleration along one axis results from both gravity and the animal's movements; therefore, it is more complex to analyze due to the challenge of separating these two components.

The collar can be installed at different heights and inclinations due to various factors, such as the animal's size, shape, and human error. To minimize the impact of these factors, the analysis was performed on the standard deviation of the resultant vector of the acceleration components. The equation for the resultant vector is:

$$r = \sqrt[2]{x^2 + y^2 + z^2}$$

where x , y and z are the acceleration components along their respective axes.

Applying the general formula for error propagation, the standard deviation of the resultant vector is:

$$\sigma_r = \sqrt{\left(\frac{x}{r}\sigma_x\right)^2 + \left(\frac{y}{r}\sigma_y\right)^2 + \left(\frac{z}{r}\sigma_z\right)^2}$$

Where σ_x , σ_y and σ_z are the standard deviation of the average acceleration along x , y and z axes, respectively. Since raw data are converted to acceleration by multiplying by a constant, the results obtained from raw data can be extended to the converted values.

To conduct a preliminary analysis of the sensor data, two 15-day data sets from November and August were selected. After calculating the standard deviation of the resultant vector for each sensor, an interquartile range (IQR) filter was applied to remove outliers. Data from nineteen sensors were analyzed for August, and six sensors for November. The hourly average standard deviation across all sensors was calculated, along with the average hourly Temperature-Humidity Index (THI) from the sensors and the THI from a meteorological station for both periods. The results are presented in Figure 24.

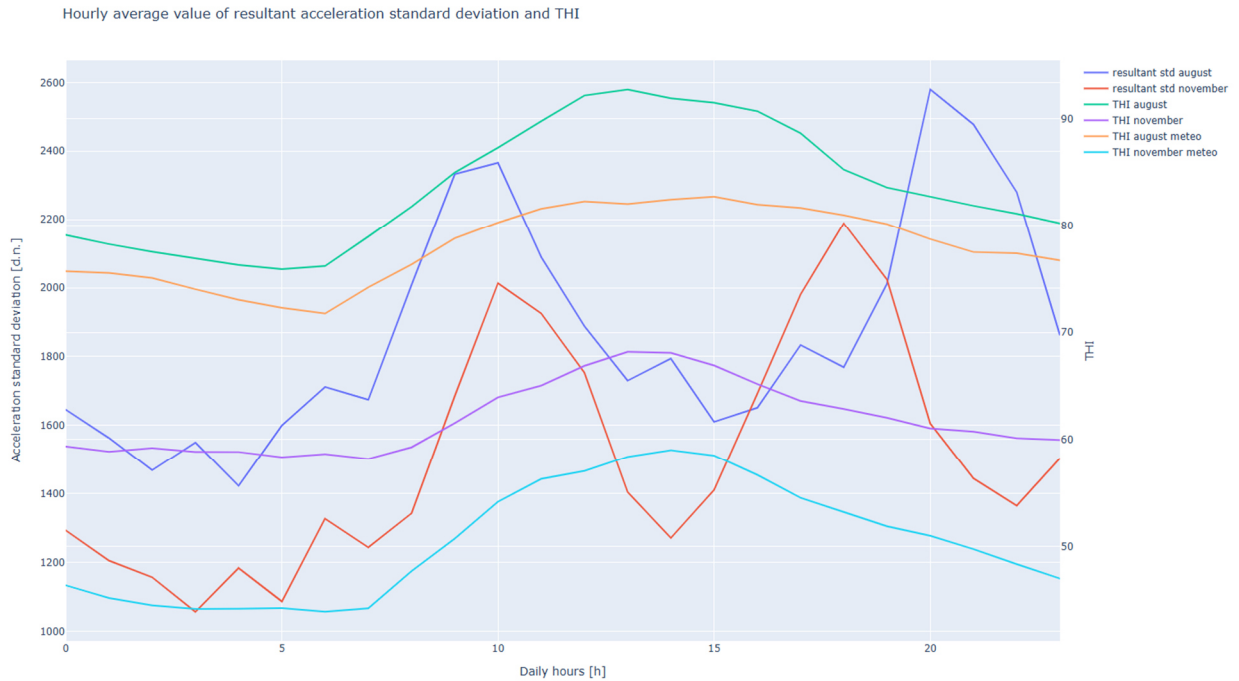


Figure 24 Average hourly standard deviation, THI from sensors and THI from a meteorological station over 15 days in August and November

The plot shows a clear difference between the THI calculated using temperature and humidity data collected near the animals—who generate heat—and the THI recorded at a meteorological station in the area. Additionally, the hourly average standard deviation reveals that the animals' activity decreases during the night and at midday compared to the overall average activity for the period, both in summer and autumn. The average activity is higher in summer than in winter, with "activity" defined as any movement detectable by the sensors, including head movements. This seasonal difference may be influenced by environmental factors, such as increased head movements to repel flies or to seek shade during the day. The daily activity pattern also varies between months. While both August and November show two peaks of activity - one around 10 a.m. and the other at 6 p.m. and 8 p.m., respectively - the duration of resting periods differs. Specifically, in November, activity steadily increases after 2 p.m. and decreases again after 6 p.m. when the sun begins to set. In contrast,

in August, the resting phase lasts much longer throughout the afternoon, with the second activity peak occurring around 8 p.m., when temperatures are cooler.

To further analyze the relationship between activity and environmental conditions, a Spearman correlation was performed between the hourly average standard deviation and the THI of the period between the two peaks of activity for each dataset, ignoring the resting phase associated with night sleep. The results are presented in Table 2.

	Sensor THI	Meteorological station THI
August	-0.5727	-0.9500
November	-0.7273	-0.9667

Table 2 Pearson correlation between hourly average standard deviation and average THI calculated using temperature and humidity data from the sensors and from a meteorological station in August and November.

The statistical analysis reveals a strong negative correlation in both autumn and summer, indicating a decrease in activity as THI increases, as observed in Figure 24. However, it is important to note that in both cases - particularly in winter - this correlation could also be influenced by the natural circadian rhythm, which is more closely related to light availability rather than environmental conditions. Ongoing studies aim to further investigate these findings, particularly by linking the collected data to specific animal behaviors and conditions, such as estrus, rest, rumination, and feeding.

3.2.2.1 Sd card version for large data acquisition

To better understand animal behaviors and the subsequent data, single sensors have been designed to collect data with higher frequency and save them on an SD (Secure Digital) card. SD cards present a relatively high power consumption (up to 100 mA) but allow the collection of all the evolution of the signal without being limited to collecting the averaged value owing to limits of bandwidth and power. The association of the collected data with the corresponding behaviors observed leads to improvements in the algorithms that can be subsequently embedded in the device to provide more information. The SD version of the accelerometer is composed of an SD reader, a STM32L072CBT6 microchip as the collar, the LIS3DHTR accelerometer and a battery. It is programmed to collect data with a frequency of 600 Hz and save them on the SD card along with the milliseconds passed from its activation. A sudden energetic initial movement must be provided to start the registration, which allows easy coordination of timestamps when more SD sensors are used together. The SD version of the accelerometer was applied to the leg of a racehorse to assess its use in analyzing its gait. The results of the experiments are shown in Figure 25.

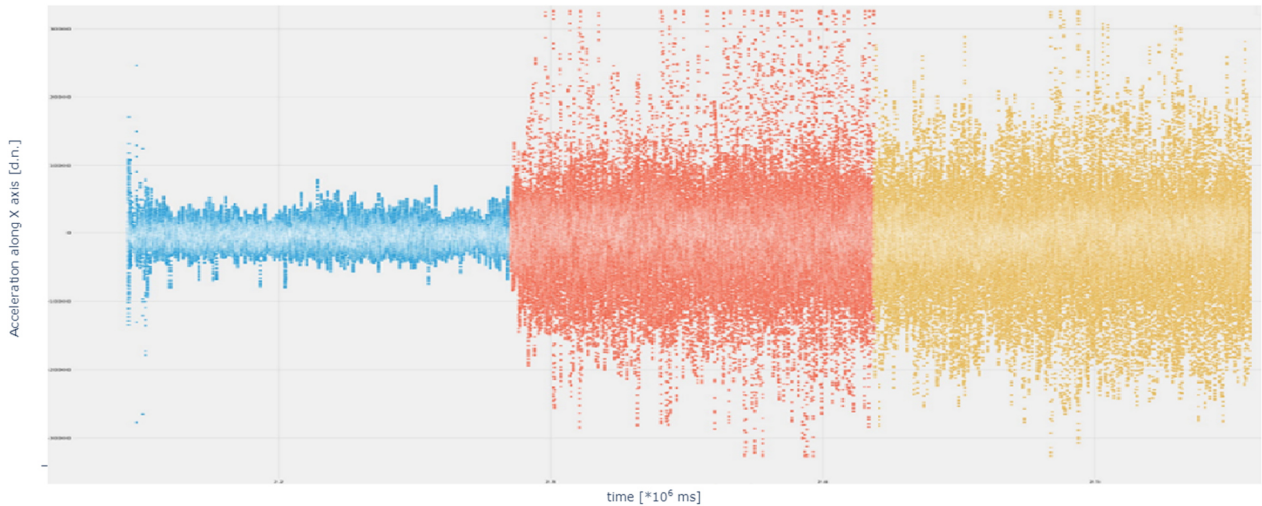


Figure 25 Accelerometric data collected at 600 Hz along X axis from a device placed on a leg of a horse walking (blue), trotting (red) and galloping (yellow)

Three different gaits were tested: walking, trotting, and galloping, which could be clearly identified in the plot. The application of this sensor can help improve the algorithm applied to IoT devices but also test different applications, such as breath frequency measurement by accelerometers.

3.2.3 GNSS position

In Figure 26, the latitude and longitude of the cow position are indicated by the red dots. GNSS data were collected once every hour. GNSS presence can help develop applications such as virtual fencing and provide farmers with the position of the animal, which is particularly useful for grazing herds^{72,92-94}. Moreover, it can provide information on the feeding areas of herds or individual cows.



Figure 26 Collected GNSS positions

3.2.4 Surface temperature

The body temperature of cows is related not only to heat stress but also to illnesses⁹⁵. The reference for the body temperature of cows is rectal temperature, which has been demonstrated to be correlated to surface

one^{93,96}. However, the skin temperature is more influenced by the external temperature and requires good contact and isolation to be properly collected; moreover, its correlation depends on the area from which it is collected. In Figure 27, a comparison between the skin temperature and air temperature collected by the collar is reported.

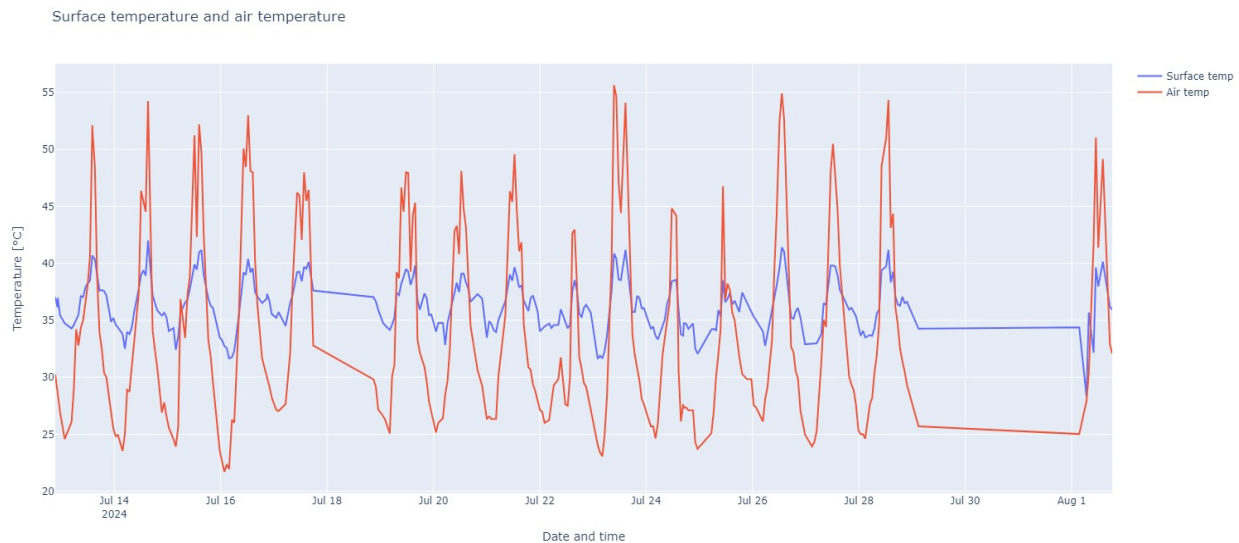


Figure 27 Animal surface temperature and air temperature over the period 12/07/2024 - 02/08/2024

The influence of the air temperature is clearly visible; however, the variations are smaller near the animal skin and its temperature oscillates around a higher average value than the air temperature owing to the proximity of the animal. The average temperature is 36.3°C that is compatible with surface measurements reported in the literature⁹³. The limited fluctuation of the surface temperature compared to the higher ambient temperature fluctuation demonstrates the efficacy of the bovine thermoregulatory system and adaptive behaviors, such as panting and seeking shade, as well as increased water intake, reduced rumination and feeding, and decreased milk production, which result in economic losses for farmers. As previously stated, mitigating the thermal stress to which the animal is exposed, and subsequently its physiological responses, can significantly enhance production. To use surface temperature measurements effectively, their correlation with rectal temperature must be calibrated, and the measured values must be corrected to account for the contribution of environmental temperature and the effect of the animal's hair. Improving insulation can also enhance measurement quality by reducing the influence of air temperature.

