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"Design and development of a low-cost soil moisture sensor based on solenoid coils"

TRABAJO FINAL DE GRADO

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Abstract:

The use of sensors is common in precision agriculture. Moisture sensors are one of the most used sensors in the systems to control the irrigation. Nonetheless, the currently available sensors to measure the moisture require electrodes to be in contact with the soil. In this study we present a new sensor for soil moisture monitoring which can be encapsulated and could be used for several sorts of soil. The sensors are composed of two copper coils (solenoids) and they are powered with a voltage of 10 peak to peak volts. Fifteen prototypes are tested in order to find the best design for soil moisture monitoring. After obtaining the best prototypes, they are tested in five different sorts of soils. The best prototype has 5 spires on the powered coil and 10 spires on the induced coil. Three of the soils could be modeled with regressions lines with R^2 values higher than 0.85. Another prototype, with 80 spires on the powered coil and 40 spires on the induced coil (both on eight layers), shows a similar response to the other two sorts of soil. These two prototypes could be combined to create a soil moisture sensor for different sorts of soil.

Keywords: soil moisture sensor, WSN, precision agriculture, urban lawns, IoT

Resumen:

El uso de sensores es común en la agricultura de precisión. Los sensores de humedad son los sensores más utilizados en los sistemas de riego. No obstante, los sensores disponibles actualmente para medir la humedad necesitan tener los electrodos en contacto con el suelo. En este estudio, presentamos un nuevo sensor para el seguimiento de la humedad del suelo que puede encapsularse y usarse para varios tipos de suelo. Los sensores están compuestos por dos bobinas de cobre (solenoides) y se alimentan con un voltaje de 10 voltios pico-pico. Se prueban quince prototipos para encontrar el mejor diseño para el seguimiento de la humedad del suelo. Tras obtener los mejores prototipos, se prueban en cinco tipos diferentes de suelos. El mejor tiene 5 espiras en la bobina alimentada y 10 espiras en la inducida. El comportamiento de tres de los suelos podría modelarse con líneas de regresión con valores de R^2 superiores a 0,85. Otro prototipo, con 80 espiras en la bobina alimentada y 40 en la bobina inducida (ambas en ocho capas), muestra una respuesta similar a los otros dos tipos de suelo. Estos dos prototipos podrían combinarse para crear un sensor de humedad para diferentes tipos de suelo.

Palabras clave: sensor de humedad del suelo, WSN, agricultura de precisión, jardines urbanos, IoT

Resum:

L'ús de sensors és comú en l'agricultura de precisió. Els sensors d'humitat són un dels sensors més utilitzats en els sistemes de reg. No obstant això, els sensors disponibles actualment per mesurar la humitat requereixen tindre els elèctrodes en contacte amb el terra. En aquest estudi, vam presentar un nou sensor per al seguiment de la humitat del sòl que pot encapsular-se i usar-se per diversos tipus de sòl. Els sensors estan compostos per dues bobines de coure (solenoides) i s'alimenten amb un voltatge de 10 volts pic-pic. Es proven quinze prototips per trobar el millor disseny per al seguiment de la humitat del sòl. Després d'obtenir els millors prototips, es proven en cinc tipus diferents de sòls. El millor té 5 espires a la bobina alimentada i 10 en la bobina induïda. El comportament de tres dels sòls podria modelar amb línies de regressió amb valors de R^2 superiors a 0,85. Un altre prototip, amb 80 espires en la bobina elèctrica i 40 en la bobina induïda (totes dues a vuit capes), va mostrar una resposta similar als altres dos tipus de sòl. Aquests dos prototips podrien combinar-se per crear un sensor d'humitat per a diferents tipus de sòl.

Paraules clau: sensor d’humitat del sòl, WSN, agricultura de precisió, jardins urbans, IoT

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1. Introduction

1.1. Introduction

1.1.1. Necessity of the study

Considering the demand for food, there is an undeniable necessity for monitoring agricultural fields. This necessity is most present in countries and areas prone to droughts, where water is a scarce resource and cannot be wasted. In these places, rather than irrigate the fields periodically, they should be monitored in order to know their water demand to adjust the irrigation. This information should be passed to the farmers, who play a key role in the water management, as Urquijo et al [1] proved.

Agriculture is the principal economic activity in most rural areas of the world. In most parts of the globe it is the economic activity with the highest water requirements. Regarding the water scarcity and its exacerbation with climate change, the regulation of water usage is a crucial issue. Precision agriculture proposes the use of sensors and remote sensing (both with satellite and drones) to monitor the performance of agriculture with the aim of adjusting the inputs (water, fertilizers, nutrients, etc.). Several papers have presented different systems for precision agriculture.

Moreover, the maintenance of urban lawns is an ever-growing problem in developed countries. As with agriculture, this is an especially pressing issue in countries prone to droughts due to the evapotranspiration [2]. In these countries, water is a scarce resource and it should not be wasted. It is already an issue for people to have enough water to irrigate their crops [3], it is no surprise that they often see urban lawns as a waste. When people do not come across enough water to maintain their agriculture, it is normal that they do not want to waste it on the aesthetic of an urban lawn. However, people thrive in environments endowed with gardens. It has been proved that exposure to green spaces not only lessens the stress levels of the population, it also improves their overall health [4]. It is to be noted that people usually prefer well-maintained, blooming gardens over dry, neglected ones. Therefore, it is important to keep the gardens thriving in order to keep the health benefits they possess. We find ourselves dealing with a dilemma of whether it is more important to go through with the high demand for water or renounce to the health benefits presented by green spaces.

Therefore, we can assert that there is a water management issue both in agriculture and in urban lawns and gardens. The solution to this quandary is to improve the management of these spaces. Nevertheless, since socioeconomic dynamics play an important part in the decisions taken for urban lawns [5], this solution ought to be low-cost. A water management system that would reduce the water demand at the cost of a great monetary investment would not work. Moreover, most sensors used nowadays are too expensive for local farmers. This neglects them the opportunity to better manage the water.

1.1.2. Relevant parameters for soil monitoring

In order to better understand how water affects the vegetation it sustains; two parameters are key. These parameters are the Field Capacity (FC) and Wilting Point (WP) [6]. The FC is the ideal quantity of water in the soil, it usually happens one to three days after irrigation, be it from rain or from sprinklers. It is, by definition, the state in which water has drained from larger pores in the soil. The remnant water is available for plants to use and it is not recommended to irrigate over the FC. Depending on the soil texture the FC is higher or lower, being around 40 percent in clay soils and 20 percent in sandy soils [7]. The WP is characterized by an extremely low water quantity. It is the point when there is not enough water for the plant to take and cover its water demands. At the WP water is retained in the soil particles, which makes it hard for plant roots to extract it. The WP percentage is different depending on the soil texture. In soils rich in clay and silt the WP is reached at 24 percent, in sandy soils it is reached at 7 percent [7].

Other parameters are often monitored in order to manage agricultural fields. Temperature is a key factor that affects both water availability and performance of crops. Some soil moisture sensors include a temperature sensor. The productivity of the crops is affected by the solar radiation they receive, while other important factors are their levels of chlorophyll and nitrogen. Biddoccu et al [8] demonstrated that the monitoring of these parameters is of utmost importance to secure the yield and the integrity of the soil.

Nowadays, there are several sensors that monitor the water content on the ground, be it on a culture or on a garden. The most common used method, and the one we will use as well, is through conductivity. It is a reliable method, as Martini et al [9] showed.

1.1.3. Current solutions and sensors

Currently, there are several alternatives to deal with water management on lawns. One of the most widespread solutions is the use of automatic sprinklers. This system waters the garden at a specified time of the day, which can be fixated by the owner. Although the first models of these devices were not highly efficient (they kept irrigating the garden at the designated time even if it was raining) currently there are systems that take into account the weather [10]. These smart sprinklers are designed to accommodate their irrigation to the climatologic conditions. It is important to note that not all the garden has the same coverage. While it is easy to manage and account the plants in a small garden, it is not as simple to handle an urban lawn. There are methods to determine the coverage of the sensor [11] in order to better estimate the water demand. Some of said methods include the use of Smart Autonomous Vehicles (SAV) equipped with color sensors. They are able to determine, based on the brightness, the coverage of the vegetation in large gardens [12]. Different vegetation coverages require different water supplies. Therefore, this method improves water management in smart city gardens. Moreover, determining the coverage is important to reduce energy consumption [13]. The monitoring of the irrigation is yet another important factor in this situation. Implementing a model based on real-time feedback lets the irrigation adapt to external disturbances [14].

