Cyberphysical Network for Crop Monitoring and Fertigation Control

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Dedication

I dedicate this work to my mother, Lucimara Aparecida Vendramini, who has been by my side at all times of my life guiding and supporting me. This work is a way of thanking her for her efforts throughout my life to make me an accomplished man.

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Finally, my girlfriend Anaize Fernanda Costa who has always been by my side at all times supporting and giving strength. And to all of my friends who over these 5 years of graduation are by my side fighting together for a common goal.

Resumo

A fertirrigação é uma técnica de cultivo que recorre à aplicação precisa de soluções nutritivas de acordo com os requisitos da planta, condições ambientais e de substrato. A utilização desta técnica tem-se popularizado devido às vantagens promovidas onde se destacam a redução de fertilizantes, fitofármacos e consumo de água. No entanto, este desempenho é conseguido à custa de um rigoroso monitoramento e regulação de fatores tais como soluções nutritivas, condições ambientais e estado vegetativo da cultura.

Este trabalho descreve a arquitetura de uma rede baseada em agentes e elementos ciberfísicos que serão implementados em uma unidade de produção de morango por fertirrigação. O sistema deve ser responsável pelo fornecimento correto de água e insumos agrícolas tendo por base informações locais fornecidas por conjuntos de sensores.

Cada conjunto de sensores, chamado de nó de medida, é responsável pela aquisição da informação em torno de um determinado local. A comunicação destas informações é realizada através de uma rede sem fio baseada no protocolo LoRa até uma plataforma digital onde a informação provinda de todos os nós, juntamente com dados meteorológicos, é agregada e processada.

O resultado do processamento desta informação levará à definição da quantidade exata de solução nutritiva bem como a otimização da utilização da água levando a um aumento da eficiência de produção.

Palavras-chave: Rede de sensores, LoRa, Agricultura de precisão, Controle de fertirrigação.

Abstract

Fertigation is a cultivation technique that uses the precise application of nutrient solutions according to the requirements of the plant, environmental conditions and substrate. The use of this technique has become popular due to the advantages promoted, which include the reduction of fertilizers, phytopharmaceuticals and water consumption. However, this performance is achieved at the expense of rigorous monitoring and regulation of factors such as nutrient solutions, environmental conditions and the vegetative state of the crop.

This work describes the architecture of a network based on agents and cyberphysical elements that will be implemented in a strawberry production unit by fertigation. The system must be responsible for the correct supply of water and agricultural inputs based on local information provided by sets of sensors.

Each set of sensors, called a measurement node, is responsible for acquiring information around a given location. The communication of this information is carried out through a wireless network based on the LoRa protocol to a digital platform where the information from all nodes, together with meteorological data, is aggregated and processed.

The result of processing this information will lead to the definition of the exact amount of nutrient solution as well as the optimization of the use of water leading to an increase in production efficiency.

Keywords: Sensor network, LoRa, Precision agriculture, Fertigation control.

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Acronym

3D Three Dimensions. 41, 42

A/D Analog to Digital converter. 21, 36, 45, 46

EFS Effective Forage Space. 10

ESTiG School of technology and management. iv

FMIS Farming Monitoring Information System. 6

GIS Geographic Information System. 6

GPIO General-Purpose Input/Output. 21, 32

GPS Global Positioning System. 6

IoT Internet-of-Things. 14–16, 32

IPB Instituto Politécnico de Bragança. iv, 25

kg kilogram. 43

LCAR Control, Automation and Robotics Laboratory. 25, 42

LPWAN low-power wide-area network. 17, 18

motes sets of measurement nodes. 2

MQTT Message Queuing Telemetry Transport. 33

PaaS Platform as a service. 2

PCB Printed circuit board. 41, 42

PLA Plastic polylactic acid. 42, 43, 48

SoC System on a chip. 20, 25, 32, 35

UAV Unmanned Aerial Vehicle. 7

UTFPR Universidade Tecnológica Federal do Paraná. iv

WSN Wireless Sensor Networks. 12, 16

Chapter 1

Introduction

The availability of water resources is a fundamental aspect to stabilise the human activities and maintain the balance of the ecosystems. In addition to the need for drinkable water, societies depend on supplies water for industrial activities and agriculture. However, a considerable decrease in the amount of percapite water is expected in the not so distant future. This reduction is due for the several reasons.The two most cited ones are the climate changes felt all over the globe [1] and the increasing population growth, specially in Africa and Asia [2].

1.1 Theoretical framework

About 70% of the water used worldwide is for agricultural use [3], [4]. Agriculture is the basis of the modern social structure and supports many other sectors such as industry and services. The supply of food to the entire world population places a heavy load on natural resources in general and water in particular. Several strategies are currently being developed and applied to mitigate such impact such as the integration of rainwater catchment systems, fertigation cultivation systems [5] and the integration of cutting-edge technologies in the production cycle.

1.2 Objectives

The search for adequate use of water resources directly impacts the development of systems and element that assist in this task. However, it is necessary to collect a large amount of data to arrive at a correct decision with this data coming from various sources. For this it is necessary that the data collection be carried out efficiently.

This work proposes the development of the cyberphysical component to be used in a multi-agent control system. The planned control model depends directly on the local information collected by a array of sensors scattered along the production area that, after data acquisition, performs a wireless transmission by LoRa protocol to an Platform as a service (PaaS) that performs the processing of this data.

Figure 1.1 shows the strategy of this decentralized control system. Based on this proposal, a control system will be developed where sets of measurement nodes (motes) are installed on the growth beds in order to perform data collection and transmit them to a location controller via the LoRa protocol. After receiving the data, the user with access to the controller can use the data to make the necessary decisions regarding agricultural management.

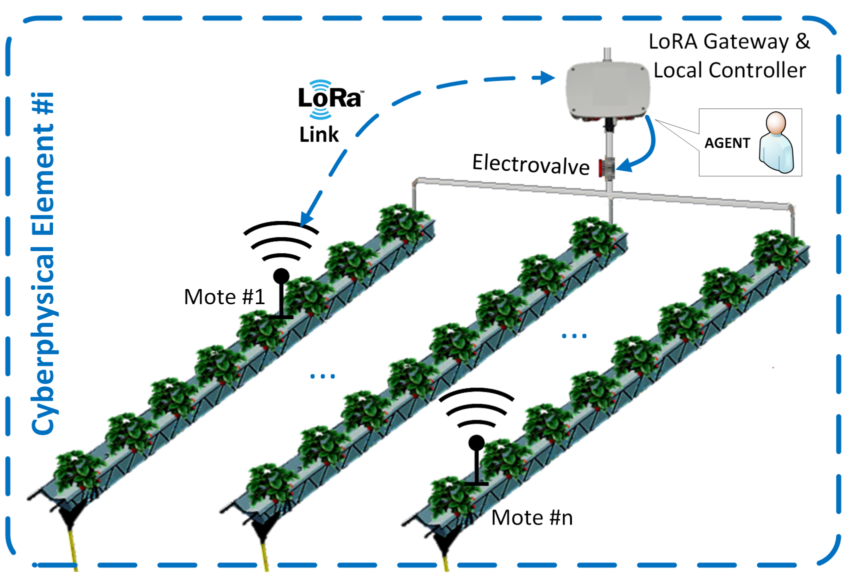

Figure 1.1: Schematic diagram of a cyberphysical fertigation element.

1.3 Structure of the Document

The present work is discribed in 6 chapters whose contet will be briefly presented here. Chapter 1 presents the problem that will be address as well as the objectives to solve this problem.

Chapter 2 presents the state-of-the-art, that is, the themes that served as the basis for the creation and development of the practical and theoretical part, as well as the bibliographic review used for all the work, including historical concept, operations and tools.

The methodology carried out during this work, as well as the proposed solution is presented in Chapter 3. It also present the architecture that will be used in carrying out the work.

Chapter 4 presents all the steps for the development of the work, from the choice of components to the development of firmware, hardware, tests and physical structures.

The discussion of the results obtained is carried out in Chapter 5 following in Chapter 6 the final conclusions about the work together with ideas for future work.

1.4 Published papers related to work.

During the development of this work, three papers were submitted to international congresses where two are accepted and published and one is in the process of being evaluated.

The two papers already published had an oral presentation at the respective congresses. [6] was published in the 19th EPIA Conference on Artificial Intelligence in the city of Vila Real, Portugal,3-6 of September, 2019. [7] published at the 2nd XoveTiC Conference in the city of A Coruña, Spain, 5-6 of September, 2019.

Cyberphysical Network for Crop Monitoring was submitted to the 14th International Conference on Automatic Control and Soft Computing that will take place in the city of Bragança, Portugal, 1-3 of July, 2020.

Chapter 2

State of the Art

This chapter presents the bibliographic revision carried out for the development of the current work. In Section 2.1, the concept of precision agriculture will be introduced. In Section 2.2 the concept of fertigation is presented and discussed following, in Section 2.3, the application of sensor networks in agriculture. Finally, in Sections 2.4 and 2.5, the contribution of the internet of things and the LoRa communication protocol for agriculture respectively will be highlighted.

2.1 Precision farming

Classical cultivation practices tended to treat cultivation area as having uniform characteristics ignoring possible soil and even climatic variations within these large areas. Variations within the same production field may induce that each small area needs inputs in different amounts and at different times from the rest of the crop.

Another problem involving agricultural production that has gained ground in worldwide discussions is the growing demand for food based on the growing world population. Many current studies point to the need for developing agricultural production techniques that return a higher performance using smaller growing areas since over the years the urban areas due to urban growth accelerated [8].

Based on these challenges came the concept of precision farming. With the technological advancement of recent years, this concept has gained a lot of support since such practice was made possible by the information technologies that enables to have greater control over the state of the production. More clearly, the practice of precision farming, coupled with information technology, enables the monitoring of the agricultural production chain and control the quantity and quality of products [9], [10].