3.2.5 Heart rate

Performing heart rate measurements using an optical sensor placed on the neck of an animal is challenging. These readings can be influenced by animal movement and solar radiation. Figure 28 shows the pattern of a cow's heart rate. It is not possible to efficiently transmit all the points collected to measure the heart rate; therefore, the signal is sampled and elaborated on the device.

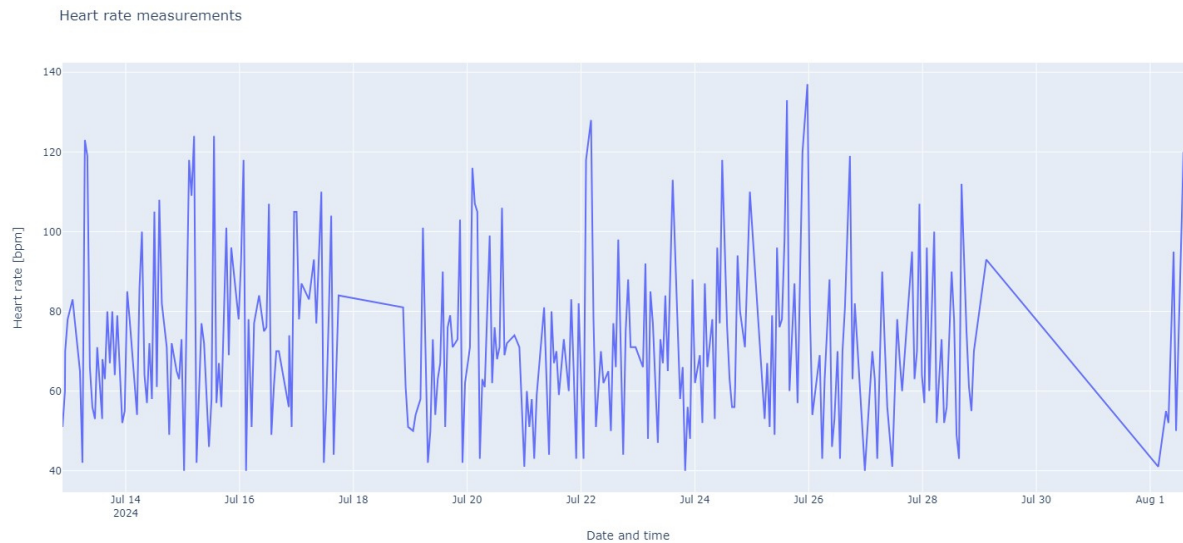


Figure 28 Heart rate measurements over the period 12/07/2024 - 02/08/2024

The heart rate of a cow can vary from 40 to 90 under normal conditions^{97,98} but can increase with stress or physical activity. Heart rate is measured for 30 s every hour. The data collected are mostly within the range found in the literature; however, validation in a real field environment by comparison with another validated device and an enhancement of the algorithm are required to better distinguish the case of false contact between the sensor and the skin or incorrect measurement and discard them.

3.2.5.1 Sd card version for large data acquisition

A SD card version of the heart rate sensor was developed to collect the complete pattern of reflected light to determine the heart beat rate by the optical sensor, study its variation and improve the heart rate detection algorithm. Figure 29 shows the measurement of the heartbeat of a sheep with the sensor placed on the animal's ear. Heart rate is defined as the number of peaks per unit time and is observed to be approximately 65 bpm in the figure.

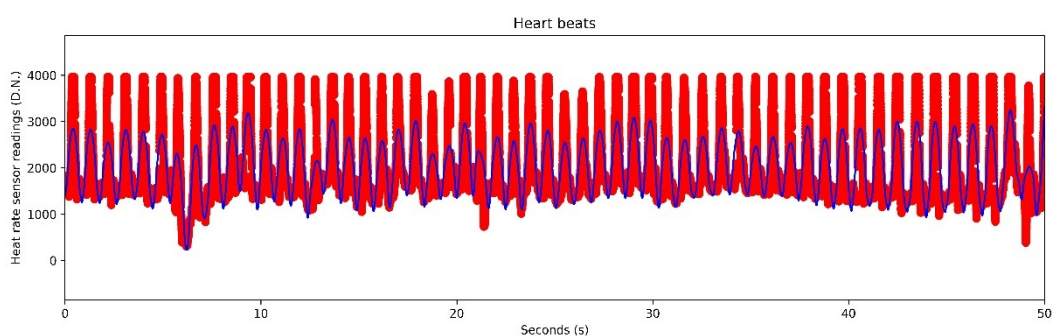


Figure 29 One minute of SD version heart rate sensor readings applied to the ear of a sheep

In the previous case, the signal was very clean; therefore, it was straightforward to extrapolate the heart rate. Figure 30 shows the application of the sensor on a racehorse's ear during its activity. The retrieved signal presents a flat segment where no signal is detected, likely due to excessive detachment between the sensor and the skin. It also includes areas of periodic low-intensity signals, which could be related to the heartbeat, and zones of strong signals where the heart rate can be clearly estimated. One example of the latter is shown in a zoomed-in view in the figure where the peaks are highlighted by red points. From the image, the oscillation in red light absorption following the dilation and contraction of the blood vessels is clearly visible. The algorithm on the device should be able to distinguish these areas from possible periodical noises to increase its accuracy;

moreover, a stronger contact between the skin and the sensor and a stronger emitter could help to obtain a clearer signal. The variation in the intensity of the signal is not strictly relevant for the calculation of the heart rate, as long as the signal itself is retrievable, with the heart rate estimated by the number of peaks over the time of measurement. Further studies are currently in progress.

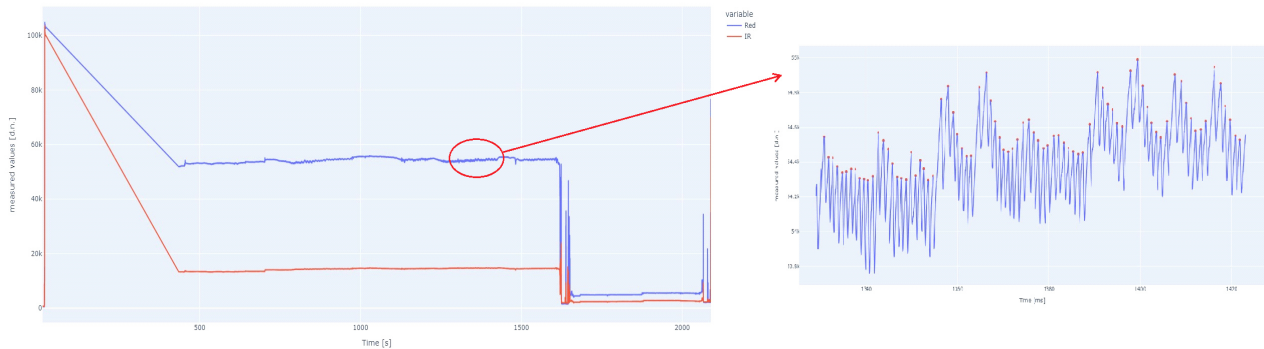


Figure 30 Data collected over 30 minutes by a SD version heart rate sensor applied to a racehorse's ear. A segment with a clear heartbeat pattern is zoomed in on the right.

3.2.6 Battery voltage

LiPo batteries do not provide a constant voltage but present a discharge curve that starts from a value higher than its nominal value and ends at a lower value. A 3.7 V LiPo battery is considered fully discharged when it reaches 2.8 V. However, it becomes unusable by the device when its voltage drops below the minimum input requirement of the low-dropout regulator (LDO), which is nominally 3450 mV for the one installed. The battery pattern illustrated in Figure 31 exhibits an initial voltage of 4069 mV, which decreases to a final voltage of 3353 mV over a total operational duration of 34 days.

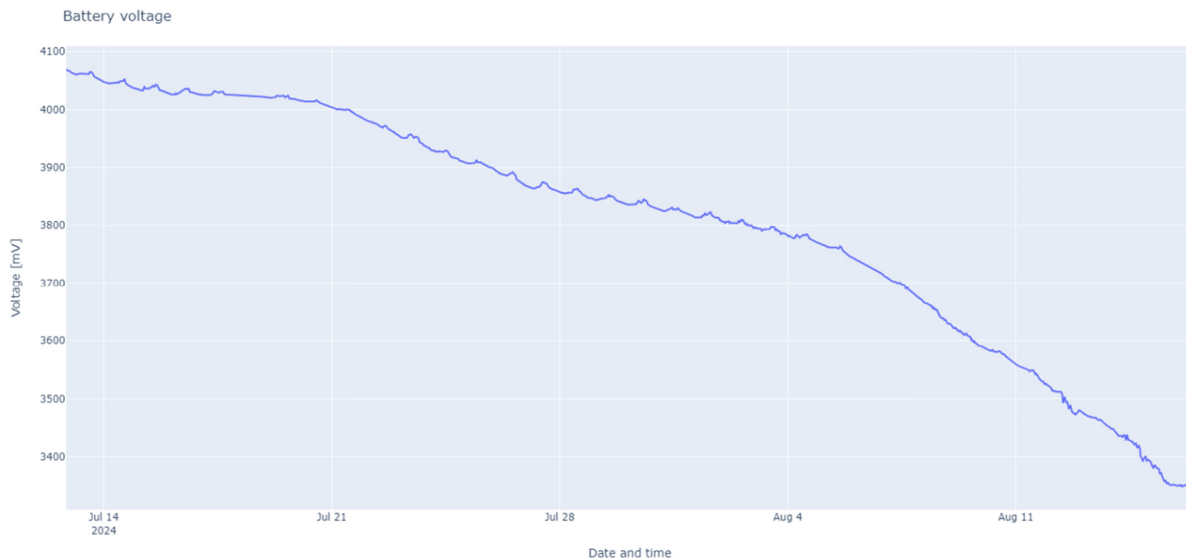


Figure 31 Battery voltage trend between 12/07/2024 and 16/08/2024

3.3 CONCLUSION

A device for collecting multiple parameters related to grazing animal welfare and productivity was designed and tested. This system can be utilized in production environments and in research to investigate the correlation among measured parameters and to examine real-time physiological changes in livestock. Its implementation could help farmers monitor food intake and detect illnesses, reducing the time before treatment and thus the cost and potentially reducing the use of antibiotics with benefits from an economic and health point of view.

Furthermore, this technology can be utilized for animal position tracking, which, in conjunction with an acoustic emitter, has the potential to mitigate livestock theft and facilitate the implementation of virtual fencing systems. Additionally, it can detect heat stress and could be integrated with appropriate countermeasures such as barn refrigeration. Moreover, it can contribute to the study of individual and herd patterns to develop early detection systems and enhance the knowledge of animal behavior.

Multiple sensors have been integrated into a single device, each of which presents a specific challenge. Its applications necessitate an in-depth study of the collected data as well as specific algorithms for effective implementation. The collected data are promising and a sample was presented in the previous section to demonstrate the preliminary results obtained through the application of the devices. Studies on the collected data are currently underway.

Further improvements can be achieved on both the hardware and software fronts. The utilization of a Kapton PCB has been investigated to enhance the flexibility of the device to better adapt to the animal neck and reduce its thickness, thereby decreasing its exposure to impacts. An extension of the battery duration can be achieved by adding solar panels. The implementation of NB-IoT connection on the device is also under development.

Changes in the software are also expected. Reducing the power consumption of the microprocessor by decreasing the clock speed could enable continuous monitoring and data collection by the accelerometer over the entire hour. The other sensors could be activated by the accelerometer to implement functionalities such as virtual fencing. An alternative approach would be to utilize accelerometer interrupts to wake up the system if a significant event is detected. The study of the patterns of some physiological parameters using the SD version of the sensors can help develop advanced algorithms to embed in the device itself, thereby improving its effectiveness. An improved algorithm for heart rate detection is required to perform data quality assessment directly on the device.

Although research is still ongoing, the goal of this thesis to design and test an innovative wearable sensor to measure multiple individual animal physiological parameters has been successfully achieved. A total of 143 devices have been distributed.

