An Integrated Multi-Sensor System for Remote Bee Health Monitoring

1st Francesco Bellino
Dept. of Electronics and Telecommunications
Politecnico di Torino Torino, 10129 Italy

2nd Giovanna Turvani
Dept. of Electronics and Telecommunications
Politecnico di Torino Torino, 10129 Italy
giovanna.turvani@polito.it

3th Umberto Garlando
Dept. of Electronics and Telecommunications
Politecnico di Torino Torino, 10129 Italy
umberto.garlando@polito.it

4rd Fabrizio Riente
Dept. of Electronics and Telecommunications
Politecnico di Torino Torino, 10129 Italy
fabrizio.riente@polito.it

***Abstract*—Over 75% of the world's food crops depends on pollination and in particular by the inestimable value of the service provided by bees. Besides, the bee colony health is a good indicator of the quality of the environment and it is strongly affected by many aspects such as beekeepers' management practices, policies adopted for cropping and land use. However, the climate change, the intensive agriculture, pesticides, biodiversity loss, Varroa mites and pollution are the leading cause of bees death world wide. The role of beekeepers is of extremely importance to mitigate this damage. Apiaries are usually located in remote environment an require frequent visit by the beekeepers. Indeed, the beekeeping sector lacks of suitable tools for risk assessment and decision making that can be used by stakeholders. Smart monitoring systems assessing the health of the colony and the honey production would be beneficial for such community. In this work, we present a prototype of an embedded multi-sensor system for beehive monitoring with the aim of providing a simple solution to beekeepers. Indeed, the proposed system do not require modification of the beehive and it is compact enough to be simply inserted in the brood box. It measures the vital parameters of the beehive, such as temperature, weight, humidity and CO_2 concentration. It exploits the low power communication protocol LoRaWAN for the data transmission. The collected data are made available to the beekeeper through a web application. We show the effectiveness of such compact, non-invasive embedded system with its installation in an apiary.**

***Index Terms*—Beekeeping, agriculture, internet of things, environmental monitoring, sensor networks**

I. Introduction

The role of the honey bees (Apis mellifera L.) as pollinator in nature is extremely important for several reasons. Among them there is the highly valued service provided by animal-mediated pollination and the production of honey [1], [2]. In the last decades, the Apis mellifera population is significantly declined due to a combination of several factors, including the effects of the parasitic mite Varroa destructor, pollution and the increase of agrochemicals used in conventional agricolture [3]. Indeed, honeybees are strongly influenced by the environmental conditions, policies adopted for cropping and land use, beekeeping practices and socio-economic conditions. It is a common belief that wild Apis mellifera no longer exist in nature, but recent studies found that tree cavities in beech forests appears to be good habitat for feral bees [4]. The role of beekeepers is extremely important to alleviate the damage caused by pathologies, meeting their nutritional needs with the planting of plants useful for collecting pollen, propopolis and honey, offering source of water necessary for the growth of the colonies. Apiaries are usually located in isolated and remote areas, requiring a significant travel time to reach the site and inspect the bees, especially in the case of nomadic beekeeping. In this case the beekeepers transport the beehive where specific flower are in bloom. The Colony Collapse Disorder (CCD) is strongly affecting the bee colonies in Europe and the rest of the world since 2006 [5]. The CCD is characterized by a sudden death of the bee colony [6]. Unfortunately, the causes of CCD are not known but researchers suspect that many factors may be involved (mites, viruses, pesticides, electromagnetic radiation, etc..) [7]. These facts motivate the development of solutions aimed at supporting beekeepers and researchers in understanding the motivation of death and preserving the existence of honey bee.

