Automatic sampling of water content in the soil using lysimeters

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Abstract—**As more awareness is given to the effects of air pollution on ecosystems and human health, new measures and laws are established in order to better understand these effects and legislate emission ceilings. A great number of these measures are focused on studying and monitoring the concentration of pollutants in the ecosystems, namely, in plants, water and soil. Lysimeters are devices often used in soil water sampling given their accessibility and ease of use for monitoring soils. Nevertheless, they usually are operated manually which can be often inconvenient, as the user needs to wait for optimal sampling conditions before extracting a sample, which may be hard to predict. Furthermore, countries and areas with low precipitation rates have shown difficulty in keeping monitoring and sampling frequencies similar to those indicated in reference manuals provided by the European Commission. This happens due to lack of water in the soils, perpetuated by diminishing precipitation levels, which are expected to further decrease due to global warming. This research project proposes two devices capable of simplifying the sampling extraction process. One device built around a lysimeter, capable of automatically detecting optimal soil water sampling conditions and extracting a sample with minimal user intervention. Once a sample is extracted, the user is alerted and proceeds to collect the sample. The second device is a simpler iteration of the first one, where the user is alerted, when optimal soil water sampling conditions are detected, and proceeds to extract and collect the sample manually. The device communication is based on IoT technologies, and through a platform it is possible to manage and interact with the devices installed. These devices, together with the platform developed, will significantly ease the sampling procedure, increase sampling frequency, and allow the user to easily manage a large number of devices spread throughout a large area.**

Index Terms—**Pollution, Soil Monitoring, Water Sampling, IoT, Lysimeter**

I. Introduction

In order to better the air quality and reduce the pollution impact on human health and ecosystems, the European Union established the Directive EU 2016/2284 [1]. This Directive states that the Member States should reduce anthropogenic atmospheric emissions of polluting gases. Furthermore, each nation needs to implement national air pollution control programmes, so that those emissions are monitored and reported. In the case of Portugal, the implemented program and its measures are defined in the Portuguese decree-law nº 84/2018 (23rd October 2018) [2]. One of the measures delineated in the decree-law is collecting and analyzing several chemical components in the soil, vegetation and water within the soil, in several sampling sites throughout the Portuguese territory.

The sampling sites stationed in Portugal are equipped with manual sampling systems composed of lysimeters, which are devices that allow the extraction of water from the soil for analytical purposes [3]. There are several types of lysimeters with different structures and extraction methods, depending on the purpose for which they were designed [4]–[6]. The ones installed in the Portuguese sampling sites are Suction Lysimeters [7]. Lysimeters of this type can extract water when under vacuum pressure and, normally, require the operation to be performed by an in-situ operator.

In Portugal, the sampling sites are installed in relatively isolated areas where the water source is precipitation. So the probability of a lysimeter being able to extract a sample successfully depends heavily on the occurrence of precipitation. Given the type of lysimeters used, to collect a sample, the operator needs to proceed to the sampling site after a precipitation event, to collect the sample. These events are often hard to time and it is not guaranteed that the soil is humid enough for a sample to be extracted. These factors make extracting samples a very complicated process resulting in sampling frequencies much lower than the stipulated values.

Due to the global warming, high water deficit is expected to became a frequent phenomenon which among other important issues, affects the sampling rate in monitoring sites of the effect of air pollution in terrestrial ecosystems, which should be of two weeks, maximum, ideally shorter. According to the European Environment Agency [8], Southern Europe, and specially Portugal, have shown considerable decreases in the precipitation level of up to 90 mm per decade.

At times, the precipitation level is not enough to saturate the soil to acceptable humidity values, other times soil saturation decreases within the necessary time for the operator to reach the monitoring site, rendering water sample extraction using manual suction lysimeters impossible. This is not cost-effective, since sampling sites are spread throughout Portugal, with large distances between them, and plans to increase its quantity are under way, following the European Commission suggestions. Besides, it is not possible for the operator to know which soil humidity levels allow for extractions nor to measure the soil humidity remotely. Another important factor is that trips to the sampling locations come with costs, in time and money, so unsuccessful samplings can unnecessarily increase these costs. Another important aspect that impacts the extraction process is the soil texture. Different types of soil retain different amounts of water for different time periods, which influences the time window for when a sample is available for extraction. This added complexity hampers the scheduling of the extraction even further.

The main objective of this research project is to ease the sampling process explained beforehand. This was achieved through two devices developed throughout this project:

- **Full Collector:** Electro-mechanical device that collects water samples from the soil after raining, when the

water content in the soil is optimal. A Soil Humidity Sensor will measure the soil water content allowing the system's controller to detect its optimum level. This device automates the majority of the extraction process, so when a sample is collected the system will store it and alert the operator that a sample is ready for collection. In order to pull the water out of the soil, a Suction Lysimeter is used in conjunction with an Electric Vacuum Pump. The device messages a central server which alerts the operator through an email message, where the operator will only need to collect the extracted sample and reset the device.
- **Notificator:** This device is a simpler iteration of the first one. It only detects when the soil water content is adequate for sampling extraction and alerts the user, of this event. In this case, the operator will need to travel to the sampling site promptly, while the soil conditions still allows for extraction, and manually extract the sample.

Both devices need to be of low maintenance, meaning the only physical interactions with the user should be limited to collecting a sample and/or changing the battery, ideally only once or twice a year. They will also provide useful data of the sampling site's soil water content progression throughout the year. The operation of these systems also needs to take into account the soil texture, because different types of soil require different humidity threshold values in order to successfully collect the required quantity of water for laboratory analysis.