Nowadays, regarding soil moisture sensors, there are a few options on the market [15]. The Stevens Hydraprobe II uses two probes to calculate the amplitude ratio of reflected waves. The dielectric permittivity is calculated using the Maxwell equation. Using empirical methods, the dielectric permittivity is related to the water volume in the soil. The working frequency for this sensor is 50 MHz, which requires high energy consumption. The Acclima TDR 315 sensor calculates dielectric permittivity using the time it takes for a wave to go from one probe to the other. Using an equation similar to Topp's model the dielectric permittivity is related to the water volume. The frequency used by this sensor is 3500 MHz. The GS 1 volumetric soil moisture sensor forms a capacitor with the water on the soil and the capacitance sensor which uses a 70 MHz wave. After a determined period of time, the charge stored in the probes can be related to de dielectric permittivity and water volume. The design and fabrication of self-powered capacitance sensors which could be installed in the sprinklers has been tested [16].

In summary, there are already existing methods for the better management of water resources in smart city urban lawns, as well as for precision agriculture [17]. Nevertheless, most of them are expensive and require a huge investment in order to install and keep them running. The use of sensors has been proved to be useful for water management in agriculture [18]. Therefore, we can assume that we could use this system for estimating the water demand in urban lawns. The problem with the use of a Wireless Sensor Network (WSN) is the cost. Usually, the investment required for the acquisition and installation of these methods is not well regarded among the people due to the high prices of commercial sensors. We can determine that the principal issue with water management using sensors is the economical input necessary to implement it. There is no doubt of the benefits of using WSN for urban areas [19].

If we pretend to boost the adoption of these systems, we need to offer low-cost systems, which have been tested in different farming systems and are robust and reliable. This will enhance the approval by the farmers. Currently, many systems have been proposed for monitoring agriculture. Generally, the proposed systems are composed of sensors which measure different physical variables, a smart algorithm that according to the measures triggers different actuators [20]. Most of the proposals are presented for a specific farming system, for exemple greenhouses and grain fields. Most of the systems for greenhouses include the aforementioned sensors and actuators. On the other hand, in grain fields is more common to find systems based on remote sensing to monitor the performance of crops and the actuators are located in the machinery. When sensors are to be used in the field or on urban lawns, they must be properly designed and tested under different scenarios.

One of the most used sensors in precision agriculture is the soil moisture sensors. However, the current low-cost soil moisture sensors are based on electric conductivity. Those sensors have two downsides (i) the sensing element (electrodes) must be in contact with the soil; and (ii) some sorts of soil might have salts and given the same water content the measure of conductivity can be different. The use of inductive soil moisture sensors was reported in [21], nonetheless the authors only tested their prototypes with one sort of soil. Therefore, more tests are needed to ensure the suitability of this soil moisture sensor for precision agriculture and management of urban lawns. With the rise in the trend of using the local vegetation for urban lawns, we can no longer assume the sort of soil used in them. Therefore, soil moisture sensors used for them should be tested on different soils as well.

1.1.4. IoT and WSN in smart cities

Internet of things (IoT) has become a hot topic in the last years. The interconnection of different devices to share information and send data have multiple applications. It has been applied in many different fields, since industry [22], or surveillance [23] to e-health [24] or smart cities [25]. The IoT is a valuable tool that can be applied in smart cities as well. It has been proved to serve several purposes in this kind of progressive new urban model [26]. IoT systems are already being used for real-time traffic monitoring [27]. The recognition of vehicle license plates, monitoring of parking spots and the security control of restricted areas are just some of the advantages this kind of technology presents [28].

The objective of a smart city is to enhance the lives of citizens, as well as the environment. It uses technology to improve the energy and resources consumption and disposal, for example waste management [29]. Moreover, smart cities aim to implement the IoT to guarantee the well-being of the citizens. A method for the detection of emergency conditions using smartphones has already been developed [30]. It is based on the average speed at which someone is running and how many people are running in the same direction. It is useful for extreme situations like a natural disaster or a terrorist attack when time is key to assess the response and possible evacuation of civilians.

A more environmental related aspect of smart cities is the use of WSN for air quality monitoring [31]. Moreover, sensors are already being studied as a mean to monitor the water quality and level [32] thus proving their usefulness for the water management. IoT systems and algorithms are essential for smart cities. Moreover, IoT can be applied in conjunction with precision agriculture to reach the sustainability of the activity. The main drawbacks that are deterring the adoption of precision agriculture are: (i) the cost of sensors; (ii) the lack of specialized systems for different farming systems; and (iii) the little trust of the farmers on these systems.

1.2. Precedents at EPSG

Few works were found regarding soil moisture sensors, we are going to cite some of them. Ausias Benavent Prats realized in October 2018 a study on how soil moisture, conductivity and temperature affect the fertility, in "FERTILITAT DEL SÒLS DE DOS PARCEL·LES I LA EVOLUCIIÓ DE LA HUMITAT, CONDUCTIVITAT ELÉCTRICA I TEMPERATURA AL LLARG DE TRES MESOS EN LA PARTIDA DEL TOSSALET EN BENICOLET".

Moreover, Daniel Fenollar Tecles presented in October 2017 "ANÁLISIS DE LOS PARÁMETROS DEL SUELO UTILIZANDO SENSORES APLICADO A UNA PARCELA EXPERIMENTAL", in which he tested the effect different vegetal covers have on several parameters of the soil.

1.3. Objectives

The aim of this study is to design and develop a low-cost conductivity-based soil moisture sensor. The proposed sensor should identify the water demand in cultures, gardens and urban lawns. In order to improve the yield or the grass quality and health in green spaces, the water supply is key. Moreover, this device could also be used on golf courses, where water management is a problem and the homogenic characteristics of the field allow for a generalization of the measures.

The moisture sensor must accomplish with some requirements:

i. the *Vout* must be high
ii. the Δ of *Vout* between different moisture must be high
iii. the *Vout* for all tested moistures must be different
iv. the working frequency must be as low as possible
v. it must work for different types of soil.

The gap on the current solutions are that the systems proposed for monitoring the water use in different agricultural applications are based on commercial sensors and those have a high cost. On the other side, most of the proposals present a single sensor but it is not integrated into a whole system for environmental monitoring. The main difference between the proposed sensor and the current sensors are the following:

i. the sensor will be integrated in a wider system to manage the water use in gardens and will work with other sensors and actuators creating an IoT system
ii. the sensor is a low-cost device compared with the commercial solutions
iii. the set requirements and the testing of 15 different prototypes promotes to find an optimal device for soil moisture monitoring.

1.4. Our purpose

In this study, we present a water management system based on a WSN that uses IoT to efficiently determine the irrigation needs in order to minimize the water waste for irrigation by monitoring the soil moisture before, during and after the irrigation. The proposed system is similar to the one presented by Sui [33]. The sensors used for this system are made of two solenoid coils that detect conductivity variations in the soil [34] based on the changes in the dielectric constant of the soil. The sensing element is composed of two copper coils, one of them is powered and generates a magnetic field. The second one is induced with this field and the induced voltage changes with the value of the dielectric constant of the soil. These changes are due to the water content in the soil. Therefore, we can estimate the soil moisture based on the conductivity readings.

This is a low-cost alternative to commercial sensors.

Fifteen prototypes will be tested in order to determine the best ones. Those will be tested on five different types of soil. The first soil is a substrate commonly used in gardening, with a high content of organic matter and nutrients and a high percentage of sand. The second soil is a fallow land with low percentage of organic matter, low nutrients, a significant quantity of silt (about 30%) and a high percentage (about a 60%) of sand. The third soil comes from the hillside of a mountain, is made mostly of sand (about a 70%) with the second most present component being silt. The other two soils used come from cultures near the beach, composed mostly of sand (about 95% and 90% each).

The final sensor will be composed of one or more prototypes inside a single casing. This will be done in order to cover the widest soil moisture range possible. The casing will make the sensor easy to install and clean, thus reducing the cost of installation. It can be left underground for long periods of time due to its durability and the low energy consumption of the system (node and algorithms). Moreover, the sensor will not be continuously taking measures, it will take one measure every two hours, extending the lifetime of the batteries. In addition, a solar panel will be included for energy harvesting. Its location in the soil should be carefully done to ensure the uniformity of the soil.

1.5. Structure

The study is structured as follows. Chapter 2 resumes several works related to the object of study as well as identifying the gap they present. It also presents the usefulness of sensors based on mutual inductance.