Several systems have been presented in the literature for beehive monitoring. In [8], the authors installed many sensors inside the beehive in order to collect data from specific positions. The electronic system is able of recording temperature, humidity, carbon dioxide (CO_2) concentration and weight. Holes have been created on the beehive to insert the sensors at specific positions and cables connect them to a processing system that send the data to a web server. Authors in [9], presented a wireless sensor network composed of embedded devices capable of collecting, elaborating and transmitting data. The nodes exploit the Zigbee radio to upload the data to a base station that over a 3G/GSM connection are made available to the cloud. Also in this case vital parameters are recorded and image recognition algorithm are applied to detect infestation of Varroa mites. Other systems proposed in [10], [11] perform real-time digital video processing counting the amount of bees entering and exiting the hive. In **Lebrero2017**, the authors proposed a scalable monitoring system that ex-

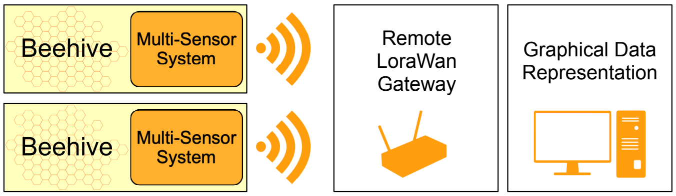

Fig. 1. Architecture of the proposed multi-sensor system. Multi-sensor nodes communicate with a LoRaWAN gateway that transfer the data on the internet to be visualized by the beekeeper.

ploits the Wifi network over TCP/IP for collecting data and transmit them to the cloud server. Those systems require large equipments and in some cases require a modification of the beehive.

Starting from the above consideration, we present a multi-sensor beehive monitoring system that exploit the long range LoRaWAN [12] network, which is one of the possible solution to build a low power wire area network (LPWAN). The prototype of the embedded system is designed with the aim of avoiding the disruption of the beehive and reducing at minimum the beekeeper work. The system has been validate in the lab and recently installed in an apiary.

The paper is organized as follows: In section II, the beehive structure and colony concepts are described. In section III, we present the architecture and implementation of the proposed solution exploiting the LoraWan network. Section IV present preliminary measurements collected by the in-field installation and finally section V concludes the paper.

II. Apiaries and Beehives

Beehives are usually located in high ground to avoid the collection of moisture from the terrain and require a consistent water source in the proximity of the apiary. The general components building the beehive are schematically represented in Fig. 2. Starting from the bottom of Fig. 2 is it possible to find the bottom board positioned right below the brood box. The brood contains the living colony with the queen. It has enough space to hold between 45000 to 60000 workers. Inside the brood box, frames are positioned where the queen lays her eggs and workers store pollen and honey. On top of the brood the queen excluder is located and restrict the queen to lay eggs in the lower part and raise the brood. Only the workers are allowed to go above the brood box, in the honey super where the honey is collected and can be easily removed by the beekeeper. Multiple supers can be stacked one on top of the other. The last two elements are the ventilation cover, which provides insulation and the top cover that protects the hive from bad weather. Monitoring the hive requires the installation of devices and sensors in a limited amount of space and should not require its modification. Our multi-sensor system prototype is positioned at the bottom of the brood box, as depicted in Fig. 2. Under the hive, a self-build balance is inserted and connected to the multi-sensor system to monitor its weight. In this work, we applyied the sensing system into a Dadant beehive. However, the same system could be applied also to other hives.

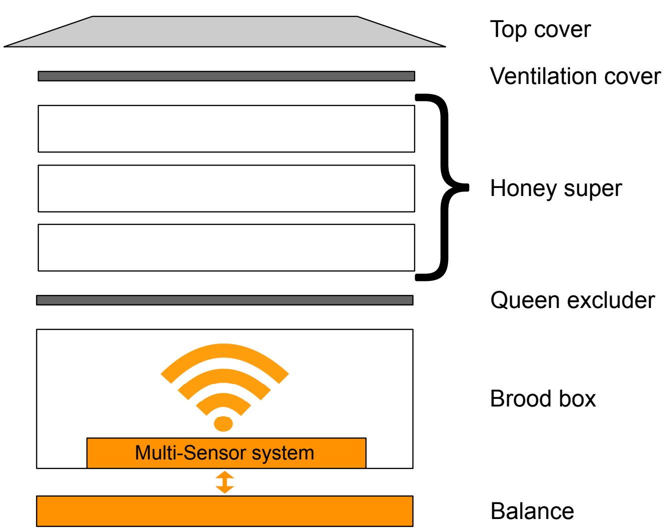

Fig. 2. Exploded representation of a typical beehive in which the multi-sensor is installed.

