To the Green from the Bl(u)e: An innovative system for monitoring urban green areas

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***Abstract*—The relation between the health of the green areas and the health of the citizens is part of the One Health concept. People's health is something widely debated by the scientific community while urban greenery health study is at its beginning. IoT technologies have been recently applied for monitoring environmental parameters such as humidity, wind speed, temperature, and so on. These technologies can be applied to monitor biophysical parameters of green subjects, too. The realization of a network of low-cost and low-cumbersomeness wireless sensors may help in obtaining a precise snapshot of the conditions of urban green areas. A prototypal sensor network has been realized making use of devices that are normally used in industry 4.0 realizations.**

***Keywords*—remote monitoring, wireless sensor network, urban green, one health, industry 4.0**

I. Introduction

The thriving of urban green areas is becoming a topic of increasingly strategic importance for citizens' well-being, not only for the undoubted effects on air quality and climate, but also for their positive impact on people's psycho-physical conditions and, more in general, quality of life [1].

Urban green turns out to be a real complex system made up of a set of heterogeneous surfaces and vegetal structures, whose effective monitoring implies the evaluation of their vegetative, phytosanitary and stability conditions. Safety issues are therefore expected to play a critical role in responding to the need of having a full enjoyment of these areas guaranteed for the citizens. In this regard, damage causes for green subjects can be divided into two main areas [2]: i) unpredictable causes, as result of particular climatic conditions originated from the extraordinary nature of atmospheric events; ii) predictable causes, mostly belonging to known categories of problems e.g., wood parasites, growth defects, and damages caused by excavations.

Currently, monitoring activities for urban green areas [3-4] are generally carried out on a periodic basis by technical specialist figures who, mostly through visual assessments, certify the levels of green subjects' biophysical parameters and report about eventual related risks. Nonetheless, it is often more likely to get similar information from citizens themselves. More in general, the sole activity carried out by technical experts may reveal not to be efficient enough. This could lead to late intervention activities conducted due to late evaluations reporting, or due to a sudden change of the pointed mast because of external factors. In addition, extensive conditions checking to be conducted (for a single subject) after the occurrence of large-scale weather events may weaken the efficiency of monitoring activities as well.

The translation of industrial–based monitoring processes and technologies, such as cyber–physical systems and IoT, into the wide environmental field can help in achieving effective monitoring-related results, thanks to both the possibility of (near) real–time data transmission, and the deployment of an elevated number of low-cost sensors [5-8].

The present paper showcases some preliminary results from the deployment, in a couple of different urban green areas in South Italy, of a WSN (Wireless Sensor Network) making use of Bluetooth Low-Using Energy (BLUE or, more commonly, BLE) technology. Green subjects were equipped with one or more sensors capable of detecting parameters such as stem's and branches' oscillations, and the temperature of the crown and the base. Data coming from sensors' readings are also cross-referenced with that coming from environmental condition survey stations to provide an even clearer picture of the whole context. The adoption of user-friendly interfaces for what concerns the visualization of the collected data, is then supposed to help performing better control on the green areas, in order to integrate the mentioned (subjective) evaluations of citizens and technical staff with sensor-based objective data. The network aims at providing substantial aid in setting priorities to carry out an efficient and scalable process of monitoring urban green areas, in terms of time and resources used.

II. Technical discussion

The WSN architecture was firstly designed to pursue goals of low cost, high scalability, and low cumbersomeness of the solution. To this end, the WSN features two different categories of devices meant to operate in synergy, namely Gateway Stations (GSs) and sensors. Sensors (II level spokes) collect data from the green subjects under monitoring and transmit it as an encrypted over-the-air radio signal acting as radio beacon. Each GS (I level spoke) then collects signals coming from the sensors and processes them to extract the data contained in the payload, in order to send it to a central server (hub) for information storage and visualization.

Such tree network-based design allows to keep costs low, and does not directly depend on the number of the monitored subjects: adding subjects to the monitoring site, in fact, only requires embedding more sensors, while the rest of the architecture can remain unaltered. For what concerns the architecture's scalability, it depends on the number of GSs deployed in the monitoring campaign. A high scalability rate is anyway possible: each GS is able to collect radio signals coming from an area of more than 200 meters of radius, because sensors chosen to be placed on the green subjects are equipped with Power Amplifiers (PA). This means accordingly, that the GS does not need to be supported with PAs to receive the signals broadcasted by the sensors the network is composed by. Figure 1 provides a brief overview of the described architecture.