II. Legislation

A. European Legislation

On December 2016 the European Parliament approved the Directive (EU) 2016/2284. It states that in order to reduce the levels of air pollution and its effect on human health and ecosystems, every Member State needs to establish national air pollution control programmes. These programmes are primarily focused on reducing the anthropogenic atmospheric emissions of sulphur dioxide (SO_2), nitrogen oxides (NOx), non-methane volatile organic compounds (NMVOC), ammonia (NH_3) and fine particulate matter (PM2,5) [1]. Besides these objectives, the directive also aims evaluate the effectiveness of national emission reductions through monitoring its impacts on terrestrial and aquatic ecosystems. The Directive (EU) 2016/2284, also named the NEC (national emission ceilings) directive, specifically legislates the establishment of ecosystems monitoring networks to collect a set of defined indicators, that include soil solution chemical analysis [1].

According to the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) [9], in order to get coherent samples, the sampling period should be no longer than two weeks. Ideally, it should be done fortnightly or weekly sampling. If this sampling frequency is not possible, a monthly sampling could be performed, depending mainly on climate. As for the sample size, a volume of about 50 ml is sufficient for measuring the required concentrations using the analytical techniques available at the national environmental agency (Agência Portuguesa do Ambiente). It is mandatory to sample at fixed selected depths: 0-20 cm, 20-40 cm and 40-80 cm.

B. Implementation of the Directives in Portugal

The Portuguese decree-law noº84/2018 [2], implemented on 23rd October 2018, marks the transposition of the Directive EU 2016/2284 by Portugal and the implementation of the said National air pollution control programme. The required monitoring is described in the National Report 2019 for Ecosystem Monitoring in Portugal [7].

Three terrestrial and three freshwater sampling sites are situated throughout Portugal, with the terrestrial sites being located in Mata Nacional de Leiria, Área Florestal de Sines e Mata Nacional Terras da Ordem. Each of these sites has different temperature and precipitation profiles [7]. Currently, there are no lysimeters installed in Mata Nacional Terras da Ordem since the soil is poorly developed and it doesn't reach the required sampling depths. Therefore, taking the IPC Forest recommendations into account, 9 lysimeters were installed per location, making 18 lysimeters installed in Portuguese territory in total.

III. Sampling of Soil Water Content

In situ soil water sampling systems can be divided into two categories, active sampling and passive sampling. In situ systems are characterized by being installed directly at a certain depth within original soil, so the samples maintain their quality and characteristics allowing for accurate measures and data [10]. Passive systems, are normally formed of containers that define a boundary for water collection through water displacement or other passive methods [4]. On the other hand, active sampling systems, such as those used in this work, are not very intrusive to the soil but require an external force to extract water samples [10], [11].

Singh et al. [12] analyzed over 300 research articles on water sampling and collection. Methods like drainage lysimeters, pan lysimeters, ion exchange resin bags and membranes being the most common passive samplers, while wick lysimeters, suction lysimeters and suction plates appear as the most common active samplers.

A. Suction Lysimeters

Suction Lysimeters are the type of lysimeter installed in the monitoring sites and, consequently, used in this project. They are often referred as Suction Cups [11]. In these lysimeters, the sample extraction happens when vacuum pressure is exerted in a tube inside the lysimeter with a porous segment at the end, that allows the water to pass through its pores. They are, normally, attached to a tank or container, so when a sample is extracted it is placed in the container. Once the sample is inside the container, it won't be under pressure anymore, thus remaining in place until its collection [13]. The installation setting of a lysimeter is depicted in the figure 1.

The manual operation implemented in the monitoring sites has a price of 341.03€ including the three lysimeters, the manual vacuum pump and other extraction equipment, such as clamps and tubes. The price can also be considered of 224.49€, if the lysimeters are excluded.

Q. Wang et al. [11] analyzed the characteristics of conventional lysimeters, identifying that the main advantage of

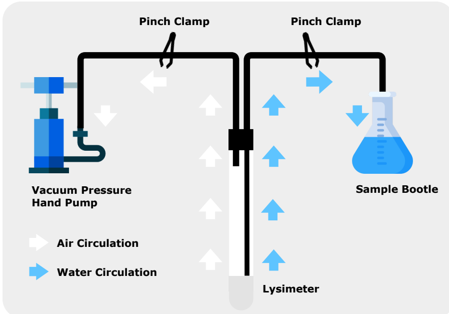

Fig. 1: Installation setting of a Suction Lysimeter [13]

suction lysimeter is the facility of installation and operation, which allows for undemanding incorporation of lysimeters in autonomous systems, at low capital cost.

B. Automated Lysimeters

Several devices were implemented with the objective of automating the process of soil water sampling through lysimeters. Currently, there are several commercial automated lysimeters referred as smart lysimeters. From the options available in the market, two stand out: the Smart Field Lysimeter from Meter [14] and the Eijkelkamp Smart Lysimeter [15]. There are also other devices, based specifically on suction lysimeters, named Automated Vacuum Lysimeters (ASL), although their market is limited [16].

These devices provide accurate and diverse data but are mainly used for measuring precipitation, evapotranspiration, and deep drainage, and not for water sampling. Besides, since they are based on weighing lysimeters, their installation is hard and disturbs the existing soil profile, despite the Smart Field Lysimeter being capable of simulating true field conditions.

ASL use electronic controllers as well as a set of vacuum sensors to keep the vacuum applied to suction lysimeters or suction plates [16]. ASL use tensiometers, or other methods, vacuum sensors and electronic controllers to measure soil-water tension and estimate the optimal level of vacuum that a suction sampler needs in order to extract a sample. This process makes ASL the most accurate method of soil water sampling. ASL can operate and record data for long periods of time, with minimal supervision, while also being easy to replicate [16].

C. Water retention in different types of soil

Water retention and availability depend heavily on the type of soil. Characteristics such as grain size and chemical composition affect the moisture content, water potential of a soil and as its ability to retain water [17]. This characteristics have a great effect on the ability to extract water from the soil. In the case of a suction lysimeter, water retention of the soil directly affects its ability to extract water. In order for the lysimeter to extract water, the surrounding soil needs to be saturated, or close to, in water content at field capacity [13].

