Development and assessment of an IoT system for monitoring air and soil quality in the agricultural sector

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Abstract:

Currently, there is a set of variables that directly and indirectly influence the level and quality of life of human beings. Climate change, pandemic situations and wars raise questions about their survival. Thus, the development of systems allowing efficient monitoring of the surrounding environment seems appropriate. In this sense, since the agricultural sector is a pillar of modern societies, the application of technologies such as IoT (Internet of Things), for its sustainable development is the motivation for this multidisciplinary work. The work carried out uses emerging technologies, wireless communication networks, alternative energy sources, control systems and friendly human-machine interfaces. Communication between the devices uses LoRa (Long Range) technology due to its low consumption. Depending on the location to be monitored, alternative sources of energy, solar and hydropower, are selected individually, using an algorithm that monitors the power available at each instant. Data acquired such as temperature and humidity by several network nodes (peripheral towers), communicate to a gateway (main tower). These data are stored, treated statistically, and presented in a user-friendly application for different users. The system was installed in an urban vegetable garden in the Vila Nova de Famalicão municipality. After its operational validation, the temperatures and humidity values were registered. In conclusion, the developed system is low cost, autonomous, modular, flexible, has a low energy consumption and uses alternative energies, allowing the optimization of techniques and types of cultivation.

Keywords:

IoT systems; LoRa technology; Renewable energy; Agricultural sector; Sustainability.

1. Introduction

The internet of things, also known as IoT, is a current concept that continues to demonstrate great relevance, mostly because it allows autonomous interaction between different entities of a system endowed with technology. In practice, the IoT consists of a system of devices that are related to each other, which can represent equipment with a mechanical or digital operation, intelligent objects and people or animals monitored by sensors. Each entity in the system must have a unique identifier in order to enable communication/data transfer over a network without the need for human interaction. According to Fortino et al.[1], the IoT represents a seamless interaction between dynamic communities of users, smart objects and traditional computer systems that have the possibility to interact with each other and with the surrounding environment. When building an IoT system from smart objects, another important aspect is being able to differentiate several types of smart objects.

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In [2], Kortuem and his co-authors present a classification of these types of objects where they highlight their most relevant differences. The authors refer to three fundamental aspects of intelligent objects, such as "Awareness", "Representation" and "Interaction". The first represents the ability of an object to interpret and react to events and activities that occur in a real physical context. The second denotes the digital representation of the object obtained through an applied programming model. The latter represents the ability of the object to interact with the user concerning the input, output and data visualization. The authors also mention that IoT systems based on smart objects raise research questions such as *“What is the right balance for the distribution of functionality between smart objects and the supporting infrastructure? How do we model and represent smart objects’ intelligence? What are appropriate programming models? And how can people make sense of and interact with smart physical objects?”*. These questions may have different answers according to the context of the problem. However, they must be considered when defining the project objectives.

Over time, different architectures for IoT systems have been defined, some more detailed than others (number of layers in the model) that are being adapted to emerging technologies. An exhaustive literature review of the IoT architecture evolution and main concerns was provided by [3]. The review considered architectures from 2008 to 2018 and the IoT challenges, for example, security and privacy issues. More attention to data security is being paid over the last years due to the massive data gathering and analysis. IoT can be applied to different areas of activity, however, all systems provide an architecture where data collection and transport, data storage, processing and data availability are required [4]. In general, the most comprehensive system must incorporate the requirements identified in Table 1 that are associated with an inherent technological process.

Table 1. Summary of IoT system requirements and respective process description

IoT system requirements	**Process description and inherent methods or technology**
Transport and collect data	The system in real physical context contains objects connected to local data collection points that can establish communication through wired technology such as fibre optics or ethernet or through wireless networks such as Wi-Fi or LoRaWAN.
Storage data	The transmitted information is stored in databases appropriate to the context of the problem, using database management systems as MongoDB or SQLServer.
Processing data	Data processing occurs through data analysis techniques, based on statistical procedures, data mining, programming models and artificial intelligence techniques. Several methods can be used, such as exploratory data analysis, exact methods, heuristics, among others.
Make data available	The data must be made available to the user in a summarized form, providing only the information necessary for the process under analysis. This can be available through APIs or GUIs, such as a web application or a dashboard.