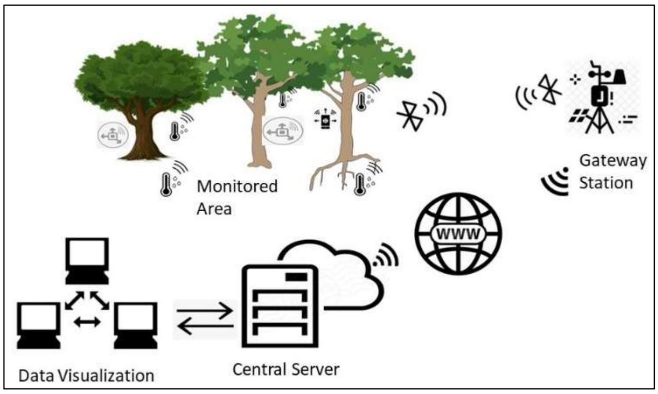

Fig. 1. Overview of the proposed architecture. Data flows from the sensors to a central server through the Internet by means of Gateways stations.

The designed architecture makes use of Bluetooth Low Energy (BLE) wireless technology to transmit the collected data laying on the so-called iBeacon protocol for data transmission, as such specifics are widely used for Industry 4.0 applications [9-10]. BLE technology, also called Bluetooth Smart, stands as an improvement of the classic Bluetooth (BT) technology. The main difference between BT and BLE lies in the modalities of data transmission [11-12]: on the one hand, with BT technology data is transmitted from one device to another, thus establishing a single and permanent connection (master–slave architecture); on the other hand, in Bluetooth LE - that usually supports the star network topology - data is broadcasted in the same manner as a radio beacon. This means, in other words, that a device that needs to receive information from others sources does not need to establish as many single fixed connections as the number of the transmitters, but manages to receive data from different devices at the same time (client–server architecture) [13].

The iBeacon protocol, on top of the BLE technology, allows the use of a standard data packing so that signal transmitters and receivers can easily recognize the portion of the broadcasted data packet that contains the information of interest, namely the payload.

A. Sensors

The sensors embedded in the network, called to monitor physical parameters like temperature, humidity, and acceleration, were chosen amongst those already available on the market, as fitting as possible with the mentioned goals the entire architecture was designed to achieve. Sensors were in fact in the first place intended to be positioned on green subjects in wide green areas, and frequently on not-easily accessible spots, unless using dedicated machinery. Accordingly, it appeared critical for them to host large batteries, in order to guarantee at least six months of uninterrupted functioning. A second caveat was not to spoil the plant life populating the areas in any way, therefore it was as necessary to choose non-invasive sensors - i.e. not causing incisions or breakages of the greenery. Moreover, sensors needed to be waterproof and dustproof due to the outdoor placement. The sensors chosen to be embedded in the architecture are shaped as 10 x 2,5 x 5 cm-sized parallelepipeds. They are rated IP68, so not likely to be damaged by dust, rain or irrigation water and are equipped with a CR123 battery, capable of getting the operation time to almost one year, along with the aforementioned PA that can spread the radio signal to almost 200 meters away in open air. Sensors' electronics relies on a Nordic Semiconductor nRF52820 system-on-a-chip (SoC) for handling physical sensor reading and data communication. Sensors' SoC also hosts a lightweight customized firmware through which it is possible to change a few settings such as PA's amplification, broadcast frequency, sampling rate and password for settings change. Figure 2 shows the three main different types of sensors embedded into the system.

