Research platform to study sheep behavior

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***Abstract*— We present the design, manufacturing, and testing of an online sheep behavior monitoring research platform for extensive livestock conditions. This kind of system can contribute to animal well-being and assist farmers in decision-making for better productivity. Our proposal comprises a wearable electronic collar device and a cloud server that stores data and provides a user interface.**

The device has an Icarus IoT Board from Actinius, which allows for motion data collection with a three-axis accelerometer, location data measurement, Narrowband IoT communication, and two portable power sources: solar panels or battery, both in the collar. Our application acquires encoded accelerometer data at 100 Hz, location data obtained every 10-30 seconds, and battery and cellular signal level data every 50 seconds and sends them to the cloud server. We use the Amazon Web Services as a cloud server for deploying our software solution.

We manufactured thirty collars which are currently under test. The devices successfully collect data and send it to the cloud server. Cloud data can be remotely accessed and viewed via a web-based user interface. The research platform allows the implementation of data processing techniques, like machine learning algorithms, to perform behavior classification, both on the collar and on the server side.

I. Introduction

In Uruguay, sheep production is mainly developed in extensive systems based on grazing natural pastures in large paddocks, often grazing together with cattle [1]. A central production issue in these conditions is the high lamb mortality rate, which limits the system's efficiency. Therefore, recording, or ideally predicting, the main events of the process, such as estrus or lambing, would impact productivity and welfare. In this context, it is essential to have online behavioral information about the ewe to propose strategies for reducing neonatal lamb mortality. The behavioral information includes the "use of time" in different activities, grazing budget, social cohesion, response to handlings (shearing, breeding), and unusual behaviors. With this information, it could be feasible to apply different management strategies, such as using protected spaces or farrowing crates, offering specific diets, or aiding during lambing. Likewise, if it would be possible to determine restlessness in the herd, this could indicate the presence of predators. Therefore, online animal monitoring systems provide the opportunity to develop research that allows the farmer to make decisions based on flock information. These systems should be low-cost, comfortable for the animal, and require low maintenance.

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Several research solutions have proposed systems for monitoring sheep behavior (see [2]) and particularly for studying behavior with accelerometer data (see [3]). Prior studies noted changes in sheep's behavior before birth, but it is ongoing research to understand these modifications better [4]. Commercial systems developed with accelerometers are portable, low cost, and comfortable for the animal [4], [5], [6]. However, they fail to be low maintenance and to provide online information. An example of a hybrid solution (online and offline classification) is presented in [7]. [8] and [9] develop their own device for behavior monitor systems. [8] does not target on-animal classification, as [9] does. The latter, however, does not have wireless raw data transmission.

In this work, we propose a research platform that represents the next generation of our prior work [10], [11]. The proposed platform allows experiments on animals with a remarkable capacity to handle large amounts of data, including data collection, processing, and real-time transmission.

II. Proposed Solution

The proposed system (see Fig. 1) consists of a wearable collar electronic device that collects movement and location data and a cloud server that stores data and provides the user interface on a Personal Computer (PC), cellphone or similar. The device sends encoded accelerometer data collected at 100 Hz, location data obtained every 10-30 seconds, battery, and Long-Term Evolution (LTE) signal level data every 50 seconds, to the cloud server. It uses the Message Queuing Telemetry Transport (MQTT) protocol and Narrowband IoT (NB-IoT) communication.

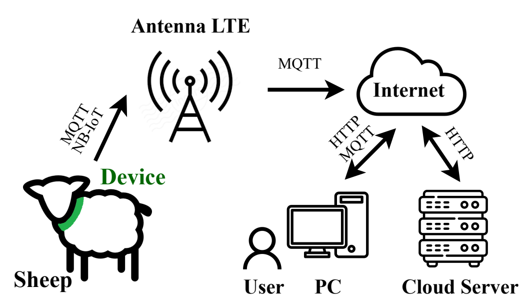

Fig. 1. System's functional diagram.

A. Hardware

A hardware diagram of the device can be seen in Fig. 2. The device features Actinius' Icarus IoT Board, which includes Nordic Semiconductor's nRF9160 chip. This chip is a low-power system in a package that includes an NB-IoT modem and a Global Navigation Satellite System (GNSS) chip. The nRF9160 chip is equipped with an ARM Cortex-M33 processor, which includes 1 MB of flash and 256 kB of RAM. The board incorporates the LIS2DH 3-axis accelerometer from STMicroelectronics. Additionally, a power management circuit allows the device to be powered from various sources, including three solar panels (totaling $2.8\,\mathrm{W}$), a $2500\,\mathrm{mA\,h}$ Lithium Polymer battery, and/or a USB cable.