2.1.1 Connection between technology and agricultural processes.

The profitability of production at the end of each harvest is the main objective of agricultural producers and should be used as a basis for the development of a control and monitoring system. Precision agriculture combines studies carried out and applications of proposed solutions to problems that hinder production effectiveness.

Studies based on Geographic Information System (GIS), Global Positioning System (GPS), sensors, among others, were carried out and the relevant results were taken to farmers who used such data as a basis for making certain decisions. What can be seen is that there has not only been an improvement in production but also a reduction in environmental impacts [11].

Over the last decade and with the realization of the viability of this production technique, investments in this area have become greater in the search for the development of new and more advanced technologies seeking application in this field [12]. Farming Monitoring Information System (FMIS) have received greater attention and the development of cyberphysical systems has gained new bases and new directions while new challenges have emerged.

Electronic communication systems, different types of sensors and even the communication with the Internet started to be applied to the FMIS, enabling monitoring, of system performance, in a decentralized architecture with greater coverage in terms of production area and perspective of application scalability.

The decentralized monitoring architecture can be characterized as having separate data acquisition and control elements. Generally, the elements responsible for data acquisition are installed throughout the entire production area while the control elements are then strategically located in a place that is easily accessible to the user. Figure 2.1 show this architecture.

Currently, the main focus is on precision farming and the dosage and application of agricultural inputs and fertilizers. This is a relevant concern because it encompasses two issues: inadequate application of fertilizers, whether soluble or solid, can interfere with the state of development and production of the crop and the possibility of infiltration and contamination of springs or other water sources [13]–[15].

Figure 2.1: Precision farming architecture [16].

In addition to this set of pillars that help in the advancement and execution of precision farming, we have the Unmanned Aerial Vehicle (UAV), popularly known as drones. They are gaining space in this style of production while the most varied forms of sensing are embedded on it. The UAV are usually used in mapping, characterization of geographical topology and identification of production failures, but in the near future the contributions of this new technology may be even greater, for example, in assisting intelligent agricultural machines in the issue of irregularities in the application of pesticides and fertilizers [17], [18].

2.2 Fertigation

With the advancement of precision agriculture, other concepts of agricultural production emerged. One of them is the production by fertigation system that provides an alternative way of production and can also allow different input control models. However, the greatest positive point is the results of this technique in the growth of productivity with an efficient and reduced consumption of water and nutrients.

2.2.1 Fertigarion concept

The fertigation production system is a technique that allows a great opportunity to increase the production yields with considerable minimization in the use of water, fertilizers and also in the environmental impacts that may occur in the future. In this system, several factors such as time, quantity and concentration of nutrients are considered before application.

The architecture of this process allows the nutrients to be applied solubilized in the water destined for irrigation, ensuring a conscious use of this resource and guaranteeing an application directed to the active roots of the crop [19]. The need for the quantity and proportion of nutrients can be varied between types of cultures and also during each stage of growth.

This system allows the optimization of the physiological activities seeking the best performance by means of monitoring and optimization in the application of nutrients and the supply of the plant's water needs according to each stage of its development. In that manner, it is possible to control the production of humidity around the active roots based on the limitation of the quantity of solutions supplied, guaranteeing an ideal volume.

Due to the applications of the nutrient solution in small quantities and controlled frequencies, it is possible to minimize evaporation losses, since the exact amount of water is applied to supply the needs of the plant directly at the focus of absorption. This practice also allows a prolongation of the harvesting period once increasing the production and improving the quality of the final product since during all its development it received the exact quantities of inputs [20]–[22].

The most common form of fertigation production consists of growth platforms above ground level connected to the fertilizer supply network. Figure 2.2 show, in a strawberry production, the growth platforms where they are independent from each other and are directly connected to the nutrient solution distribution network.

The nutrient solutions are stored in deposits and are transferred to the substrate through the drip lines located in parallel and above the growth platforms. The drip lines, Figure 2.3, have a constant flow of nutrient solution and the drip frequency depends on the pressure applied to the tubes that take the solution with the excess solution, which was not dripped and continued in the tube, returned to the initial deposit avoiding waste. However, this application is not related to the substrate absorption capacity and may cause applications excess.

Figure 2.2: Strawberry Production by fertigation.

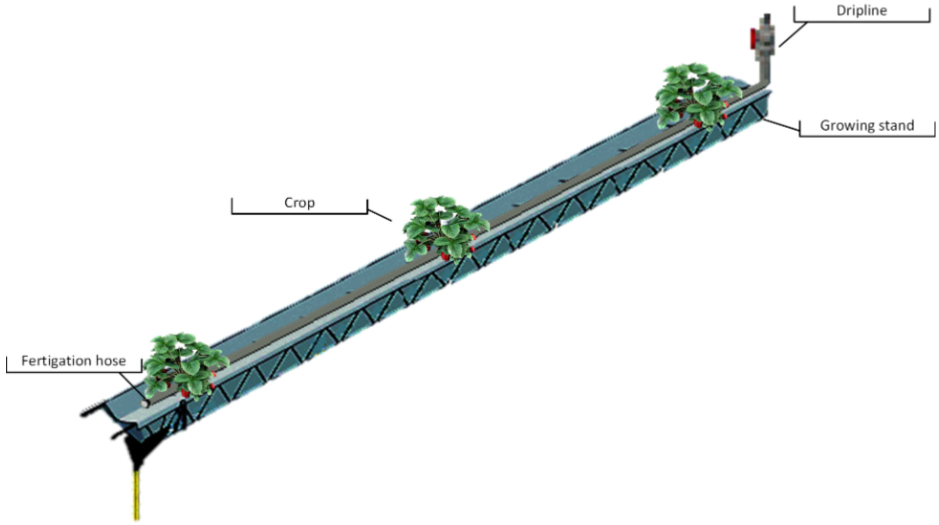

Figure 2.3: Production bed.

2.2.2 Advantages of fertigation

One of the most relevant advantages of the fertigation production process is the nutritive application directly in the area of root activity. Every nutrition solution that is sprayed or dripped on an area other than the root zone can be considered an unusable expense and is not nutritionally and economically viable.

To avoid this, there is the concept of Effective Forage Space (EFS), which is defined as the space that corresponds to a portion greater than 80 % of the root's area of activity [23], [24]. Based on this it is possible to make a direct application in the area that comprises a greater absorption and utilization ensuring sufficient supplies for development in all stages of vegetative development.

It can be considered that this concept contributes to a great profitability with minimized losses and qualitative monitoring besides the reduction of time and labor [24]–[26].

However, the expensive investments in the application and monitoring system end up imposing some barriers in the implementation of this production system and therefore, fertilizer formulations should be studied and developed composed of the whole range of nutrients according to the soil, physiological stage and climate, that is, a fertilizer adapted to the conditions of the cultivation place. Irrigation planning and nutrient supply based on soil, climate and physiological status ensure the high quality of production [27].

Like any production system, some precautions must be taken in order to implement the fertirrigation process. These precautions range from the quality of the nutrient solutions to the quantity and frequency at which the crop is supplied. some of the main precautions that should be taken before and during the fertirrigation production process.

According to [24] some of the main precautions that should be taken before and during the fertirrigation production process are:

- Fertilisers must be completely dissolved in water before fertigation;
- The fertilizers chosen must be compatible with the type of crop to which they will be applied;
- Water quality should be checked before dissolution;
- Excessive irrigation can cause damage to the bases of production;
- The proportion of nitrate sources should correspond to a mixture composed of 80% nitrates and 20% of a pH regulator.

After all precautions have been taken, the solutions are stored in tanks until the moment of application. That's occurs in a pre-scheduled way by the producer who activates the pumps by injecting the nutritive solutions in the irrigation lines.

2.3 Sensors network in agriculture

While precision farming is gaining ground, it forces new systems and technologies to be developed. A large amount of investment began to be destined to this area in search of improvements in performance and monitoring, the typology of sensors became larger and more refined and the communication between monitoring points became fundamental.

The need for communication between the points of data collection gave rise to the implementation of Wireless Sensor Networks (WSN) that focused on monitoring environmental conditions with pre-defined knowledge help in the growth of crops and guide in yield properties [28].

The collection of data, monitoring and application of inputs allows the final results to be attributed a higher yield with cost reductions in addition to the considerable reduction in environmental impacts [28]. Each area receives only the amount needed at appropriate time intervals. The contribution of wireless sensor networks does not depend on location and purpose, being able to monitor and transmit data to external interference or to act autonomously.

Monitoring is usually done in real time, when a network of sensors is defined to contain detection and computing stations that help the user to make decisions about the tasks to be performed. The implementation of wireless sensor networks can be characterized by two different types of architectures, the terrestrial and the underground depending on the functions and the need for range [29]–[31].

The wireless sensor networks can be characterized in two ways according to [29]:

- Terrestrial sensor network: its main characteristic is the implementation of systems above ground level, which allows for greater communication range, smaller antenna sizes and reduced energy consumption.

- Network underground sensors: Unlike the terrestrial, in this architecture the detection points are placed below ground level and therefore has as characteristic a reduced communication range with larger antennas and requiring a larger source of energy.

Independent of the chosen architecture, the same can still be subdivided in other three subcategories being.

- Stationary architecture: The data collection nodes are positioned in chosen locations and their position does not change during the entire use of the system.

- Mobile Architecture: In this architecture, the nodes change their positions according to time.

- Hybrid Architecture: This model comprises in the mixture of the two previous architectures where there may be fixed nodes in communication with some mobile nodes.

The operation at communication and access levels of a wireless sensor network is such that wireless monitoring nodes transmit information directly or node-by-node to a gateway. The gateway acts as a bridge between physical mapping and Internet access, so the information that reaches this bridge can be used remotely by data servers, mobile or remote users as seen in Figure 2.4.