In the agriculture sector, IoT systems are increasingly used to allow better monitoring, support decision-making and, consequently, an increase of the business value. IoT can be applied in different ways in agriculture, from telemetry systems, computational software, data collection and efficient automation control. IoT enables data generation, which can be analysed to improve how agricultural activities are carried out [5]. The applications in irrigation are emerging in the literature [6–8]. Syrmos et al [5] presented an intelligent modular water monitoring IoT system for real-time data collection to sustain operational reliability. The authors discuss the relevance of IoT communications and infrastructure maturity, which are the foundation for a robust smart water metering solution. The proposed system uses LoRaWAN as the communication protocol and the flowmeter is equipped with a gyroscope for detecting movements. The limitation of the system is the cost since the proposed system cannot be adopted for domestic use due to frequent sensor replacement costs and an increased energy consumption. LoRaWAN defines the communication protocol and system architecture for the network, while the LoRa physical layer enables the long-range communication link. LoRaWAN is also responsible for managing the communication frequencies, data rate, and power for all devices [9]. Cheema et al. [10] proposed an IoT applied in a farm, based smart system equipped with accessible and economical devices and sensors to capture real-time parameters, such as temperature, soil moisture and pH level or humidity at frequent intervals of time. The IoT system evaluates these environmental factors, facilitating the decision-making.

Ragnoli et al. [11] proved that implementing low power wide area network technologies in IoT-oriented wireless sensor grids because it can help to good energetic performances, which are essential for energy harvesting in powered devices.

Thus, there is a need for emerging technologies to reduce energy consumption and cost-effectiveness in control and monitoring systems [12,13]. It has been predicted that the global energy consumption of IoT edge devices will reach of about 46TWh by 2025 [14]. Thus, it is of utmost importance to use renewable energy sources to power IoT devices, in line with the ambitioned sustainable development of modern society. Outdoor IoT devices can use photovoltaic panels to power themselves. Liu and Ansari [14] presented an example of a green energy solution to power IoT devices.

This study proposes the development and implementation of a monitoring system based on open IoT hardware and software platforms. Also, a LoRa supporting low-power long-distance network is applied through a low-cost solution. The IoT system can be powered by alternative energy sources, solar panels and a μhydroelectric plant. An algorithm was developed to monitor and collect several parameters, such as temperature and humidity by the different network towers, which communicate with the main gateway. These data are stored, statistically treated and presented in a user-friendly application.

This system's novelty is related to the possibility of using different renewable energy sources since the microcontroller can switch from solar to hydroelectric, which ensures constant battery power. Also, to increase their efficiency, the peripheral towers were programmed to remain in active mode only during the data sending and receiving. Otherwise, the microcontroller of the peripheral tower remains on standby. This aspect also enhances the batteries' useful life span.

2. System design and architecture

The IoT monitoring system consists of three main parts: the First is an energy IoT node that collects data, a second is IoT gateway that receives and stores data from nodes at remote locations, and the last is the low-cost LoRa network which is support wide area networking and low costed wireless solution. In this research work, when referring to IoT systems, one should keep in mind their properties and limitations. In this sense, an IoT system should be, when possible, battery-powered, have a small size, low cost and perform simple tasks. The assigned restrictions imply a study of consumption, autonomy, computational power, and specific tasks.

2.1. Schematics of the system design

The methodology used in this work for monitoring air and soil quality in an agricultural environment is based on the principles of IoT systems in which it seeks to find adequate solutions for its limitations. Figure 1 presents a general design of the developed system. The system is composed by peripheral towers for acquisition of soil-related variables; a main tower for monitoring variables related to air quality and to serve as a gateway of all information; a server to store and analyse data and an informatic application to query and monitor it.