F. Meskini-Vishkaee et al. [18], predicted the soil moisture retention curve for different textures of soil. It was concluded that clayish soils retain the most water and sandier soils retain the least water, while loamy soils roam in the middle of the two. When a soil is saturated, the more water content there is, the easier it is to extract. Although, since soils with lower saturation degrees require less water to saturate, they may reach saturation faster than soils with higher saturation degrees, and provide faster extractions.

IV. Supporting Technologies

Given the device's communication component, it is important to understand the diverse IoT technologies in order to chose an adequate technology for the device, more specifically the IoT wirelles technologies and the Application Layer Protocols built atop of those technologies. Furthermore, additional supporting technologies include humidity sensors, both described below.

A. Internet of Things (IoT) wireless technologies

The IoT wireless technologies can be divided into five categories, according to their coverage area: Proximity, WPAN, WLAN, WMAN and WWAN [19]. Wireless Wide Area Network (WWAN) technologies are used to connect devices on a national or global scales and are built on top of existing infrastructure. Inside the WWAN, some technologies are designed for long range communications and battery powered devices, which can be grouped into the LPWAN (Low-Power Wide-Area Network) technologies [20]. Four technologies were studied in this work: LoRaWAN, SIGFOX, NB-IoT and LTE-M, and classified according to their coverage in Portuguese Territory, Range, Data Rate and Cost, as seen in table I.

TABLE I: IoT wireless technologies comparison

Technology	Coverage	Range [m]	Data Rate [b/s]	Cost
LoRaWAN	Medium	$<$15km	0.3-38.4k	Low
SIGFOX	High	$<$40km	100	Low
NB-IoT	High	$<$35km	Up to 1000k	Medium
LTE-M	None	-	Up to 100k	Medium

From the many protocols used in IoT systems, there are four widely accepted: MQTT, CoAP, AMQP and HTTP [21]. A simple comparison between the protocols is shown in table II.

TABLE II: IoT Application Layer Protocols comparison

Technology	Architecture	Protocol	Security
MQTT	Publish/Subscribe	TCP	TSL/SSL
CoAP	RESTful Request/Response & Resource/Observer	UDP	DTLS
AMQP	Request/Response & Publish/Subscribe	TCP	TLS/SSL
HTTP	RESTful Request/Response	TCP	TLS/SSL

Several successful projects, in the Natural Environment context, have been implemented with IoT technologies. Projects such as forests monitoring, precision agriculture [22], [23], greenhouse control systems [24], etc. G. Valecce et al. [25] carried out several field experiments on the evaluation of the NB-IoT performance in rural areas, where the technology showed good coverage and specially good results in underground areas.

B. Soil Humidity Sensors

The soil humidity sensor is another very important component in both the Full Collector and Notificatior devices. A great part of the soil humidity sensors can be divided into two categories: resistive or capacitive sensors. The resistive sensor measures the soil resistance through probes, that can be calibrated to a humidity value. The capacitive sensors measure the capacitance of the soil through a pair of electrodes.

S. Adla et al. [26] tested several low-cost sensors, of both types, and verified that the capacitive sensors provided better precision scores and that their performance can match the standard sensors if soil-specific calibration is used. The capacitive sensors, despite being more expensive, can be built of less corrosive material.

V. Requirements

Given the project objectives, both devices need to follow the ensuing steps: assembly and calibration, installation, sample detection, user alert, sample collection. The devices are planned to be used on a national scale, by several different people, in several different locations with different types of environment and soil. Given these characteristics it is necessary that the system complies to several requirements:

1) **Low cost:** The final cost should be in the same order of the current operation costs.
2) **Efficient use of power:** In most cases, the systems will be located in isolated places, where access to power networks is not possible, needing to resort to batteries and maximize its lifetime.
3) **Reachable:** Since the devices can be installed in remote locations, they need to be able to maintain communications even in areas with low network coverage.
4) **Ease of use:** Most users of the systems may not have an engineering background or knowledge about the system structure. Therefore the user interface must provide a friendly method for the user to interact with the system.
5) **Adaptable to multiple soils:** The devices will be installed in many different types of soil. So its essential that the operator installing the equipment is able to calibrate it in accordance to the soil where it is installed.
6) **Reliable:** The devices need to be able to deal with unexpected errors and conditions and the sensors need to be accurate, in order to avoid unnecessary trips to check the device.

VI. Architecture

A. Sampling Hardware

The sampling hardware used in the Full Collector device was changed from the manual operation described in the figure 1. In this architecture, shown in figure 2, an Electric Vacuum Pump exerts negative pressure, or vacuum, in the tubing system. A set of normally closed Electric Solenoid Air Valves blocks the negative pressure from being exerted on the corresponding lysimeter and container and allows each lysimeter to be pressurized independently. When the valve is activated and opened the vacuum is propagated to the corresponding lysimeter and container. After some time, the lysimeter cup's pores will be filled with water that will start flowing through the lysimeter tubes. Once the water starts reaching the container, its flow will be stopped and the sample will be kept in the container. Using a water level sensor it is possible for the system to detect if the sample reached the required volume and stop the extraction. This sensor should be contact-less, meaning it can be installed outside of the container. A vacuum pressure sensor allows the system to measure the pressure exerted by the pump and control it so that the optimal pressure level is exerted.