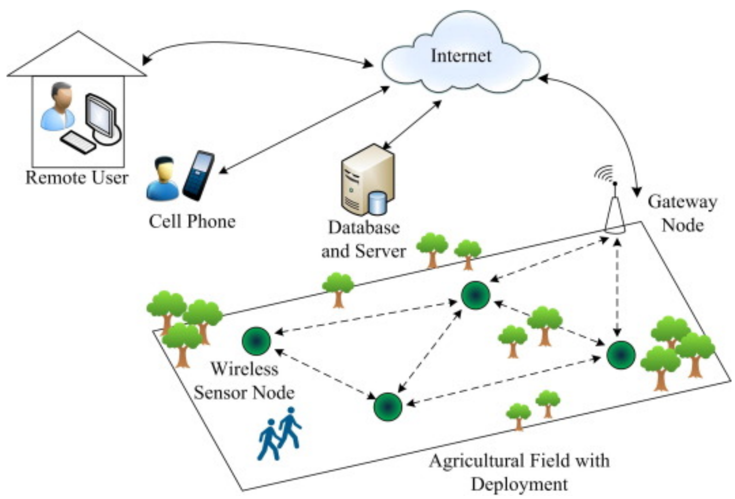

Figure 2.4: Wireless Sensor Network Architecture.

It is worth remembering that the monitoring carried out by these networks is in real time, that is, the time interval between data collection and computational presentation is considerably short, ensuring that the tasks are performed at the appropriate times. The main present focus of these networks is the management of irrigation systems with a focus on conscious and targeted use, however this focus can be opened to:

- Forest monitoring.

- Biomass study.
- Tracking of animals.
- Improved crop yields.

For each application, there is a different choice of sensor range that will compose the measurement nodes. Examples of sensors that can be used in the composition of the monitoring scheme are presented below [28], [32].

- Temperature.
- Humidity.
- Soil moisture.
- Soil acidity.

Like every new technology, some challenges must be overcome in order to achieve greater acceptance. There is a large investment in research destined for agriculture [33], [34], however, the acceptance of investment by producers is still a barrier to the popularization of this form of management.

The producers inexperience in interpreting the data pointed out by the monitoring system impairing efficiency and consequently the final results adding negativity to the technique [35].

Finally, forms of communication between detection and computing points are growing in search of optimizing data management allowing transfer over greater distances ensuring a greater coverage area for each node, thus minimizing the number of equipment that must be installed.

2.4 Internet of Things

The Internet-of-Things (IoT) is a current concept with a great application, its concept is the digital interconnection of everyday objects with the internet [36], [37]. In other words, IoT refers to a network of physical objects capable of gathering and transmitting data enabling remote control and even these objects to become service providers. Another characteristic is the connection of devices to the network through low power radio signals having as main reason that signals of this type do not need Wi-Fi or Bluetooth.

Currently, IoT is applied in the broader areas of cotidian life, however, have a constant search for insertion in agricultural areas, mainly as an alternative to circumvent the problem of water consumption and the deterioration of soil properties. Several communication protocols are suited to this need, the main ones being NB-IoT, LoRa and Zig-Bee [38], [39].

Some considerations should be taken into account when choosing the wireless communication technology because each one is composed of its own characteristics and could be a good choice for the application or not. Therefore, it is necessary to be aware of the limitations of each technology before choosing as well as the characteristics of the communication bandwidth of each one. Generally the division is performed in three categories according to the communication distance and can be classified as short, medium or long distance.

When dealing with agricultural productions, we work with long cultivation areas, requiring long range communications in order to minimize the number of equipment installed. Another factor that must be considered is, within the long range technologies, the energy consumption of each one [38], [40], [41].

2.4.1 IoT in agriculture.

The major contribution of the IoT in agriculture is the possibility of remote monitoring of the behavior of production indicators. This monitoring can help mainly in the control of applications of inputs, water, climatic interferences among other factors that directly interfere in the quality and yield of production.

Since there is the possibility of remote action, IoT has been very helpful in the concept of precision farming since there is the collection of data, they are sent via Internet to a control center that makes the right decisions. This decision making can be autonomous once the system has been designed for this, or carried out by the producer who analyzes the data and performs what he judges to be the best decision.

As said before, for agriculture there is a need for far-reaching technologies with low energy consumption. Among those classified as long-range, i.e. with a communication range greater than 100m, are NB-IoT, LoRa and Zig-Bee, SigFox, however when energy consumption is taken into account, LoRa can be considered as the most suitable for agricultural production in long áreas [38], [42].

Some works have already been developed in this scenario. In [43] a control system was developed for crops in general with sensors and actuators connected to a gateway installed with a software platform for IoT which in turn is communicated with a service server providing management with better management of farm. In [44] the concept of WSN is applied with the transmission of information collected by sensors to smartphone applications for the purpose of irrigation control.

In [45], different industrial agricultural facilities are studied in order to design new features based on the implementation of IoT paradigms. [46] applies the concept of IoT in predicting the occurrence of pests in crops with the intention of controlling the application of pesticides. [47] showed an IoT-based environmental control system for pigs.

Monitoring the quality of the water used by measuring physical and chemical parameters such as temperature, pH, conductivity and dissolved oxygen [48].

A brief comparison of wireless communication technologies is shown in the Table 2.1 [38].

Parameters/ Technologies	Bluetooth	ZigBee	Wi-Fi	LoRa
Standart	IEEE802.15.1	IEEE802.15.4	IEEE802.11	IEEE802.15.4g
Frequency	2.4GHz unlicensed	868/915MHz and 2.4GHz unlicensed	2.4GHz unlicensed	869/915/433MHz unlicensed
Modulation	GMSK	BPSK/OQPSK	BP-SK/OPQSK	GFSK
Data rate	1Mbps	20,40 and 250kbps	11-54 and 150Mbps	50kbps
Power consumption(Tx)	10mW	36,9mW	835mW	100mW
Range	indoor:20m and outdoor 100m	100m	100m	Urban 2-5km and suburban 15km

Table 2.1: Characteristics of Wireless Networks

The application of LoRaWan wireless communication technology is presented in the following section pointing out the contributions and some challenges encountered in its implementation.

2.5 LoRa in agriculture.

LoRaWan or LoRa applied to the LPWAN space is a resource that can be used to implement field connectivity with a monitoring center [49]. The applicability of this protocol can be found in several different functions, from data transfer as well as irrigation control system and fertilizer application in the fertigation production [50].

This communication protocol offers numerous advantages with regard to its application. Its scalability can be greatly exploited as well as its robustness and transmission security [51].

We can divide the implementation of an low-power wide-area network (LPWAN) monitoring system into steps from data acquisition to cloud storage for later use as shown in the Figure 2.5 [5], [52], [53].

Figure 2.5: LoRaWan Architecture.

End nodes are detection units consisting of a set of sensors defined for monitoring the desired variables. These nodes collect data and send them to an aggregation point responsible for receiving all data from the sensors and transferring it to a server. Once transmitted, the data is available for remote access and enabling interventions over long distances. However, for this transmission to be possible, this last point must be configured with a gateway. Gateways are network hardware that act as bridges between the user and the network [54].

The LPWAN architecture can be applied in several areas of agriculture and animal management. In [55], such architecture was used for the study of two cases, the first consists of monitoring the temperature of a horse stable and the second in the permeability test of agricultural land. Underground transmission was tested on [56], [57] based on the characteristics of the soil.

In [52], [58], [59] they use LoRa or LoRaWAN to perform data collection and transmission with an emphasis on low consumption and long communication range. Irrigation controls can also be mixed with LoRaWAN with em [60].

Chapter 3

Problem Statement

This chapter describe the problem for the development of the work as well as the detailed solution proposal, citing all the implementation steps and the equipment that was used.

3.1 Introduction

One of the greatest difficulties in agricultural activities is achieving financially profitable production results through the conscious and appropriate utilization of available resources, whether natural or not [12]. For this, the development of technologies aimed at the agricultural sector aid to obtain satisfactory and profitable results.

With a focus on hydroponic production, or fertigation, one of the biggest problems is performing real-time monitoring of data that is considered critical for decision-making in performing tasks such as irrigating and providing the fertilizer solutions at the right times [61], [62].

The need for this efficient monitoring is due to the fact that the lack of water can inhibit the growth and development capacity of the crops and the excess can contribute to the proliferation of fungi and pests in the roots. With regard to the fertilizer solution, each stage of plant development needs different amounts with different concentrations focused on meeting the momentary physiological needs. Another imposition of this type of agricultural production is to keep the pH of the nutrient solution supplied to the crop under control.

However, maintaining control of these factors is not an easy task, because, in addition to interference in agricultural management activities and the climatic conditions, physical characteristics of each planting region should be considered.

3.2 Proposed strategy

The proposed solution is the implementation of a monitoring system that performs real-time measurements of all parameters considered fundamental for the development of the culture and, based on an information bank, guide to the better decision in terms of management.

This requires the implementation, not only of the measurement nodes which are responsible for collecting the information, the entire network that includes communications between collection points and an interface where the producer can access and view what is happening.

The measurement nodes are composed of a set of sensors that will be responsible for the acquisition of the selected parameters. In addition, they are composed of the rechargeable power supply and also a System on a chip (SoC) that acts as a control center. It is programmed to perform functions such as reading sensors, processing acquired information and transmitting it later. Three different sensors were previously stipulated to monitor three variables: soil moisture, air humidity and temperature.

As stated above, having performed the data collection by the measurement nodes, the next step is to transmit the data either to a gateway. Transmission must be performed over long distances so that the number of nodes is reduced and the monitoring efficiency is maintained without the need for internet use. The reason for the latter condition is that access to the Internet in agricultural areas remote from urban areas is precarious or inconstant.

The flowchart of Figure 3.1 illustrates the schematic of the measurement nodes and also the processes applied to the data until its transmission. The tasks are performed as follows: The node receives the request for the information that the master wants via LoRa, wireless communication. Upon receiving the information, the node activates the sensors that are initially turned off, performs the reading through a General-Purpose Input/Output (GPIO) and performs the Analog to Digital converter (A/D) conversion of the response, which then undergoes internal processing that consists of converting the format of this information and it is sent as response from the request to the master, again via LoRa.