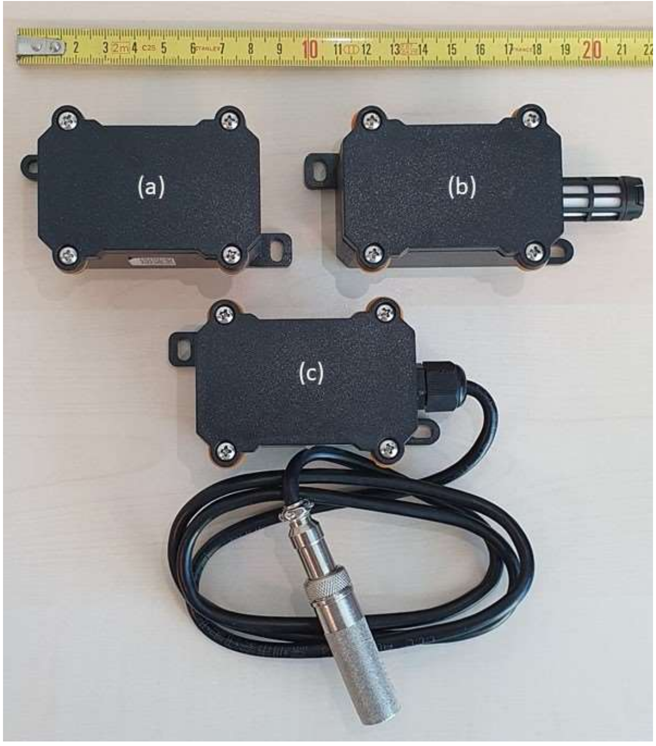

Fig. 2. The three different sensors used in the system: a) Tree Axes Acceleration Sensor; b) Air Temperature and Humidity Sensor; c) Temperature and Humidity Sensor with Probe.

The first sensor (Fig. 2a) is a triaxial accelerometer (ACC), used to evaluate the inclination of masts' branches and trunks over time, starting from the acceleration detected from the sensors themselves. Using a fixed coordinate reference system where the Z axis is perpendicular to the ground, it is possible to calculate the inclination value with respect to the X axis (Pitch) and to the Y axis (Roll), starting from the acceleration value components, by making use of (1) and (2):

$$Pitch = \theta = arctan\left(\frac{A_x}{\sqrt{{A_y}^2+{A_z}^2}}\right) \quad (1)$$

$$Roll = \phi = arctan\left(\frac{A_y}{\sqrt{{A_x}^2+{A_z}^2}}\right) \quad (2)$$

The second one (Fig. 2b) is a temperature and humidity sensor (TH) with a small probe attached to the body. This is mainly used to monitor temperature and humidity of the masts at crown height. The third one (Fig. 2c) is a temperature and humidity sensor (THP) endowed with a long metallic sharp probe connected to the main sensor body through a 50 cm cable. THP sensor is mainly used to monitor temperature and humidity of the terrain close to the masts' roots.

Both TH and THP sensors are anyway employed also when it is necessary to monitor temperature and humidity conditions under foliage, or beneath the land close to any kind of green subject.

B. *Gateway Stations*

Gateways assembled by the research team and used in the tree-shaped network are self-sufficient stations embedding an Espressif model ESP32 microcontroller that carries out the business logic of the data collection. ESP32 microcontroller use is already widely diffused in Industry 4.0 applications due to a high versatility paired with contained costs, and low power consumption. Figures 3a and 3b showcase the Gateway Station (GS) inside and outside.

GSs are equipped on the front side with a solar panel capable of producing up to 30 W, while the energy produced is stored in a 12V 12Ah Ni-Mh battery placed into the main body. Although it could have been possible to force the GS to operate in locations with access to the power line, the decision to opt for a self-sufficient solution originated from the need to maximize the area of each monitoring site, thus overcoming any possible constraints related to GSs' placement: the solar panel orientation requires in fact to face south to have as many hours of direct sunlight as possible during daytime. GSs' height was an as relevant feature to be paid attention to during the design step, as the solar panel needs to be high enough not to be in the shadow cone created from trees' crowns.

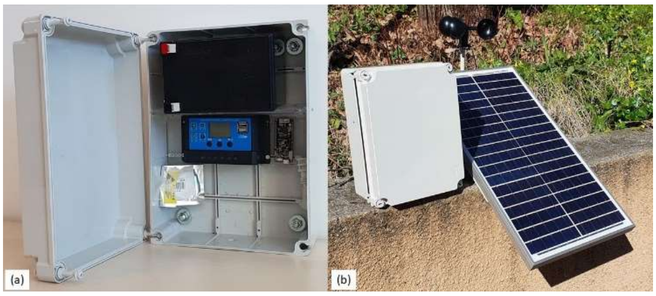

Fig. 3. a) Open Gateway Station. Cable connections between Battery, Solar Charge Controller and ESP32 Microcontroller are omitted for better vision. b) Closed Gateway Station with solar panel and anemometer.