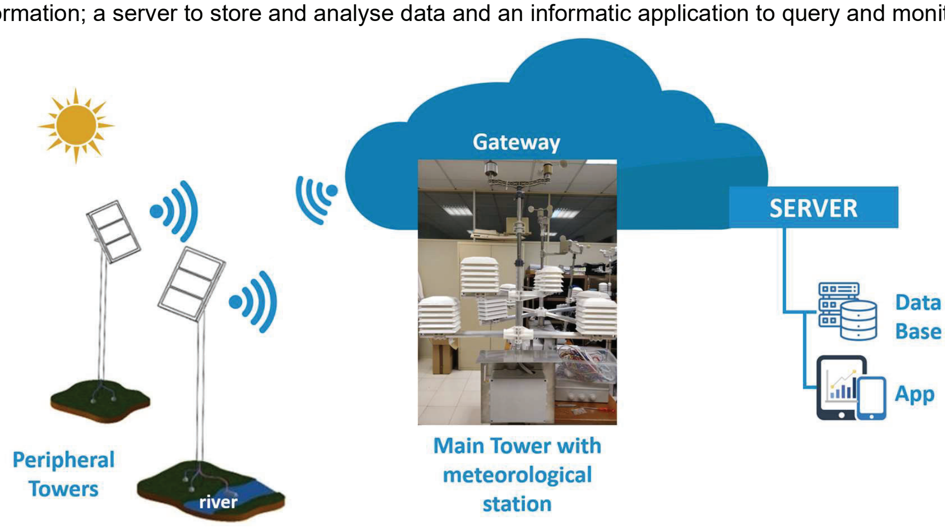

Figure. 1. Schematics of the system design.

2.2. Characterization of data acquisition towers

The data acquisition subsystem includes the main tower and the peripheral towers, both equipped with sensors and communication systems. Each peripheral tower, Figure 2 (a), is composed of temperature and soil humidity sensors. These sensors are connected to a data acquisition developed board capable of communicating with the main tower through a wireless network (LoRA at 868 MHz).

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Regarding the power supply of each tower (battery), this is charged by using renewable energy that comes from the solar panel installed. Figure 2(b) depicts a peripheral tower installed to collect soil parameters.

The main tower, Figure 2(c), serves as a gateway to the data acquisition system. In this tower, there is also a meteorological station that provides information on atmospheric pressure, air temperature and humidity, wind direction and speed and precipitation rate, as well as, CO_2, O_3 or particles (e.g., PM2.5, PM10). The air quality information is provided through sensors installed. Data is sent over the internet to a remote server.

(a) (b) (c)

Figure. 2. Data acquisition subsystem: (a) detail of peripheral tower with the solar panel to feed the battery and the antenna; (b) peripheral tower installed in the urban garden near the river flow; (c) main tower with the meteorological station.

2.3. Architecture of the energy feeding system

One of the requirements of this project is that the peripheral towers are powered by using renewable energy. Renewable energy sources cause some disturbances in electrical power grids. In this sense, designing a system that monitors the available power in real time is required, whereas the energy is provided from solar panels or hydroelectric plants, with the use of small generators.

The monitoring system comprises two components: hardware and software. Regarding the hardware, it is necessary the physical interfaces connected to the current and voltage intensity sensors, necessary for the calculation of the available power. Power drives were also developed to charge the battery responsible for powering the electronic system (microcontrollers, relays, development board and others) implemented in each peripheral tower. In addition to the software that controls the hardware, an algorithm was also developed to articulate historical or via satellite information regarding the seasonality and predictability of the variables to be monitored, for a specific location (agricultural zone) with the data coming from physically implemented sensors. Figure 3 shows the flowchart of the developed algorithm.

The algorithm developed is based on the history of available information and it was created to consider two types of energy input, i.e., solar energy and/or hydroelectricity. For instance, on a summer day, the hours from sunrise to sunset and the hours of highest solar irradiance are both known. So, if the power available from the solar panel is below the nominal power to charge the battery, then, the algorithm commutes to the alternative energy source. In case there is only solar energy available, its current intensity is calculated to power the system during the night.

Figure 4 shows the flow of information between the different components. The available power from each of the alternative energy sources are measured (product of the current intensity by the voltage) and compared to determine the highest one. Afterwards, the microcontroller (development board) activates an output for the relay drive. Through a relay contact, the current intensity is physically routed to the circuit that charges the battery. Once the alternative energy source has been chosen, the others are blocked by the auxiliary contacts of the relay associated with that source. A hysteresis cycle was also implemented in the algorithm, which prevents the switch whenever the instantaneous power available is of a higher energy than the current one that is charging the battery.