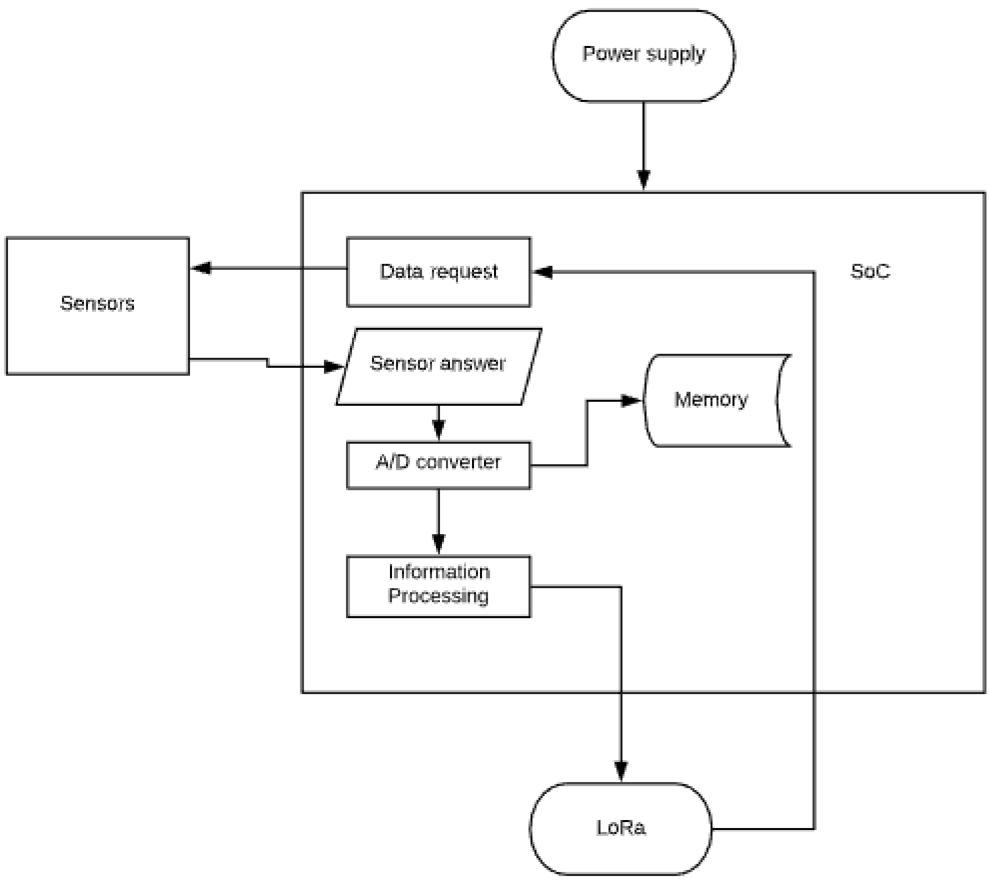

Figure 3.1: Information processing at the end-node

A second flowchart, Figure 3.2 is presented to illustrate data handling upon arrival at the end-node.

At the end-node, the requested information is received via wireless communication. An internal processing is performed and at each reception the information is sent to a server. Instantly after sending the information to the server, a new request is made for the slaves. In this way, there is a cyclical and intermittent communication.

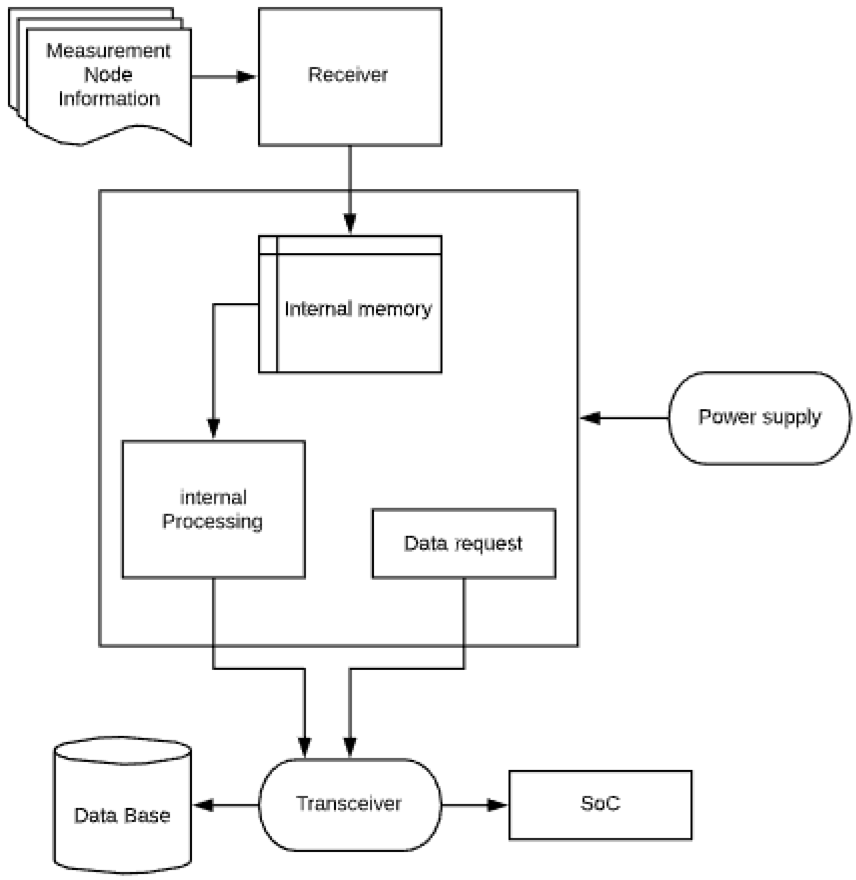

Figure 3.2: Information processing at the Server

For this, the LoRaWan communication protocol was chosen. Some conditions for choosing this protocol were the ability to communicate at long range with low energy consumption, the frequency of communication without internet connection.

This unnecessary internet connection does not apply to the last node as it needs to have access to the network in order to be able to send the information to the server and finally the information is available for remote access.

The firmware will be developed in using the ARDUINO-IDE, software available for download at [63], as provides all the requirements necessary for carrying out this work.

In terms of hardware, the sensors used are those found commercialy. Prototyping and testing was performed in the laboratory at the Polytechnic Institute of Bragança. This part will be further described in Chapter 4.

Chapter 4

Measurement node development

This chapter presents the steps taken for the development and construction of the measurement note. In particular, presenting the techniques applied and the technologies used in this context. The work was conducted in the Control, Automation and Robotics Laboratory (LCAR) located in the School of Technology and Management, IPB.

After this, the prototype for what would be the final product is presented. The logic of thought in the development of the design of the protective box and the images of the development of the project are presented. A cost analysis was also carried out on the parts comparing values between local and foreign markets.

4.1 Measurement node

The measurement node attached to a set of production stands will become a cyberphysical element responsible for monitoring the area through a series of sensors performing, whenever requested, a packet with the data collected at a gateway. For this work a sensorial block composed by sensors of relative air humidity, soil humidity and ambient temperature was defined and, in addition, ESP32 was used as the main SoC.

The Figure 4.1 shows the measurement node operating flowchart.

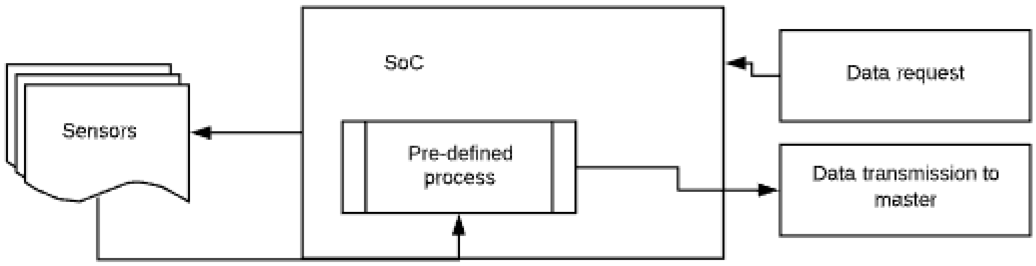

Figure 4.1: Sequence of treatment and orientation of information.

The chosen sensors were DHT11 and HL - 69, in which the first one reads the relative humidity of the air and temperature, and the second one the soil humidity. The operation of both is displayed in the Subsection 4.1.1 .

These sensors were available in the laboratory where the work was developed.

4.1.1 Sensors

The first sensor to be displayed is DHT11. It consists of a sensor capable of measuring relative air moisture between 20% to 90% and temperature in a range from 0 to 50 °C.

The temperature sensor element is an NTC type thermistor and the humidity sensor is HR202 type in which an internal circuit reads the sensors and communicates with the microcontroller by wire through a serial signal.

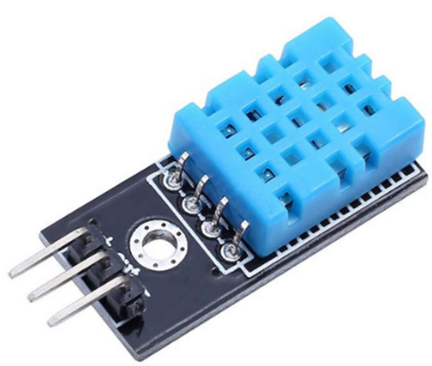

Figure 4.2: DHT-11 humidity and temperature sensor.

Specifications:

- Humidity measurement range: 20% to 90% RH.
- Temperature measurement range: 0º to 50ºC.
- Power: 3-5VDC (maximum 5.5VDC).
- Current: 200μA to 500mA, in standby from 100μA to 150 μA.
- Measurement humidity accuracy: $\pm$ 5.0% RH.
- Temperature measurement accuracy: $\pm$ 2.0 ºC.
- Response time: 2s.

The sensor used to read soil moisture is the hygrometer-type HL-69. A comparator is used as a data format converter between the sensor and the microcontroller in such a way that the input of this comparator receives the reading from the sensor transfering them to the microcontroller in the form of voltage.