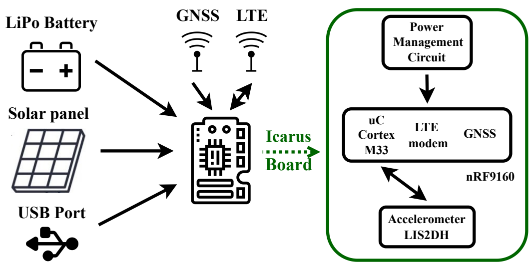

Fig. 2. Hardware diagram of the device.

B. Embedded software

The embedded software, developed in *Visual Studio Code* using *nRF Connect*, utilizes *Zephyr RTOS* and C programming language. The software is based on the *Asset tracker v2* application from Nordic Semiconductor [12]. The *Asset tracker v2* software architecture is modular, featuring an event manager for module communication. Modules can submit and subscribe to events. Modules with threads convert events into messages and enqueue them on the system work queue. Modules without threads directly process events by converting them into messages. Certain modules have dedicated threads for handling time-consuming messages.

We made several adaptations to the *Asset tracker v2* application to customize it for our specific requirements. The main modifications included: (a) integrating a driver for the LIS2DH accelerometer, and (b) modifying the overall software's operation to acquire acceleration data up to 100 times per second. We also (c) disabled the retrieval of environment data since it is not required for our application, and (d) modified the collection of battery level to work with our power management circuit. Additionally, (e) due to the high volume of accelerometer data, we encoded this data before sending it to the cloud server.

Due to memory limitations, approximately 5000 acceleration samples (50 seconds) can be stored on the nRF9160 chip. 5000 acceleration samples are 15000 values (one value for each accelerometer axis). As the sensor is configured with a $\pm$ 4000 mg scale, samples take values from -4000 mg to 4000 mg. We need five characters (four digits and one character for the sign) to represent the acceleration samples in a human-readable format. Then, if we represent each sample with five characters, it gives a total of 5 x 15000 = 75000 characters. To reduce this data, we encoded the acceleration samples in base64 according to the RFC4648 standard. In this way, we represent each sample with three characters (no padding characters are sent since the samples have a fixed width), reducing the number of bytes needed from 75000 to 3 x 15000 = 45000 bytes, which is 60 % of the original value.

These samples occupy most of the packet that is transmitted to the server every 50 seconds. The transmission of this packet takes the modem about 20 seconds. The nRF9160 has one limitation, its GNSS can not obtain a location while the modem is transmitting. Therefore, while the modem is not transmitting, up to three locations per packet are acquired (at 10, 20, or 30 seconds) and sent to the cloud server.

C. Accelerometer data processing

A signal processing technique running on the device must have reliable performance and be simple enough to be implemented in a constrained resource environment (like the microcontroller) to achieve on-animal classification. For instance [13] and [14] compare different algorithms' performances (Support Vector Machine, Linear Discriminant Analysis, Deep Neural Network, among others), whereas in [15] excellent results are obtained using Principal Component Analysis to select significant features and Random Forest (RF) to classify activities.

We are currently developing an on-animal classification of five behaviors (standing, grazing, walking, trotting, and running). Our first approach uses RF, which utilizes multiple decision trees for both classification and regression tasks. In RF each decision tree independently predicts a class (sheep behavior), and the final prediction is determined by selecting the most frequent class prediction among all the trees. The simplicity of RF makes it suitable for implementation in a microcontroller with limited resources. We present preliminary results in Section III-A.

D. Cloud server and user interface

The software solution architecture shown in Fig. 3 includes the back-end (MQTT Broker and Computer resource), which processes the received device messages; the front-end (Website), which provides a user interface to trace device information; and the Database, which stores the information. We deployed the solution using the Amazon Web Services (AWS) ecosystem as a cloud server.

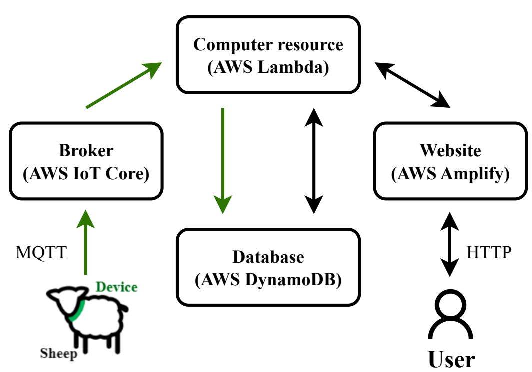

Fig. 3. Software solution architecture.