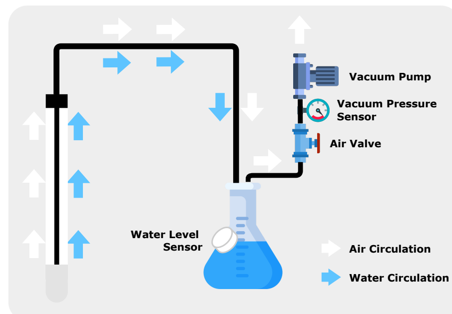

Fig. 2: Device extraction process using an electric vacuum pump and a suction lysimeter

B. Hardware Architecture

The device's hardware components can be grouped into several sections: the sampling hardware, the power supply, the operation control and the communication. The power supply consists in a battery powerful enough to support the electronics and the extraction hardware, in the Full Collector device. The capacity of the battery should also allow the device to have a battery lifetime large enough to avoid frequent battery changes. A solar panel may also be used to to prolong the devices battery lifetime. Some solar panels require charge controllers protect batteries from overcharging and overheating, however they are generally recommended for batteries with over 20Ah capacity. On the other hand, solar trickle chargers, if chosen correctly, provide a reliable way of maintaining a battery level without overcharging risk and need for additional circuitry.

The operation control section is based on two hardware components: the MCU, which is connected to the other all the other components, reads sensors output and controls the sampling hardware; the soil humidity sensor, which should be installed at the defined depths.

The device communication section is implemented trough a communication module, described in the following section.

The figure 3 shows the Hardware Architecture Diagram, where it is possible to discern the different hardware components and their respective sections.

C. Communication

This communication module exchanges messages between the server and the device, through IoT wireless technologies. Given their characteristics, LPWAN technologies are adequate

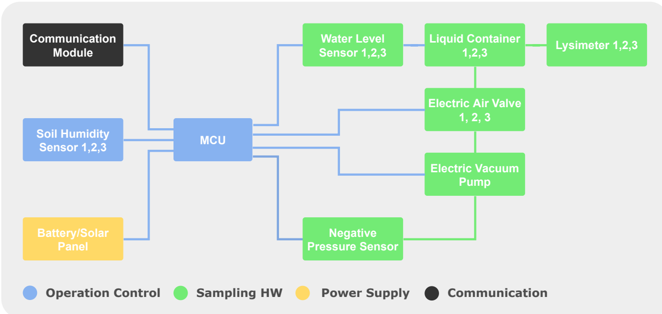

Fig. 3: Full Collector Hardware Architecture Diagram

for the system and comply with its requirements. The technology chosen needs to be prominent in Portuguese Soil, capable of reaching the defined sampling locations and affordable.

D. Operation Control

The operation control software can be divided into two main components: the humidity sensors control and the sample extraction control. The humidity sensors control verifies if the soil humidity level is superior to the humidity threshold and triggers the extraction mechanism, which is controlled by the sample extraction control. The sample extraction control is responsible for keeping the lysimeters pressurized and detect when samples are collected. When an alert needs to be sent to the operator, such as samples being ready for collection, a message should be sent to the server, that in turn alerts the operator. The device should also be able to receive messages from the server such as sleep timestamps or other configuration data.

E. Server

The server can be divided in five sub-modules: the device control, the data storage, data visualization, user alerts and forecast data fetching. The user/operator interacts with the server,through the data visualization module, where it is possible to register new devices, configure them in real-time and view the data sent by them. When a device is installed, it sends data to the server, such as the sensor's values and events like an extraction starting or ending, and others, which are also stored in the server data storage module. When the server receives an event it alerts the user device, through the user alerts module, so that the user can collect or extract the sample. The server stores the received data and responds to the devices with information such as configuration data. Which data is sent to the device is defined in the device control module. This module receives the device messages and according to the message content and the data stored in the server, decides which data to send back to the device. By having the device entering sleep mode until raining periods, the device effectiveness and battery usage will be more efficient. This can be achieved by having the server request meteorology predictions an external service, through the forecast data fetching module, and sending the data to the device. The figure 4 illustrates the software and hardware components, and their interactions.

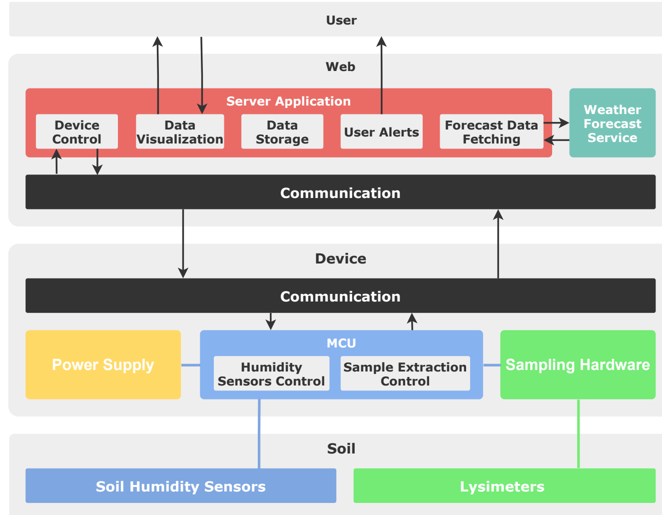

Fig. 4: Full Collector Device Architecture Diagram

VII. System Implementation

During this work, a implementation of the Full Collector was assembled, following the architecture previously described.

A. Sampling Hardware

The lysimeters used in this implementation were the Soil Solution Access Tubes from the Irrometer Company. These lysimeters are sized according to their installation depth, meaning they are 20, 40 and 60 cm in size, respectively, where the top part of the lysimeter is placed on soil level. Their recommended vacuum pressure for extraction ranges from 70 to 80 kPa. It was also used the D2028 Electric Air Pump from Airpon. This pump is powered through a 12 V voltage and exerts negative or positive pressure ranging from -70 to 250 kPa. As for the valves, three Normally Close 12V Electric Solenoid Air/Water Valves, from Hoypeyfiy, were used, and three 50 ml glass containers as well.