III. System Implementation

A. Overview

The aim of the system is to acquire information inside the beehives, through a custom designed system, and to transmit them to a remote gateway via the LoRa communication protocol. This long rage modulation technique operates on the license free sub-gigahertz bands and in our country the frequency band used is the 868 MHz. We adopted TTN (The Things Network) as a LoRa provider and therefore the sensor nodes are registered on the TTN dashboard. In this way, the nodes are part of the LoRaWAN network and the data collected can be forwarded to the TTN console through any LoRa gateway registered in TTN. Once the data are available in the TTN dashboard, a better visualization and analysis is performed with InfluxDB [13]. Thanks to the MQTT protocol (Message Queuing Telemetry Transport) data are sent from the TTN console to a specific topic. InfluxDB listens the topic and creates a database where it is possible to perform query and show the trend of the data with clear dashboards. The system does not require any modification of the beehive and can be easily installed into the brood box.

Acquisition and transmission operations performed by the system must be programmed to minimize power consumption. In fact, since the positioning of the hives takes place in remote places, the battery life should last as long as possible. The entire system is powered by a Lithium Polymer (LiPo) battery with a nominal voltage of 3.7 V.

Our first prototype of the multi-sensor system is based on the STM32WL55JC1 development board produced by ST Microelectronics as it already includes a radio module for LoRa transmission. It has different ultra-low-power-features that makes it possible to save power when the system is in idle condition. It offers a variety of available peripherals and a dual-core 32 bit ARM Cortex M4/M0+ running at $48\,\mathrm{MHz}$. All the sensors are power-gated once the measurements are performed.

B. Sensors and specifications

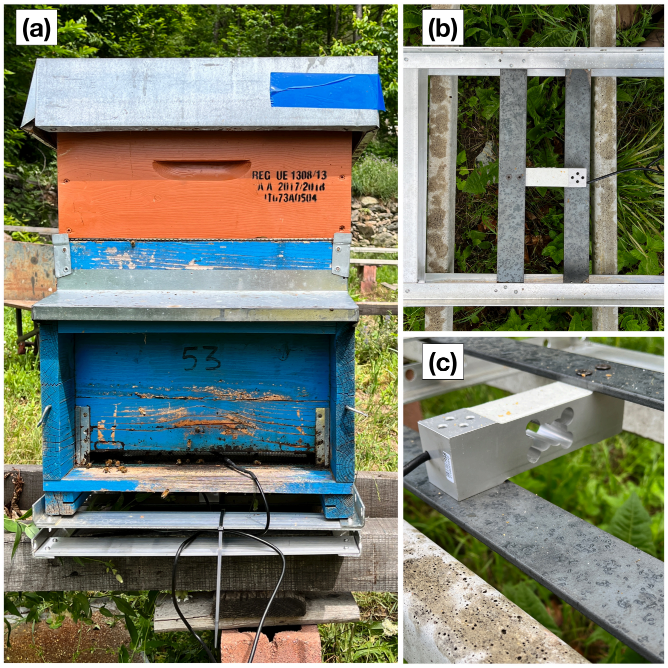

Fig. 3. a) Installation of the multi-sensor system within the beehive with self-made balance under the brood box; b) Top view of the balance; c) Detail of the single bending load cell connected to the frame by two iron bars.