4 RFID TEMPERATURE MONITORING

The importance of body temperature in the assessment of animal health, illnesses and heat stress has been broadly documented⁹⁹. The reference temperature is usually measured by a rectal thermometer; however, this procedure usually requires restraining the animal with subsequent stress and is not suitable for continuous measurement. The surface temperature is related to body temperature but is influenced by the behavior of the animal as well as environmental conditions¹⁰⁰. Different systems have been proposed to measure the core temperature of livestock, including subcutaneous microchips^{96,101,102}. Subcutaneous temperature RFID tags require low maintenance and can be applied to a wide variety of animals owing to their small size. However, the chip is usually read manually, making the solution less stressful than rectal temperature but still not suitable for automatic reading. In this thesis, RFID subcutaneous microchips were applied to chickens for heat stress detection and an RFID antenna for the automatic reading of the microchip was designed. This technology is particularly noteworthy in instances where the presence of a device and battery could potentially disrupt the behavior of the animal, whereas the chip could be implanted and carried without interfering with the standard behavior of the chicken. RFID microchips were provided to the Scala-Medi project to test the effects of heat stress on chickens in Tunisia, Algeria and Morocco.

4.1 RFID TECHNOLOGIES

Radio Frequency Identification (RFID) is a widely used wireless communication technology that uses electromagnetic fields to identify and track objects using tags (Figure 32). This technology is primarily utilized for the identification of goods through automated systems, such as those employed in warehouse management. Tags can assume various forms, ranging from stickers to capsules, and can be placed inside and outside the object.

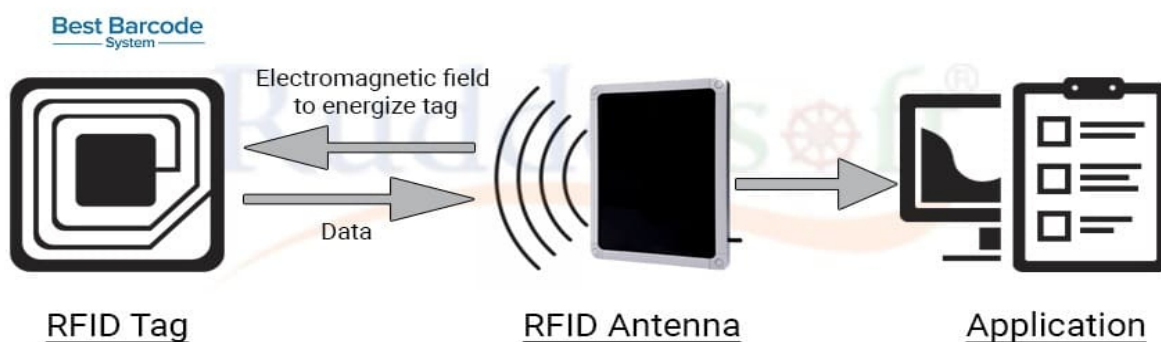


Figure 32 Operation of RFID technology¹⁰³

Unlike barcodes and QR codes, they are also readable even when distant or not visible. An important distinction is related to the frequency used by tags:

Low frequency (LF): it covers the range 30 kHz to 300 kHz, but RFID systems typically operate at 125 KHz or 134 KHz. This frequency range provides a reading range of approximately 10 cm (passive) and has a lower data rate but is less sensitive to radio wave interference from water or metal.

High frequency (HF): it covers the range between 3 and 30 MHz but most of the systems operate at 13.56 MHz providing a reading range between 10 cm and 1 m (passive). It is typically used for payments and data transfer.

Ultra-high frequency (UHF): it is in the range 300 MHz – 3 GHz, presents the highest data rate and the distance reached by the signal can be up to 12 m, but it is sensitive to interference.

RFID tags can also be classified into three categories based on their functioning: passive, semi-passive and active.

Passive tags: contain an integrated circuit and an antenna without a battery. They are powered by the reader and transmit stored data when within the range of the antenna. The absence of batteries and moving parts generally ensures a long lifespan, high reliability and low cost but they cannot usually perform complex tasks because of the lack of batteries, resulting in minimal data storage.

Semi-Passive tags: they are composed of an integrated circuit, an antenna and a battery. They can perform more complex tasks than passive tags, such as data collection, but are not equipped with an onboard transmitter; therefore, they are still activated by the reader. They can reach a longer distance than passive tags; however, their duration is limited by the duration of the battery.

Active tags: they are usually larger than the other types because of the addition of the transmitter. Active tags transmit the signal to a receiver and have the highest range but shorter lifespan among RFID devices owing to energy consumption; moreover, they also have a higher cost. These devices possess the capability to transmit continuously or upon activation by a radio signal from the reader and are typically utilized for high-value goods that require real-time tracking and data collection, such as environmental monitoring.

In passive and semi-passive tags, the energy required by the device to operate is provided by the reader through inductive coupling. The magnetic field created by the reader induces an electric current in the tag antenna that is used to power the integrated circuit. In half duplex tags (HDX), the tag is first completely charged and then the message is sent to the antenna while the magnetic field is switched off. In full duplex tags (FDX), the powered tag changes the load on its antenna, reducing the power consumption and thus, the power absorbed from the reader. By modulating the load, the tag can change the current drawn from the reader, which interprets the variations in the current as bits and retrieves the information. FDX tags transmit data while the magnetic field is still on; therefore, they can be read faster and more often than HDX tags.

Microchips used on pets as identification chips belong to the category of low frequency passive tags. The absence of a battery and thus, the absence of maintenance requirements, allows the implantation of a single chip for lifelong monitoring under the skin of the animal. The low frequency can pass through biological tissue, which can be challenging for other frequencies owing to the presence of water, but it does reduce the reading range to 10 cm. The radio-frequency identification of animals, including the frequency used and protocols, is regulated by international standards ISO 11784/11785^{104,105}. ISO 11784 outlines the structure and content of the identification code transmitted by the tag, which is crucial for uniquely identifying individual animals. An example of an identification code read from an FDX tag is presented below:

989_001025044274_1_0_8448_000000

The transmitted code is composed as follows:

- start bits (11 bits)
- 001025044274 - identification number (38 bits)
- 989 – manufacturer country code according to ISO 3166 (10 bits)
- 0 – application indicator: indicates whether an additional data block exists. A value of 1 indicates that the transponder contains an additional 24 bits data block (1 bit)
- 14 bits allocated by the ISO for future uses (e.g. information about vaccines)

- 1 – animal indicator: indicates if the transponder is used for animal identification (1 bit)
- 8488 – CRC checksum (16 bits)
- 000000 – additional data block (24 bits)

ISO 11785 describes the technical aspects of communication, such as the frequency, modulation techniques and protocols. Additional ISOs related to animal transponders are ISO 14223¹⁰⁶ that regulates advanced transponders for radiofrequency identification of animals and ISO 24631¹⁰⁷ that regulates the evaluation of the compliance of a transponder with ISO 11784 and ISO 11785.

4.2 SENSOR AND READER DESCRIPTION

Passive tags capable of reading an animal's temperature in conjunction with its identification are currently available on the market. This technology can prove to be particularly useful for continuously monitoring animal temperature without affecting stress levels as well as for controlling the cattle-stealing phenomenon through a subcutaneous identification number. However, two main issues were identified for the application of this technology both related to RFID tags sellers. The first obstacle was the lack of an automatic reader for the tags that could be placed near the animals to collect data, and the second was the incompatibility proclaimed by most sellers between their tag and a generic reader compatible with ISO 11784/11785. Market research for possible readers was conducted to find a suitable component to begin designing an IoT reader. Most devices use the EM4095, an analogical front-end that can generate carrier frequencies between 100 and 150 kHz to produce a resonant magnetic field. This component requires a microprocessor to process the output signal and convert it into data. The market offers multiple solutions for readers declared ISO 11784/11785 compliant based on EM4095; however, the compliance pertains specifically to the transmission of the identification number, whereas the majority of readers are not programmed to interpret the bytes containing the temperature value. A suitable reader was found from Priority1Design, an Australian company specialized in RFID boards. RFIDRW-E-TTL¹¹³ is a 66 x 37 mm reader module specifically designed for animal tags that can communicate with a microprocessor using the UART protocol. The module can be controlled by serial commands and comes with a copper-coiled antenna with a diameter of 49 mm. The information retrieved by the chip are decoded and transmitted to the user's device in a human-readable format. Another market study was conducted on RFID subcutaneous chip that sends the animal temperature in the bytes reserved by the ISO for additional information. Five FDX tags from five different companies (FAREAD, Avery Dennison, Biolog-ID, MSD Animal Health and Biomark) were acquired to test their temperature response and compatibility with the reader; the results are reported in Table 3.

Name	Supplier	Dimension [mm]	Temperature range [°C]	Resolution [°C]	Compatible with the reader
Biotherm13 ¹⁰⁸	Biomark	13 x 2.2	33 - 43	0.1	Yes
FRD-LF-GT12-224BT ¹⁰⁹	FAREAD	12 x 2.12	NA	NA	No
Thermochip Mini ¹¹⁰	MSD Animal Health	10.5 x 1.7	33 - 43	0.1	Yes
Glass Tag Thermosensor ¹¹¹	Avery Dennison	12 x 2.12	30 - 45	0.1	No
Biolog-Temp ¹¹²	Biolog-animal	13 x 2.1	NA	0.1	Yes

Table 3 Tested RFID subcutaneous temperature tags

Some tests have been performed on this technology to assess its limitations. The sensors were tested in a thermostatic bath showing thermal inertia in reaching the final temperature, but this is not a concern when injected into the body of the animal because the temperature is not expected to change suddenly. Furthermore, tag orientation plays a critical role in reading range. The sensor coupling is at its peak when it is orthogonal to the antenna plane, whereas it is zero when the tag is parallel; the tags remain readable until an orientation of approximately 30° from the antenna plane. Finally, the presence of multiple tags in the reading area as well as the presence of metals can strongly disturb the magnetic field. The results of the tests show that three out of the five tags are readable using a generic reader compliant with ISO11784/11785. The next step was to test it when inserted into a chicken body. From the first test performed during the general meeting of the Scala-Medi European project in June 2023, the range of the antenna was judged to be insufficient to read the sensor inside a chicken's body, but it was read without failure whenever the chicken passed through the antenna. The maximum size of the tuned commercial antennas found on the market was 25 cm, which is too narrow for a chicken (Figure 33).

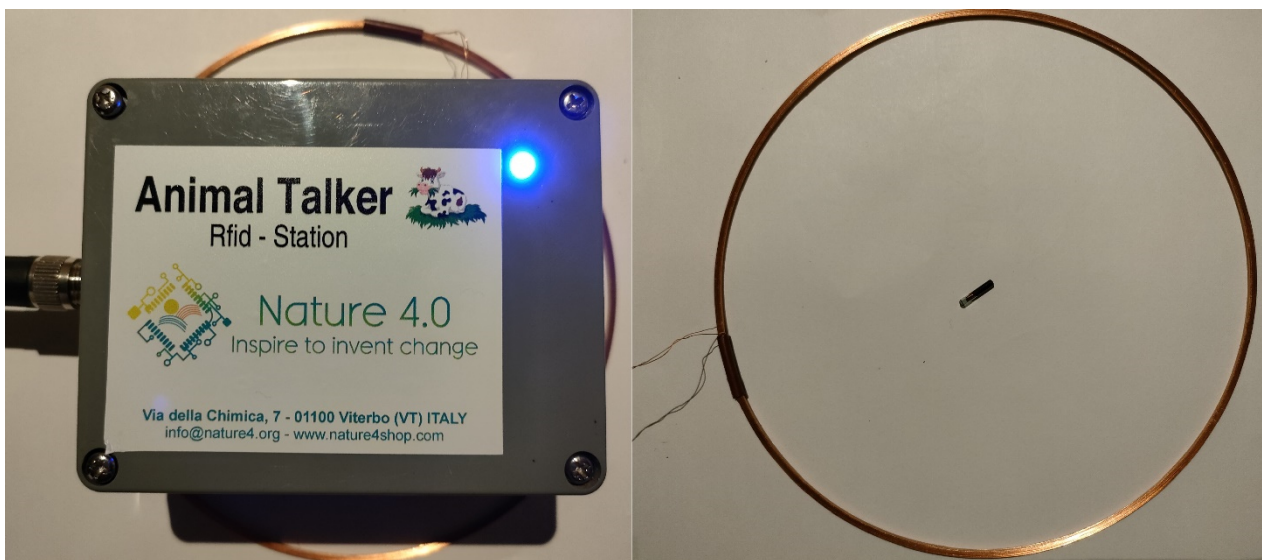


Figure 33 First prototype of the RFID reader with a close-up of the antenna and the RFID tag

A suitable antenna with an internal diameter of 35 cm was constructed and tested using a commercial copper wire with a diameter of 1.5 mm. The wire was coiled around a plastic support to reach a resonating frequency near 134.2 kHz and then fine-tuned using a parallel capacitor to reach the right frequency. The thickness of the wire was increased from 0.4 mm to 1.5 mm to reduce the wire resistance and increase the current flowing through it increasing the resulting magnetic field and range. The system was tested successfully on a chicken in which the tag was placed below the wing (Figure 34).



