Design of a flexible, expandable, and customizable sensor network for monitoring livestock behaviour and welfare

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***Abstract*—In recent years concerns for animal health and food traceability arose and, at the same time, the number of animal per farm increased as well. In this setting, new technologies for precision livestock farming have been developed in order to monitor the animal behavior and health and provide information to the farmer. Here an innovative system for animal monitoring is presented. It is composed of multiple types of sensors that can be placed on different parts of the animal body. Collected data are then sent through BLE (Bluetooth Low Energy) 5.0 to a central devices that can elaborate them and make them available over the internet using MQTT (Message Queuing Telemetry Transport) protocol. All components are described, starting from the central device and following with the first set of developed or under development sensors (movements, cutaneous temperature, pulse oximetry, subcutaneous temperature). Moreover, the use of a high sampling frequency version and its benefits are discussed. The described system can be easily expanded pairing a new BLE sensor and for the same reason it is very customizable, flexible and cost effective when more that one parameter is required. A first prototype of the concept has been developed and tested and the patenting process is currently ongoing.**

***Keywords*—precision livestock farming, animal health, animal behavior, Internet of Things (IoT), GNSS positioning, animal movements, temperature, pulse oximetry**

I. INTRODUCTION

Several IoT sensors (more than 60) are already commercially available for monitoring livestock welfare. They are generally composed by a battery, a data transmitter and one or more sensors (triaxial accelerometer, thermometer, electrode pH, microphone, etc.), which are mounted on the animal's body to measure and collect biometric data [1,2,3]. However, these sensors consist of a single device positioned at a specific point on the animal's body. This factor limits the number of animal physiological and functional parameters that can be collected [1]. Another important limitation is the cross-talk of sensors from different brands or manufacturers, because they have proprietary systems that are incompatible with each other [4]. The presented system aims to solve some of the previously reported issue with an expandable system where all the BLE (Bluetooth Low Energy) sensors are coordinated by a central device. The use of multiple sensors on a single animal may have an important impact on animal research while the possibility to customize the system depending on needs is interesting for commercial purposes. Moreover, the choice of BLE connection makes the system potentially compatible with other BLE third-parties sensors that have be read through a phone application.

II. ANIMALTALKER SYSTEM

A. AnimalTalker

AnimalTalker is an innovative concept for livestock welfare assessment. The idea is to place multiple sensors, called AnimalButtons, in different positions on the animal body, to measure multiple parameters (e.g. movements, feeding, temperature, etc.) as proxy of physiological stress, discomfort and behavioral attitude, and make them available remotely using Internet of things (IoT) technologies. The sensors send the collected and elaborated information to a device called AnimalCollar that makes them available over the internet. The strength of this system is its high flexibility and customability, depending on field requirements. The AnimalButtons are paired with the Collar by Bluetooth Low Energy (BLE) 5.0 technology, requiring low power while ensuring high transfer speed.

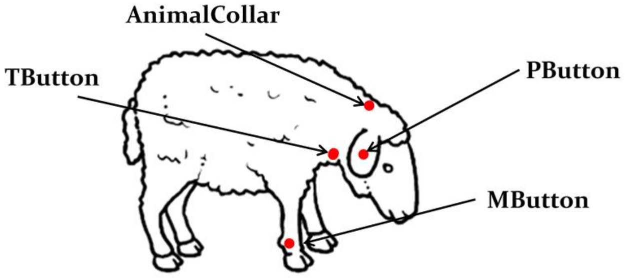

Fig. 1. Schematization of the AnimalTalker system.