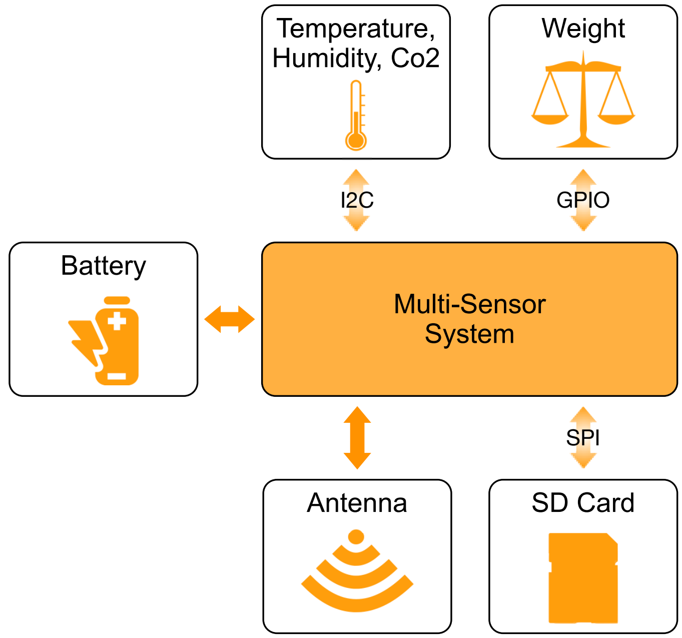

Fig. 4. Schematic representation of the multi-sensor system prototype proposed with the main communication buses involved.

As discussed in sec. I, the weight, temperature, humidity, CO_2 concentration are the vital parameters to be considered when monitoring bees' health. The overall multi-sensor board is schematically represented in Fig. 4. The weight measurement is performed considering a self-made balance composed of two aluminum frames interconnected by a single bending beam load cell (Fig. 3.b). In order to have a rigid connection between the two frames two perpendicular iron bars have been used, has reported in Fig. 3.c. Within the load cell four strain gauges are located, two on the upper part and two on the lower part. This load cell is setup in a way that the applied load creates a distortion of the load cell. The four strain gauges measure the bending condition. Two strain gauges are subjected to compression and the other two to tension. The four strain gauges are configured in a Wheatstone bridge. The adopted load cell is characterized by a maximum nominal capacity of $100\,\mathrm{kg}$. The rated output of the load cell is $2\,\mathrm{mV/V}$. The load cell is connected through a IP67 grade cable to the multi-sensor board located within the brood box. The Wheatstone bridge is excited and measured through a 24 bit Analog-to-Digital Converter (ADC) dedicated for weight scale measurements. We adopted the HX711 ADC that offers the possibility to amplify the acquired signal. The programmable gain amplifier is set to 128. The HX711 is powered by $3.3\,\mathrm{V}$, resulting in a full-scale differential input of $\pm 12.89\,\mathrm{mV}$. When the load cell is fully loaded, it outputs a signal of $6.6\,\mathrm{mV}$. In our case, half of the ADC dynamic range is used, from 0 to the full-scale produced by the full-load of the cell. The HX711 noise-free bit are 13 resulting in a balance resolution of $24\,\mathrm{g}$. The measured weight is transferred to the STM32WL55JC1 board via a serial protocol. We developed a dedicated driver to interface the HX711 with the MCU. The driver initializes the peripheral, perform the measurements, subtract the tare and check the validity of the data. The acquired data needs to be converted into grams by multiplying the measured signal expressed in 2's complement by a constant $c = 0.026$. The constant has been determined by a calibration of the weight scale. The remaining quantities, temperature, humidity and CO_2 concentration are acquired with the SCD30 sensor manufactured by Sensirion. The sensor is able to acquire the three measurements in a single cycle and provides them as a digital value via the user selectable I2C or UART protocol. It uses a MEMS infrared emitter to detect the CO_2 concentration. Table I reports the SCD30 specifications: In addition to the sensors, a micro-SD card module is made available within the multi-sensor for logging purposes. It uses the Serial Peripheral Interface (SPI) to communicate with the MCU as reported in Fig. 4. The power supply is provided to all sensors through a low leakage MOSFET controlled by

TABLE I
SENSOR SPECIFICATIONS

Data	Range	Accuracy
CO_2	400 ppm - 10000 ppm	±30 ppm
Temperature	0°C - 50°C	±0.4°C
humidity	0% - 100% (@25°C)	±3%
Load cell	0% - 100%	±24g

the MCU. Fig. 3.a shows the in-field installation of the multi-sensor system prototype and the self-made balance after the lab validation.