Figure 34 Experiment performed on an RFID tag injected in the chicken and on the right the final version of the RFID reader. Thanks to the “Istituto Zooprofilattico Sperimentale del Lazio e della Toscana M. Aleandri” in Viterbo and Dr. Erminia Sezzi for her valuable assistance and suggestions during the experiment.

An ESP-32¹¹⁴ was selected as the microprocessor for this application. It is a powerful low-cost microprocessor with embedded Bluetooth and Wi-Fi connectivity. The number of readings to be performed and sent and their frequency are not known in advance, so the device should provide reliable connectivity and should always be ready. The collected data were sent to the server through a Wi-Fi connection using the MQTT protocol. When the device is not transmitting data, it continues to scan and search for tags. A MQTT broker based on Mosquitto¹¹⁵ was deployed on a server along with a Python program to read the received data and order them in folders. The configuration of the Wi-Fi username and password on the reader as well as every other interaction with it were implemented through webpages, reachable by the connection to the local network of the devices accessible by the access point provided by the device itself. The device was finalized by protecting the antenna with a rubber cover coated with a hardener spray and placing the electrical components in an IP67 enclosure. Two leds were exposed to indicate the status of the device and successful reading of the sensor. Five readers and 250 “Biotherm13” tags were distributed to five partners of the Scala-Medi project in Tunisia, Algeria and Marocco and are currently being installed.

4.3 LABORATORY TEST

A total of 5 antennas and 250 subcutaneous tags were dispatched to be installed in poultry farms for the Scala-Medi project. The devices have been tested in laboratories both in Italy and Algeria with real chickens, but the installation of the network is still ongoing. Figure 35 shows the temperature measurements performed in one of the experiments. This plot demonstrates the necessity for a subcutaneous tag to attain thermal equilibrium with its surrounding environment prior to providing accurate temperature measurements. The body temperature of a chicken can vary from 41.4 to 42.9 °C⁹⁹; thus, the final temperature reached (41.56 °C) is within the expected range. The serial number of the sensor is reported on the upper-right side of the figure.

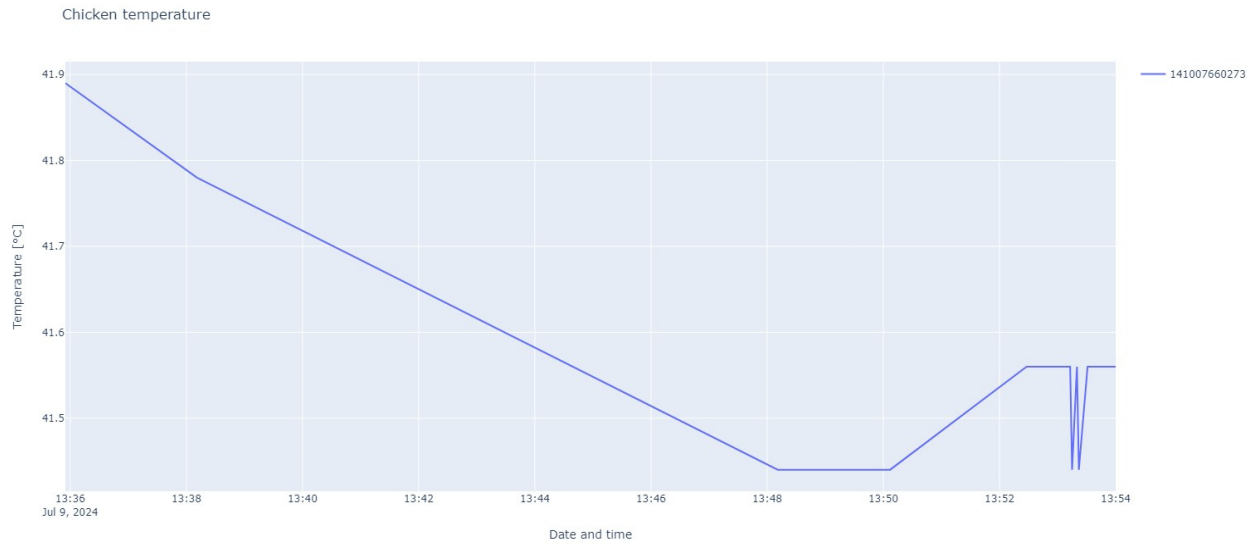


Figure 35 Chicken subcutaneous temperature during a laboratory experiment

4.4 CONCLUSION

Market research was conducted to find suitable RFID subcutaneous temperature microchips, five different models were compared and a RFID reader with Wi-Fi connection was designed and tested on chickens. The data are sent via MQTT and collected on a server. The obtained results were satisfactory, and five readers and 250 microchips were produced and distributed.

The market cost of chickens is relatively low; therefore, the cost of commercial tags is still too high for large-scale adoption outside research or national-level projects. The next step in the implementation and distribution of this technology will be to reduce the cost of both antennas and tags. Market research to identify companies capable of manufacturing tags is ongoing. A reader based on the EM4095 integrated circuit to directly decode the signal has been designed and the software for its test is currently being written. An automatic tuning system for the antenna is also being studied.

Possible alternative applications could be the use of microchips on different species, such as grazing animals, or the application of the reader in laboratories, as in mice. The migration of the transponder is a major concern and a strong issue for wider adoption, thus an extensive study on the best position for the injection of the sensor has been carried out.

5 AIR QUALITY MONITORING

Numerous studies have explored the relationship between air quality in stables and human and animal diseases^{116,117}. Evidence has been found that high concentrations of gasses such as ammonia (NH_3) can increase the probability of respiratory disease in animals¹¹⁸. Diseases and injuries also impact animal production, representing a significant cost. Another key factor is thermohygrometric comfort, which influences heat stress in animals and directly affects both production and well-being. Moreover, livestock farming has an impact on greenhouse gas emissions (GHG) of approximately 12%, taking into consideration the entire productive chain¹¹⁹. Air monitoring inside animal shelters is extremely important for animal and human health and can also help evaluate the efficiency of barn ventilation, as well as the activation of suitable countermeasures whenever unhealthy conditions are detected. A flexible low-cost air quality monitoring system was designed and developed to measure the concentrations of selected gasses.

5.1 DESCRIPTION OF THE SYSTEM

The main goal of the designed system is to be as customizable as possible to adapt to various scenarios, from animal shelters monitoring to drone campaigns for air quality assessments. The device comprises two printed circuit boards (PCBs), one housing the gas sensors while the other containing the microprocessor and the communication module (Figure 36).



Figure 36 On the right the control board and on the left the sensor board with six electrochemical sensors inserted

They are connected through a 14-position Flat Flexible Cable (FFC) to communicate and power the sensor board. The sensor board is a 90 x 90 mm PCB capable of accommodating up to 11 sensors, either analog or digital, depending on the configuration of their footprint and their respective communication protocol:

- 5 electrochemical sensors with a 5 pins connector
- 1 CH_4 sensor with a 5 pins connector
- 1 PM (Particular Matter) sensor with an 8 position Picoblade Molex connector
- 1 CO_2 sensor with a 7 position Picoblade Molex connector
- 1 CO sensor with 2 mm heigh headers

- 1 UART connection with standard female headers
- 1 I²C connection with standard female headers

All the sensors are powered by a 5V power supply and expose at least an UART serial connection but an analogical pin for direct electrical measurements was also included whenever possible. Most commercial sensors provide an UART connection to control the sensors using serial commands for concentration reading, calibration and sensor characterization. Moreover, the use of the serial connection allows the use of the factory calibration. Analogical signal reading is added to the board to ensure compatibility with a wider range of sensors, considering that not all sensors provide a UART connection. Furthermore, the utilization of analog signals enables the implementation of customized calibration curves, application of algorithms such as oversampling to enhance the resolution of collected measurements and acquisition of raw measurement values. This capability is particularly valuable for sensor status evaluation as well as for certain experimental setups. The connectors were chosen to be compatible and plug-and-play with most of the sensors sold on the market. Nine UART lines and as many ADC pins are usually unavailable on a microprocessor. Three 16:1 multiplexers were installed on the sensor board to address this issue. A multiplexer is an electronic component that connects one line to X different possibilities. The microprocessor needs only four digital pins to select all 16 (2^4) addresses of the multiplexer plus a UART serial port (two pins) and one ADC pin to read the signals. An identical multiplexer address is assigned to the Rx, Tx, and analog signals of a sensor, ensuring that all channels of a sensor are activated when the corresponding pin combination is selected. The described solution allows the reduction of the 27 pins required to read all possible signals to seven pins. The sensors installed on the board are strictly related to the application. Two pads provide 12V to a fan that speeds up the air exchange inside the control volume of the device for applications that are time-constrained, such as air sampling on a drone. The control box is 3D printed and its structure is shown in Figure 37.

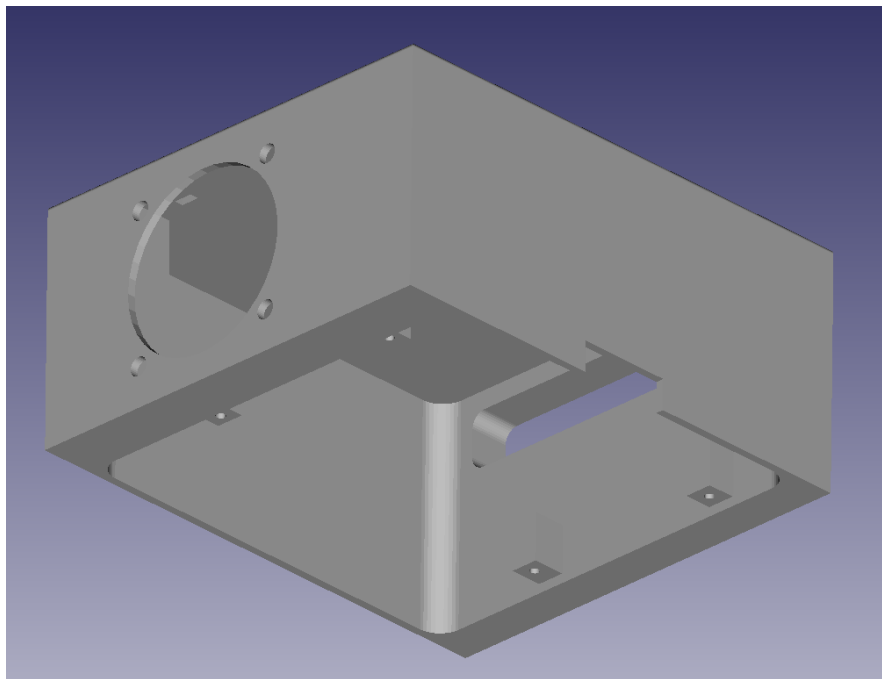


Figure 37 Control volume of the sensor board

The $110 \times 94 \times 50$ mm control volume has pockets to install the fan and the CO₂ sensor, as well as a hole to expose the particular matter (PM) sensor on the outside owing to the presence in this sensor of its own fan. The sensor board closes the box when screwed on the four mounting points corresponding to the four apertures on the printed circuit board. The aperture of the fan and the rectangular opening on the wall opposite the fan are in direct contact with the air to be sampled, creating a laminar flow in the control volume when the fan is

operational. The FFC connector is connected to the main board, which can be placed in front of the control volume or on its top. The use of an easily detachable connection as well as the connection of the fan to the sensor board and its placement in the control volume allows for fast replacement of the entire set of sensors, simplifying the operations of maintenance and periodic calibration. The control board contains the microprocessor, the communication module, two LDOs for power supply and an I2C connection for a SHT41 sensor; furthermore, it can optionally host a GNSS board depending on the application.

The microcontroller board currently used for this device is the Arduino MKR Zero¹²⁰, an Arduino development board based on an Arm[®] Cortex[®]-M0 32-bit SAMD21G18A processor. The device provides 256 kB of flash memory, 32 kB of RAM, an internal Real-Time Clock (RTC), a maximum clock frequency of 48 MHz and support for SD cards.

The communication module is based on the SIM7020 module¹²¹, a low-cost, low-power NB-IoT module developed by SIMCom that can be controlled using AT commands. It provides an uplink speed of 62.5 kbps and a downlink speed of 26 kbps and supports multiple protocols such as HTTP, MQTT, and MQTTS, as well as multiple low-power modes, including eDRX and PSM, achieving a potential current consumption as low as 3.4 μ A. The communication module was developed during this thesis and can be interfaced with the microprocessor via UART. The module is mounted on a removable board to facilitate future updates with different pin-compatible boards and enable component replacement in the event of failure. The device is powered by supplying a voltage between 7 and 12 volts to the control board. The chosen communication protocol for the device is MQTT, because it allows bidirectional, real-time communication. Some devices have been connected to a mosquitto-based broker implemented on a private server, while others to HiveMQ¹²², a commercial solution that supports MQTTS, depending on the requirements.