B. *AnimalCollar*

The AnimalCollar is the central device that retrieves data and coordinates all other sensors (AnimalButtons). It is composed of a BLE built-in microchip, a Narrowband Internet of things (NB-IoT) or LoRa transceiver and a Global navigation satellite system (GNSS) module, plus an accelerometer (LIS3DHTR) and a TRH sensor (temperature and relative humidity – SHT40). Its task is to collect data from each device, save and send them to a central server or to the LoRa gateway. NB-IoT solution was chosen because it requires lower power, has multiple sleep modes and has a higher coverage than 4G. Moreover, the use of a direct connection to internet makes each device standalone. On the other hand, LoRa technology is not able to send data directly over the Internet and cannot send as much data as NB-IoT, however it works over a local network and has the possibility to localize a device if the signal reaches three or more gateways are reachable by the sent signal. It is also less expensive. The last module that can be mounted is a GNSS one that is able to mount an active or a passive antenna and supports four GNSS (GPS, GLONASS, Galileo and BeiDou). The next generation modules have also the possibility to speed up the acquisition phase and to reduce power consumption during the tracking phase. The use of a central device as the AnimalCollar allows the connected devices (AnimalButtons) to spare some energy for data transmission. Data from more devices can be analyzed locally if required. This permits the miniaturization of the sensors (e.g. a bigger antenna is required only on the collar, the Bluetooth can use a circuit printed antenna). In particular, the use of an nRF52840 based board allows embedding complex algorithms on the device, having plenty of space for useful libraries built on micropython and the possibility to develop some BLE feature such as the distance estimation between BLE devices (useful for detecting livestock relative position). Sensors mounted on the Animalcollar are an accelerometer and a TRH. The accelerometer is used to measure movements of the animal head, related to animal behavior and welfare while the TRH sensor transmits information on the environmental conditions, making the AnimalCollar a standalone basic animal monitoring device. BLE technology makes the AnimalCollar potentially compatible with each device used on animals that has a BLE connection .

C. *AnimalButtons*

Each Animalbutton is designed on the same basic structure: a battery, a BLE module, a very low power microchip (now from automatic voltage regulator - AVR family) and a sensor. While the software that regulates pairing, sampling time and communication with the collar is the same in all AnimalButtons, sensors mounted on the device are different. Consequenly, the software used to collect and elaborate data differs depending on the sensor. Data are exchanged with the AnimalCollar at fixed time intervals (typically 1 hour, customizable and selectable by users) while current timestamp and other parameters are received from it. Overall, similarities allow the quick development of Animalbuttons featuring new sensors, making the system ideal for research and commercial purposes. The devices are powered by a 1100 mAh battery and are built on a 4 x 4 cm pcb but further miniaturization is possible.

1) *Sd version*

A specific version of AnimalButton is able to save collected data on an sd card, instead of sending them to the AnimalCollar. As the amount of data that can be reasonably sent through BLE and NB-IoT is limited, the possibility to have continuous data collection on an sd card (up to 600 samples per second) allows the analysis of all available data and not only of elaborated ones (e.g. average and standard deviation). This version can be developed for each sensor associated to an AnimalButton in order to obtain a more in depth knowledge of animal condition and related behavior. Collected information can also be used to improve edge computing algorithms, to choose the best sample frequency for BLE sensors and to implement suitable power saving feaures on “trasmitting devices”.

2) *MButton*

The MButton mounts an accelerometer in order to collect information about animal movements that can be related to animal conditions such as heat stress [5,6]. The three-axis accelerometer range is between ±2 g to ±16 g while its sampling rate is up to 5.3 kHz (usually it is set to 400 Hz). Collected data are the timestamp, the average value and the standard deviation of acceleration on the three axes over each minute. Another important feature is the presence of two programmable interrupts that can be used to implement low power features collecting only the movements that are relevant for the analysis. The accelerometer can be installed on a belt wrapped around the animal ankle or on other systems already in place.

3) *TButton*

The TButton is a double sided device which mounts on the top layer a temperature and relative humidity sensor and on the bottom one a thermistor. The thermistor is surrounded by thermal paste and is in contact with the animal skin through a metal plate placed on the bottom face of the device. Skin temperature and environmental conditions can be related to animal core temperature.

4) *PButton*

The PButton stands for pulse oximetry (heart rate and blood oxygenation), moreover an IR temperature sensor and an environmental temperature and relative humidity sensor is also present. All three sensors are optical ones and the data, differing mainly in the light wavelength they analyze. More in depth, temperature is measured through IR wavelengths while the pulse oximetry is based on two main wavelengths (660 nm and 940 nm). The heart rate and blood oxygenation measurement is based on the absorbed light; in particular, the HbO_2 (oxyhemoglobin) absorbs mainly the 940 nm wavelength while the Hb (hemoglobin) absorbs the 660 nm wavelength. From the difference between the two, the blood

Fig. 2. Image of AnimalTalker devices installed on sheep.

oxygenation can be obtained. The hearth rate is instead estimated through absorption due to the increase or decrease in concentration of red blood as the blood vessels expand and contract. The wavelength used is the green light. The pattern obtained can easily been converted into animal heart rate. Finally, the IR temperature sensor can be used in order to measure the skin temperature to be compared with the environmental one. The advantage of the IR sensor is that it is less dependent from the distance from the skin compared to the previously described version of the TButton and that it can be easily implemented on the PButton. The described sensor can be placed on the animal ear or in another accessible and vascularized point.