B. Sensors

Three Capacitive Soil Moisture Sensors v1.2 from DF ROBOT were used. They are made of corrosion resistant materials that gives the sensors extended lifetime and can be powered by voltages in the 3.3 to 5.5VDC range, while the output voltage ranges from 0 to 3VDC. The vacuum pressure sensor used was the MPX4250DP, which supports a maximum pressure of 250 kPa and has a supply voltage of 5.1V. It also has a liner relation between the applied pressure and output voltage, that allows for easy calibration. The water level sensors used were the DF Robot XKC-Y25-T12V Non-contact Digital Water/Liquid Level Sensor. They can be powered by voltages in the 5 to 24V range and work on non-metal surfaces such as glass, plastic, ceramic, etc..

C. Communication

The LPWAN spectrum provides adequate options for the device communications, given the requirements. Inside this spectrum, NB-IoT is a suitable option, has full coverage in Portuguese territory and provides an array of several hardware modules compatible with the technology. Taking this into consideration, an agreement was made with Altice where a SIM card was provided for this project. This SIM card allows its device to be connected to the Altice NB-IoT network. One of the compatible modules with the Altice NB-IoT SIM cards and network is the BC66 from Quectel. The BC66 is a high-performance multi-band LTE Cat NB1 module that supports several protocol stacks and frequency bands. The module used in this implementation was the BC66-TE-B, which is a testboard that incorporates the BC66 module and provides additional features for easier integration with other devices and micro-controllers, while maintaining important characteristics like low power consumption and high durability. The BC66 module can also be programmed and used as an independent micro-controller. Although, its hardware specifications are not compatible with this device, therefore another more capable micro-controller should be used.

The protocol used was CoAP, since the CoAP request/response architecture is fitted to the device architecture and is easy to integrate with HTTP servers. Nor the BC66 module nor the CoAP library used support DTLS security. The module was programmed to constantly check if a message was received from the MCU and, when received, send it to the server and redirect the server response back to the MCU. If the server response is not received, the module re-sends the message.

D. MCU

The micro-controller used in this implementation was the 5V 16 MHz Arduino Pro Mini, which is a well documented and easily acquirable micro-controller. The Pro Mini includes the ATmega328p micro-controller and is a more cheap and power efficient alternative to other Arduino micro-controllers. It provides enough interfaces to connect the sensors, communicate with the BC66-TE-B module and control the pump and valves. This MCU doesn't have a precise timer, so an external DS3231 RTC was used. The DS3231 has an alarm feature that can be programmed to wake up the Arduino. Since the sensors require GND and Vcc lines, the Arduino doesnt have enough pins to support all the components. Therefore, a Grove Base Shield V2.0 was used, which provides multiple analog and digital grove connections that contain a Vcc and a GND lines, and two pins that connect to the Arduino. However, the Base Shield is not pin compatible with the Arduino Pro Mini, so a Pro Mini UNO Shield Adapter Board, from OPEN-SMART, was used. This board allows the Base Shield and Arduino to be connected while providing other features such as a 5V voltage regulator that allows the board to be powered by voltages of up to 15V. The Arduino is able to measure the battery level by comparing its Vcc voltage with an internal 1.1V, given that when the supply voltage drops the Vcc also faintly drops.

The Arduino was programmed according to the diagram 5. Firstly, it checks if the soil humidity surpassed the threshold. When this happens the extraction process is triggered on the respective lysimeter where it is pressurized. If a sample is collected the extraction stops and an alert is sent to the server. Lysimeters that are in the extraction process are constantly being pressurized in order to keep the required pressure level. When no lysimeter is extracting, the device sends the sensors data and receives a response with a sleep timestamp or configuration data to be updated. The sleep timestamp indicates that the device needs to enter in sleep mode and wake up at the time specified in the timestamp. The configuration data includes new humidity threshold values that need to be updated and when the device receives them, it should send a confirmation message to server.

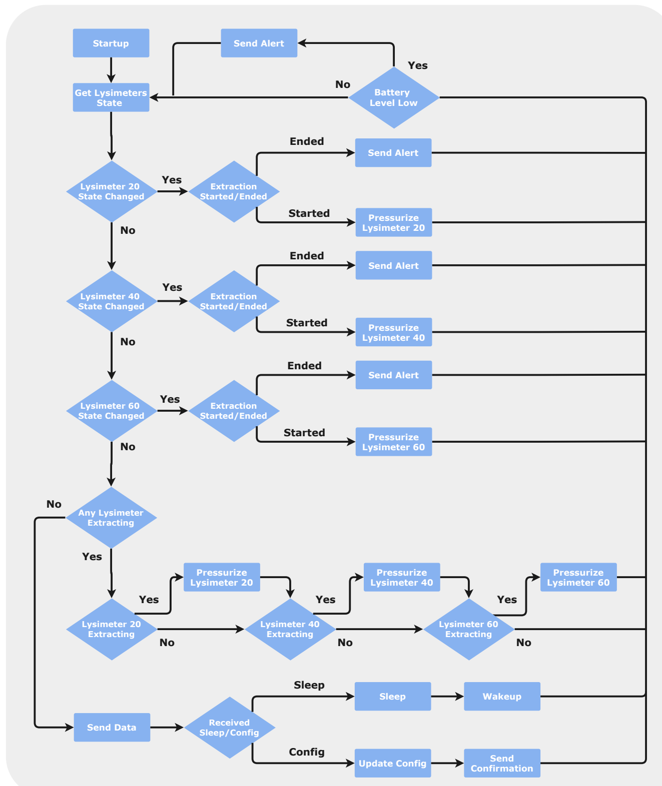

Fig. 5: Arduino Pro Mini Software Architecture

E. Battery and Solar Panel

In order to power the 12V pump and valves, a 12V sealed lead acid (SLA) battery was used. This battery has a capacity of 8.4Ah. A solar battery trickle charger was attached to the battery and provided, at most, 167mA. Since the power of the solar charger is short, there is no risk of overcharging and no need for a charge controller. However, since the pump and valves are not directly connected to the MCU, a driver circuit, was used to activate the pump and valves through 5V digital signals from the Arduino.