Chapter 3 describes the experiments to the minimum detail. Furthermore, the background and the system where the final sensor would be integrated are clarified. The fifteen different prototypes are explained, as well as the tests performed with them. Moreover, the different samples used are described. The method through which the five sorts of soil are collected and processed is also thoroughly explained in this chapter. Finally, the process for the measures on the five sorts of soil is explained.

Chapter 4 deals with the results. The outcome of preliminary tests, as well as those from the tests done using all fifteen prototypes can be found in this chapter. Moreover, the soil moisture variation on each soil is presented, as well as the effect temperature has on the readings. The final tests, as well as the possible mathematical models derived from them, are shown in this section.

Finally, chapter 5 presents the conclusions and further investigation.

2. Related Work

In this section we summarize the related work and identify the gap in the current solutions for soil moisture monitoring. First, we discuss the current solutions to this problem. For example, papers that bring up the needs which agriculture presents in terms of water management. Different WSN will be analyzed as a method for the aforementioned water management. Moreover, we are going to discuss some papers regarding how IoT and other smart technologies have been implemented in the management of lawns. Besides, we are going to focus on how to monitor the well-being of these gardens using determined parameters. Second, we will review the background for our research. We will discuss the advantages of using smart technologies for the handling of urban lawns. Furthermore, the utility of mutual inductance coil sensors will be proved. All of this with an objective set in the sustainability of green spaces and cultures.

2.1. Current solutions

Susha Lekshmi et al. [35] showed 13 techniques to estimate soil moisture in their review in 2014. Among those methods; dielectric, thermal and optical methods were included. Nevertheless, sensors cannot be of use for the entirety of these procedures. One of the most reliable techniques is the dielectric method. However, the installation of commercial sensors presents some difficulties due to their probes. Moreover, these sensors require high economic investment. In 2008, a series of low-cost capacitive effect-based soil moisture sensors were contrasted by Kizito et al. [36]. They came to the conclusion that temperature did little to no effect on the measures. Moreover, to obtain a calibration curve useful for every soil tested, the frequency 70MHz was determined the best. Nonetheless, this frequency is too high if we pretend to have a system with low energy consumption. Although the measuring frequency is too high, in [21] other sensors are presented with lower measuring frequency. The measuring frequency is directly related to the energy consumption. If we pretend to have sensors deployed for long-term measures, we need to reduce their energy consumption, and decrease the measuring frequency is one option. Although the effect of temperature changes must be checked.

Many authors have claimed the importance of using soil moisture sensors in precision agriculture systems in many different crops. Gendrona et al. in 2018 [37] shown the benefits of water use and productivity for monitoring real-time irrigation in strawberries. They measured the soil matric potential as an indicator of soil moisture. They presented a decision-making tool for growers regarding the adoption of irrigation techniques. The use of soil moisture sensor for monitoring drip irrigation in dwarf cherry trees was proposed by Dursun and Ozden in 2011 [38]. They suggest the use of a commercial soil moisture sensor (from Decagon) and a series of valves and pumps for irrigation. They showed the data gathered by the commercial sensor for two and a half hours and the volumetric soil moisture changed from 16 to 19 (m3/m3). The sensors used was a low low-cost sensor based on two electrodes. The sensors were not calibrated according to the characteristics of the soil. The utilized sensor must be in contact with the soil and the authors do not report the performance of this sensor in the long term.

Katsigiannis et al. [39] remarked the importance of monitoring fields in order to keep the crops in top health condition. They developed an autonomous multi-sensor unmanned aerial vehicle imaging system. It was able to process the images it took and determine different parameters, one of them being the hydric stress.

A WSN which could determine the water needed for a field was developed by Nikolidakis et al. [40]. It used historical data, as well as the change of the climate values, and was completely automatized. Thresholds were set so if the datum did not change greatly from the previous one the sensor did not take another one for a longer period of time. This was done in order to improve the energy consumption of the sensor.

Navarro-Hellín et al. [41] reflected the water consumption for agriculture in areas prone to drought, like Spain. They delved into the developing of a WSN which sends the information to a remote database. Users could access the database using different devices (phones, laptops, tablets…), and their goal was to offer the information everywhere. They used commercial sensors though, which are expensive and unattainable for local farmers.

Ferrández-Pastor et al. [42] showed the efficiency of a Ubiquitous Sensor Network (USN) platform which used the IoT in precision agriculture. They discussed the need for a method, which could be less expensive, easier to operate, and uses less energy. They developed one and tested it on a hydroponic crop production in a greenhouse, proving important benefits, both economic and ecologic.

The utility of mutual inductance solenoid coil sensors for the detection of conductivity variations was demonstrated by Parra et al. [43]. They tested different prototypes and developed a system to manage groundwater in smart cities. This type of sensors was widely explained in their paper. A similar system based on other prototypes was proposed in [44].

Mittelbach et al. in 2012 [45] set out the comparison of four low-cost commercial soil moisture sensors for 1 year. They compared the 10HS, CS616, TRIME and SISOMOP sensors. They established that no one of the tested sensors accomplishes with the level of performance specified by the manufacturers. They pointed out that a specific soil calibration will be needed to improve the accuracy of the sensors. Furthermore, they affirm that some of them have a serious lack of sensitivity and a suspicious dependence on soil temperature. Therefore, the low-cost commercial sensors must be improved before boosting the adoption of those sensors in precision agriculture.

Soulis and Elmaloglou in 2018 [46] stated the importance of sensors location for soil moisture monitoring in the case of layered soils. They proposed the combination of different sorts of sensors, with different sensibilities, in one probe. Each sensor was located at a certain depth. Thus, in one probe they can measure the soil moisture at different depths. Up to 6 probes were deployed jointly to obtain a map of soil moisture in the vicinity of the roots.

Sui [33] presented an interesting study in which commercial soil moisture sensors were used to determine the irrigation schedule of a crop. The sensors were deployed at different depths in order to better assess the water available for the roots. The data taken by the sensors could be accessed online due to them being sent through a WSN. The only visible part of the system was an antenna and the crop practices were unaffected by this. However, the sensors used for this experiment are pricey and in case to need a low-cost solution this would not work.

Capraro et al. [47] tested a method for the management of an olive orchard based on the control and monitoring or drip irrigation. Using sensors and weather stations they collected data that were sent through communication devices to web-based software. The data could be accessed anytime, anywhere. The test lasted for two agricultural seasons and was deemed successful in the control of soil moisture levels. Nevertheless, the use of commercial sensors makes the system expensive.

Dasgupta et al [48] used the monitoring of several parameters from both the soil and the air to predict the water necessities of crops. Soil moisture was among the parameters that were studied. The objective of this experiment was to develop an autonomous irrigation system, which would need no human intervention. Eliminating human error, this type of irrigation would save time and supplies.

Sudduth et al [49] tested the accuracy of using electrical conductivity as a mean to calculate soil properties. They used a commercial sensor mounted on a cart endowed with a GPS. They were successful in obtaining a correlation between electrical conductivity and topsoil depth. Nevertheless, this experiment only considers soil moisture a parameter that affects the topsoil depth measures, not as a measure on its own.

Garg et al. [50] proved the relation between soil moisture and other soil parameters, such as electric conductivity, relative humidity, and temperature. Four sites with varying degrees of coverage were monitored during two months in order to obtain the data necessary. They asserted that electric conductivity is strongly tied to soil moisture regardless of the sort of cover. This correlation is strongest on vegetated soil. Nonetheless, the temperature was the parameter that showed less relation to soil moisture, showing no decisive pattern.

Blado et al. [51] presented a Smart Automated Water Sprinkler (SAWS) method for efficient irrigation based on mapping techniques. This system avoids wasting water by directing it only to vegetated areas. First, the area has to be mapped by rolling the device, which is equipped with an Inertial Measurement Unit (IMU), along the borders. The mapping is stored indefinitely. The device is then moved to the interior of the mapped area and a garden hose is attached to it. The system detects its specific location within the map and starts directing water without overflowing the boundaries.

Cheema et al. [52] showed a water management method for smart gardens based on sensors. Parameters such as soil moisture level, light intensity, humidity, and temperature are to be monitored daily. The data obtained from these measures are to be processed in order to determine the adequate watering schedule. The server is to send commands to actuators and microcontrollers in order to turn on or off the water pumps. Moreover, the user can interact directly with this system via an application for Android, Smart Vegetable Garden (SVG) (Prototype). Moreover, it can determine which plants should be grown due to environmental factors.