AWS IoT Core enables us to connect multiple devices and efficiently direct received messages to other services. Messages received by the Broker in a topic are immediately sent to AWS Lambda functions via an AWS feature called Rules. For each message, a new instance of a Node.js environment (that runs JavaScript code) is created, ensuring scalability without bottlenecks. We also opted for AWS DynamoDB to achieve scalability. This service offers a key-value non-tabular database (NoSQL) that suits our needs as it prioritizes writing data over reading, and messages may not always have the same fields.

The cloud server also hosts a website for interacting with the stored data (see Fig. 4). We developed the website using NextJS 13, a React framework that provides server-side rendering. This decision was made with our end users in mind, considering they may access the application from various devices.

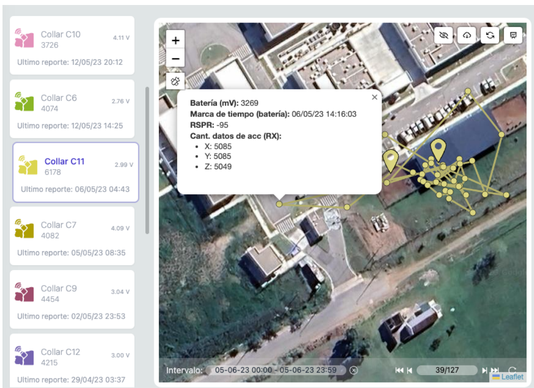

Fig. 4. User interface showing sheep activity data.

Our devices connect to AWS IoT Core using X.509 certificates over a secure Transport Layer Security connection.

E. Mechanical design of the case

The device's case was designed to ensure proper functioning while also considering animal welfare (Figs. 5 and 6). The device must withstand adverse weather and endure impacts resulting from the interactions of the sheep. Regarding animal welfare, weight (the goal was 500 grams or less), volume, and color were important. In the initial stages, it was decided to use fluorescent/bright colors for visibility purposes. However, using these colors would not be advisable as they could attract predators. Therefore, neutral colors such as white or light gray were chosen. Black was discarded due to its tendency to accumulate heat.

Furthermore, a variation in neck size due to wool growth/shearing was a challenge, as well as the lanolin fat. Regardless of the collar adjustment system, different-sized enclosures were necessary to accommodate morphological differences in sheep: a small enclosure with a filled pad for small animals, a small enclosure with an empty pad for medium-sized animals, and a big enclosure with an empty pad for larger animals. This helps with collar fixation, preventing it from rotating.

Because of the quantity needed (thirty collars), the Fused Deposition Modeling (FDM) 3D printing technology was chosen, with the addition of transparent polycarbonate windows in the solar panel areas. Production was done us-

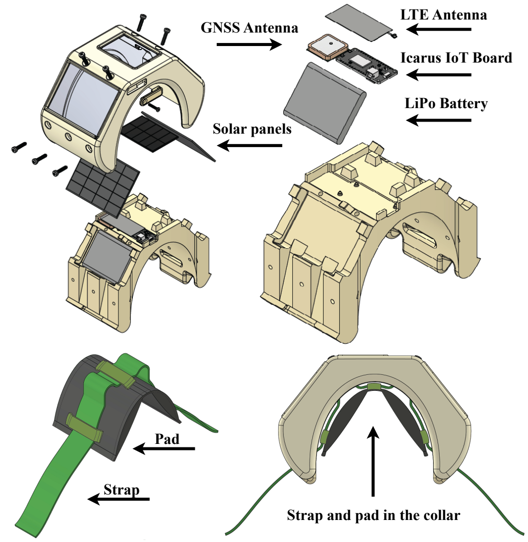

Fig. 5. Device's mechanical design: complete collar (left, up), bottom case with internal components (right, up), strap and pad (left, down), strap and pad in the collar (right, down).

ing polyethylene terephthalate glycol-modified (PETG) filament considering the high mechanical resistance requirements. This was complemented by an internal cellular structure, which allowed weight reduction without compromising strength, achieving a weight of 480 grams (no ill-being caused to the sheep).

III. Experimental results

Prior to manufacturing, several testing stages were conducted. A resistance study was executed using Autodesk's Inventor software. Also, tests with volumetric models without internal components were performed. This validated sealing, attachment, and resistance. These experiments were performed on a single collar and sheep at our research facilities in Facultad de Veterinaria, Universidad de la República.

The manufactured collars were tested, including electronics (see Fig. 6). The case has adequate robustness, is watertight, suitable for outdoor operation, and does not cause any discomfort to the animals. Furthermore, we verified the system's functionality in its entirety, including data collection, real-time transmission to the cloud server, and data display on the user interface.