A specific software designed by the research team using C++ language runs on the ESP32 microcontroller, which is in charge of: detecting the iBeacon signals coming from the sensors deployed in the monitoring system; extracting sensor data from the iBeacon packet; writing the information to a file stored on an SD card; and periodically sending sensors' data written in the file to a central server. The software decodes iBeacon packets to obtain trees identifications and the related sensors' readings. In this regard, it is important to highlight that the software only processes information coming from the network's sensors, thus not querying – for obvious privacy protection reasons – any other Bluetooth iBeacon device that may be active within the range of the GS.

Once the sensor is recognized as belonging to the monitoring system, sensor data encapsulated in the iBeacon packet is decoded by means of a proprietary protocol designed from the sensors' manufacturer, to extract the value of the sensor reading. Sensors' readings are then stored on a microSD card from where they will be retrieved on a schedule and sent to the central server. The choice of sending data on a schedule derives from the mentioned need of power saving: keeping the GS always connected to the internet, although making it ready for sending data in real-time, would in fact drastically increase the power consumption of the microcontroller. However, the proposed monitoring is targeted to the green subjects' parameters' variation evaluation, so that a real-time information update is not actually needed, and delays from half an hour to two hours between two consecutive buckets of information updated on the server, have been considered as acceptable. Data upload to the central server is carried out via a Wi-Fi internet connection - nowadays, most of the urban green areas are provided with Wi-Fi internet access. Should it be unavailable, a mobile 4G / Wi-Fi router can be added inside the GSs. This mobile router can be powered by the battery already present in the GS. To pursue the goal of minimizing GS' power consumption, router's "on" and "off" states can be controlled with a relay connected to the ESP32 microcontroller.

This kind of solution would allow the monitoring of even large and remote green areas, thus inducing the possibility of (theoretically) extending the field of application of the proposed solution to woods and forests. GSs are also equipped with (i) an anemometer directly connected to the microcontroller, to retrieve information on the wind gusts within the monitoring site. Anemometer data provides additional information on the status of the green subjects monitored, because the different reactions of the greenery to the wind gusts strictly depend on the health condition of the subjects themselves; and (ii) an internal and external temperature and humidity sensor to evaluate both the status of the electronic equipment inside the box, and the surrounding environmental conditions. External temperature and humidity monitoring, alongside the wind gusts information, make the GS itself a sensor node of the network, besides its gateway-related tasks. Data sent to the central server is then saved in a dedicated storage space, whose structure traces the unique identifier of each GS. A data parsing script (DPS) running on a Linux daemon periodically extracts the information on the sensors' readings to insert data in an ad hoc-designed database. The latter keeps a trace of the readings, the registry of both green subjects and sensors, and the time frame related to each sensor/subject association. More in particular, green subjects' registry keeps information on its position, namely latitude and longitude, taxonomy and unique identifier; sensors' registry has information on the kind of sensor (ACC, TH, THP), date of battery change and unique identifier.

A dedicated website was designed by the research team, to organize and timely display the information stored in the database, so as to be used as an active interface for the entire monitoring system. After credential login, a map shows a complete view of the different monitoring sites with all the green subjects under monitoring. GSs' pins are reported on the map too, so that the detection radius is easily recognizable. A graph view can be accessed from the map, where all the collected data for each green subject and GS is available.

III. Preliminary Results

A first implementation of the tree-based WSN for the remote monitoring using BLE technology, has been conducted in a couple of different urban green areas in South Italy: in each site, about fifty green subjects, selected within the GS' detection range, were equipped with the sensors described. A first important output that emerged so far from the field testing is that the system keeps on working despite the different sunlight availability over seasons.

This kind of result has also been made possible by the small power consumption of the ESP32 microcontroller that stays less than 100mA while performing the assigned tasks. The monitoring activities allowed a detailed observation and a further analysis of some among the main biophysical parameters of the green subjects. It is the case of e.g., foliage temperature and soil humidity, characterized by peculiar variation cycles whose assessment makes it possible to get information as to the environmental conditions the green subject is liable to (see Figure 4 as an instance). Temperature readings coming from GSs, as well as from TH and THP sensors, show an increasing trendline during the warmer seasons with respect to the colder ones, although differences are observed between sensors placed in the ground (THP) and open air (TH). In addition, Figure 4 also reports that humidity values show an increase during rainfalls while still following the sunset / sunrise environment humidity cycle: this allowed to highlight situations of water stress and consequent drying.