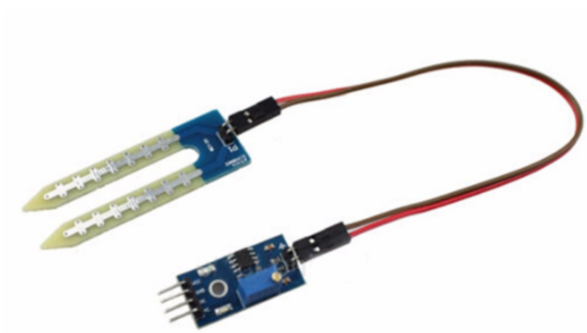

Figure 4.3: Soil moisture sensor HL-69.

Specifications:

- Operating Voltage: 3.3-5V.
- Sensitivity adjustable via potentiometer.

- Digital and Analog Output.
- Probe Dimensions: 6 × 2 cm.
- Comparator LM393.

4.1.2 SoC board

The microcontroller used is the ESP32 WiFi-LoRa. Its characteristics are extremely low consumption and extremely versatile in IoT, remote access, webservers and datalogger applications.

Figure 4.4: ESP32 WiFi-LoRa module.

- ROM: 448 KBytes.
- RAM: 520 Kbytes.
- Flash: 4 MB.
- Maximum clock: 240MHz.
- Wireless standard 802.11 b / g / n.

- 2.4Ghz Wifi connection (maximum 150 Mbps).
- Micro-USB connector.
- Wi-Fi Direct (P2P), P2P Discovery, P2P Group Owner mode and P2P Power Management.
- Operating modes: STA / AP / STA + AP.
- GPIO Ports: 11.
- GPIO with PWM, I2C and SPI functions.
- Operating voltage: $4.5 \sim 9$V.
- Analog to digital converter (ADC).

4.1.3 Hardware and Firmware

The firmware was developed in C language Arduino IDE thanks to compatibility in programming language. The assembled architecture is of the master-slave type which the End-Nodes, slaves, are in constant communication with a master gateway.This communication is performed exclusively by LoRa protocol being independent of the network presence, that is, it is possible to communicate from the master to the slaves without coverage of an internet network on site.

Figure 4.5 shows the master-slave architecture. This architecture can be implemented in two ways: request-response and request-action. In the first model, the master waits for responses coming from the slaves after the request, in the second, the task directions are given to the slaves in a unidirectional way, that is, without call-back.

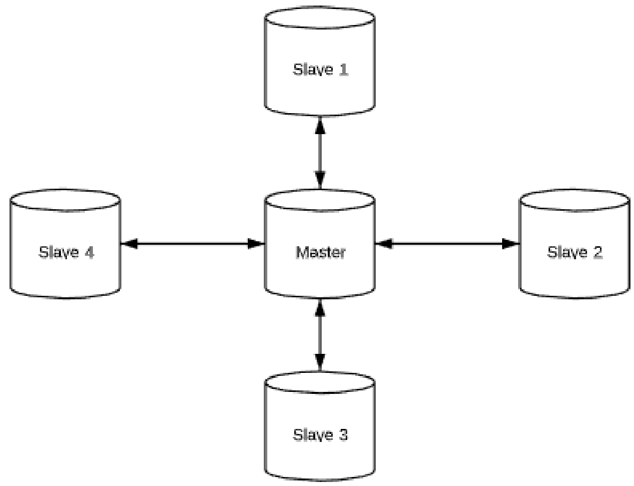

Figure 4.5: Master-slave architecture.

The measurement node act independently as regards the reading of the sensors carrying out the measurements at certain intervals of time. Each application requires different sensor reading intervals so it is necessary to study the application to finally stipulate the interval in an optimal way.

Due to the fact that they are configured as slaves, the measurement node only send the information read by the sensory block when requested by the master. In short, the master requests the information, the measurement node receive this request and send a data packet with the last reading.

Based on the comparison between the database and the instantaneous information acquired, the corresponding inputs is requested, being it substrate, water, air humidifiers activation, among others. The comparison thresholds are obtained through the knowledge of the producers in intersection with laboratory studies, always looking for the best development of the crop with the least waste.

In the model adopted for the work, only the master makes this comparison. Each index is analyzed separately, as well as the presentation of results, facilitating interpretation. A Figure 4.6 shows the electrical part of the measurement node prototype that was used for laboratory tests.

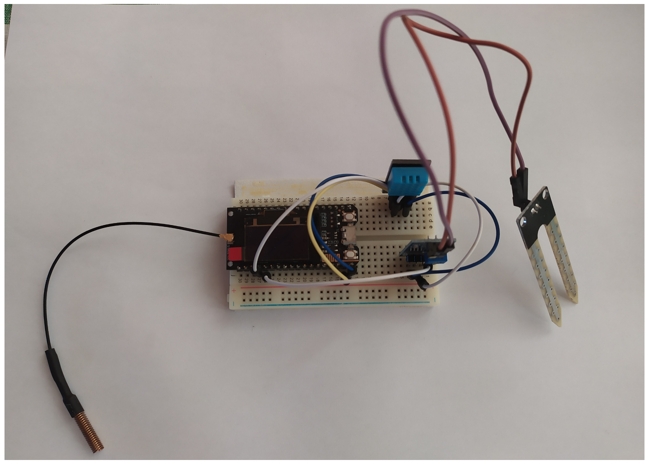

Figure 4.6: Electrical scheme measurement node prototype.

In the Figure 4.7 it is possible to see how the sensors are arranged when installed. The soil moisture sensor must be covered so that the two terminals are completely in contact with the soil, thus avoiding false measurements. On the other hand, DHT-11 must be on display, and must not inside the protection box or close to equipment that may interfere with local temperature and humidity.

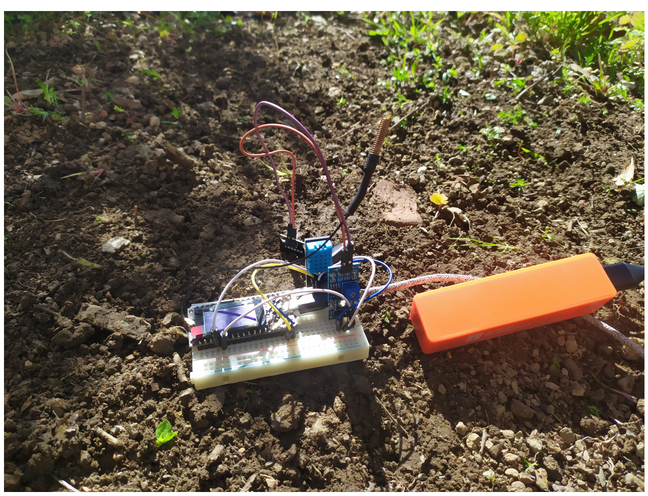

Figure 4.7: Electrical scheme measurement node prototype applied.

The firmware responsible for this treatment was developed in C language through the ARDUINO IDE and can be seen in the attachment A at `https://github.com/`

HigorRosse/Higor with the name "SlaveWiFi.INO".

It is valid to indicate that the sensors used in this work do not have high precision, which can impair the interpretation of data. In the case of sensors with greater precision it is possible to perform a more detailed analysis of the data and thus have a better final result. The number of sensors that can make up the block depends on the application of the system and can range from a single sensor to the total corresponding to the number of GPIO ports available on ESP32.

4.2 Platform as a Service

For the use of the collected data it is necessary to make it available and for this, a service platform was used. The sending of this information to the server is the responsibility of the master and, like the slaves, the SoC ESP32 WiFiLoRa was used, which connects to the server through the local WiFi network.

A header follows the data package so that upon receiving the response from the slave, the master knows that this is information and not memory junk. All this communication is carried out using LoRa protocol and is independent of internet connection. However, the main function of the gateway is only to bridge the data collected by the measurement nodes with the server, facilitating the visualization of the data and offering the possibility of remote intervention.

The availability of the information requires direct connection to a local internet network since the gateway works like a broker and connects to the local WiFi to upload the information. In this work we used the IBM page available at https://quickstart.internetofthings.ibmcloud.com/#/ destined for IoT project developments. The free version of the page was used where it is possible to see the data being sent by the gateway just by entering the device ID. However, there is the paid version that offers a greater number of interaction options.

On the page you can see all the information being uploaded, ie, if several information is uploaded together, the page configuration itself separates the information and prints it in different graphics. However, in order to do this, it is necessary to upload the information in a format compatible with the page. This way, after receiving the data from the master, it is necessary to convert the information to a String composed of all the data in order to upload it. This conversion is performed using the JSON library, the excerpt of the code that performs this conversion is presented in the figure below.

```
String createJsonString() {
  String json = "{";
    json+= "\"d\": {";
      json+="\"temperature\":";
      json+=String(data.temperature);
      json+=",";
      json+="\"humidity\":";
      json+=String(data.humidity);
      json+=",";
      json+="\"soil humidity\":";
      json+=String(data.umisolo);
    json+="}";
  json+="}";
  return json;
}
```

Figure 4.8: Excerpt from source code

It is worth remembering that for this operation it is necessary that the gateway is acting as a broker and connected to the local network. All this configuration is also done in C language using the Message Queuing Telemetry Transport (MQTT) package.

The diagram of the Figure 4.9 exemplifies the operation.

As said before, the firmware was developed in C language also in the Arduino interface and can be seen in Appendix A at `https://github.com/HigorRosse/Higor` with the name "MasterWiFi.INO".