A. Classifying sheep's behavior on the PC

We developed the first PC version of the sheep's behavior classifier using RF and the dataset from [13]. Our goal was to classify five behaviors (standing, grazing, walking, trotting, and running) every five seconds. The dataset provides raw accelerometer data from two sheep recorded at 200 Hz with a commercial device. We used Python language to calculate nine different features in a 5-second sliding window (mean, standard deviation, minimum value, zero crossings, crest factor, 25% percentile, entropy, kurtosis and skewness). Calculations are performed both for each acceleration axis and for the acceleration magnitude vector (36 features total = 9 features x 4 variables). Also, we selected the five most

Fig. 6. Designed device being tested in a sheep.

relevant features with a K Best technique. The selected features were standard deviation and mean in the magnitude vector, minimum value, and standard deviation in the z-axis, and zero crossings in the z-axis. A specific RF with 625 trees was selected with 5-fold cross-validation and achieved a general 85 % accuracy. We are currently implementing this RF algorithm in C language to perform on-animal classification.

B. Autonomy

Fig. 7 shows the reported battery level on four different versions of our device. The first versions exhibited an autonomy of 60 hours. Currently, the autonomy exceeds 100 hours in continuous operation (streaming of GNSS and accelerometer data). These results are promising as we still have several improvements to implement: low-power techniques on the communication side (Power Saving Mode and Extended Discontinuous Reception), on the GNSS side, and in the microcontroller.

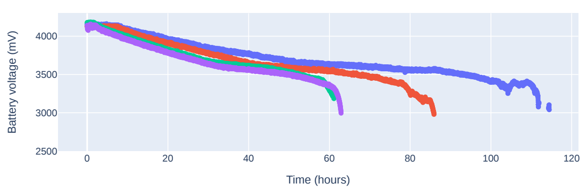

Fig. 7. Discharge of the device's battery.

C. Accuracy of the GNSS

Fig. 4 shows some points outside the paddock, but the sheep can not have been there. Based on these observations, we did tests on still collars. The mean of the reported error is $14.4\,\mathrm{m}$ (meters) with a standard deviation of $13.9\,\mathrm{m}$. These experiments show that GNSS accuracy needs to be improved. Preliminary analysis shows that filtering outliers significantly increases accuracy. Moreover, differential correction on the server will be evaluated in next stages.

D. Assessment of the Device - Cloud server communication

Table I presents the results of tests performed using the national carrier's NB-IoT service. These tests are conducted as part of an ongoing collaboration and provide valuable feedback for the carrier to enhance their infrastructure. However, it is important to note that the NB-IoT infrastructure in the Uruguayan countryside still requires improvements.

TABLE I
DEVICE - CLOUD SERVER COMMUNICATION

Location of the facility	Received packets	RSRP (dbm)	Date rate (packets/min)	Payload (bytes)
suburban	95,9 %	N/A	3	300
suburban	99,6 %	N/A	0,5	300
rural	54,7 %	-135	12	300
rural	83,3 %	-105	12	300
urban	95,8 %	-95	1	45k
urban	96,0 %	-75	1	45k

RSRP=Reference Signal Received Power

IV. CONCLUSIONS

The end-to-end platform for data acquisition and storage is completed. Studies and tests have been conducted on 30 collars using the national carrier NB-IoT service and an AWS cloud server. This achievement has been possible thanks to the close collaboration between researchers from Veterinary, Engineering, and Industrial Design.

Preliminary tests indicate that GNSS accuracy requires enhancement. The autonomy exceeds 100 hours in continuous operation. However, the infrastructure for NB-IoT in the Uruguayan countryside seems to need improvement. Initial results are adequate for research or intensive production but are still far from an extensive production scenario.

The implemented platform enables research on animal behavior for extensive livestock production and allows us to glimpse the generation of concrete online and offline services for farmers. With the data that will be collected using the developed platform, it will be possible to design algorithms that can run in the cloud or the collars, enabling the creation of behavioral analytics, alarms, and other relevant services. As part of this development, work is currently underway on behavior classification. We conducted tests using public databases to study the best features that can be obtained from raw data and identify possible classifiers that can be used in the collar with limited computational resources.

Once we have a functional on-animal classification algorithm, the device will be able to transmit processed sheep behavioral data (instead of raw data) to the cloud server. This will reduce the transmitted data and hence improve the device autonomy allowing the researchers to conduct long-term behavioral experiments.

ACKNOWLEDGMENT

This work was partially funded by CSIC and CAP, both from Universidad de la República (Udelar), Uruguay, and FCE from Agencia Nacional de Investigación e Innovación, Uruguay. The procedures with animals were approved by the Ethics Committee, Fac de Veterinaria, Udelar. The authors are grateful to V. Fernández, L. Sirio, A. M. García, A. Fernández, A. Freitas de Melo, L. Pinto, and N. Zambra.

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