F. Server

The server is divided into four applications: the CoAP server, the HTTP server, the database and the OpenWeatherMap service, as seen in the figure 6. The CoAP server functions as a proxy between the devices and the HTTP server, that exchanges messages between them. The HTTP server exposes a Website where the users can access and manage the devices, read their data history, manage other users, etc.. The HTTP server uses a database application where it stores all the device and user data. The HTTP server also has an interface that allows email messages to be sent to the users/operators with device alerts. Lastly, the Weather Forecast Service used was the OpenWeatherMap which is an online service that provides global meteorology data, including weather forecasts data for any geographical location. Through this service it is possible to calculate sleep timestamps during precipitation events.

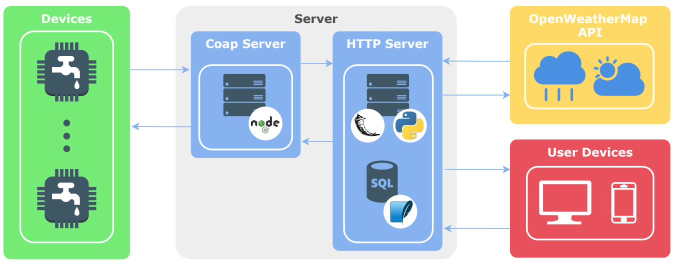

Fig. 6: Server Software Architecture Diagram

VIII. System Evaluation

After assembling the Full Collector device, it was submitted to several tests in order to evaluate the operation of each component, calibrate several device parameters and, ultimately, install the device in a monitoring site. Each test is detailed in the following sections.

A. Device Calibration

Both the soil humidity and pressure sensors need to be calibrated. The respective calibration processes are described bellow.

1) Pressure Sensor: As previously stated, the relation between the negative pressure applied on the sensor and the output voltage is linear. Therefore, a manual vacuum pump with a barometer was attached to the pressure sensor. Increasing levels of vacuum pressure were exerted in the sensor and its output voltage was compared with the barometer reads, in kPa. The manual pump is hard to control which caused the values to be spaced irregularly. The output voltage levels are mapped to an integer value between 0 and 1023.

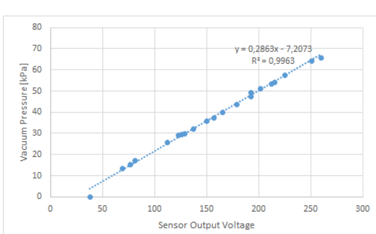

Fig. 7: Barometer negative pressure values as a function of MPX4250DP sensor output voltage

The graphic in the figure 7 shows the output voltage in the horizontal axis and the barometer values in the vertical axis. The linear relation between the negative pressure and the sensor value is verified, and is described as:

$$y = 0{,}2863x - 7{,}2073$$

Where the x corresponds to the sensor output value, mapped between 0 and 1023, and the y to the negative pressure value, in kPa. This result is verified by the high correlation coefficient present in the graphic.

2) Soil Humidity Sensors: The soil humidity sensors also need to be calibrated, in order to obtain a relative humidity percentage. In this calibration, the sensor voltage output, mapped between 0 and 1023, is measured secondly during 2 minutes. This process is done with the sensor fully submerged underwater and repeated with the sensor placed on air. Since there is an inverse ratio between the sensor output value and the soil moisture, the output value is higher when the sensor is placed on air then on water. Considering that the maximum output value, when the sensor is placed on water, corresponds to 100% humidity and the minimum value, when the sensor is placed in the air, corresponds to 0%, it is possible to calculate humidity percentages by interpolation, using those values.

This process was performed on three different sensors and the final results are described in the table III.

TABLE III: Minimum and maximum sensor output values obtained during the calibrations of three sensors

Sensor	Minimum Value	Maximum Value
Sensor 1	887	585
Sensor 2	895	585
Sensor 3	892	580

B. Soil Humidity Threshold Study

Before installing the device it is also necessary to study the soil of the installation location, in order to obtain the humidity threshold values specific to that soil. This study consists of several iterations, where a 30cm lysimeter and a soil humidity sensor are installed in a container, with known dimensions, that is filled with the soil in study. By pouring water in the container, it is possible to mimic a precipitation event, where the volume of poured water can be related to the precipitation level. The container used had a shape similar to a cylinder with a diameter of 49.5cm. Therefore the poured water volume can be calculated through the cylinder volume definition

$$Volume[ml] = BaseArea[cm^2] \times WaterLevel[cm]$$

$$= 2734cm^2 \times 0.1 WaterLevel[ml]$$

where a water level of 1mm corresponds to 273ml. The container has holes at the bottom that allow water to flow to a different container and be collected.

By having the lysimeter continuously try to extract the sample, it is also possible to relate the amount of water extracted with the soil humidity level and precipitation level. Each iteration lasts at most four hours and consists in pouring water evenly in the container and pressurizing the lysimeter. Every minute, the soil humidity value is logged. At the end of the iteration the volume of the extracted sample and water leaked out of the container are also logged. In the next iteration, the water level is increased, the collection sampled is ditched and the process is repeated. New iterations are performed with increasing water levels until the collected sample reaches 50cc in volume or the sample size stabilizes.

The study was performed in two soil textures: organic soil and coarse sand, where the coarse sand has a higher granulometry. The results, depicted in the figures 8 and 9. The volume of water added, water leaked and water in the container is shown in the left vertical axis, while the volume of water extracted is shown in the right vertical axis. In the horizontal axis, the water levels of each iteration are represented.