5) *Subcutaneous temperature*

The use of subcutaneous temperature presents some noticeable advantages compared to skin temperature devices such as a good correlation with rectal temperature [7] combined with an easier maintainability and durability. Furthermore, they can provide the animal with a unique id readable from electrical devices for technological applications, are difficult to substitute without trace and could replace in the end the ear tags at an affordable price. Moreover, passive RFID do not need a battery but the energy is provided by the reader making them very easy to maintain despite their been placed underskin. Major drawback is their need to be removed from the animal body at the end of its life and the possibility of migration if not properly installed, plus the compatibility of some sensors with selected readers only. A broad set of different sensors have been acquired in order to test them using third parties readers and find the best fit taking into account accuracy and price. The idea is to use them into an IoT system, collecting the data using mini-readers placed on the animal body or alternatively bigger ones on specific points where the animals are used to go depending on the case. The information collected by the readers can be transmitted using LoRa or NB-IoT technology. These sensors usually works between 33 °C and 43 °C with the stated accuracy on datasheet of ±0.5 °C to ± 0.1 °C depending on the sensor. The main challenge is to built a system that is able to overcame the issue posed by the limited reading range of this type of sensors (up to 40 cm) with readers that can be placed on the field.

D. *Server*

The last component of the AnimalTalker system is the server that has the role to collect, organize and make available the received data. The collected data are sent to an MQTT broker (Message Queuing Telemetry Transport) broker (in this case, Eclipse Mosquitto) that is in charge of dispatching all the messages sent by the senders (that is the publisher, i.e. IoT sensors) on a certain topic to one or more receivers subscribed to that topic (that are subscribers, i.e. Telegraf agent). The use of the MQTT standard allows to implement also security features such as authentication and message cryptography. The messages received are delivered to a data collection agent (i.e. Telegraf) that formats the data and insert it into a database (i.e. InfluxDB). InfluxDB offers all the advantages given by the use of a database, among others an easy way to perfom queries and the possibility to add metadata. Finally, the data are visualised through a Grafana dashboard that shows the elaborated data to the final user in a fast and easy to understand way. The use of an IoT standard framework (i.e. MQTT/Telegraf/InfluxDB/Grafana) guarantees a well-established order among data and increases the likelihood of compatibility.

III. EXPERIMENTAL TESTS

A preliminary test of a first batch of devices and technologies was performed in Sardinia on 16 sheep. In particular, each sheep had an AnimalCollar and a MButton installed. A subgroup of 4 animals were also equipped with RFID temperature sensors in 2 different positions in order to test the best configuration for subcutaneous temperature measurements. Finally, a TButton, 3 MButtons sd version and 1 prototype of sd heart rate sensor were tested. In this chapter, the obtained data are briefly presented and discussed.

A. *Sd versions*

Data collected from one of the three Mbuttons sd version are reported in Fig. 3. The long term aim is to find the best sampling frequency and correlate it with the animal welfare and behaviour. During the experiment, approximately 600 points per second over x, y and z axes were collected for several hours. Performing a Fast Fourier Transform on the data obtained, the frequencies below 100 Hz seem to be the

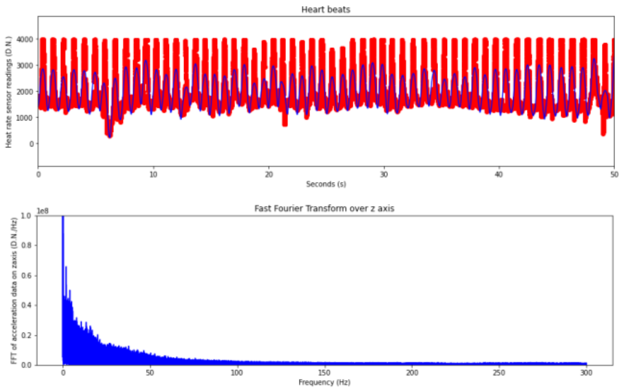

Fig. 3. From top to bottom, pattern extrapolated from data collected by the heart rate sensor over 50 seconds and result of a Fast Fourier Transform analysis performed on data collected along the z axis by the sd version of a MButton.