Kwok et al. [53] proposed a water management method that uses deep learning. The system is based on the premise that different plants do not present the same water necessities. Fulfilling the water needs for each plant is important in order to not waste water overwatering. The types of plants can be asserted through plant recognition with the aid of cameras. The software determines the amount of water necessary using databases. This information is then passed to the selected method of irrigation. Therefore, an adequate amount of water is dispensed.

Marín et al. [54] presented an Arduino-based system for monitoring the grass state. The system uses a drone equipped with a camera to assess the quality of the grass. The drone takes pictures of the grass which are later processed in order to estimate the grass cover. The pictures can be sorted into three categories: high coverage, low coverage or very low coverage. Moreover, the performance of this system was compared to the performance of a small autonomous vehicle (SAV) in different garden sizes. For areas bigger than 1000 m2 the performance of the drone was outstandingly better than the one presented by the SAV.

Gupta et al. [55] remarked the importance of urban green spaces (UGS). The beneficial effects of UGS, both the environmental and health effects, were widely explained. Moreover, the challenges these spaces face were also addressed and explained. The case of study was Chandigarh, a planned city in India. It is asserted the need for a smart approach to the managing of UGS. It is proved that Information and Communication Technology (ICT) tools, as well as geospatial technologies, are key for the management of these areas.

As we already established in the previous chapter, these methods are very interesting. Their purpose, the monitoring and better management of lawns, is of utmost importance in smart cities. Nevertheless, they lack one thing that would improve their social acceptance: a lower cost. Almost all the experiences previously cited used commercial sensors, which are expensive. Moreover, all the improvements that have been presented focus on where and how to distribute the water supply. These methods fail to fulfil another question on when plants should be watered. Being able to tell when the soil dries is as important as knowing when to administrate pesticides, which areas of the garden are less covered or which areas do not have plants at all. The current moisture sensor must be improved to avoid contact between sensor and soil.

2.2. Background

The sensor proposed in this study is composed of sensors that use the phenomenon of mutual inductance. This principle states that when in a situation where there is a powered coil (PC), powered with an electric current (EC), a magnetic field will appear. This magnetic field depends on several parameters such as the number of spires (N) of the coil, the diameter of wire (ØW), diameter of the powered coil (ØPC), and the used signal to power the coil (including the voltage and the frequency). According to the Ampère's circuital law the magnetic flux density (B) of a solenoid depends on the permeability of the core (µ0), the number of spires (N) and the intensity of the current (I) as shows Eq. 1. Nonetheless, Eq. 1 is for an infinite solenoid in the free space, in our case the solenoid is introduced in the soil which has its own relative permeability (µr). Therefore, the length of the solenoid (l) should be included as shown in Eq. 2. In our case, when the moisture of the soil changes its µr is modified and it will produce a change in the generated magnetic field. We expect an increase in the permeability of the soil when the moisture rises. Therefore, the magnetic field will increase. The magnetic field is maximum in the center of the solenoid, where the ferromagnetic core is generally placed. In our device, the magnetic field will be higher in the center of the powered solenoid and the core will be the soil (with different moistures in the different tests).

$$B = \mu_0 N I \qquad \text{(Eq. 1)}$$

$$B = \mu_0 \mu_r \, NI/l \qquad \text{(Eq. 2)}$$

If there is another coil in the proximity of the PC, the aforementioned magnetic field will cause that coil to be induced. This phenomenon is known as mutual inductance. The lines from the magnetic field of the PC will go through the induced coil (IC), thus creating a magnetic flux. The theoretical description of the mutual inductance can be seen in [56]. In case that the medium which the magnetic flux goes through is modified, for example, changing the water content of the soil, the *Vout* should change. The mutual inductance, M, of two solenoids can be described by Eq. 3. Where L1 and L2 are the inductances of each coil and k is the coupling coefficient. L1 and L2 depend on the core ($\mu_0\mu_r$), on N, l and A (which is the cross-sectional area in m2) as can be seen in Eq. 4. Again, the result, the mutual inductance, depends on the medium which acts as a core, the soil. When the permeability of the soil changes, the k changes. The value of k is maximum (1) when the coils are perfectly coupled and minimum (0) when there is no inductive coupling. When k is 1 it means that 100% of the lines of flux of PC cuts all the turns of the IC, it assumes a high permeability of the soil and perfect geometry of the coils. In our experiments, the characteristics of the core (permeability) are one of the studied factors. Moreover, the testing of different prototypes (different N, l and A) is aimed to evaluate the effect of different geometries. The position of coils is a fixed factor, however the distance between PC and IC and the total length (of both coils) changes from one prototype to another.

$$M = k\sqrt{L1\, L2} \qquad \text{(Eq. 3)}$$

$$L1 = \mu_0 \mu_r N A/l \qquad \text{(Eq. 4)}$$

According to the experiments performed in previous work [56], the induced voltage will depend on the characteristics of the coil such as N, ØW, and the diameter of the induced coil (ØIC). Moreover, the induced voltage, also known as the output voltage (*Vout*), depends on the B and µr. Generally, this principle is used with coils which have a ferromagnetic core which acts as the medium and is the principle of the power transformers.

In Figure 1 we show a summary of the considered variables in our experiments. According to the polarization of the PC and its relative position to the IC, when the generated magnetic field increases, the *Vout* can increase or decrease. In our experiments we maintain the same polarization in each coil. Furthermore, to limit the number of variables in our test, the input signal (the signal to power the PC) will have two fixed parameters, intensity and voltage; and one variable parameter (frequency). This is done based on the results of [56] when the authors showed that each combination of coils has different peak frequencies.

This type of sensors has been revealed as a good sensor for monitoring water conductivity. In previous papers [56] it was demonstrated that the variation of different parameters as NS, ØW, and ØIC or ØPC is important to find the correct configuration of coils to sense a specific parameter. In this case, the parameter will be the water content in the soil, which is known as soil moisture and generally is expressed as the percentage of water in volume as Eq. 5 shows. The water content is crucial for the correct development of plants. When the moisture of the soil changes, the dielectric constant and the permeability will change, causing a difference in the *Vout*.

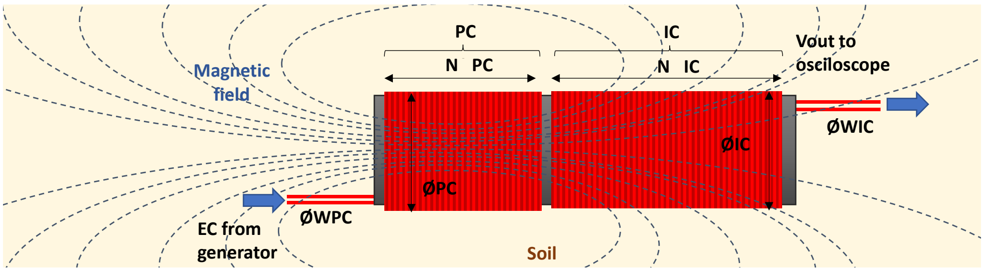

Figure 1. Electric circuit of the coils and its variables

$$Soil\ moisture\ (\%vol) = \frac{Volume\ water\ (L)}{Volume\ soil\ (L)} \quad \text{(Eq. 5)}$$

In this study, we will try to satisfy the need for an affordable monitoring system for water management in crops and urban lawns. Our system is made of two solenoid coils inside a PVC tube. The cost of this type of sensor is minimal compared to the commercial sensors used nowadays. Moreover, due to the casing, these sensors are easy to install, maintain and clean. They are easy to operate and, thanks to the possibility of combining several of them, they provide a wide working range. Moreover, they require little energy. Therefore, they could be buried and working for long periods of time. Being able to know the amount of water a determined part of the soil needs would save both money and water. When we deal with urban lawns, gardens and cultures, these quantities are not exactly insignificant. The proposed method provides a new approach to sustainable cultures and green spaces in smart cities, something that is an important necessity nowadays.

3. Test bench

In this section we will explain the procedure through which the experiment was conducted. Moreover, we will list all the materials needed for the process. In order to better understand this, we will divide this section into five sub-sections. First, the system in which the sensors would be integrated is explained. In the second sub-section, the developed prototypes and their features are described. Next, the utilized equipment and the assays carried out in order to determine the best prototypes are defined. The fourth sub-section one explains how the samples for the different sorts of soil test will be prepared. Finally, the last subsection deals with the procedure for the measures with the sensors.