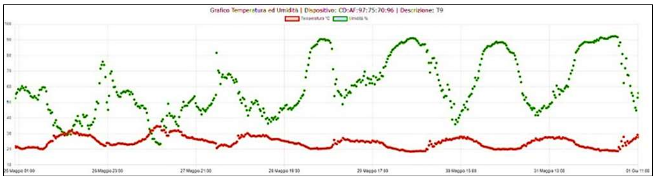

Fig. 4. Temperature (red) and Humidity (green) readings during one week in the month of May 2022 from a TH sensor placed in the crown of a green subject.

Further, monitoring of the inclinations made it possible to keep trace of accelerations and inclinations of the branches and the trunks where the ACC sensors have been placed, thus getting valuable information related to the resistance to traction and oscillations of the trees due to external stresses, especially in relation to weather conditions.

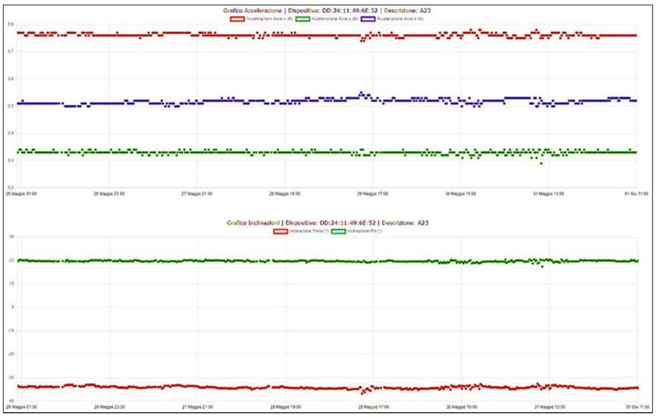

Fig. 5. Accelerations (upper) and inclinations (lower) values during one week from an ACC sensor placed on a branch of a green subject.

What can be highlighted in this case is that accelerations along the three axes over time (upper side of Figure 5) are organized as a band varying around a mean level: this gives on the one hand, an indicative idea of the green subject condition, and means on the other hand that inclinations follow the same behavior (lower side of Figure 5). As long as the mean oscillation value remains within a narrow range, conditions of stability for the green subject are preserved. Acceleration and oscillation values, like those reported in the Figure, relate to the behavior of the green subject following wind gusts - no branch stands still over time.

The analysis of such data allowed more in general to highlight those situations where strong water imbalances could cause, especially during the occurrence of important climatic events, damages such as detachment of the root collar or structural injuries to the crown. A huge repository was eventually created for the data coming from the monitored areas, to be analyzed with techniques able to visually represent the evolution through time of the mentioned parameters for carrying preventive interventions out as early as possible [14].

IV. Conclusions

In this paper a Wireless Sensors Network making use of BLE technology has been described, which is capable of performing an effective monitoring of urban green areas. The research team worked towards a twofold objective: (i) customize the firmware of existing sensors equipped with Power Amplifiers; and (ii) design ad-hoc low environmental impacting Gateway Stations to collect signals coming from the sensors via iBeacon protocols. The results obtained so far clearly suggest that the application of Internet of Things technology makes it possible to design and implement sustainable architectures capable of pursuing goals of sustainability, low costs, high scalability rates, and low invasiveness.

Keeping the environment safe has become in the last decades a critical matter, mainly due to the impact provoked from the vast advancements in the fields of technology and economy. The rising importance of the One Health concept has, on the other hand, shed a light on the strong and multifaceted relationships between environmental, human, and animal domains. This has also reverberated on the increased capacity to somehow borrow from models originally implemented to support the remote monitoring of patients' conditions [15], which led to the deployment of "data-driven" approaches based on scalable architectures for both animal health (Precision Livestock Farming, see e.g. [16]), and environmental monitoring (see e.g. [17]), thus leading in the latter case to new opportunities in terms of forest and green urban infrastructures management, and of eco-physiological research too [18].

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