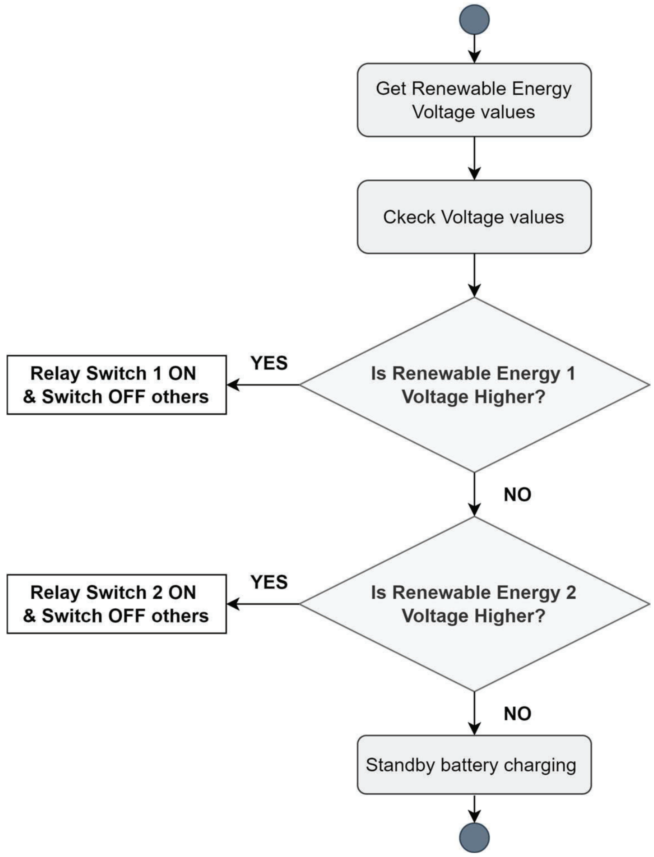

Figure. 3. Flowchart of the developed algorithm to manage the architecture of the energy feeding system.

The implementation of renewable energies in the project facilitates the acquisition of data in remote locations, mostly where there are no conventional energy sources. The supplying companies offer a set of equipment solutions with several sizes and available capacities. However, regarding the hydroelectric production, it is difficult to obtain components with potentials available for IoT applications. In this sense, this project includes the design of an innovative µhydroelectric plant.

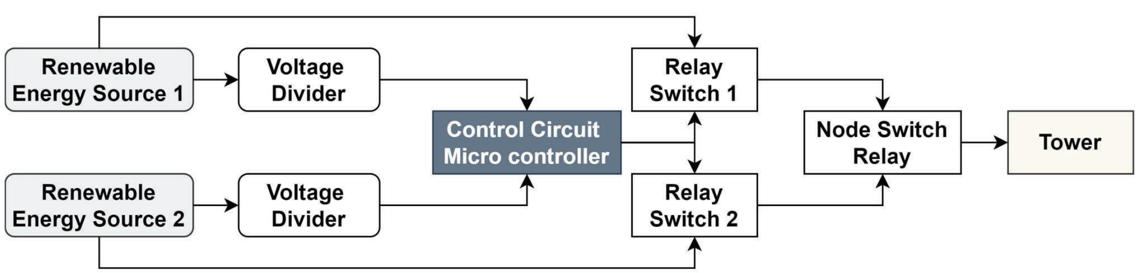

Figure. 4. Information flowchart between the system components.

An optimized printed circuit board was developed with hardware improvements, allowing a better efficiency of the switch system between alternative energy sources. Despite to the fact that, in this study, only solar and hydroelectric energy sources are assessed, the developed printed circuit board allows the switch between 3 different types of alternative energies. The optimized printed circuit board layout is presented in Figure 5.