C. Firmware implementation

The firmware is written in C language and exploits the LoRaWAN Middleware made available by ST Microelectronics for what concern the radio communication. The STM32WL software architecture offers a sequencer to execute the tasks in background and enter low power mode when there is no activity. It is possible to create timers dedicated to specific tasks, similarly to an operating system. We implemented a dedicated driver to interact with each sensor. The flow chart of

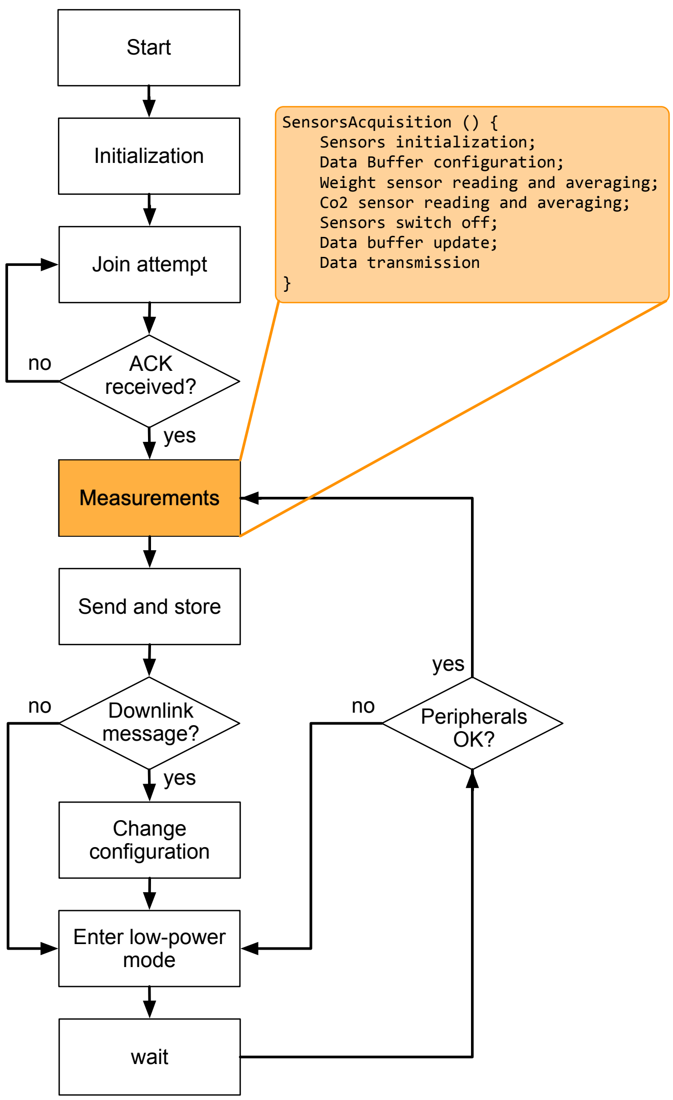

Fig. 5. Flow chart of data acquisition routine, considering system start-up, Lora join operation, measurements, transmission and when to put the system into a low power state.

the multi-sensor system is schematically represented in Fig. 5. It depicts the steps from its power-on up to the measurement routine. At first, the system is initialized by creating tasks and timers, configuring the low power mode settings and initializing the peripherals. Then, the join operation is performed. In particular, the join operation is repeated unit an acknowledgment signal is received by the remote gateway. The join operation is required only when the connection is established. Afterwards, data are gathered from the sensors and sent to gateway.

More in detail, three tasks have been created: the first is devoted to the join operation in order to establish the LoRaWAN communication. At this time, the proper data rate (spreading factor) is defined based on the distance from the gateway. This operation is performed only once, at the system startup. The second task deals with the acquisition of data from the sensors, the related pre-processing and their sending to the remote gateway. In this step, the sensor power is switched on to start the acquisitions by controlling the low leakage MOSFET. Finally, the third one is in charge of handling downlink messages. Downlink messages represent commands sent remotely to the board to change its configuration, i.e. changing the acquisition interval or rebooting the system.