The software, whose flowchart is shown in Figure 38, provides three distinct modes that can be selected remotely:

1. Single measurement: the device remains in an idle state until it receives a command from the user to initiate the measurement. Upon completion of the measurement cycle, the device returns to its idle state.
2. Time driven: the device conducts measurement cycles at predetermined time intervals. The user can select the time interval. This operational mode serves as the default setting.
3. Position driven: This mode can only be utilized when a GNSS board is connected to the device. The device continuously monitors its GNSS position and velocity until the difference between the previous and subsequent positions as well as the velocity fall below a predetermined threshold. The measurement cycle starts when the coordinates of the device remain constant for 5 s. At the end of the measurement cycle, the device resumes checking its GNSS position. This mode has been implemented for use on mobile objects, such as drones or buses, without the necessity of directly interfacing the two devices. The hovering of the drone serves as the trigger for the measurement; this mode is particularly advantageous for sampling campaigns.

When the device is not measuring, it continues to monitor the MQTT connection and reestablishes the connection if it is lost. The initial phase of the measurement cycle involves the activation of the fan to facilitate air exchange within the control volume. This step is particularly beneficial when data points need to be collected at different locations in the shortest time possible, precluding the establishment of a natural equilibrium between the atmosphere and the control volume. The flush time is set to 2 minutes, after which the fan is deactivated to prevent interference with the measurements. The sensors are read sequentially by switching the multiplexer channels, and the mean of 10 measurements is calculated for each sensor.

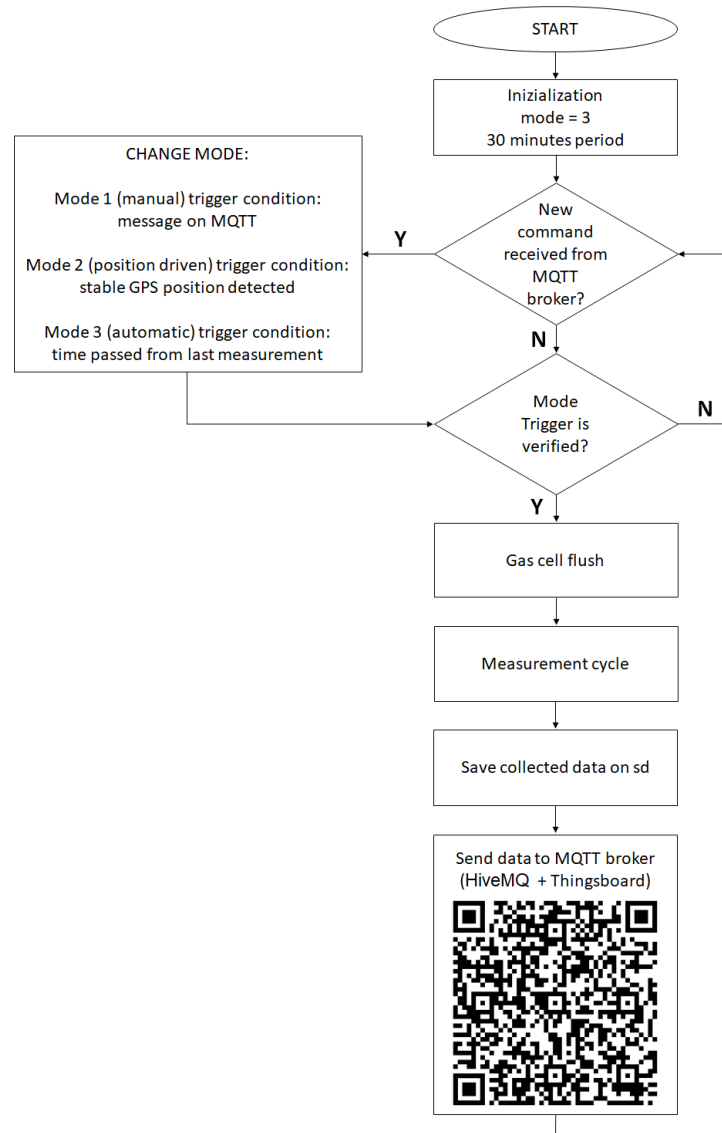


Figure 38 Gas analyser software flowchart

The measurements are formatted in JSON, stored on the SD card and transmitted to the MQTT topic. An example of a JSON message is provided below:

```
{
  "device_id": "31246000",
  "measure_number": 103,
  "timestamp": 1723325875,
  "NH3": 0.355,
  "CH4": 280.00,
  "H2S": 0.019,
  "CO2": 434.000,
  "PM1": 9.00,
  "PM2.5": 12.00,
  "PM10": 13.00,
  "T": 31.63,
  "H": 44.85,
  "Battery": 12272.92
}
```


The NB-IoT connection was chosen to provide bidirectional, real-time communication and to obtain a standalone device that can be used and moved without constraints. Sensors are never switched off because some of them require a warm-up time that can range from minutes to hours. A Python program running on the server is subscribed to the topic to retrieve the data and save them on a txt file in csv format. Furthermore, a visualization platform known as Thingsboard¹²³ was implemented, which is an open-source IoT platform for data visualization (Figure 39). It offers multiple ways to collect data in the JSON format using different protocols, save them in a database and visualize them using suitable widgets. Some calculations can also be



Figure 39 Example of a Thingsboard dashboard for a gas analyzed prepared for the presentation of the device at EGU23

performed before visualizing the data and alarms can be triggered if a certain threshold is reached. Fine granularity in the definition of a new device on the platform allows the effective management of access permissions to dashboards or parts of them. Widgets for communicating with devices such as buttons or toggle buttons are available, and they have been used to switch working modes on devices. The device, shown in Figure 40, is patented.



Figure 40 Gas analyzer mounted below a drone and close-up of the device

The cost of the device is highly dependent on the number and resolution of the selected sensors. Therefore, it is important to carefully select the sensors to be installed based on the application to reduce the cost. Two main types of gas sensors have been used for gas concentration measurements: electrochemical and NDIR sensors. Electrochemical sensors convert chemical information to electrical information. They are usually composed of a selective membrane, an electrolyte, an electrode and a reference electrode, along with an electronic circuit for signal amplification. Gas diffuses through the membrane and reacts with the electrode, generating a measurable electric effect. A Non-Dispersive InfraRed (NDIR) sensor emits an infrared beam through a sampling chamber where the gas flows, and the intensity of the infrared light reaching the opposite side of the chamber is measured by a detector. Each gas absorbs specific wavelengths, and the concentration of the gas is calculated from the variation in light intensity due to absorption by the targeted gas. NDIR sensors are usually more accurate and have longer lifespans; however, their cost is usually higher than that of electrochemical sensors.

Different versions of the device were produced depending on the objective. Seven devices were designed for atmospheric monitoring in urban environments and landfill sites. Landfill emission measurements were conducted by mounting the device on an unmanned aerial vehicle, whereas air quality assessment in urban areas was performed using stationary installations. Multiple sensor configurations were tested to analyze air quality in an urban environment and the basic set selected for the task is presented in Table 4.

Sensor	Target	Supplier	Type	Range	Resolution	Accuracy
MH-Z16 ¹²⁴	CO ₂	Winsen	NDIR	0-10000 ppm	1 ppm	± (50ppm + 5% reading value)
ZE03 ¹²⁵	NO ₂	Winsen	Electrochemical	0-20 ppm	0.1 ppm	NA
ZE03	SO ₂	Winsen	Electrochemical	0-20 ppm	0.1 ppm	NA
ZH07 ¹²⁶	PM1	Winsen	Laser scattering	0-1000µg/m ³	NA	0-100 µg/m ³ : ±15µg/m ³ 101-1000 µg /m ³ : ± 15% Reading
	PM2.5					
	PM10					
TB600B-TVOC-10 ¹²⁷	TVOC	ECSense	Electrochemical	0.01-10 ppm	0.001 ppm	±5% F.S.

Table 4 Basic set of gas sensors for air quality monitoring in urban environment

All the chosen gasses are related to vehicle emissions and their allowed concentrations or emissions are regulated at the national level. Carbon dioxide is one of the main causes of global warming, while the remaining elements contribute to the generation of smog (TVOC) and negatively influence human health depending on the concentration, resulting in respiratory irritation and various respiratory problems. Each device is equipped with two SHT41 sensors, one placed inside the control volume and the other outside. These devices not only provide information about air humidity and temperature but can also be utilized to correct the measurement, taking into consideration the heating caused by the sensors.

Two other systems were built for continuous air quality monitoring in animal shelters. They are equipped with one SHT41 sensor to monitor heat stress and barns thermohygrometric conditions; the installed set of sensors is reported in Table 5.

Sensor	Target	Supplier	Type	Range	Resolution	Accuracy
MH-Z16	CO ₂	Winsen	NDIR	0-10000 ppm	1 ppm	± (50ppm + 5% reading value)
ZE03	NH ₃	Winsen	Electrochemical	0-100 ppm	1 ppm	NA
TB600B-NH3-10 ¹²⁸	NH ₃	ECSense	Electrochemical	0-10 ppm	0.01 ppm	< 5% F.S.
TB600B-H2S-2 ¹²⁹	H ₂ S	ECSense	Electrochemical	0-2 ppm	0.01 ppm	< 5% F.S.
MH-441D ¹³⁰	CH ₄	Winsen	NDIR	0-50000 ppm	100 ppm	NA
ZH07	PM1	Winsen	Laser scattering	0-1000µg/m ³	NA	0-100 µg/m ³ : ±15µg/m ³ 101-1000 µg /m ³ : ± 15% Reading
	PM2.5					
	PM10					

Table 5 Set of gas sensors for air quality monitoring in stables

The devices were produced for Sebastien project; the main criteria for the inclusion of a sensor was the impact of the targeted gas on the health of humans and animals¹¹⁷. Data were sent to the Mosquitto on-premise implementation and visualized by the platform of the Sebastien project.

The applications of air quality monitoring devices are numerous depending on the type of sensors installed, from outdoor to indoor applications, from urban to rural ones. Six devices were built to monitor urban environments, while the first prototype was installed on a drone for spatial measurements. Two additional devices were built for use in animal shelters. In this paragraph, an example of each working mode is reported and commented.

An indoor application is shown in Figure 42. The device was installed in a kitchen to monitor gas concentration trends over the course of the day, with particular emphasis on carbon dioxide levels.



A periodic pattern was observed, with peaks occurring around mealtime. On two occasions, the occupant dined outside the residence, resulting in the absence of two peaks typically associated with dinner preparation.

Table 6 presents a comparison between the values obtained from a gas analyzer operated by ARPA and the prototype in a fixed outdoor location.

	ARPA (environmental protection regional agency) 24 h average	Prototype 24 h average
SO ₂ (ppm)	0.0014	0
NO ₂ (ppm)	0.027	0.022
PM2.5 (µg/m ³)	18	17.28
PM10 (µg/m ³)	24	21.1

Table 6 Comparison between the ARPA values and the concentrations measured by the prototype on a 24 h average

ARPA are public entities that operate at a regional level in Italy with the objective of protecting the environment and public health. Each region has its own ARPA, which is responsible for monitoring and controlling the state of the environment, conducting analyses and assessments of environmental risk factors, and providing technical-scientific support to local and national institutions. ARPA provides the average gas concentration over 24 h, which has been compared to the average of the measurements performed by one gas analyzer prototype installed in proximity to the ARPA device. The results demonstrate a notable correlation between the two devices, indicating a high degree of concordance.

5.3 CONCLUSIONS

A customizable Internet of Things (IoT) gas analyzer was designed and tested in different environments and with different usage modes. It can equip up to 11 sensors of different types and can be used both as a stationary measurement unit and equipped to a UAV to perform emission inspections. It is connected to the Internet by NB-IoT and uses the MQTT protocol to send data and receive commands. A dashboard was built to interact with the device in real time, based on Thingsboard. Nine devices were produced in total, two of which were equipped for livestock air quality monitoring while the rest for urban monitoring. A comparison with an ARPA gas analyzer produced satisfactory results. The device is currently under patent.

Some minor adjustments, such as the use of Sim7022, a more recent version of Sim7022, and the replacement of the Arduino development board with an STM32 microchip for cost reduction, are under implementation.

The lifespan of the sensors is an important topic. Electrochemical sensors tend to drift over time; therefore, they must be checked before a measurement campaign and periodically recalibrated to guarantee measurement accuracy regardless of the lifespan declared by the manufacturer. A laboratory calibrator is currently being developed.