3.1. System description

The proposed sensor will be included in a smart garden management system in the area of smart irrigation. Moreover, it could be of use for precision agriculture. The system will be composed of a WSN which includes several actuator nodes (AN) and sensor nodes (SN) forming an IoT system. The complete system, in terms of architecture and communication protocol is described in [43]. It is proposed to use an Arduino node and a Bluetooth module when the scenario includes a high-density network. Moreover, a LoRa module can be used when the nodes are deployed in a sparse scenario. The data will be stored in the cloud as a database in order to allow the application of Artificial Intelligence (AI) to integrate the data of different sensors (moisture sensor, meteorological sensors, smart meters and presence sensors among others) to define the best interval to irrigate the lawns. Figure 2 shows a summary of the architecture of the whole system, an example of deployment of sensors and actuators of the irrigation subsystem in a garden, and a scheme of the moisture sensor location.

The node of the soil moisture sensor will be composed of the SparkFun Arduino node, the Bluetooth module, a battery and a solar panel, and the soil moisture sensor. The solar panel and the communication module will be placed on the surface, meanwhile the node and the sensor will be buried at 20 cm, in order to measure the soil moisture at root level. The installation of the sensor on the ground should be made so it generates no preferent water flow channels, which could create a difference in the soil moisture outside and inside the sensor. Moreover, to avoid the presence of sensor and its magnetic field generating changes in the soil properties at long term, the sensors will be checked at variable intervals.

The aforementioned nodes will be low power and will be endowed with an algorithm which will control the activation of the sensors. The algorithm allows activating the sensor for a short period of time, as the soil moisture changes slowly during the day. The coils will be powered for one measure every two hours, which means to power it only 5 seconds each 2 hours. This methodology helps reduce the power consumption of our system. Moreover, as it is powered only for a few seconds, the potentially harmful effects on the environment are greatly reduced. Nonetheless, in some periods of time, as during adverse meteorological situation of excess or lack of rain the sensor can be activated with other periodicities according to the AI decisions.

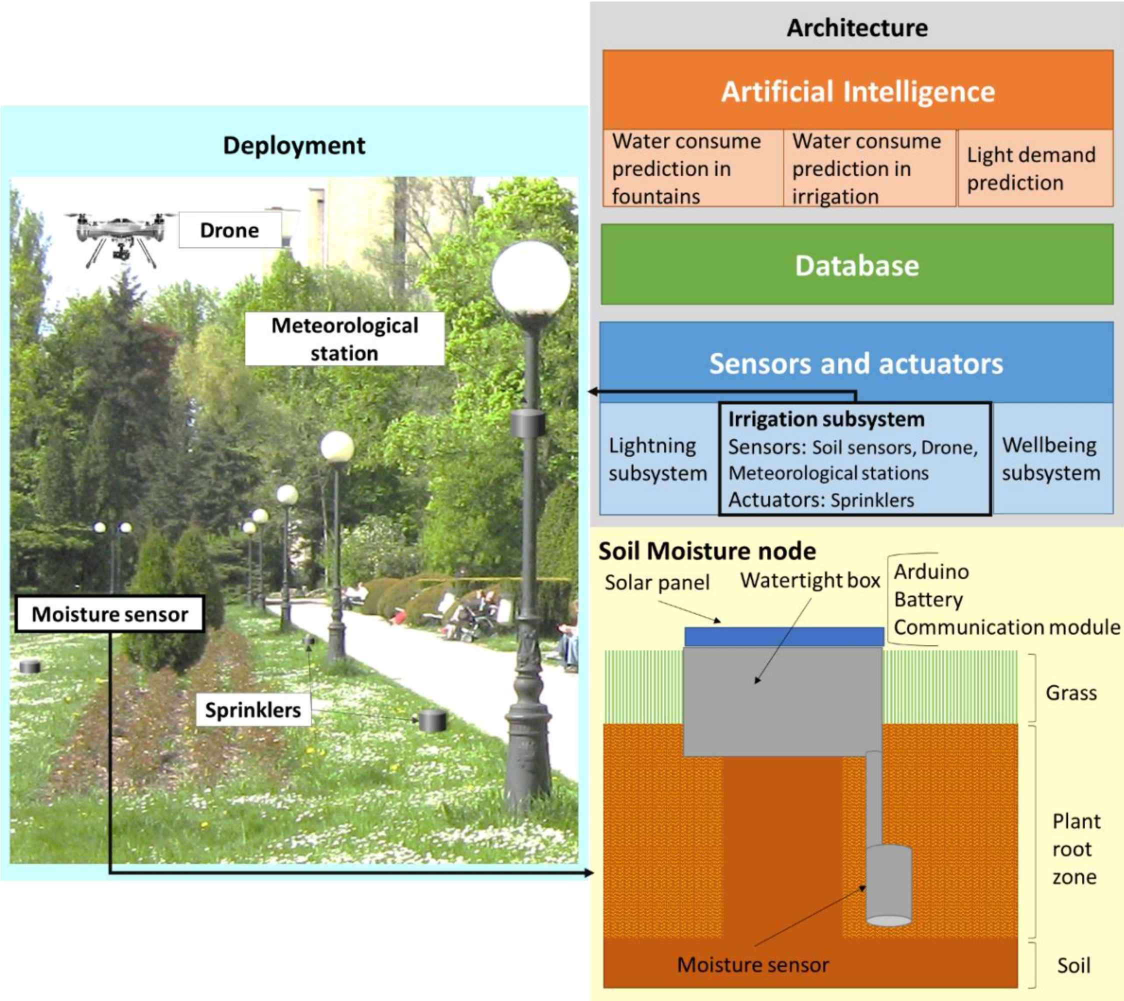

Figure 2. Architecture and deployment of the system

3.2. Prototypes

Several prototypes will be developed in order to test which combination of coils is better for the determination of the soil moisture. All of them will have the same basic design, a PVC tube where the coils will be winded. The inside of said PVC tube is where the magnetic flux is stronger. Therefore, during the test, it is important to check that this part is full of soil and that this soil has the same characteristics as the rest of the soil.

Fifteen prototypes, named P1 to P15, will be developed. The prototypes will have different NS, ØW, ØIC, ØPC number of layers, presence or absence of casing, windings ratio (coefficient between the NS of PW and NS of IC). The resulting prototypes will be sufficiently diverse to offer different responses, see Table 1. In previous papers, authors demonstrated that the best combination of coils for monitoring the water conductivity is the ones with a windings ratio of 1:2 and 1:0.5 [56]. Therefore, most of the used prototypes in this test (P4 to P15) have this winding ratio. The other prototypes (P1 to P3) have windings ratios of 1:1, 1:2.5, and 1:0.4 which are similar to the aforementioned ones. To simplify the experiment, we maintain the same ØW for the IC and for the PC and the same Ø of the coil (ØC) for both coils in all the cases, 25mm. The majority of the prototypes (p1 to P13) have been done using ØW of 0.4mm due to it being the ØW which offered best results in [56] whereas the P14 and P15 will be formed with ØW of 0.6mm.

As a novelty, the use of coils with casing was tested to evaluate the possible negative effect of having an extra PVC tube isolating the coil. This extra PVC tubes will be needed in the final version of the sensor to ensure the protection of the coils to face unfavorable external influence. Finally, we include four prototypes with the winding ratio of 1:2 and 1:0.5 but which have their winding in more than one layer, specifically in 4 and in 8 layers. This is aimed to test the effect of having the same number of spires, 40 and 80 in this case, in less space, which will intensify the magnetic field. Some of the tested prototypes can be seen in Figure 3. We can see the plastic protection of the covered sensors and the coils in the case of the uncovered sensors.

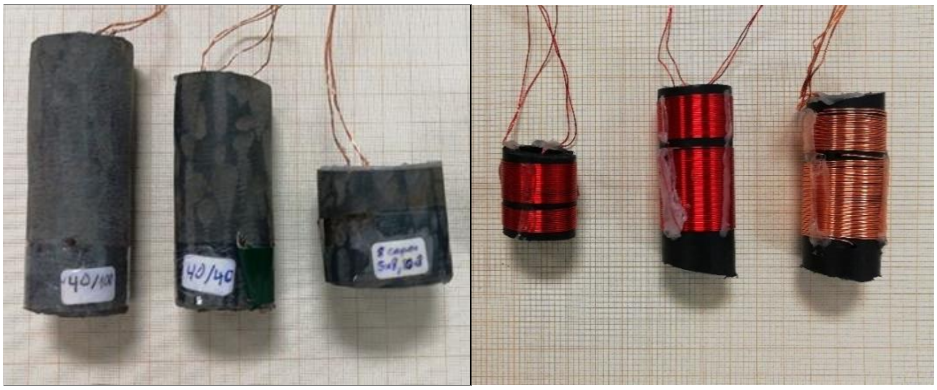

Figure 3. The covered and the uncovered prototypes

Table 1. Features of the different prototypes.