most relevant. The maximum frequency could still be increased in order to further explore possible frequencies of interest however the found result is reasonable. The same analysis performed on x and y axes produced similar results. The identification of the main frequencies is of utmost importance in order to select the minimum required frequency and reduce the power consumption accordingly choosing suitable technologies. The use of a camera in order to correlate collected data with animal behaviours and to develop suitable algorithms is planned. In particular, the movements of the animal over some days is going to be recorded during the MButton sd version data collection. Analyzing saved data, patterns can be found and can be interpreted using the video recorded in order to develop a suitable algorithm. The other sd sensor tested is the heart rate one that was placed on the sheep internal ear taking advantage of the high presence of blood vessels in the area. Data collected are reported in red while the blue line shows the trend that is the first information needed in the calculation of the heart rate. The described test clearly demonstrates the potential of the technology; the first version of the PButton (BLE) is currently under development.

B. *AnimalTalker system*

The main purpose of AnimalTalker data chain testing was to assess performances and limits of the technology in real field conditions. A subset of data collected by one complete system (TButton, MButton and AnimalCollar) is reported in Fig. 4. The MButton was placed on a sheep ankle while the TButton was placed under the collar to be in contact with the animal skin. Collected data, both Mbutton and TButton ones, clearly show daily patterns. The TButton data were collected every 10 minutes and show a strong correlation between the skin temperature and the ambient temperature as expected (the resistance of the NTC used to measure the skin temperature has an inverse relationship with the temperature itself). The development of the algorithm to clear skin temperature data from the effects of ambient temperature is currently ongoing. The Mbutton collected data for one minute every two, that is 20 points per hour. Every point consists of the average and the standard deviation of 300 measurements of acceleration components on the three axes performed over one minute. On the reported plots, the color of the points represents the standard deviation of the average value; in particular, it shifts toward blue if the value is lower while it is nearer red for higher values. The analysis of the standard deviation clearly shows period of activity that are characterized by an higher variation (red) alternated by period of inactivity (blue). Animal activity is strictly related to stress and behaviour, however further tests combined with the information collected by the sd version of the sensors will be essential to obtain the most from the data.

C. *Subcutaneous temperature*

Two RFID subcutaneous temperature sensors (FAREAD) made by Ø 2.12 x 12 mm glass ogives were placed in the neck and in the leg of four sheep. The temperature measured by the tags was compared with the rectal one measured by a thermometer; in addition, a thermal camera was used to assess the temperature of different body parts. Temperature data collected by the two subcutaneous sensors is very similar and inside the accuracy range declared by the producer (± 0.05 °C). However, there is a substantial difference between the rectal temperature and the one measured by the RFID device despite a similar patter can be observed. The thermal camera was used on the head, the eye and the udder. While the head temperature turned out to be similar to the one registered by the RFID sensors, eye and udder temperature measurements are comparable with the rectal one. This outcome suggests that the sensor position has a major impact on the measured temperature, thus a more extensive experiment should be carried on in order to find the best spot for subcutaneous temperature measurements. The position should be as external as possible to ease the readibility of the sensor by an external IoT reader without major signal losses; at the same time the RFID tag should be easily removable being the sheep an edible species. In any case, the impact of external temperature has been reduced by the use of subcutaneous sensors compared to skin temperature sensors.

D. *THI index*

The Temperature Humidity Index (THI) is an indicator used to assess the thermal stress an animal is exposed due to the combination of air temperature and relative humidity and the thermal stress is an important factor when it comes to livestock welfare and productivity. In Fig. 5 the calculation of the THI for one sheep is reported. The real time hourly measurements of air temperature and relative humidity performed by the AnimalCollar have been used in (1) to obtain the THI:

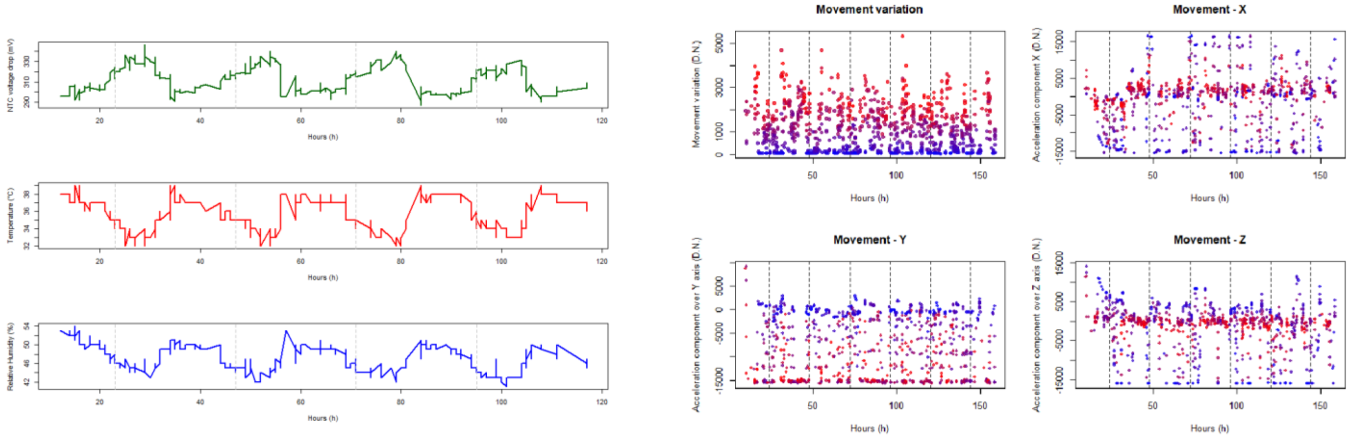

Fig. 4. Data obtained from a TButton (on the left) and a MButton (on the right) and sent by the AnimalCollar to a server during the test.

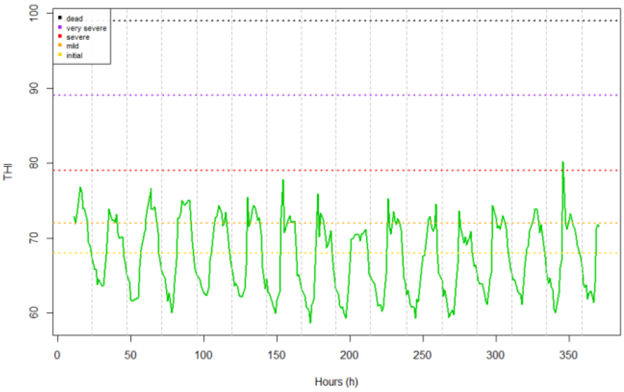

Fig. 5. THI for one sheep calculated using the air temperature and relative humidity data from an AnimalCollar.

$$\mathrm{THI} = t_F - (0.55 - 0.0055 * h) * (t_F - 14.5) \tag{1}$$

where t_F is the temperature in Fahrenheit and h is the relative humidity. In Fig. 5, five different stress levels have been taken into account going from “initial”, indicated by the light yellow line, to “dead”, indicated by the black one. During the night the THI is far below the “initial” level while during most of the days the THI exceeds the “mild” value reaching the “severe” one in one case. It is worth pointing out that the values reported are the real time condition of one single animal estimated using information on its own microclimate. In particular, while the THI is often calculated using values retrieved by weather stations, the use of an IoT sensors allows a better estimation taking into account additional factor such as the time spent in the shade.

E. *Further development*

Tests performed on an early version of the system have been described in this chapter. While the results are promising, broader datasets are needed in order to use the AnimalTalker in an effective way. A simultaneous use of the sd version of the sensors and a camera will help interpreting the data obtained and relate them to the animal behavior. The complete system will be also used and continuously improved both from an hardware and software point of view. In particular, the PButton is currently under development following the results obtained in the first phase. An IoT reader for the RFID subcutaneous sensors is also beign designed. In the meantime, different spots for the chip inoculation should be tested, aiming to obtain a temperature similar to the rectal one; alternatively the integration of a TRH sensors in the reader to correct data should be considered.

IV. CONCLUSION

Multiple technologies and approaches for animal behavior and welfare assessment have been described. An innovative system called AnimalTalker composed by multiple sensors coordinated by a BLE central device has been presented. Its structure is aimed at obtaining a complete, customizable and expandable technology for livestock monitoring. A first prototype has been developed and tested in order to explore issues and opportunities offered by this approach. Moreover, an actual use case has been presented consisting of THI real-time calculation for a sheep. While the system is still in an early stage, the preliminary results obtained during the described field tests are promising and further steps will be taken in the near future to improve the usage of the data and expand the functionalities of the devices. In particular, additional sensors are currently being developed and new parameters can and will be surely measured taking advantage of the extreme flexibility assured by the system.

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