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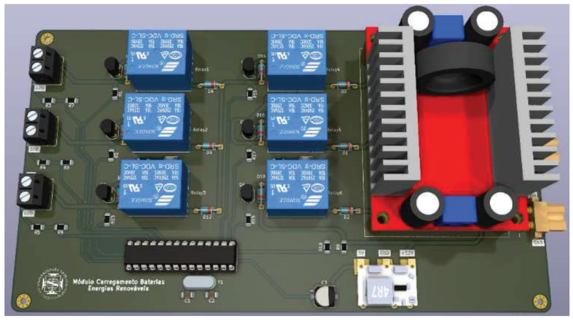
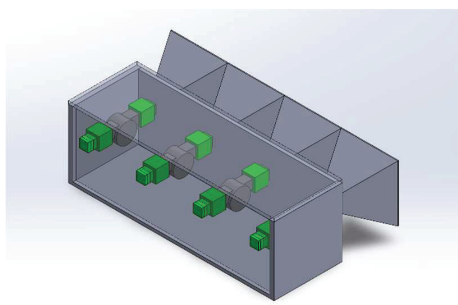


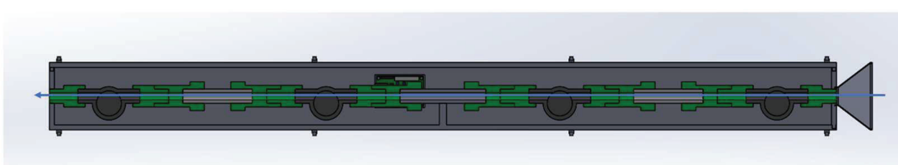
Figure. 5. Optimized printed circuit board layout.

The µhydroelectric plant was designed based on a modular architecture, capable of adapting to the most diverse scenarios related to its installation. Different configurations were studied, according to the environmental conditions related to natural water courses. The two basic configurations, turbines arranged in series (Figure 6(a)) or in parallel (Figure 6(b)), can be adapted to different natural river bed scenarios. The number of turbines can also change according to the intensity of electrical current required to power IoT devices.

As technical specifications, the turbines used in this work have the output Voltage of 5V DC and a maximum intensity of electrical current output of 150 mA for a constant water flow rate (4L/min). Solidworks® software was used for the development and testing of components. Depending on where the water is collected, for example, in a small river, if the bed is flat, the best turbine configuration is in series. That is, a use of the kinetic energy caused by the natural current of the river. On the other hand, if the riverbed is uneven, the best configuration is parallel. That is, the use of potential energy at a height of about one meter of distance towards to the turbine position. Mixed configurations (series/parallel) of turbines are also possible.



(a)



(b)

Figure. 6. CAD files of turbines developed for the project: (a) turbines arranged with a parallel flow architecture; (b) turbines arranged with a series flow architecture.

2.4. Definition of the communication protocols

Recent studies show a wide variety of IoT applications using the LoRaWAN Protocol. This defines the system architecture as well as the communication parameters in relation to LoRa technology.

In this work, the technologies involved were considered, seeking to standardize the power supply voltages of the devices, powers involved and communication networks. In this sense, the WEMOS TTGO ESP32 SX1276 LoRa development board was chosen. As main features, this board is low cost, composed by the ESP32 microcontroller and a LoRa SX1276 radio communication module.

The ESP32 is a 32-bit microcontroller with integrated Wi-Fi and Bluetooth connectivity, which has several advantages, such as low power consumption associated with high processing performance. The SX1276 LoRa radio communication module allows you to communicate with other LoRa devices over long distances, usually in the range of a few kilometres (about 10 km with an unobstructed view), depending on the environment and device configuration. It is usually used in projects that require long-range wireless communication with low data transfer rate and low power consumption.

The TTGO development board allows the use of an external antenna, in order to provide a greater performance of the LoRa technology. When choosing an outdoor antenna, it is important to consider the type of antenna that will best meet the specific needs of each project. There are two main types of antennas: omnidirectional and directional. Omnidirectional antennas emit signals in all directions, while directional antennas emit signals in a specific direction. Omnidirectional antennas are ideal in situations that require signal coverage in all directions, such as in urban areas or places with many obstacles. On the other hand, directional antennas are best suited in situations that require a strong signal in a specific direction, such as in rural areas or places where there are few obstacles. As presented in Figure 7, an omnidirectional antenna was chosen. Omnidirectional antennas provide easier installation compared to directional antennas, which require prior positioning in relation to the other nodes in the network. It is possible to add new nodes (sensors) to the LoRa network, which is one of the objectives of future work. The solar panel as a nominal capacity of 20 W.