6 DATA COLLECTION AND ELABORATION

Data storage is an important component of an IoT system because it determines how data can be accessed and queried. A good data management policy can make data sharable with other projects, increasing their value and impact on research, making them compatible with external systems and plug-ins, improving portability to other platforms and speeding up the development of applications based on them. Data that are not easily reachable require additional work to make them compatible with the application in which they should be used, resulting in additional complexity and costs. European Union is supporting data harmonization by multiple initiatives such as Sebastien and Open-Earth-Monitor projects¹³¹ that aims to collect data from different sources and/or datasets and provide them in a standardized format to the final user. Further significant developments in this direction include the release in December 2023 of a report titled "Report on Data Homogenisation for High-value Datasets"¹³² that defines the concept of High-value dataset (HVD), which imply the interoperability of data, and the INSPIRE directive that “aims to create a European Union Spatial Data Infrastructure (SDI) for the purposes of EU environmental policies and policies or activities which may have an impact on the environment. This European Spatial Data Infrastructure will enable the sharing of environmental spatial information among public sector organisations, facilitate public access to spatial information across Europe and assist in policy-making across boundaries.”⁵⁵ . The OGC SensorThings API is a standard explicitly mentioned in the Good Practice Library of the INSPIRE project. During the PhD, a data server structure based on the SensorThings API was designed and a demo was successfully implemented on a server to collect data from IoT devices.

6.1 SERVER DESCRIPTION

A schematic representation of the data server is shown in Figure 43; it comprises:

- A web server (NGINX)
- A python application for data ingestion
- An implementation of the OGC SensorThings API (FROST)
- A platform for data visualization (Grafana)

All the components of the described system are open source, making it deployable without license-related issues.

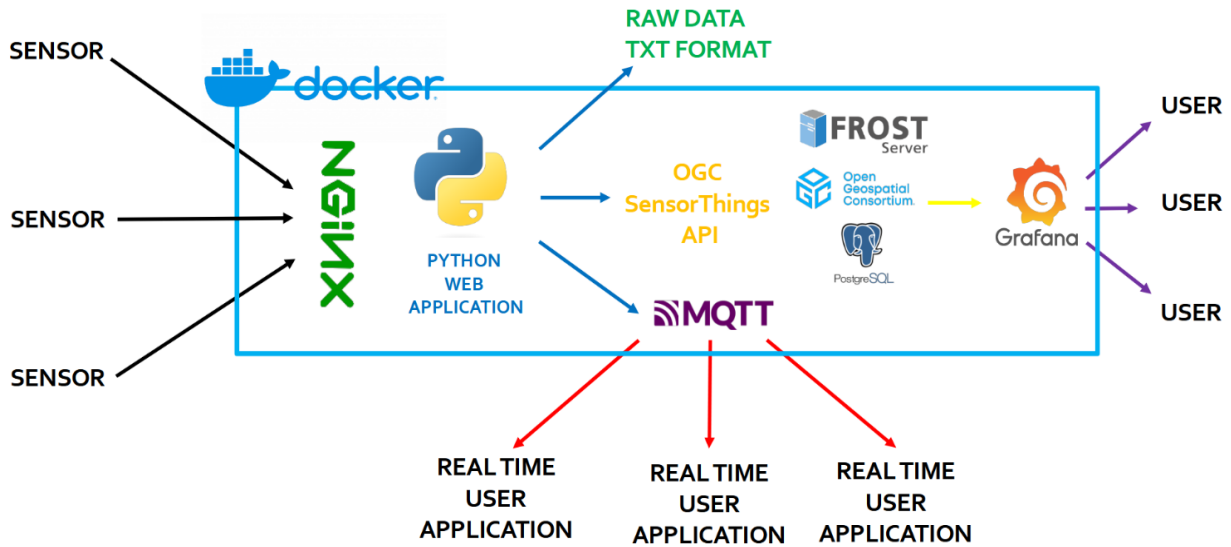


Figure 43 Data server structure

NGINX web server^{133,134} was created in 2004 to overcome some of the Apache web server limitations, handling a large number of requests with a low memory footprint. Its performance is obtained by its asynchronous, event-driven architecture, in which NGINX is the main process and creates a thread for every request, allowing a non-blocking approach in request management. Beyond its traditional role as a web server (HTTP requests handling), Nginx's versatility extends to encompass:

- reverse proxying: rerouting of incoming traffic to different servers or addresses
- load balancing: distribution of incoming traffic among different servers or microservices
- mail proxying: handling email traffic
- HTTP caching: storing frequently access content to reduce server load and improve response time

NGINX was implemented in front of other components to manage incoming requests and offer a reliable barrier to possible attacks, such as denial-of-service (DoS) attacks. It is also used as a reverse proxy to assign all traffic related to the data server to a single port, further increasing the security of the server itself.

The Python application consists of a web application based on Starlette¹³⁵ which is a lightweight, asynchronous framework for building web applications and APIs using Python. It is built on top of asyncio library, which enables it to manage concurrent requests and asynchronous protocols such as WebSocket while maintaining high throughput and low latency. The Starlette framework facilitates the design of applications compatible with the Asynchronous Server Gateway Interface (ASGI), a standard API for Python web servers that execute asynchronous code. Consequently, applications developed using the Starlette framework must interface with an ASGI server for effective functioning. Uvicorn¹³⁶ is an ASGI web server implementation for Python. It performs a function analogous to NGINX in managing incoming requests; however, the latter was selected as the front-end server because of its reliability and security features. The Starlette application receives incoming data and stores them in a text file within a folder named after the device ID as a backup mechanism. The data are subsequently processed if necessary and ingested into the database after an initial elaboration to make them usable by the final user. The Python application for data ingestion automatically creates an instance of a device not previously registered in the database; the entities are defined into configuration files based on the string type. The application also verifies data integrity and eliminates duplicates based on the timestamp of the

received data. If the received data string type is unknown and cannot be properly defined, it is saved "as is" in a text file for backup purposes. Concurrent with the Starlette application, Python programs for MQTT message ingestion based on the paho-mqtt library are executed on the server to retrieve data via the MQTT protocol. All pertinent information regarding the broker, credentials and data format received by the subscribed topic are specified in configuration files to enhance system manageability. The MQTT subscribers and the Starlette application serve equivalent functions for different protocols.

FROST (Fraunhofer Open Source SensorThings API) server^{137,138} is an open-source implementation of the OGC SensorThings API by the Fraunhofer Institute. It is built on top of a PostgreSQL database with PostGIS extension to allow the user to assign customized IDs to the entities. PostgreSQL is a mature, open-source relational database that is widely utilized for its extensive features and reliability and has been refined over its 35-year existence. FROST server provides a RESTful API for data ingestion and retrieval through queries while also supporting the MQTT protocol for transmitting real-time updates to third-party applications. Data retrieved via MQTT can be filtered by adding parameters to the subscription topic; however, this may result in performance degradation. MQTT support is a core feature of the database because it allows real-time sharing of elaborated data with other applications or final users interested in real-time data visualization or monitoring in an easy and straightforward manner.

FROST server instance is provided in two different Docker packages represented in Figure 44.

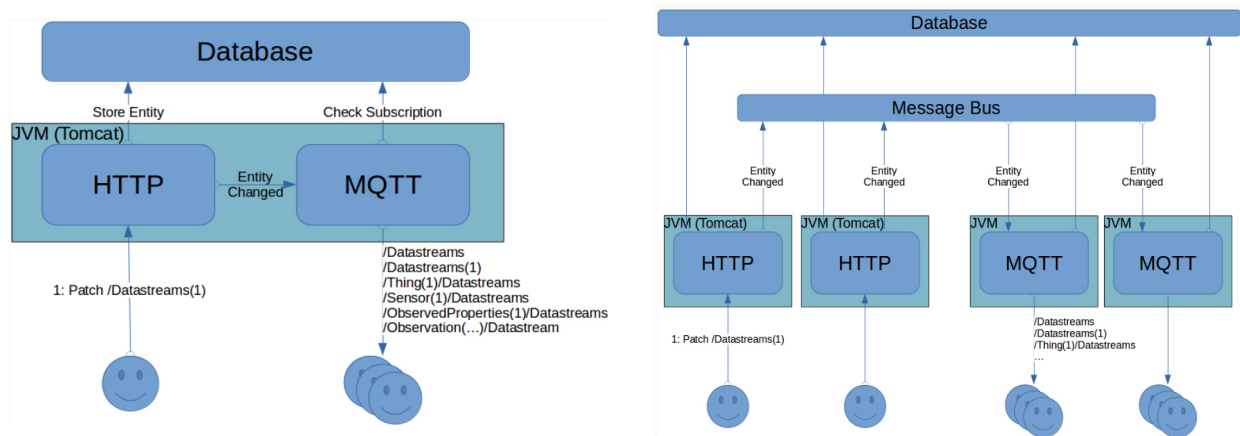


Figure 44 Versions of FROST server provided as docker images¹³⁹

The first package is an all-in-one package that is easier to implement and faster in terms of data ingestion and MQTT publishing but lacks scalability. The second option provides the HTTP and MQTT features as separate packages, allowing to run as many instances as needed and coordinate them using a common bus. Every MQTT and HTTP instance connects to the same (replicated) database, thereby enhancing the scalability of the system when a high number of concurrent requests is expected.

Various formats are available for data retrieval:

- **CSV**
- **GeoJSON**: an open standard format for encoding geographical data
- **OpenAPI**: industrial standard for defining RESTful API. It provides information about the structure of the resources
- **SensorThings API**: a JSON formatted message containing the required information

Multiple formats increase the compatibility of data with existing applications and facilitate their integration in existing workflows. Data visualization was performed using the Grafana open-source software^{140,141}. It is an

“open source visualization and analytics software. It allows you to query, visualize, alert on, and explore your metrics, logs, and traces ...”. It can be installed on premises and its primary function is to create dashboards to facilitate data visualization. It offers many widgets for data visualization and, owing to its extensive plugin offerings, it can support more than 155 different data sources. In particular, the “FROST SensorThings API data source for Grafana” plug-in allows the query of a data source following the SensorThings API format; an alternative is to query the PostgreSQL database directly using another plug-in in case a particular query is not permitted by the API, making Grafana a great integration to the FROST server. It can also set alarms when a variable is outside a selected range and perform operations on the queried data. The dashboard can be shared with external users configuring proper authentication parameters and permissions. The use of a data visualization tool facilitates the comprehension and accessibility of data for end users. Furthermore, Grafana graphs can be embedded in HTML pages for real-time data visualization.

All the aforementioned components were dockerized to facilitate the deployment and management of the entire system on any server. Docker^{142,143} is an open-source platform designed to automate deployment, scaling and management of applications. It uses containerization to allow developers to package applications along with their dependencies, libraries, and configurations into a single container. Containers are lightweight, standalone, and executable software units that include everything needed to run an application, including code, runtime, system tools, libraries and settings. They are isolated from one another and from the host system, ensuring portability and consistency across environments. The containers are run according to the instructions contained in the corresponding docker image, which is immutable. The instructions for constructing the image are specified in a Dockerfile, which can be edited by the user before the construction of the image itself. This structure ensures that the application can run consistently across different environments, from development to production, provides higher scalability and manageability owing to the utilization of containers, and offers a secure and stable environment for the application as the container is isolated from the host machine.

6.2 CONCLUSION

A data server compliant with FAIR principles for the collection, storage and visualization of IoT data was designed. It makes use of open-source software solutions to manage incoming data from data ingestion to data visualization. It can ingest data sent by the MQTT or HTTP protocol and make them available following the OGC SensorThings API as well as other formats. Moreover, it allows the user to subscribe to MQTT topics to receive processed data in real time. The entire system was dockerized to improve its manageability and scalability. The server can adapt to different IoT sensors; a demo was tested during the HIGHLANDER project on forestry data from IoT devices. The devices were successfully described following the OGC SensorThings API architecture, automatically ingested into the database and visualized.

The next steps consist of implementing Kubernetes for container management, authorization and access management and configuring the server for data ingestion from different devices, including those designed during this thesis.

7 CONCLUSIONS

This thesis describes a research on innovative solutions for livestock welfare, monitoring and management. The goal was to develop IoT prototypes for a livestock network management concept composed of the following elements:

1. An innovative wearable sensor to measure multiple individual animal physiological parameters, such as geographical coordinates, air temperature and relative humidity around the animal, average acceleration and standard deviation over three axes, heart rate and cutaneous temperature (animal well-being monitoring).
2. RFID subcutaneous temperature reader from a RFID subcutaneous microchip (animal well-being monitoring).
3. A customizable IoT gas analyzer designed to measure the atmospheric concentrations of NH_3 , CH_4 , H_2S , CO_2 , PM_{10} , $\text{PM}_{2.5}$, and PM_{10} , as well as air temperature and humidity (gas sensing for air quality assessment in animal shelters and quantification of animal greenhouse gas emissions).
4. A data server compliant with FAIR principles for the collection, storage and visualization of IoT data.