4.3 Obtained Results

The whole set was tested first in the laboratory and then in the field. Due to the limited antenna power available, a maximum communication distance of 130 meters was achieved

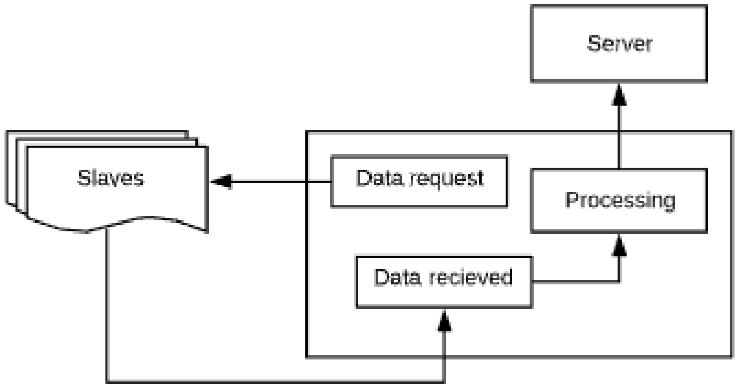

Figure 4.9: Operation flux

in the field in which the master/gateway was kept inside a room with an internet connection and the slave was gradually distanced until the signal was lost. The test was performed in an urban area, which reduces the communication range due to the presence of the buildings.

Figure 4.10: Esp32 module communication range - urban area

At first, a point to point communication was established, i.e. with only 1 slave. However, for real applications a greater amount of end-nodes is required and by changing the architecture to point - multipoint there was the problem of conflict in receiving the information since all the devices have the same frequency of operation and in addition, all the slaves sent the information at the same time to the master.

The solution found for this was to assemble a directional information request. Each device contains a unique MACaddress and therefore it was possible to build an architecture on which the master requested the information from each slave separately. In that sense each slave sends the data packet at different times minimizing the possibility of corrupt information reaching the master.

All settings were made manually, the SoC used contained only the basic communication settings. Various forms of communication and information management were tested, being in point-to-point and point-to-multipoint architecture, however, the one that best met expectations was the one presented above with the directional request.

In figure 4.11 it is possible to see using the serial monitor feature available in Arduino IDE the information received by the master and that is being sent to the cloud. Considering the same instant, the graphs presented on the web page corresponding to the measurement variations over time are also shown.

```
WiFi connected
Connecting to MQTT Server...
connected
Publish message: {"d": {"temperature":8.00,"humidity":38.00,"soil humidity":2.00}}
Publish message: {"d": {"temperature":8.00,"humidity":38.00,"soil humidity":2.00}}
Publish message: {"d": {"temperature":8.00,"humidity":40.00,"soil humidity":2.00}}
Publish message: {"d": {"temperature":8.00,"humidity":40.00,"soil humidity":2.00}}
Publish message: {"d": {"temperature":8.00,"humidity":39.00,"soil humidity":2.00}}
Publish message: {"d": {"temperature":8.00,"humidity":39.00,"soil humidity":2.00}}
Publish message: {"d": {"temperature":8.00,"humidity":38.00,"soil humidity":2.00}}
Publish message: {"d": {"temperature":8.00,"humidity":38.00,"soil humidity":2.00}}
Publish message: {"d": {"temperature":8.00,"humidity":38.00,"soil humidity":2.00}}
Publish message: {"d": {"temperature":8.00,"humidity":38.00,"soil humidity":2.00}}
Publish message: {"d": {"temperature":8.00,"humidity":38.00,"soil humidity":2.00}}
Publish message: {"d": {"temperature":8.00,"humidity":38.00,"soil humidity":2.00}}
Publish message: {"d": {"temperature":8.00,"humidity":39.00,"soil humidity":2.00}}
Publish message: {"d": {"temperature":8.00,"humidity":39.00,"soil humidity":2.00}}
Publish message: {"d": {"temperature":8.00,"humidity":39.00,"soil humidity":2.00}}
Publish message: {"d": {"temperature":8.00,"humidity":39.00,"soil humidity":2.00}}
Publish message: {"d": {"temperature":8.00,"humidity":39.00,"soil humidity":2.00}}
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Publish message: {"d": {"temperature":8.00,"humidity":39.00,"soil humidity":2.00}}
Publish message: {"d": {"temperature":8.00,"humidity":39.00,"soil humidity":2.00}}
Publish message: {"d": {"temperature":7.00,"humidity":39.00,"soil humidity":2.00}}
Publish message: {"d": {"temperature":7.00,"humidity":39.00,"soil humidity":2.00}}
Publish message: {"d": {"temperature":7.00,"humidity":39.00,"soil humidity":2.00}}
```
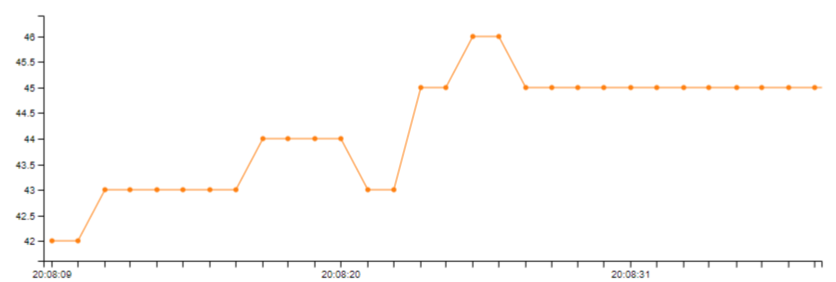

Figure 4.11: Data sent to the server.

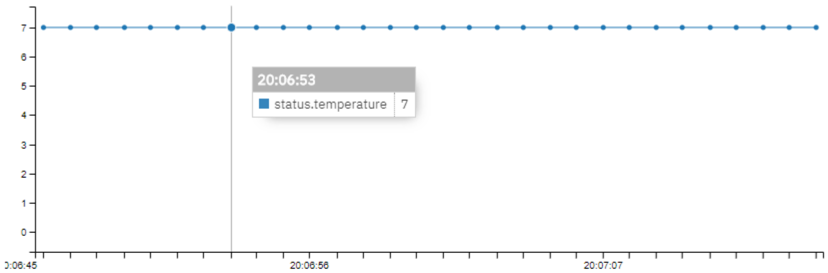
The following graphics show the information received by the IBM server and can be viewed from any interned connected device. The temperature is shown in °C and the relative humidity in %. As for soil moisture, a scale was established with three grading intervals in “Dry”, “Ideal” and “Excess water” where each interval is characterized by values obtained by the A/D.



Evento	Ponto de dados	Valor	Horário Recebido
status	temperature	7	19 de fev de 2020 20:08:39
status	humidity	45	19 de fev de 2020 20:08:39
status	soil humidity	2	19 de fev de 2020 20:08:39

Figure 4.12: Humidity graph.

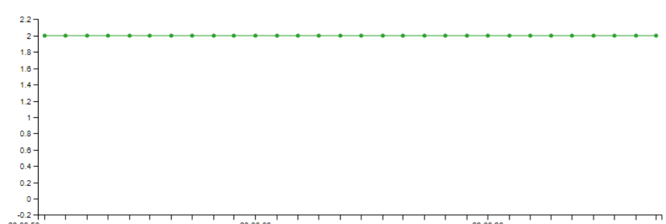
and



Evento	Ponto de dados	Valor	Horário Recebido
status	temperature	7	19 de fev de 2020 20:07:15
status	humidity	41	19 de fev de 2020 20:07:15
status	soil humidity	2	19 de fev de 2020 20:07:15

Figure 4.13: Temperature graph.

For visualization purposes, each interval received a corresponding mask from "0", "1" and "2" respectively for "Dry", "Ideal" and "Excess water". This mask is displayed on the serial monitor and can be seen on the web page. The system interprets this mask directly, however it is up to the user to interpret it when viewing it remotely.



Evento	Ponto de dados	Valor	Horário Recebido
status	temperature	7	19 de fev de 2020 20:09:28
status	humidity	48	19 de fev de 2020 20:09:28
status	soil humidity	2	19 de fev de 2020 20:09:28

Figure 4.14: Soil Moisture graph.

4.4 Power Suply

In order to make the system as autonomous as possible, a solar-powered battery charging system was implemented. Therefore it is only necessary to intervene for maintenance or in case there is any problem.

It was important to size the battery so that it could hold the system on for a few days in view of the problem that on rainy or cloudy days, the battery is not fully charged.

For the development of the work a solar charger v1.0 of 5V and 500mA capacity was used, presented in the Figure 4.15.

Figure 4.15: Solar charger.

The ESP32 is connected to the battery via microUSB and is connected to the charging kit directly ensuring constant charging according to panel limitations.

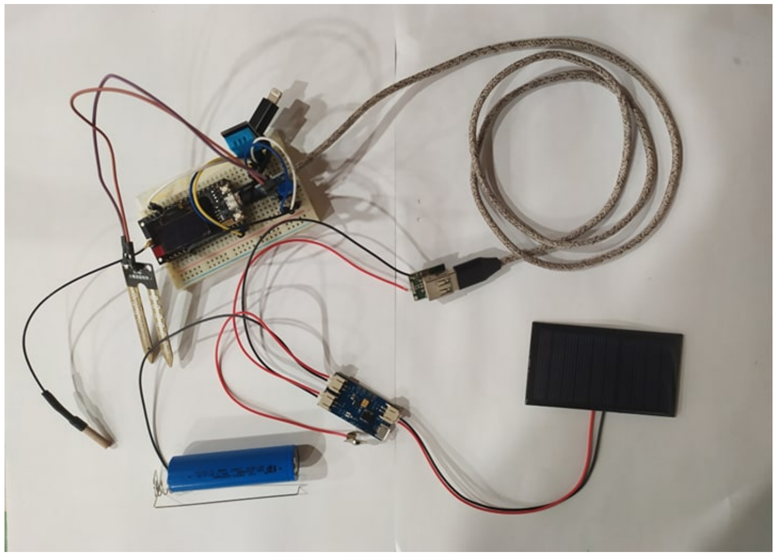


Figure 4.16: Complete layout.

The power consumed in standby mode and in transmission mode was obtained by analyzing the circuit shown in Figure 4.17. A shunt resistor was needed so that the current consumed by the system could be calculated indirectly based on the voltage variation.