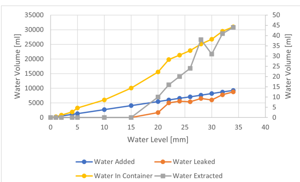

Fig. 8: Volume of water added, water leaked, water in the container and water extracted according to the water level of the corresponding iteration of the organic soil experiment

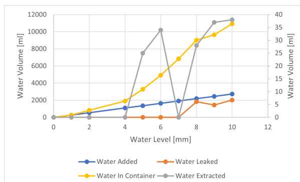

Fig. 9: Volume of water added, water leaked, water in the container and water extracted according to the water level of the corresponding iteration of the sand experiment

The results show that in the organic soil, samples start to be extracted with water levels above 15mm, while in the sand extracted samples start appearing above 4mm. In the first experiment, 15 iterations were performed, with the added water level reaching 34mm and the volume of extracted samples stabilizing around 44ml. The second experiment, 10 iterations were performed, reaching a water level of 10mm and a volume of samples around 38 ml. It is possible to observe that at a certain water level, the volume of water leaked starts catching up to the volume of water added, indicated that the soil is saturated. In the sand, this occurs with much less added water than in the organic soil.

It was verified that 15mm, in the organic soil, correspond to humidity levels between 50 and 65%, while 4mm, in the sand, correspond to levels between 30 and 50%. Therefore, the humidity threshold value for the organic soil is 65% and for the sand 50%. Despite being important to calculate the threshold values, this study also showed that the chosen hardware is capable of performing sample extraction and is also adaptable to different soil profiles.

C. Battery Performance

The power consumption of each component was measures and is shown in the table IV

Assuming that the device spends most of its time in sleep mode, consuming 63mA, and considering the battery size of 8400 mAh, the maximum battery lifetime can be estimated as approximately 133 hours. The solar panel, with a maximum power current of 163 mA, provides a higher power input than the device sleep mode consumption, thus it should be able to extend indefinitely the battery lifetime.

TABLE IV: Power consumption per component

Component	Mode	Power Consumption [mA]
Solenoid Air Valve	Operating	530
	Idle	0
Electric Pump	Operating	730
	Idle	0
Arduino Pro Mini	Active	17
	Sleep	3
Shield Adapter Board	-	18
BC66-TE-B	Active	6
	Sleep	2
	Sending Data	110
Pressure Sensor	-	5-10
Water Level Sensor	-	5
Soil Humidity Sensor	-	5
Total Sleep	-	**63**
Total Active Not Extracting	-	**81**
Total Active Extracting	-	**1341**

To verify the battery operation two tests were performed. In the first test the device is constantly in sleep mode, where it wakes up hourly to message the server. This test had a duration of 24 hours and was repeated with and without solar panel. In the second test, the device is continuously in extracting mode and the test is executed until the battery level is low. The results depicted in the figures 10 and 10, show that the solar panel is able to fully power the device during its normal execution, since the battery level is able to recover the power lost during night time. However, the solar panel is not able to keep up with the power spent in extraction mode, with the device having a maximum extraction duration of around 8 hours.

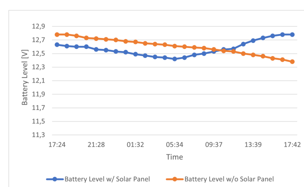

Fig. 10: Battery Level Evolution during the first test

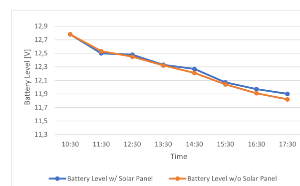

Fig. 11: Battery Level Evolution during the second test

D. Cost

The final cost of the Full Collector device implemented was 359.86€ or 243.32€, excluding the lysimeters. Comparing this value with the 341.03€ of the manual operation, it is possible to say that this device provides a cost-effective alternative to the manual operation.

E. Laboratory Experiment

The implemented device was installed in a laboratory setting, so that its overall operation could be checked and thoroughly tested. The device was attached to the solar panel and three lysimeters. The lysimeters and humidity sensors were individually placed on different containers, in order to be controlled separately and the humidity threshold value was set to 50%, on the three sensors. The communication module was active, and device exchanged messages with the server through the NB-IoT network. The server was configured so that the device sleep time varied between 48 hours, 24 hours and 1 hour. Figure 12 shows the server logs created during June 20 to June 26, where its possible to verify that the device was able to successfully communicate with the server, was responsive to changes in the sleep time and was able to control the sample extraction in the three lysimeters.

Id	Created At	Humidity 20cm	Humidity 40cm	Humidity 60cm	Pressure	Motor 20cm	Motor 40cm	Motor 60cm	Water Level 20cm	Water Level 40cm	Water Level 60cm
1	2021-06-20 10:04:23	2.1	3.3	0.2	3.5	-	-	-	-	-	-
2	2021-06-22 10:05:02	2.3	3.0	0.8	3.5	-	-	-	-	-	-
3	2021-06-24 10:05:54	94.3	3.3	1.7	48.5	ON	-	-	-	-	-
4	2021-06-24 10:33:24	95.1	2.7	1.3	48.5	ON	-	-	Collected	-	-
5	2021-06-24 10:33:56	9.3	4.1	2.3	3.5	-	-	-	Collected	-	-
6	2021-06-25 10:34:22	2.3	3.1	2.3	3.5	-	-	-	Collected	-	-
7	2021-06-26 10:34:53	3.1	4.1	3.3	3.5	-	-	-	Collected	-	-
8	2021-06-26 11:35:17	3.3	4.6	3.4	3.5	-	-	-	Collected	-	-
9	2021-06-26 12:35:45	3.6	3.8	2.7	3.5	-	-	-	Collected	-	-
10	2021-06-26 13:36:23	2.4	95.2	2.2	48.5	-	ON	-	Collected	-	-
11	2021-06-26 13:36:55	2.4	95.2	98.1	48.5	-	ON	ON	Collected	-	-
12	2021-06-26 14:06:44	1.6	95.4	98.5	48.5	-	ON	ON	Collected	Collected	-
13	2021-06-26 14:08:13	2.1	95.4	98.3	48.5	-	-	ON	Collected	Collected	Collected

Fig. 12: Server logs created during the laboratory experiment

F. Field Tests

The implemented device was installed in the monitoring site present in Companhia das Lezírias. This installation was done with the objective of gathering sensors data in real conditions and possibly try to extract a sample in case of a precipitation event. Unfortunately, due to the appearance of hardware malfunctions and communication problems, it was not possible to gather data nor collect samples. The device was able to connect to the network with signal strenghts varying between -88 and-93 dBm, however, given the low signal strength, the connection was frequently lost for long periods of time which affected the device operation.