Each device and software solution were studied and developed starting from the electronic design to the casing. Each prototype was also produced and tested in different environments. Samples of the collected data for each device are presented and discussed to show the obtained results and the possibilities of each solution. The developed devices also contributed to three European projects. This thesis focused on developing technologies for data collection; the research will proceed with the analysis of collected data for the development of algorithms. The results obtained for each technology are encouraging, paving the way for further improvements and studies that apply the instruments developed in this thesis to broader research on animal behavior and to support farmers in their daily tasks. The devices under development show great potential, both individually and in combination, to optimize resource management and be integrated into a One Health^{144,145} approach to farming.

In particular, these technologies could contribute to the development of early detection systems for animal diseases, helping to reduce both the economic impact and the consequences for the entire herd caused by a late identification of a sick animal. Furthermore, by enabling earlier intervention, they have the potential to reduce antibiotic use, which is a major concern for future human health¹⁴⁶.

At the individual animal level, early detection of abnormal conditions allows for timely medical care, reducing both the animal's suffering and the risks associated with untreated conditions. Moreover, the presented IoT-based technologies can contribute to improving traceability along the food chain, helping to validate certification, reconstruct individual animal histories, and accelerate source identification in case of unforeseen issues at the end of the chain.

Ultimately, the final goal of this research is to enhance animal well-being while optimizing resource use in livestock management, providing deeper insights into the early stages of the production chain and fostering a more efficient, sustainable, and health-conscious farming approach.

REFERENCES

1. Trapanese, L. *et al.* Precision livestock farming applied to the dairy sector: 50 years of history with a text mining and topic analysis approach. *Smart Agricultural Technology* **10**, 100827 (2025).
2. Jiang, B., Tang, W., Cui, L. & Deng, X. Precision Livestock Farming Research: A Global Scientometric Review. *Animals* **13**, 2096 (2023).
3. Morrone, S., Dimauro, C., Gambella, F. & Cappai, M. G. Industry 4.0 and Precision Livestock Farming (PLF): An up to Date Overview across Animal Productions. *Sensors* **22**, 4319 (2022).
4. Barkema, H. W. *et al.* Invited review: Changes in the dairy industry affecting dairy cattle health and welfare. *Journal of Dairy Science* **98**, 7426–7445 (2015).
5. Rotolo, M. L., Main, R. G. & Zimmerman, J. J. Herd-level infectious disease surveillance of livestock populations using aggregate samples. *Animal Health Research Reviews* **19**, 53–64 (2018).
6. Current animal health situation worldwide: Analysis of events and trends - World | ReliefWeb. <https://reliefweb.int/report/world/current-animal-health-situation-worldwide-analysis-events-and-trends> (2022).
7. Kappes, A. *et al.* Livestock health and disease economics: a scoping review of selected literature. *Front. Vet. Sci.* **10**, (2023).
8. Walaszczyk, A. & Galińska, B. Food Origin Traceability from a Consumer's Perspective. *Sustainability* **12**, 1872 (2020).
9. Jo, J. & Lusk, J. L. The Intrinsic and Instrumental Values of Blockchain to Provide Beef Traceability in Hong Kong, South Korea, and the United States. *Foods* **12**, (2023).
10. Michie, C. *et al.* The Internet of Things enhancing animal welfare and farm operational efficiency. *Journal of Dairy Research* **87**, 20–27 (2020).
11. Akhigbe, B. I., Munir, K., Akinade, O., Akanbi, L. & Oyedele, L. O. IoT Technologies for Livestock Management: A Review of Present Status, Opportunities, and Future Trends. *BDCC* **5**, 10 (2021).
12. Neethirajan, S. Artificial Intelligence and Sensor Technologies in Dairy Livestock Export: Charting a Digital Transformation. *Sensors* **23**, 7045 (2023).
13. Kleen, J. L. & Guatteo, R. Precision Livestock Farming: What Does It Contain and What Are the Perspectives? *Animals* **13**, 779 (2023).
14. Norton, T., Chen, C., Larsen, M. L. V. & Berckmans, D. Review: Precision livestock farming: building 'digital representations' to bring the animals closer to the farmer. *Animal* **13**, 3009–3017 (2019).
15. Virgilio, A. di, Morales, J. M., Lambertucci, S. A., Shepard, E. L. C. & Wilson, R. P. Multi-dimensional Precision Livestock Farming: a potential toolbox for sustainable rangeland management. *PeerJ* **6**, e4867 (2018).
16. Zhang, M. *et al.* Wearable Internet of Things enabled precision livestock farming in smart farms: A review of technical solutions for precise perception, biocompatibility, and sustainability monitoring. *Journal of Cleaner Production* **312**, 127712 (2021).
17. Benjamin, M. & Yik, S. Precision Livestock Farming in Swine Welfare: A Review for Swine Practitioners. *Animals* **9**, 133 (2019).
18. Puig, A., Ruiz, M., Bassols, M., Fraile, L. & Armengol, R. Technological Tools for the Early Detection of Bovine Respiratory Disease in Farms. *Animals* **12**, 2623 (2022).
19. Halachmi, I., Guarino, M., Bewley, J. & Pastell, M. Smart Animal Agriculture: Application of Real-Time Sensors to Improve Animal Well-Being and Production. *Annual Review of Animal Biosciences* **7**, 403–425 (2019).
20. Caria, M., Todde, G. & Pazzona, A. Evaluation of automated in-line precision dairy farming technology implementation in three dairy farms in Italy. *Front. Agr. Sci. Eng.* **6**, 181 (2019).

21. McNicol, L. C. *et al.* Adoption of precision livestock farming technologies has the potential to mitigate greenhouse gas emissions from beef production. *Front. Sustain. Food Syst.* **8**, (2024).
22. Tzanidakis, C., Tzamaloukas, O., Simitzis, P. & Panagakis, P. Precision Livestock Farming Applications (PLF) for Grazing Animals. *Agriculture* **13**, 288 (2023).
23. Caja, G. *et al.* Sensing solutions for improving the performance, health and wellbeing of small ruminants. *Journal of Dairy Research* **87**, 34–46 (2020).
24. Lopes, S. *et al.* Precision livestock farming for reproductive performance optimization: a survey. in (2016). doi:10.3920/978-90-8686-834-6_90.
25. Stygar, A. H. *et al.* A Systematic Review on Commercially Available and Validated Sensor Technologies for Welfare Assessment of Dairy Cattle. *Front. Vet. Sci.* **8**, 634338 (2021).
26. Dacosta, F. *Rethinking the Internet of Things - A Scalable Approach ..* (2013).
27. Javaid, M., Haleem, A., Singh, R. P., Suman, R. & Gonzalez, E. S. Understanding the adoption of Industry 4.0 technologies in improving environmental sustainability. *Sustainable Operations and Computers* **3**, 203–217 (2022).
28. Hananto, A. L. *et al.* Digital Twin and 3D Digital Twin: Concepts, Applications, and Challenges in Industry 4.0 for Digital Twin. *Computers* **13**, 100 (2024).
29. Pires, F., Cachada, A., Barbosa, J., Moreira, A. P. & Leitão, P. Digital Twin in Industry 4.0: Technologies, Applications and Challenges. in *2019 IEEE 17th International Conference on Industrial Informatics (INDIN)* vol. 1 721–726 (2019).
30. Singh, M. *et al.* Digital Twin: Origin to Future. *Applied System Innovation* **4**, 36 (2021).
31. Cisco Annual Internet Report - Cisco Annual Internet Report (2018–2023) White Paper. *Cisco* <https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html>.
32. Rauniyar, A., Engelstad, P. & Østerbø, O. N. An Adaptive User Pairing Strategy for Uplink Non-Orthogonal Multiple Access. in *2020 IEEE 31st Annual International Symposium on Personal, Indoor and Mobile Radio Communications* 1–7 (2020). doi:10.1109/PIMRC48278.2020.9217383.
33. Shafique, K., Khawaja, B. A., Sabir, F., Qazi, S. & Mustaqim, M. Internet of Things (IoT) for Next-Generation Smart Systems: A Review of Current Challenges, Future Trends and Prospects for Emerging 5G-IoT Scenarios. *IEEE Access* **8**, 23022–23040 (2020).
34. Al-Shareeda, M. A., Alsadhan, A. A., Qasim, H. H. & Manickam, S. Long range technology for internet of things: review, challenges, and future directions. *Bulletin of Electrical Engineering and Informatics* **12**, 3758–3767 (2023).
35. Zourmand, A., Kun Hing, A. L., Wai Hung, C. & AbdulRehman, M. Internet of Things (IoT) using LoRa technology. in *2019 IEEE International Conference on Automatic Control and Intelligent Systems (I2CACIS)* 324–330 (2019). doi:10.1109/I2CACIS.2019.8825008.
36. LoRa® and LoRaWAN®: A Technical Overview. (2019).
37. About LoRaWAN®. *LoRa Alliance®* <https://loro-alliance.org/about-lorawan/>.
38. What is difference between Chip and Chirp in LoRaWAN,LoRa. <https://www.rfwireless-world.com/Terminology/What-is-difference-between-Chip-and-Chirp-in-LoRaWAN.html>.
39. Fialho, V. & Azevedo, F. Wireless Communication Based on Chirp Signals for LoRa IoT Devices. **4**, 5 (2018).
40. LoRa Crash Course by Thomas Telkamp - TTN Announcements. *The Things Network* <https://www.thethingsnetwork.org/forum/t/lora-crash-course-by-thomas-telkamp/3981/9> (2016).
41. Network, T. New LoRa world record: 1336 km / 830 mi. *The Things Network* <https://www.thethingsnetwork.org/article/new-lora-world-record-1336-km-830-mi>.
42. ITU Region. *Wikipedia* (2023).
43. Regional Limitations of RF Use in LoRaWAN. *The Things Network* <https://www.thethingsnetwork.org/docs/lorawan/regional-limitations-of-rf-use/>.

44. What is Sigfox? *Sigfox 0G Technology* <https://www.sigfox.com/what-is-sigfox/>.
45. Coverage. *Sigfox 0G Technology* <https://www.sigfox.com/coverage/>.
46. Migabo, E. M., Djouani, K. D. & Kurien, A. M. The Narrowband Internet of Things (NB-IoT) Resources Management Performance State of Art, Challenges, and Opportunities. *IEEE Access* **8**, 97658–97675 (2020).
47. 3GPP – The Mobile Broadband Standard. *3GPP* <https://www.3gpp.org/>.
48. Power saving techniques. *Nordic Developer Academy* <https://academy.nordicsemi.com/courses/cellular-iot-fundamentals/lessons/lesson-1-cellular-fundamentals/topic/lesson-1-power-saving-techniques/>.
49. Texas Instruments. Long-range RF communication: Why narrowband is the de facto standard. (2014).
50. protocol. <https://dictionary.cambridge.org/dictionary/english/protocol> (2024).
51. MQTT Specification. <https://mqtt.org/mqtt-specification/>.
52. What is MQTT? *Twilio* <https://www.twilio.com/en-us/blog/what-is-mqtt>.
53. End Device Activation. *The Things Network* <https://www.thethingsnetwork.org/docs/lorawan/end-device-activation/>.
54. Group, P. G. D. PostgreSQL. *PostgreSQL* <https://www.postgresql.org/> (2024).
55. INSPIRE Knowledge base - European Commission. https://knowledge-base.inspire.ec.europa.eu/index_en (2024).
56. Wilkinson, M. D. *et al.* The FAIR Guiding Principles for scientific data management and stewardship. *Sci Data* **3**, 160018 (2016).
57. Jacobsen, A. *et al.* FAIR Principles: Interpretations and Implementation Considerations. *Data Intelligence* **2**, 10–29 (2020).
58. Bender, T. FAIR data mandatory as of August 2023. *NFDI4Chem* <https://www.nfdi4chem.de/faire-daten-verpflichtend-ab-august-2023/> (2023).
59. OGC Homepage. *Open Geospatial Consortium* <https://www.ogc.org/>.
60. OGC SensorThings API. *Open Geospatial Consortium* <https://www.ogc.org/standard/sensorthings/>.
61. [opengeospatial/sensorthings](https://www.ogc.org/standard/sensorthings/). Open Geospatial Consortium (2024).
62. Liang, S., Huang, C.-Y. & Khalafbeigi, T. OGC SensorThings API Part 1: Sensing. *SensorThings SWG* <https://docs.ogc.org/is/15-078r6/15-078r6.html> (2016).
63. Highlander project. <https://highlanderproject.eu/> (2024).
64. Homepage. *Scala-Medi* <https://www.scala-medi.eu/>.
65. Sebastien – Smarter livEstock Breeding through Advanced Services Tailoring Innovative and multi-source data to users' Needs. <https://www.sebastien-project.eu/>.
66. EasyEDA - Disegno online di PCB e simulatore di circuiti. <https://easyeda.com/it>.
67. Arduino - Home. <https://www.arduino.cc/>.
68. FreeCAD: Your own 3D parametric modeler. <https://www.freecad.org/>.
69. Mottram, T. Animal board invited review: precision livestock farming for dairy cows with a focus on oestrus detection. *Animal* **10**, 1575–1584 (2016).
70. Chapa, J. M., Maschat, K., Iwersen, M., Baumgartner, J. & Drillich, M. Accelerometer systems as tools for health and welfare assessment in cattle and pigs – A review. *Behavioural Processes* **181**, 104262 (2020).
71. Werner, J. *et al.* Evaluation and application potential of an accelerometer-based collar device for measuring grazing behavior of dairy cows. *Animal* **13**, 2070–2079 (2019).
72. Bailey, D. W., Trotter, M. G., Knight, C. W. & Thomas, M. G. Use of GPS tracking collars and accelerometers for rangeland livestock production research1. *Translational Animal Science* **2**, 81–88 (2018).