The use of the TTGO development board that integrates the ESP32 microcontroller has the advantage of allowing operation in different energy modes. There are five power modes available on the ESP32, ordered from highest to lowest consumption: active mode (pre-set mode by default), modem-sleep mode, light-sleep mode, deep-sleep mode, and hibernation mode.

Figure. 7. Omnidirectional antenna installed in the peripheral towers.

The monitoring of the environmental variables and their transmission by the peripheral towers are carried out every 10 minutes, which makes it unnecessary to keep the microcontroller constantly in active mode. In this work, the efficiency of the peripheral towers is a relevant aspect, since they are powered by batteries, and it is important to guarantee their efficiency. To increase their efficiency, the peripheral towers were programmed to remain in active mode while reading and sending environmental variables. After this process, the microcontroller of the peripheral tower goes into sleep mode, leaving only the sensors connected to the GPIO (programmable input and output ports) and an RTC timer responsible for waking it up after 10 minutes. With this procedure, it is possible to improve the efficiency of the microcontroller, reducing the current consumption from 50 mA to 10 mA during the respective period of 10 minutes.

2.5. Development of the application interface

On the server, data is stored in a non-relational database DB (Mongo DB) created for this purpose. Some of the attributes that contributed to its choice were: easy adaptation to new data, open source, and familiarization with this DB. Data is treated statistically and presented in the form of an application (App) for users. This application is a user-friendly application because it was thought and designed considering the different ages of users. The system architecture for data storage and visualization is divided into three main components: backend, frontend, and database. The backend is composed by a NodeJS application that provides two different API's considering the requests that are served. Indeed, there is a specific API to receive and store the data provided by the central control tower.

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The second API have methods to provide the necessary data or validations for the frontend application. The communication is based on HTTP requests and considers the different GET, POST, DELETE and PUT methods. The information is stored in a non-relational database (MongoDB). Finally, the frontend provides, through several HTML, CSS and Javascript files, the information to the user. A dashboard is made available through a web application accessible with an Internet connection. Such information contains plots with, for example, temperature and humidity data and has methods that enables the user to change the visualized data by a temporal period (e.g., reset the zoom of an axis). By separating the backend from the frontend, the system may be more responsive since the backend has the only goal of providing the information, whereas the frontend is responsible for formatting and display such information. Indeed, the backend server is not overloaded with graphical requests.

3. Results and discussion

The results obtained with this work are presented taking into account the validation of each component of the IoT monitoring system architecture, considering the improvements of each subcomponent. In this section, the process for data acquisition and communication protocol validation is presented, as well as the assessment of the µhydroelectric plant operation and the variables measurement which can be accessed by the dashboard developed for the informatic application.

3.1. Data acquisition and communication protocol validation

Although the main tower is prepared to operate, in a remote location, with a current intensity of 600 mA, for technical reasons related to the compatibility of the developed system and the existing internet devices in the urban garden, the power supply to the tower was carried out using the mains. The data from the peripheral towers are sent together with the data acquired in the tower to a remote server located in the University Laboratories. The sending cadence corresponds to a 10 minutes interval period.

Regarding the battery charging, the initial calculations were carried out for a battery capable of supplying the designed circuits for each one of the peripheral towers. It was determined a current intensity value of 480 mA. This current intensity would be required for the constant and continuous system operation.

Nevertheless, during the project development, improvements were made at both hardware and software levels, which lowered the initially calculated value to around 250 mA. Taking into account the values initially calculated for the current intensity and the inclusion of more sensors in the near future, the average current intensity stipulated for the development of battery charging systems is 600 mA.

Regarding the sensors calibration, the system was also optimized for the application in study. The sensors that are part of the peripheral towers to measure soil temperature (SONOFF SENSOR-DS18B20) and moisture (SKU: SEN0193 Analog Capacitive Soil Moisture Sensor) were calibrated according to the manufacturer's specifications.