IX. Discussion

Throughout the tests and experiments that the implemented Full Collector device was subjected to, several requirements were validated. The device cost was similar to the current operation costs, validating the requirement 1. The battery performance tests verified that the device had an extensive battery lifetime and with the solar panel attached it was extended even further, complying with the requirement 2. The soil humidity thresholds study allowed the device to extract samples from different soil profiles, verifying the requirement 5. During the tests and sensor calibration processes, the sensors provided accurate values while the laboratory experiment and laboratory study confirmed the device reliability, verifying the requirement 6. Since the device was able to connect to the network during the field tests, located in a remote location, it can be considered that the requirement 3 is verified, however there were still some communication problems. One possible solution, is to develop an alternative version of the device that uses communication based on other wireless technologies, such as other LPWAN or cellular networks, depending on the coverage conditions.

Another significant challenge faced during the device implementation and installation derived from hardware malfunctions. These malfunctions were mostly related to the sampling hardware section components and its complexity. The idea of developing an alternative device (Notificator device) arose from these challenges as a way to greatly simplify the previous device. The Notificator device is similar to the Full Collector and based on the same architecture, seen in figure 4, but without the sampling hardware and its controller. Its operation is also much simpler. The device receives the sleep timestamps from the server and, when it wakes up, checks the soil humidity. If the humidity is higher than the threshold values the user is alerted. The device than waits for the user/operator to manually collect the sample and reset it or that the humidity drops bellow the threshold, where the user is also alerted. This process is described in the figure 13.

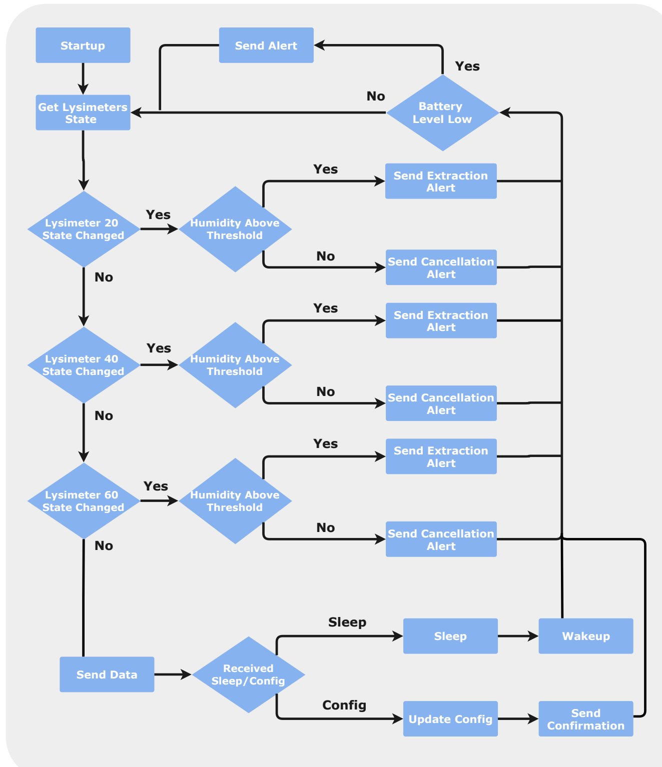

Fig. 13: Notificator Software Architecture Diagram

X. Conclusion and Future Work

This thesis proposes two devices capable of automating and easing the sample extraction process, the Full Collector device and the Notificatior device, which is a simplified version of the first.

Both devices are similar, and use soil humidity sensors to detect optimal soil water levels, that allow for the extraction of samples with the required size. When the soil humidity is optimal the Full Collector device automatically extracts a sample through an electric vacuum pump that pressurizes the lysimeter and alerts the operator that a sample was collected, while the Notificator device only alerts the operator that a sample can be extracted, leaving the extraction to the operator. These devices are battery and solar panel powered and have an important communication component responsible for communicating with a central server that alerts the operator through email messages. This communication is based on IoT LPWAN wireless technologies, more specifically NB-IoT, using the CoAP protocol proxied with an HTTP server.

An implementation of the Full Collector device was assembled and submitted to operation and battery performance tests. These tests showed that the device is adaptable and can extract samples in soils with very different textures, and that each soil requires a different soil humidity threshold that triggers the extraction process. The tests also showed that by using a solar panel the device battery lifetime can be significantly increased. However, it was verified that the hardware used in the extraction process of the Full Collector device highly increases the overall device complexity which makes it hard to reproduce and transport to other locations. This complication resulted in the Notificatior device being developed, where the sampling hardware is removed from the device, greatly simplifying its architecture which boosts reproducibility and lowers the price. Additionally, given that the sampling sites are located in isolated places, with reduced access to the NB-IoT network, it is hard to guarantee the device reliability in those locations, due to communication errors.

In conclusion, the developed devices showed favorable results and met the most part of the proposed requirements. However there is still room for testing and improvement. Firstly, a thorough review on the availability of the NB-IoT network in Portuguese territory needs to be performed, in order to verify the reliability of the network in the current and future monitoring sites. Secondly, alternative wireless technologies should be studied and tested, in order to provide a wider range of available technologies from where the most adequate for a location site can be chosen. Further in-situ extraction tests should be performed on the field, in order to test the device in real environment conditions. This tests should also allow the operator to use and interact with the device.

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