Prototype	ØW (mm)	Layers	Casing	Ø Casing (mm)	NS PC	NS IC	Windings Ratio
P1	0.4	1	Yes	28	40	40	1:1
P2	0.4	1	Yes	28	40	100	1:2.5
P3	0.4	1	Yes	28	100	40	1:0.4
P4	0.4	8	Yes	43	40	80	1:2
P5	0.4	8	Yes	43	80	40	1:0.5
P6	0.4	4	Yes	43	40	80	1:2
P7	0.4	4	Yes	43	80	40	1:0.5
P8	0.4	1	No	-	5	10	1:2
P9	0.4	1	No	-	10	5	1:0.5
P10	0.4	1	No	-	10	20	1:2
P11	0.4	1	No	-	20	10	1:0.5
P12	0.4	1	No	-	20	40	1:2
P13	0.4	1	No	-	40	20	1:0.5
P14	0.6	1	No	-	20	40	1:2
P15	0.6	1	No	-	40	20	1:0.5

3.3. Performed tests

Following, the test performed on the fifteen prototypes and the materials utilized are described. First, the materials used are described. Then, the different performed tests are detailed.

To power the PC with the EC, a power generator will be used. The selected model is the AFG1022 from Tektronix [57] which can create a sinus-wave. The selected voltage will be 10 peak to peak voltage (Vpp). This generator was selected due to its large range of generated frequencies and the possibility to change the frequency both with the scroll and by selecting it with the buttons. Moreover, it allows for generating the sinus-wave with up to 10 Vpp. All the prototypes will be tested with the same high voltage to maximize the number of tested prototypes, since the objective of the paper is to evaluate the performance of different coils as the soil moisture sensor. The higher the *Vout* is, the more accentuated the changes will be and more probabilities we will have to find suitable prototypes. Moreover, the selected oscilloscope to register the *Vout* was the TBS1104 from Tektronix [58]. This oscilloscope was selected due to its features which include the automatic measurement of 16 parameters, in our case we need to measure the Vpp as *Vout* and the possibility to auto-set and signal auto-ranging. Moreover, the PC needs a resistance of 47 Ω on the positive wire. Furthermore, the IC requires a capacitor of 10 nF connected to both wires. We can observe the complete assembling for the experiments described in this paragraph in Figure 4.

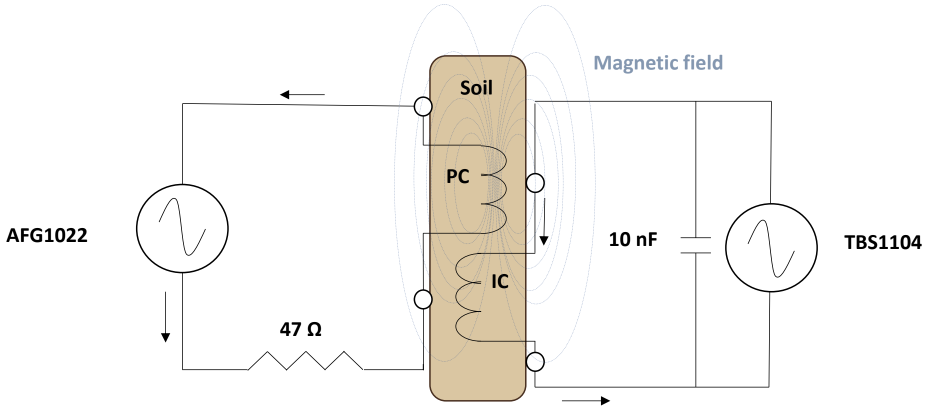

Figure 4. Electric circuit of the sensor

For the soil samples we use five plastic pots, shaped like a conical trunk. Therefore, the measures needed to calculate the volume using the conic trunk formula (Eq. 6) are the minor radius, the major radius and the height. The major radius and the height can only be measured once the soil is on the pot, but the minor radius has to be measured before.

$$V = \frac{1}{3} \cdot \pi \cdot l \cdot (R^2 + r^2 + R \cdot r) \quad \text{(Eq. 6)}$$

Their dimensions when empty are 18.9 cm of height, 16 cm of minor radius and 20.5 cm of major radius. The pots will be filled with 3L of soil and a variable volume of water for the experiments. The used soil is a mixture of peat and soil, commonly used for gardening purposes with very high sand content, therefore the different water percentages that will be tested will be around the WP and FC of sandy soil, 7% and 20% respectively [7]. Moreover, in order to prevent factors different from soil moisture affecting the readings, the soil used for the experiment will come from the same lot. Initially, the soil will have 0% of moisture as it will be dry, and water will be progressively added. The mixture will be homogenized in order to ensure the uniformity of the soil before starting the assays. For this experiment, only one type of soil will be tested. This is because it is more reasonable to obtain the best prototype before testing different soils.

Next, the assays done in order to find the best prototype or prototypes are described. To do so, we will have to run two tests. The first test will be conducted with few of the prototypes and with a wide range of frequencies, using the same frequencies for all the used prototypes and with four samples of soil moisture. The second test will be done with all the prototypes and a narrow range of frequencies, using different frequencies for each prototype and with five samples with different soil moisture. We compromise to a low number of samples in order to test the fifteen prototypes. Using five samples allows us to test all fifteen of them with a degree of certainty

It is important to note that the presented data in the results sections, corresponding to the mean of five repetitions. When the sensor is introduced in each sample, the measured *Vout* is taken in quintuplicate. Therefore, it allows calculating the mean of the five gathered values in order to work with mean values, which give more rigor to the results.

In the first test, in order to ascertain the frequencies where the difference of voltage is higher, we will prepare four samples of soil with different quantities of water. Four pots will be labeled and filled with soil and quantities of water that range from 0 mL to 500 mL will be added, see Table 2. The volume of soil changes when the water is added, the volumetric water content was measured according to the new soil volume, calculated with Eq. 6. Prototypes 1 to 7 will be used in this test. The tested frequencies in this assay will range from 20 kHz to 500 kHz, a measure of *Vout* will be performed every 20 kHz. The aim is to find in which region of the evaluated spectrum is possible to find a higher variance on the *Vout* when the moistures of samples change. This will give us an approximation to which region of the frequency range must be studied in detail in further tests. In past tests, not all the prototypes present this frequency, also known as working frequency, where the difference between *Vout* is higher between different samples in the peak frequency, where the *Vout* is maximum. Nevertheless, it always was close to the peak frequency. We need to confirm this fact with the samples of soil.

Moreover, we want to confirm that for soil moisture sensors the winding ratio which works better is the 1:2 as for the water conductivity sensor. If the P1, 2 and 3 will present better results than P4 to 7, we would consider the option of including new prototypes with another winding ratio for the second set of tests.

Table 2. Characteristics of the pots, first test

Pot	Volumetric water content (%)	Water (mL)
1	0.00 %	0
2	7.51 %	175
3	11.02 %	250
4	22.89 %	500

Once we determine the best frequencies in relation to the peak frequency for measuring the moisture, we will use these frequencies for the second tests. In this test, we will use all the prototypes described in Table 1. This time we will focus only on the useful frequencies (the peak frequency and the nearby frequencies) the ones that have a bigger Δ of *Vout* between different moisture. We will test the best frequency along with the surrounding frequencies which are multiples of five, including at least 5 frequencies for each prototype. In this case, as each prototype has its own peak frequency the tested frequencies will not be the same for all the prototypes. To conduct this second test, we will prepare five samples of soil, one more pot is used, and new volumetric water contents are selected, from 0% to 18%, see Table 3. A picture of the pots utilized for the second set of assays can be seen in Figure 5. It is possible to see that the soil has different color due to the soil humectation, which produces a variation in its color tone, making the soil darker.

Table 3. Characteristics of the pots, second test

Pot	Volumetric water content (%)	Water (mL)
1	0.00 %	0
2	3.59%	93
3	6.21%	157
4	12.57%	282
5	26.91%	532

Figure 5. Utilized pots with different moisture for the second set of tests

In Figure 6 we can see a pot being used for measuring the *Vout*, the oscilloscope, and the generator. Moreover, the wires that are powering the sensors, on the right part of the pot, and the wires that are transmitting the signal to the oscilloscope on the left part of the pot can be seen in Figure 6. Furthermore, inspecting the wires closer we can see the capacitor and the resistance. These are the components used for the circuit.