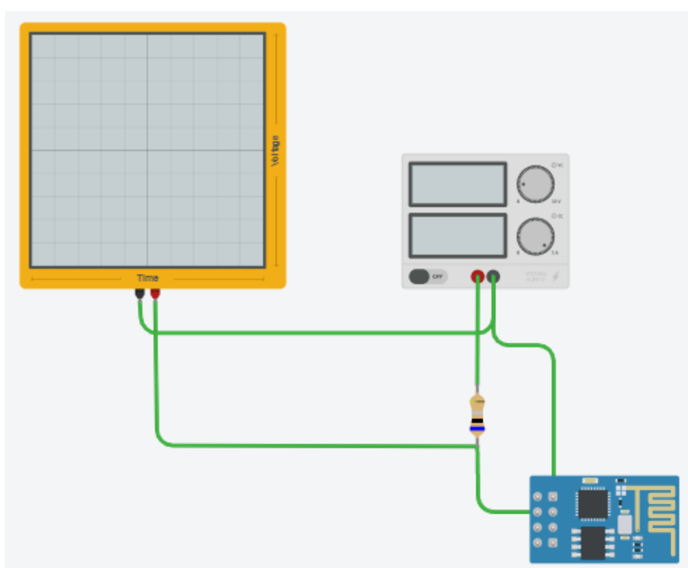


Figure 4.17: Test schematic.

When in TX mode, the system consumes more current causing the voltage on the shunt resistor to decrease. The variation of the voltage in Tx mode compared to the voltage in standbuy mode can be seen in the screen capture of the oscilloscope shown in Figure 4.18.

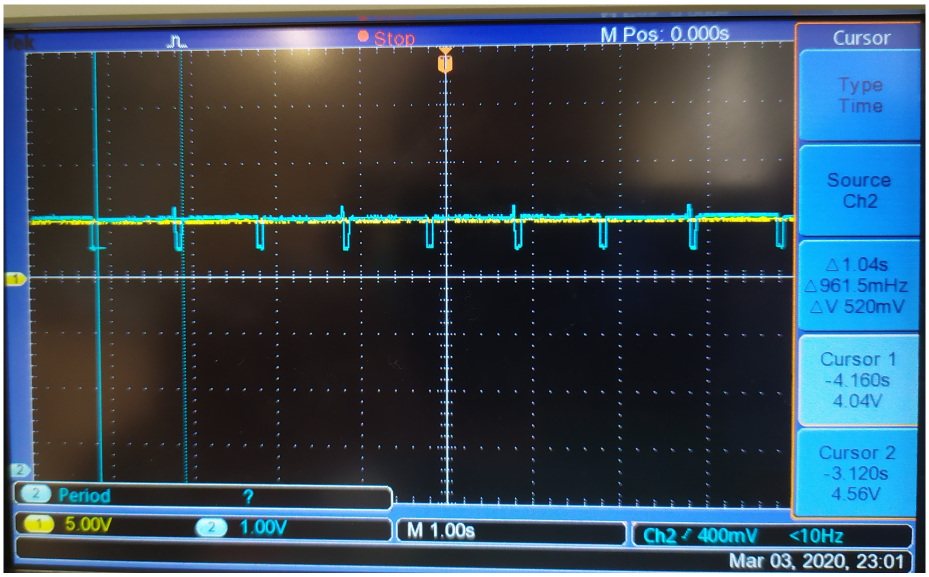


Figure 4.18: Osciloscope capture.

The consumption are listed below:

- Power consumed in standby mode: 150mW;
- Power consume in Tx mode: 620mW;
- Battery capacity: 2000mAh;
- Average power consumed per hour $\approx$ 28kW;
- Solar painel power: 2,5W.

The efficiency tests of the solar panel were realized during the winter with cloudy days and the operating threshold was with solar radiation of approximately 140 W/m^2 based on meteorological data available at `https://esa.ipb.pt/clima.php?clima=actual`.

4.5 Manufacturing processes

The Printed circuit board (PCB) was developed using the KiCad software, with download available at `https://kicad-pcb.org/download/`, in order to optimize size and cost. The Figure 4.17 shows the footprint and the Three Dimensions (3D) model of the circuit to be manufactured.

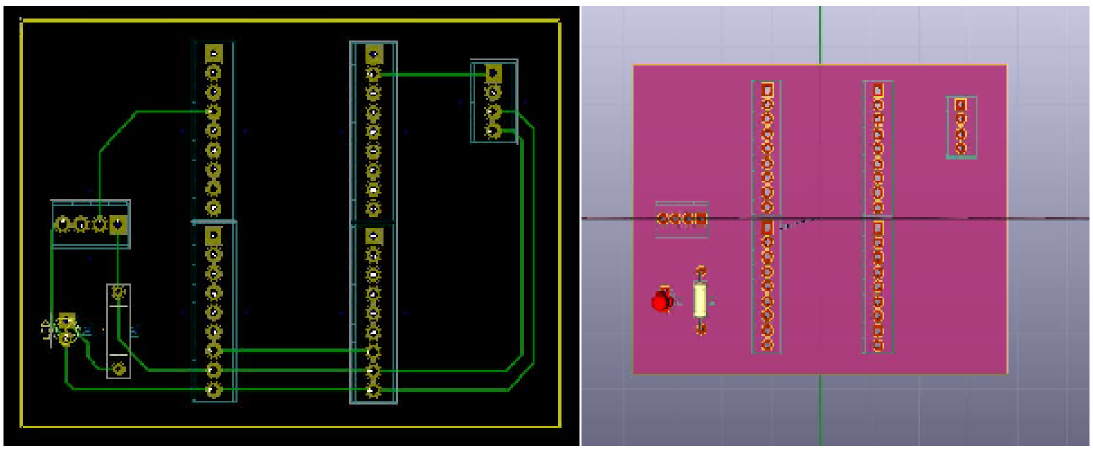


Figure 4.19: PCB layout.

After the completion of the software project, fabrication was carried out through the corrosion process following the steps: printing the circuit on transfer paper, transferring the circuit to the copper plate by means of thermal heating creating a mask for corrosion, after this corrosion with iron perchloride was carried out. The result can be seen below.

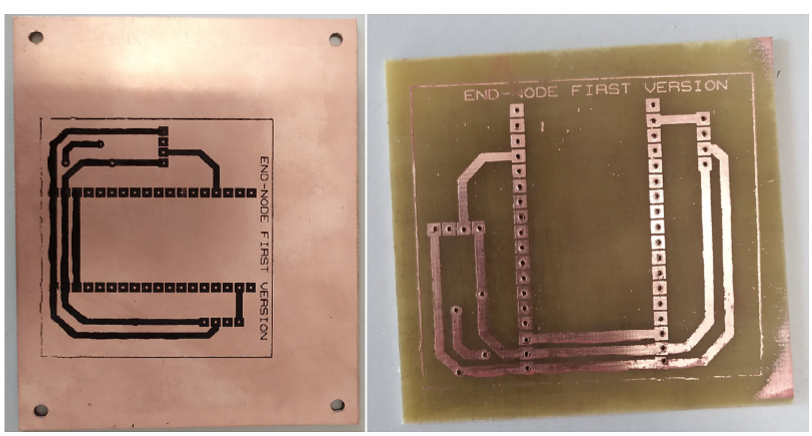
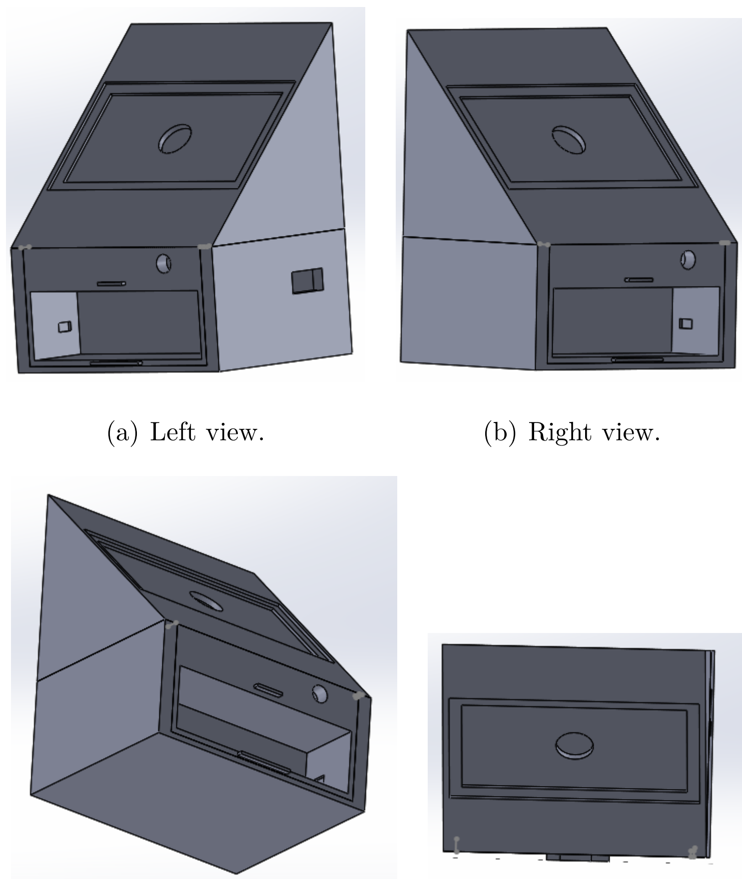


Figure 4.20: PCB manufacturing process.

Having tested the operation of the PCB and also with the physical measurements defined, a box was designed in SolidWorks in order to protect the developed electronic circuit as well as to group all system components. The design was conceived to facilitate the installation of the system in any location.

In Figure 4.19, it is possible to see the 3D model generated by the software after the end of the design. 4 views are shown for better visualization of the part.



(a) Left view. (b) Right view.

(c) Bottom view (d) Top view.

Figure 4.21: Box views.

The printing of the parts that make up the box were performed in the LCAR laboratory through the 3D printer fusion in Plastic polylactic acid (PLA) material. In the junctions of the pieces it was used silicone sealant once the system is exposed, unprotected from natural activities such as rain and fog. All joints were given a layer of silicone to ensure the protection of the internal circuitry.