73. Campbell, D. L. M., Lea, J. M., Keshavarzi, H. & Lee, C. Virtual Fencing Is Comparable to Electric Tape Fencing for Cattle Behavior and Welfare. *Front. Vet. Sci.* **6**, (2019).
74. Karvatte, N. *et al.* Shading effect on microclimate and thermal comfort indexes in integrated crop-livestock-forest systems in the Brazilian Midwest. *Int J Biometeorol* **60**, 1933–1941 (2016).
75. STMicroelectronics. STM32L072x8 STM32L072xB STM32L072xZ - Ultra-low-power 32-bit MCU Arm®-based Cortex®-M0+, up to 192KB Flash, 20KB SRAM, 6KB EEPROM, USB, ADC, DACs. (2019).
76. STM32duino. *GitHub* <https://github.com/stm32duino>.
77. STMicroelectronic. LIS3DH - MEMS digital output motion sensor: ultra-low-power high-performance 3-axis 'nano' accelerometer. (2016).
78. U-blox. MAX-M10S - Standard precision GNSS module Professional grade. (2024).
79. SENSIRION. Datasheet – SHT4x - 4th Gen. Relative Humidity and Temperature Sensor. (2024).
80. Maxim Integrated. MAX30102 - High-Sensitivity Pulse Oximeter and Heart-Rate Sensor for Wearable Health. (2018).
81. W25Q128JV - 3V 128M-BIT SERIAL FLASH MEMORY WITH DUAL/QUAD SPI. (2024).
82. RAKwireless Technology Limited. RAK3172 WisDuo LPWAN Module Datasheet | RAKwireless Documentation Center. <https://docs.rakwireless.com/Product-Categories/WisDuo/RAK3172-Module/Datasheet/> (2024).
83. Welcome to Python.org. *Python.org* <https://www.python.org/> (2024).
84. Becker, C. A., Collier, R. J. & Stone, A. E. *Invited review*: Physiological and behavioral effects of heat stress in dairy cows. *Journal of Dairy Science* **103**, 6751–6770 (2020).
85. Yan, G., Li, H. & Shi, Z. Evaluation of Thermal Indices as the Indicators of Heat Stress in Dairy Cows in a Temperate Climate. *Animals* **11**, 2459 (2021).
86. Armstrong, D. V. Heat Stress Interaction with Shade and Cooling. *Journal of Dairy Science* **77**, 2044–2050 (1994).
87. Cabezas, J. *et al.* Analysis of Accelerometer and GPS Data for Cattle Behaviour Identification and Anomalous Events Detection. *Entropy* **24**, 336 (2022).
88. Vázquez Diosdado, J. A. *et al.* Classification of behaviour in housed dairy cows using an accelerometer-based activity monitoring system. *Anim Biotelemetry* **3**, 15 (2015).
89. Schweinzer, V. *et al.* Evaluation of an ear-attached accelerometer for detecting estrus events in indoor housed dairy cows. *Theriogenology* **130**, 19–25 (2019).
90. Mattachini, G., Riva, E., Perazzolo, F., Naldi, E. & Provolo, G. Monitoring feeding behaviour of dairy cows using accelerometers. *Journal of Agricultural Engineering* **47**, 54–58 (2016).
91. Nielsen, L. R., Pedersen, A. R., Herskin, M. S. & Munksgaard, L. Quantifying walking and standing behaviour of dairy cows using a moving average based on output from an accelerometer. *Applied Animal Behaviour Science* **127**, 12–19 (2010).
92. Plaza, J. *et al.* GPS monitoring reveals circadian rhythmicity in free-grazing sheep. *Applied Animal Behaviour Science* **251**, 105643 (2022).
93. Kou, H. *et al.* Automated measurement of cattle surface temperature and its correlation with rectal temperature. *PLOS ONE* **12**, e0175377 (2017).
94. Campbell, D. L. M. *et al.* The application of virtual fencing technology effectively herds cattle and sheep. *Anim. Prod. Sci.* **61**, 1393–1402 (2021).
95. Schutz, M. & Bewley, J. Implications of Changes in Core Body Temperature. *Tri-State Dairy Nutr* (2009).
96. Dorota Godyń *et al.* Measurements of peripheral and deep body temperature in cattle - A review. *Journal of Thermal Biology* **79**, 42–49 (2019).

97. Irmawanti, S., Luthfi, M. & Prihandini, P. W. Physiological responses of several beef cattle breeds based on environmental conditions in Beef Cattle Research Station. *IOP Conf. Ser.: Earth Environ. Sci.* **1114**, 012079 (2022).
98. Aengwanich, W., Kongbuntad, W. & Boonsorn, T. Effects of shade on physiological changes, oxidative stress, and total antioxidant power in Thai Brahman cattle. *Int J Biometeorol* **55**, 741–748 (2011).
99. Perini, F. *et al.* Emerging Genetic Tools to Investigate Molecular Pathways Related to Heat Stress in Chickens: A Review. *Animals* **11**, 46 (2021).
100. Bakony, M., Kovács, L., Kézér, L. F. & Jurkovich, V. The use of body surface temperatures in assessing thermal status of hutch-reared dairy calves in shaded and unshaded conditions. *Front Vet Sci* **10**, 1162708 (2023).
101. Y. Lee *et al.* Body Temperature Monitoring Using Subcutaneously Implanted Thermo-loggers from Holstein Steers. *Asian-australasian Journal of Animal Sciences* **29**, 299–306 (2015).
102. Gundula Hoffmann *et al.* Monitoring the body temperature of cows and calves using video recordings from an infrared thermography camera. *Veterinary Research Communications* **37**, 91–99 (2013).
103. admin. RFID Technology - Best Barcode System. <https://bestbarcodeworld.com/rfid-technology/>, <https://bestbarcodeworld.com/rfid-technology/> (2020).
104. International Organization for Standardization. ISO 11784:1996. *ISO* <https://www.iso.org/standard/25881.html> (1996).
105. International Organization for Standardization. ISO 11785:1996. *ISO* <https://www.iso.org/standard/19982.html> (1996).
106. International Organization for Standardization. ISO 14223-1:2011. *ISO* <https://www.iso.org/standard/50979.html> (2011).
107. International Organization for Standardization. ISO 24631-1:2017. *ISO* <https://www.iso.org/standard/63394.html> (2017).
108. Biomark. BIOTHERM13 FDX-B HIGH-PERFORMANCE PIT TAG. (2021).
109. Faread Technology Co. New Product Release-- FRD-LF-GT12-244BT_Company News_News_About_Faread Technology Co., Ltd.,浙江法利电子科技有限公司_Faread Technology Co., Ltd.浙江法利电子科技有限公司. <https://www.microchipsyringe.com/news/company/new-product-release---frd-lf-gt12-244bt-255.html> (2019).
110. MSD Animal Health S.r.l. Thermo chip mini and suresense. (2024).
111. Avery Dennison Corporation. Smartrac launches dual-function Glass Tag Thermosensor for industrial and animal ID applications | Avery Dennison | RFID. <https://rfid.averydennison.com/en/home/news-insights/press-releases/smartrac-launches-dual-function-glass-tag-thermosensor-for-industrial-and-animal-id-applications.html> (2019).
112. Biolog-id. Biolog-Temp: Identification tag with ‘temperature sensor’. *Biolog-animal* <https://www.biolog-animal.com/en/products/research/biolog-temp-identification-tag-with-temperature-sensor/>.
113. Priority 1 Design. RFIDRW-E-TTL - Animal tag and RFID reader writer with external antenna, and TTL output. (2012).
114. Espressif Systems. ESP32WROOM32E ESP32WROOM32UE. (2023).
115. Eclipse Mosquitto. *Eclipse Mosquitto* <https://mosquitto.org/> (2018).
116. Jq, N., Ma, E., Cc, C., C, L. & Y, L. A critical review of advancement in scientific research on food animal welfare-related air pollution. *Journal of hazardous materials* **408**, (2021).
117. Banhazi, T., Aland, A. & Hartung, J. *AIR QUALITY AND LIVESTOCK FARMING*. (2018).

118. van Leenen, K. *et al.* Associations of barn air quality parameters with ultrasonographic lung lesions, airway inflammation and infection in group-housed calves. *Preventive Veterinary Medicine* **181**, 105056 (2020).
119. New FAO report maps pathways towards lower livestock emissions. *Newsroom* <https://www.fao.org/newsroom/detail/new-fao-report-maps-pathways-towards-lower-livestock-emissions/en>.
120. MKR Zero | Arduino Documentation. <https://docs.arduino.cc/hardware/mkr-zero/>.
121. SIMCom Wireless Solutions. SIM7020G NB-IoT(Cat-NB2) Modul. (2018).
122. HiveMQ MQTT Broker - Enterprise ready to move IoT data. <https://www.hivemq.com/products/mqtt-broker/>.
123. ThingsBoard — Open-source IoT (Internet of Things) Platform. <https://thingsboard.io/>.
124. Zhengzhou Winsen Electronics Technology Co. MH-Z16 Infrared CO2 Gas Module. (2022).
125. Zhengzhou Winsen Electronics Technology Co. Electrochemical Gas Detection Module - MODEL: ZE03. (2023).
126. Zhengzhou Winsen Electronics Technology Co. Laser dust sensor - Model: ZH07. (2021).
127. EC Sense GmbH. Organic Volatiles Gas Sensor Module TB600B Datasheet TB600B-TVOC-10. (2023).
128. EC Sense GmbH. Ammonia Gas Sensor Module TB600B Datasheet TB600B-NH3-10. (2023).
129. EC Sense GmbH. Hydrogen Sulfide Gas Module 0~2ppm TB600B-H2 S-2 Technical Specification. (2023).
130. Zhengzhou Winsen Electronics Technology Co. NDIR Infrared CH4 Gas Sensor - Model : MH-441D. (2022).
131. Open-Earth-Monitor project – A cyberinfrastructure to accelerate uptake of environmental information. <https://earthmonitor.org/>.
132. Report on Data Homogenisation for High-value Datasets | data.europa.eu. <https://data.europa.eu/en/doc/report-data-homogenisation-high-value-datasets>.
133. nginx. <https://nginx.org/en/>.
134. nginx · GitHub. <https://github.com/nginx>.
135. Starlette. <https://www.starlette.io/>.
136. Uvicorn. <https://www.uvicorn.org/>.
137. FROST®-Server - An open source implementation of OGC SensorThings API - Fraunhofer IOSB. *Fraunhofer Institute of Optonics, System Technologies and Image Exploitation IOSB* <https://www.iosb.fraunhofer.de/en/projects-and-products/frost-server.html>.
138. FraunhoferIOSB/FROST-Server. Fraunhofer IOSB (2024).
139. FROST Deployment Architecture. *FROST-Server Documentation* <https://fraunhoferiosb.github.io/FROST-Server/deployment/architecture-packages.html>.
140. Grafana OSS | Leading observability tool for visualizations & dashboards. *Grafana Labs* <https://grafana.com/oss/grafana/>.
141. grafana/grafana. Grafana Labs (2024).
142. Docker: Accelerated Container Application Development. <https://www.docker.com/> (2022).
143. Docker. *GitHub* <https://github.com/docker>.
144. Destoumieux-Garzón, D. *et al.* The One Health Concept: 10 Years Old and a Long Road Ahead. *Front. Vet. Sci.* **5**, (2018).
145. Mackenzie, J. S. & Jeggo, M. The One Health Approach—Why Is It So Important? *Tropical Medicine and Infectious Disease* **4**, 88 (2019).
146. Robinson, T. P. *et al.* Antibiotic resistance is the quintessential One Health issue. *Transactions of The Royal Society of Tropical Medicine and Hygiene* **110**, 377–380 (2016).

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