The temperature sensors were calibrated with ice (for a reference temperature of 0ºC) and with boiling water (for the reference temperature of 100ºC) in order to maintain their linearity in the measurements taken. The humidity sensors were calibrated according to the resolution of the analogue to digital converter (ADC) of the development board microcontroller. For a 12-bit ADC resolution, the value of 1490 corresponds to 100% humidity (immersed in water) and the value of 2980 corresponds to 0% (dry value). Figure 8 shows a cycle of reading and sending temperature and humidity values from the peripheral tower to the main tower. After the RTC timer wakes up the device, the program reads the humidity and temperature and sends the information through LoRa. Afterwards, the system enters in deep-sleep again.

```
----------------------------------------------------------------
ets             00:22:57

rst:0x5 (DEEPSLEEP_RESET),boot:0x17 (SPI_FAST_FLASH_BOOT)
configsip: 0, SPIWP:0xee
clk_drv:0x00,q_drv:0x00,d_drv:0x00,cs0_drv:0x00,hd_drv:0x00,wp_drv:0x00
mode:DIO, clock div:1
load:0x3fff0018,len:4
load:0x3fff001c,len:1044
load:0x40078000,len:10124
load:0x40080400,len:5856
entry 0x400806a8
LoRa Sender
Temperatura 18.25°C
Humidade 65%
Sending packet LoRa...
----------------------------------------------------------------
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Figure. 8. Cycle of reading and sending temperature and humidity values.

3.2. Assessment of µhydroelectric plant operation

As previously stated, a µhydroelectric plant was developed as the second renewable energy source of the IoT monitoring system. Prior to the tests to monitor the turbines behaviour, they were calibrated individually, according to the manufacturer's specifications, using information from a flow sensor and an ammeter. This process ensured an output current intensity of 150 mA. The water supply pipe diameter of was also sized to guarantee a constant flow rate of 4 L/min.

Regarding the series configuration of the 4 turbines (Table 2), it was verified that the first turbine was producing 150.0 mA, the second turbine 147.9 mA, the third 145.8 mA and the fourth turbine 142.6 mA. The fact that all the turbines were not producing all 150 mA was caused by mechanical losses and junction losses. One of the solutions to solve the problem may be to increase the flow rate. Yet, the flow rate increase results in higher wear rates of the first and second turbines since, by increasing the flow rate, the maximum intensity of the current does not increase as they are already in saturation.

Regarding the parallel configuration of the 4 turbines, the performance improves, as it was possible to obtain a maximum current intensity of 600 mA through a summation circuit. The problem lies in the need for a gap of about one meter in the riverbed.

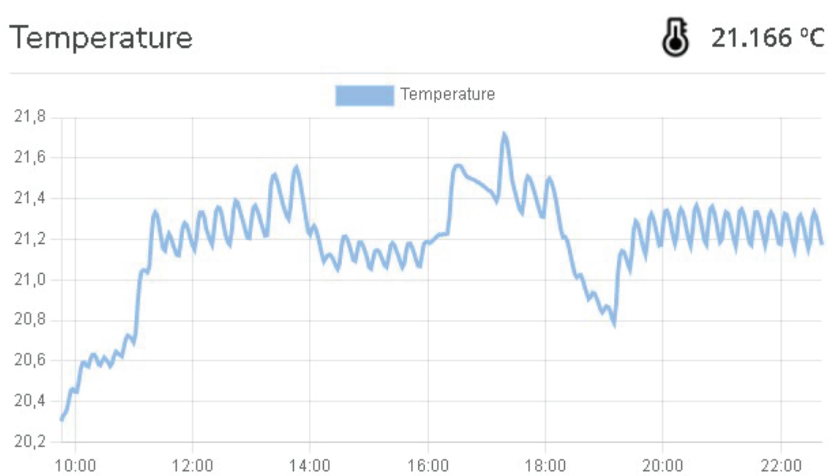
Table 2. Intensity of current produced by the turbines considering the series configuration

Generator equipment ID	Current intensity (mA)
Turbine 1	150.0
Turbine 2	147.9
Turbine 3	145.8
Turbine 4	142.6

At the moment, a hybrid system is being developed with the architecture of a parallel system of two turbines in series, capable of producing 600 mA. With this architecture it is possible to solve the problems described above. This configuration is being tested, so the data will be subject to future analysis.

3.3. Temperature and humidity measurements

The IoT system developed in this study aims to monitor environmental parameters registered at an urban vegetable garden located in the vicinity of a river stream in the Vila Nova de Famalicão municipality. Figure 9 shows the visualization dashboard obtained from the data of temperature and humidity registered in March 16th of 2023, between 10 a.m. and 11 p.m. The developed interface is able to estimate the mean obtained values.



(a)

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(b)

Figure. 8. Temperature (a) and humidity (b) registered by the IoT monitoring system in March 16th of 2023, between 10 a.m. and 11 p.m.