4.6 Cost analysis of the prototype

A price analyst was carried out for the components that make up the prototype comparing the prices found on local and international sellers. The table 4.1 shows the total value for a single unit.

Components	Portugal market	External market
ESP32 WiFi-LoRa	27,40 €	11,07 €
DHT11	3,80 €	2,15 €
HL-69	3,19 €	1,84 €
Resistor	0,01 €	0,01 €
Led	0,05 €	0,02 €
PLA plastic	3,98 €	0,52 €
Total Price	38,43 €	15,61 €

Table 4.1: Prototype cost analysis table.

The cost value of the PLA was estimated based on the total value of the kilogram (kg) and the weight of the piece that was printed. Multiply the estimated value in the table by the total number of elements that you want to install in the system. However, for large quantities of each product, a reduction in the value of each item should be considered since the purchase can be made directly, without intermediaries.

Chapter 5

Results and Discussions

This chapter presents the discussion about the results obtained in the testing processes during the development of the work.

5.1 Sensors and Communication

Before the complete assembly of the system, the calibration of the soil moisture sensor was carried out in order to find a correlation between the values of the A/D Converter and the respective humidity in which the sample was comparing the value found with other sensors in order to have credibility of data.

The sensor used in the comparison was of the capacitive type with calibration performed using the same sample of the resistive in order to minimize handling interferences. Figure 5.1 shows the two sensors. Both were subjected to the same variation in soil relative humidity so that it was possible to find the characteristic curves.

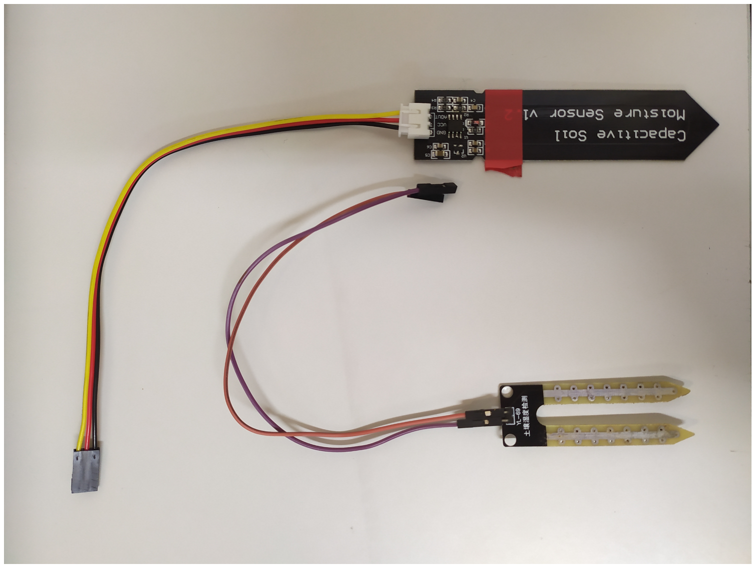


Figure 5.1: Soil moisture sensors.

The equations that represent each curve are shown below, where 5.1 presents the resistive sensor characteristic curve and equation 5.2 presents the capacitive sensor equation. After calibration, spot tests with known humidity were performed and the responses obtained were those expected for both sensors.

$$y = 0,3102x^2 - 17,295x + 424,58 \tag{5.1}$$

$$y = -3,3905x + 622,34 \tag{5.2}$$

Where y corresponds to the value of the A/D converter as a function of the humidity values.

The Figure 5.2 shows the calibration sample.

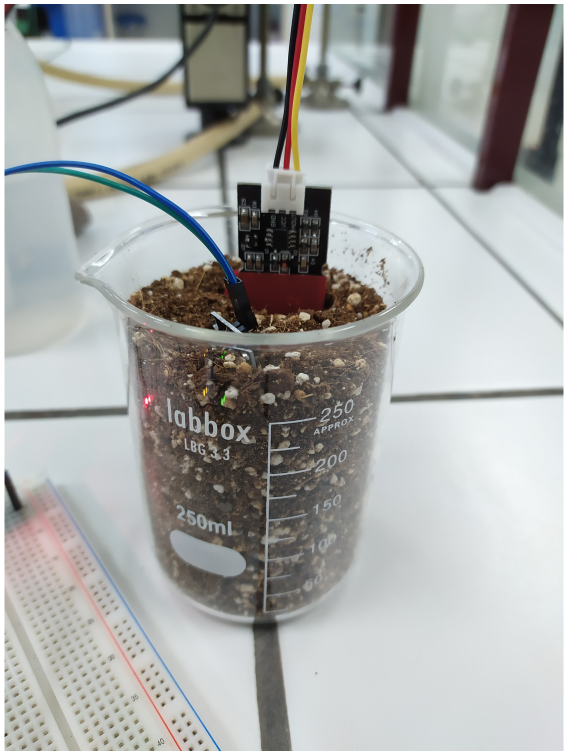


Figure 5.2: Calibration sample.

All sensory development was carried out in the laboratory, seeking the best possible performance taking into account the inaccuracies of the available sensors.

The tests for sending information were performed in different situations, however, due to the limitations of the version used, it was not possible to create a database.

5.2 Battery and physical elements

Given the power system that was used, during the presence of sunlight the system works with the energy generated by the panel, when this energy is not enough to supply the system, the rechargeable battery connected in parallel with the panel is used. However, the battery used has a capacity of 2000mAh, this capacity guaranteed the operation during the night, but not the operation for several days in cases where there were cloudy days and the supply of the panel was not enough.

The purpose of the box printed in PLA was to protect the electronic components of the element, the junctions between the parts of the box were sealed with silicone ensuring that the circuit was fully protected and waterproof.

The result of the assembly can be seen in the Figure 5.3:

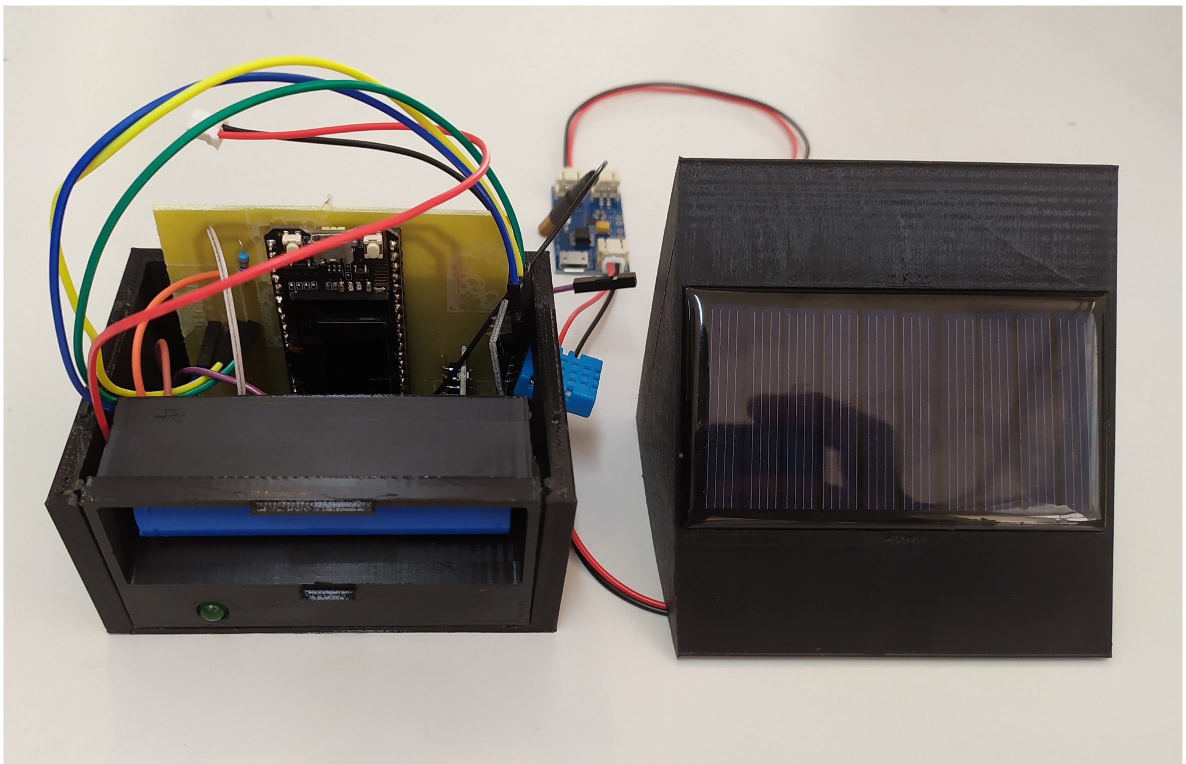


Figure 5.3: Final assembly.

Chapter 6

Conclusion

In this work, a cyberphysical system was developed with the intention of assisting and optimizing agricultural production by fertigation. A wireless communication system based on requests and receiving information from different devices was implemented in a master-slave architecture.

Given the intention of making the control process autonomous, a power system via solar panel with a rechargeable battery has also been implemented whose capacity needs to be adapted.

The greatest difficulties encountered throughout the work were the restrictions imposed by the server used to view the data, as well as the inaccuracies of the sensors that did not guarantee a good analysis of the data.

In terms of assessing the total functioning of the system, all elements worked as expected, from the cyberphysical sub-blocks within the end-node to the gateway and the upload to the server.

6.1 Future works

With the intention of optimizing the functioning of the cyberphysical network as a whole, it follows some ideas for continuing the work on topics that were the biggest problems during the development of this work.

- Optimization of the information request management, looking for a way to carry out the acquisition of the MACaddresses of each end-node in an autonomous way since the current way consists of informing the master manually.
- Adjust the capacity of the battery connected to the solar panel responsible for keeping the system active even on cloudy or rainy days.
- Improve the layout of the protective box by facilitating the placement of sensors.
- Increase the number of sensors for each end-node seeking better control.

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Appendix A

Documentation

In the link below it is possible to find the source code used as well as the 3D model of the box.

`https://github.com/HigorRosse/Higor`.