Figure 6. Assembly for the second set of tests

After finishing the second set of tests, we will select the prototype which accomplishes with all the requirements previously described in section 2. With this prototype, maybe more than one, if several accomplish with the requirements, we will conduct the experiment with different sorts of soil.

3.4. Soil preparation and characterization

To better explain the procedure through which the soil will be collected, characterized and prepared, this sub-section is divided into two parts. The first one deals with the collection and characterization. The second one explains the moisturizing process.

3.4.1. Soil collection and characterization

In order to test these prototypes on different soils, we will collect five samples. The first sample (S1) is composed of substrate for plants, rich in organic matter. The second sample (S2) will come from a field previously used to harvest citrus. The third sample (S3) will be collected from a mountain rich in calcic rocks. Soil from two cultures near the beach will be also collected (S4 and S5). The five samples will be prepared using the same protocol. First, the soil will be collected from its source. For this step we will need a shovel and a recipient to put the soil in, like a bucket. It will be subtracted with care to not grab rocks and plants. Second, the soil will be laid on a tray and with the aid of a rolling pin, we will break the possible clods. In this step we will also remove any possible rock, plant or invertebrate that could be present. Then, we will use a 2 mm aperture sieve to filter the soil. We will do it in order to make sure that we are only testing the soil. We will repeat this procedure until we have at least kilo and a half of soil.

After this, we will prepare the pots. The pots which will be used in this experiment are conical trunks, as the ones used for testing the fifteen prototypes. Moreover, in order to ensure that temperature does not affect the measures, a test will be run. The pots will be cooled, and measures will be taken both before, during and after the natural warming process. These measures will be done with the selected prototypes.

3.4.2. Moisturizing soils

First of all, the bottom of the pot will be sealed with filter paper. This way, water can get in and out, but the soil will remain inside. The pot, along with the filter paper, will be weighed. Next, pots will be filled with 500 g of soil. The pot will then be put inside a plastic box or any other sort of container. The box will be filled with water up to one centimeter under the soil level inside the pot. We will wait until the upper layer of soil looks wet. Then, we will add another 500 g of soil and raise the level of water on the outside to one centimeter below the soil level. This process will be repeated a third time until the soil is completely wet. This process makes sure that the entirety of the soil is wet. In order to get rid of the excess of water, the pot will be left at 25 Celsius degrees for 24 hours.

Meanwhile, we will weight a small portion of the filtered soil. This portion will be heated to 100 Celsius degrees in order to evaporate all the water. After the evaporation, it will be weighed again, and the percentage of dry soil will be determined with the Eq. 7.

$$Dry\ soil\ \% = \frac{Weight\ of\ dry\ soil\ (g)}{Initial\ weight\ of\ soil\ (g)} \cdot 100 \qquad \text{(Eq. 7)}$$

After the aforementioned 24 hours, the pot will be weighed. First, we will subtract the weight of the pot and filter paper. Secondly, we will multiply by the percentage of dry soil. The result should be the weight of the dry soil. We will use this weight to calculate the soil moisture each day. This will be done with the five soil samples, see Figure 7.

Figure 7. The pots filled: S1 to S3 in the upper row and S4 and S5 on the lower row

Moreover, we will measure the major radius and the height for each sample. With this data we will be able to calculate the soil volume using the aforementioned formula for a conic trunk (Eq. 6).

3.5. Measuring procedure

We will measure for five weeks, two times per week. In case the soil is completely dried the test will be concluded for that sort of soil. This experiment will be conducted under the same circumstances as the test performed to determine the best prototypes. The PC of the sensor will be powered with a current generator AFG1022 from Tektronix [57] that generates a 10 peak to peak voltage sinus-wave. The *Vout* will be measured with the oscilloscope TBS1104 from Tektronix [58]. Moreover, the PC will require a resistance of 47 Ω connected to the positive wire. Furthermore, the IC will need a capacitor of 10 nF connected to both wires. The complete set up should have the pot, the sensor, the current generator, the oscilloscope, the resistance and the capacitor, see Figure 8.

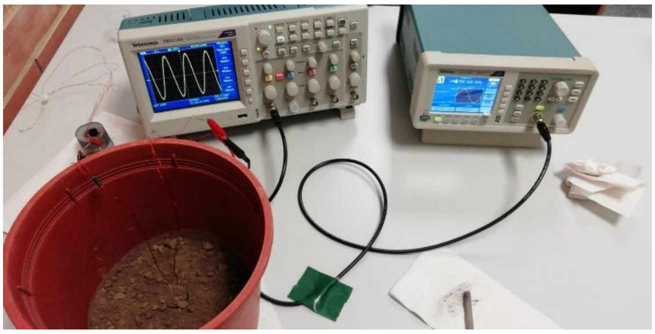

Figure 8. Photography of the circuit

We will gather the data over the course of five weeks. The selected best prototypes will be used with S1 to S5. To gather the data, we will weigh the pots before measuring. We will subtract the weight of the dry soil along the weight of the pot and the filter paper. With this, we will obtain the weight of the water. Since the density of water is 1 ml/g we will be able to know the water volume. This value will be divided by the soil volume in order to obtain the soil moisture (Eq. 5).

The PC will be powered with different EC around the peak frequency of each prototype, as well as the peak frequency. The different EC will derive 5 kHz from one another and be multiples of five, the peak frequency being the only outlier. The process through which the soil moisture was estimated is shown. The substrate used for S1 is rich in organic matter, therefore a high-water content is to be expected. We weigh 20 g of soil on a 3 g capsule, obtaining a total weight of 23 g. After drying it, the total weight of the capsule Is 10 g. Consequently, the dry soil weight is 7 g. For S2, 25 g of soil are weighed on the capsule, the same used for S1. After being completely dried, the weight of the soil and the capsule is 24 g. Therefore, the dry soil weighs 21 g. We weighed 20 grams of S3 on the same 3 g capsule. After drying it, the soil weighs 16 g. For S4 24 g of soil were weighed on the same capsule. When dried, the weight of the soil and the capsule was 25 g, that means the dry soil weighs 22 g. The same process was repeated for S5, obtaining an initial soil weight of 25 g and a dry soil weight of 20 g. The results for the five soils, after applying the proper equation (Eq. 7) and performing the needed subtractions and additions are shown in Table 4.

Table 4. Soil weight characteristics

	S1	S2	S3	S4	S5
Initial soil weight (g)	20	25	20	24	25
Capsule weight (g)	3	3	3	3	3
Dry soil weight (g)	7	21	16	22	20
Dry soil percentage	35	84	80	92	80
Total soil weight (g)	1500	1500	1500	1500	1500
Total dry soil weight (g)	525	1260	1200	1380	1200
Pot and filter paper weight (g)	149	149	125	125	149
Dry soil, pot and filter paper weight (g)	674	1409	1325	1505	1349

The volume is calculated after taking the appropriate measures (height and major radius) for each pot. The minor radius is measured before adding the soil. It is to be noted that even though all pots are conical trunks they have slightly different shapes due to the slope of the cone. The volumes for each are shown in Table 5.

Table 5. Soil volume

Parameters	**S1**	**S2**	**S3**	**S4**	**S5**
Minor radius (cm)	8	8	8	8	8
Major radius (cm)	8.5	8.75	9	8.75	9
Height (cm)	10.5	5	6	4	4.5
Volume (cm^3)	2246	1103	1363	882	1023

The initial water weight of S1 is 2362 g. In the case of S2, the initial weight was 1886 g. For S3, S4 and S5 it was 2023, 1804 and 1683 respectively. Using the pertinent formula (Eq. 5) we can obtain their water volume. Said water volume is 75.21% for S1, 43.45% for S2, 51.19% for S3, 34.58% for S4 and 32.66% for S5.

4. Results and discussion

In this section, the results of the aforementioned tests are presented, in order to better explain them this section is divided in five sub-sections. Initially, we show the data gathered with the P1 to P7 where data were collected each 20 kHz. Next, the data from prototypes P1 to P15 are presented. Following, the estimation of the water content on the pots for the experiments with different sorts of soil is shown. The graphs with the *Vout* for each sensor and pot combination are shown in the fourth subsection. Last, it is studied if the same sensor can be used for all soils.

4.1. Initial tests with P1 to P7

In this subsection, the data of the initial test with a few prototypes are shown. In this test, we measured the *Vout* of the IC each 20 kHz, without considering the peak frequency. All the prototypes were powered with a sinus-wave at the same frequencies.