When the execution of all tasks is finished, the system automatically switches to a low power mode that can be customized by the user. This condition remains enabled until a timer awake the MCU for serving another task. The wake-up event is controlled by the internal real-time clock that remains active in low power mode. The orange box in Fig. 5 shows the pseudocode that explains the data acquisition steps. In particular, the whole measurement procedure requires about 22 s, including the transmission to the gateway. Unfortunately, the CO_2 sensor requires alone about 20 s and takes most of the on-time. The CO_2 measures the carbon dioxide concentration making use of a Nondispersive Infrared (NDIR) technology and requires a certain amount of time before it is ready for a measurement after power on.

IV. Results

The system has been tested firstly in the lab and recently installed into an apiary located in Northern Italy as depicted in Fig. 3. We installed the monitoring system into a beehive with one honey super on top of the brood box. Preliminary collected data shows that the weight variation within a day follows the trend observed in [14]. Fig. 6 reports the daily weight variation over four days. Starting from midnight to the early morning the hive weight decreases due to changes in the moisture concentration of pollen, nectar and wooden parts. Then, close to dawn it is possible to observe another weight drop due to the departure of worker bees. Afterwards, there is a weight gain due to the return of the workers until dusk. Finally, the inactive period starts again, with hive weight reduction mainly due to ventilation and humidity variation as observed in [14]. In the measurements reported the honey super was already filled with honey, therefore no increment of weight was observed. Fig. 7 reports the temperature variation within the brood box as function of the CO_2 concentration over four days. During those days the temperature at the bottom of the hives varied between 18 °C to 33 °C. That period was characterized by variable weather conditions. In the same period reported in

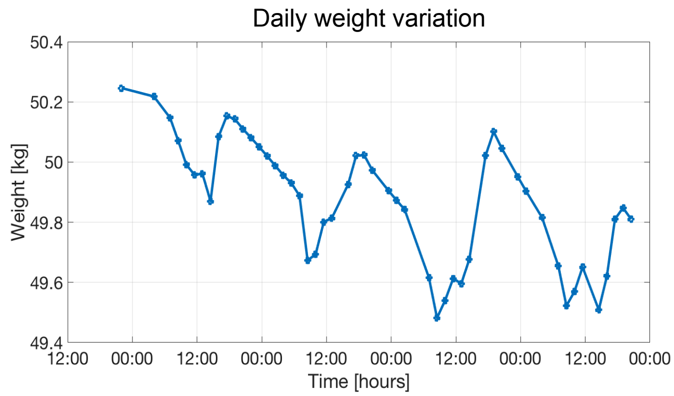

Fig. 6. Daily weight variation of the beehive over four days in May.

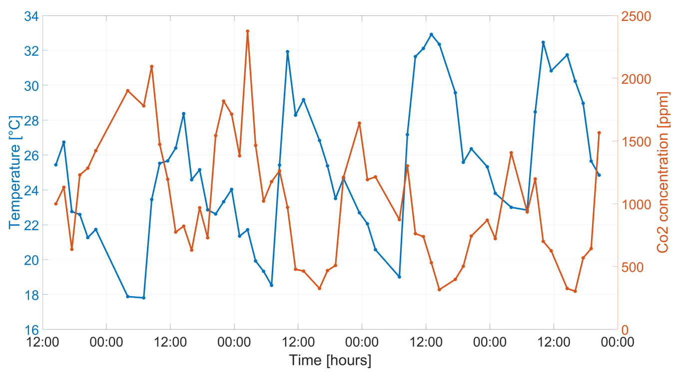

Fig. 7. Temperature vs. CO_2 concentration over four sunny days in May.

Fig. 7 it is possible to observe the increment in the CO_2 over the night, when all the bees are back in the hive.

V. Conclusion

An embedded multi-sensor monitoring system as been developed for understanding the state of health of the bee colony. This first prototype collects data from the beehive and send them to the cloud exploiting the long range communication protocol LoRa. The system can be inserted in any hive and does not required disruption or modification of the beehive for the installation. The prototype, after validation in the lab, has been recently installed in an apiary inserting below the hive a self-made balance with a single load cell that guarantee air circulation under the hive. Preliminary results show that the sensors are correctly monitoring the key parameter of the bees living in the hive. In this way, it will be possible for the beekeeper to check the status of the beehive remotely. The plan is to install additional modules into other beehive and continue the monitoring also during winter time.

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