Like the Portuguese national meteorological service (Portuguese Institute of the Sea and Atmosphere -IPMA) the interface is very user-friendly, since it uses a coloured code for variables range classification: light green (very good), green (Good), yellow (medium), orange (weak) and red (bad). In addition, the interface was programmed to disclose the collected data with statistically treated. The dashboard detailed by Figure 9 shows the average, maximum and minimum values for both temperature and humidity during the time of data acquisition. For instance, regarding the temperature data from March 16th, the application reported an average value of 21.18 ºC, with an amplitude ranging from 20.30 ºC to 21.72 ºC. The temperature standard deviation corresponds to ±0.25.

Statistic

Variable	Average	Standard Deviation	Max	Min
Temperature (ºC)	21.18	0.25	21.72	20.30
Humidity (%)	54.37	2.03	58.37	50.48

Figure. 9. Print of the statistic information provided by the interface application dashboard, regarding the registered temperature and humidity values.

Thus, with this IoT monitoring system it is possible to define the best techniques and types of agricultural crops for a certain environmental pattern. Soil humidity sensors are used in detecting the changes which are required and to adjust the irrigation practices. Minor changes in irrigation practices increases the cultures growth and saves water.

For instance, a proper irrigation management using soil humidity level variation depends on the specific soil type. The modularity of the developed system also allows to design and size an economical, appropriate and a low maintenance solution for agricultural small-scale applications, mainly in rural areas.

4. Conclusions and final remarks

This paper presented the architecture and development of an IoT monitoring system to effectively collect environmental data such as temperature and soil humidity to facilitate agriculture activities. A LoRa supporting low power long distance network was applied through a low-cost solution, the WEMOS TTGO ESP32 SX1276 LoRa. The system can be powered by alternative energy sources, solar energy and hydroelectric and it uses an algorithm that monitors and collects several parameters by the different network towers, which communicate with the main gateway tower, which is equipped with an atmospheric station to collect air quality data.

All the stored data are statistically treated and presented in a user-friendly application that can be used by different users. The system was installed in an urban vegetable garden in the Vila Nova de Famalicão municipality.

The monitoring of the environmental variables and their transmission by the peripheral towers are carried out every 10 minutes. Since these towers are battery powered, the control circuit was optimized to reduce the current consumption, from 50 mA in activated mode to 10 mA in sleeping mode. The peripheral towers can also be feed by hydroelectricity, since an optimized printed circuit board was conceived allowing a better efficiency of the switch system between alternative energy sources. Due to the irregularities of the river bed, two configurations for the turbine connexion were studied – in series and in parallel. In series configuration, due to mechanical and junction losses, it is not possible to guarantee the intensity of 150 mA from all turbines. Hybrid configurations need to be implemented. Through the dashboard developed as the informatic application interface, it was possible to validate the IoT system by monitoring the temperature and humidity.

The use of different renewable energies makes this project thrive in all weather conditions and seasons, with wind and hydro energy for nights and winters and solar energy during the day and especially in summer. The implementation of renewable energies in the project facilitates the collection of data from remote places where there are no conventional energy sources. As future work, the IoT monitoring system will be able to select the most appropriate source from wind, water or solar, since the defined architecture allows to adapt the system to operate with three renewable energy inputs.

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