The results of P1 can be seen in Figure 9. This prototype presents the maximum *Vout*, 17.4V approximately, when the soil moisture is low (250 mL or less) at 280 kHz. Nonetheless, when the soil moisture increases, the maximum *Vout* (20.4 V) is obtained at lower frequencies, 260 kHz. This fact can be used to determine the soil moisture; however, with the obtained data, this is not a promising prototype. This is due to P1 not being able to distinguish values of water content between 0 to 250 mL. We can affirm that it is possible to distinguish between 250 mL and 500 mL according to the *Vout* at frequencies from 180 to 340 kHz. At those frequencies, the differences between the *Vout* of samples with 250 mL or less and the sample with 500 mL is higher than 0.1V. Besides, the maximum differences were found at 260 (6.8 V) and 280 kHz (4.7 V).

The data of *Vout* from P2 are presented in Figure 10. As P1, the *Vout* increases slowly, from values of 0.2 V to reach a peak and then decrease again utill 0.1 mV at 500 kHz. The maximum *Vout* registered with P2 is 9.28 V at 160 kHz using the sample with the highest moisture. In this case, the maximum values for all the samples are gathered at the same frequency. P2 presents almost the same values of *Vout* for all the samples at all the studied frequencies. 140 and 160 kHz are the only frequencies where the *Vout* changes from one sample to the other. The *Vout* increases 0.08 V from 0 mL to 500 mL at 140 kHz; nonetheless, the *Vout* of 175 and 250 mL are the same. Thus, this is not a good measuring point to differentiate the four different samples. The *Vout* of P2 at 160 kHz decreases 0.24 V from 0 to 500 mL. The *Vout* of P2 at 160 kHz decreases linearly, indicating that this might be a good measuring point. Figure 10 likewise points out the values of *Vout* from the P3. This prototype presents the maximum *Vout* with all the samples at 260 kHz. The *Vout* at this frequency is nearly the same for the used samples, 15.6 V. This behavior, having the same *Vout* for the samples with different moisture levels, is found in all the studied frequencies. Therefore, P3 does not seem a good prototype according to the gathered data.

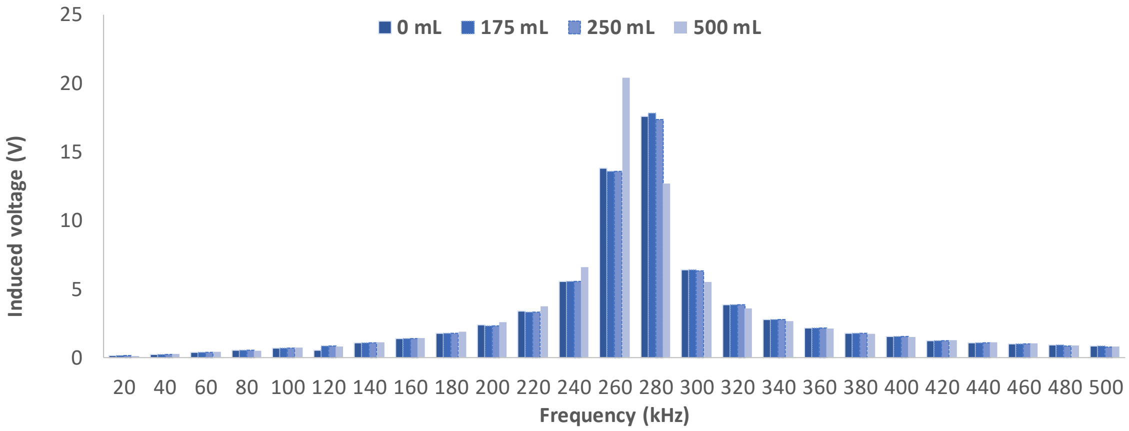

Figure 9. *Vout* of P1 in initial tests using samples with different water content

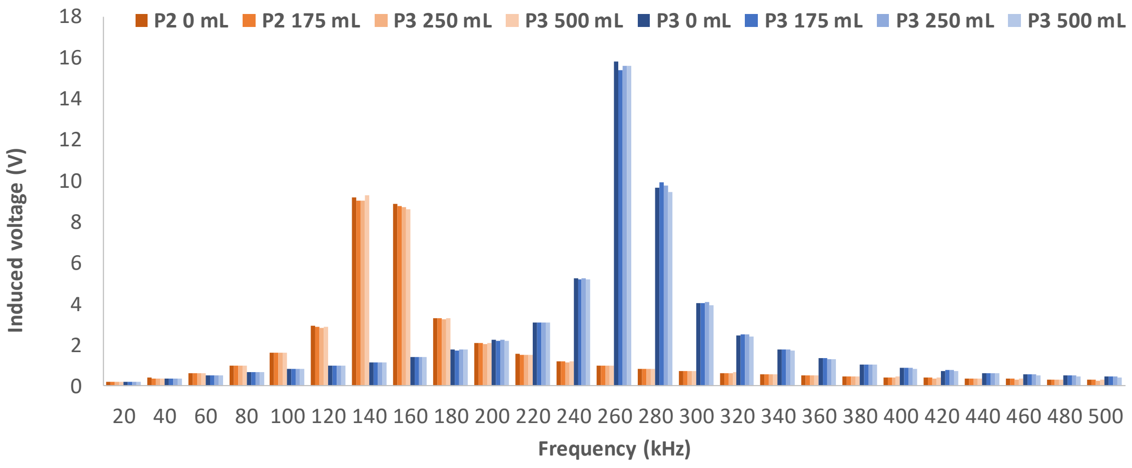

Figure 10. *Vout* of P2 and P3 in initial tests using samples with different water content

Figure 11 presents the data from P4. The maximum *Vout*, 30.8 V, was gathered at 120 kHz with a sample of 0 mL. The values of *Vout* for the different samples are almost the same, showing differences lower than 0.1 V, for all the studied frequencies. Nevertheless, at the frequency where the maximum *Vout* was reached, the difference between 0 and 500 mL is 1.6 V. Furthermore, at 120 kHz the *Vout* decreases linearly from a sample of 0 mL to a sample of 500 mL. The data can be adjusted to a mathematical model obtaining an R2 of 1. All in all, we can consider that P4 is a promising prototype. The data of P5 can be seen in Figure 11 as well. The maximum *Vout* is reached by P5 at 220 kHz. The *Vout* with samples of 500 and 0 mL was 21.8 V and with the samples of 175 and 250 mL was 21.6 and 21.4 V. As two samples with different values are producing the same lecture of *Vout*, this frequency is not useful for determining the soil moisture. Similar behavior was shown at 240 kHz where samples of 0 and 250 mL produce the same *Vout*. P5, with the evaluated frequencies, is not promising as a soil moisture sensor.

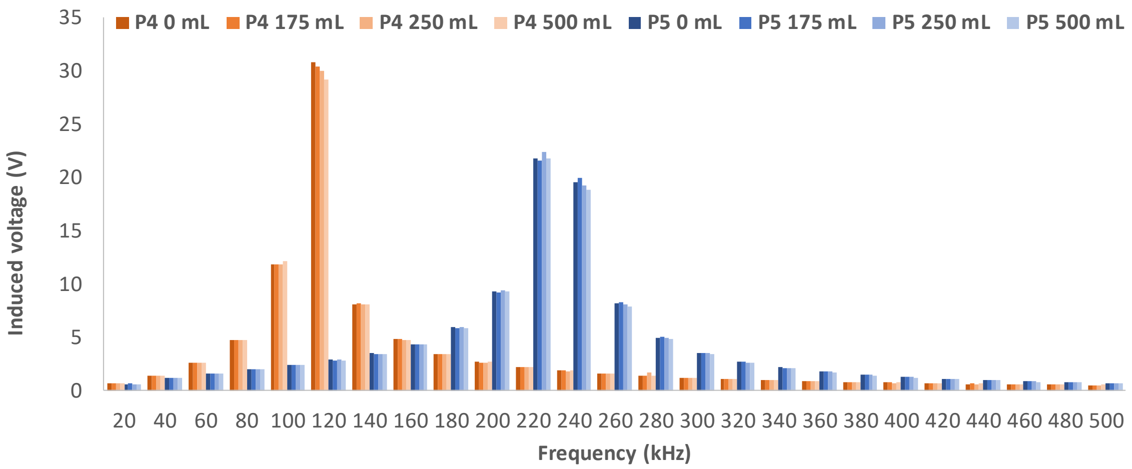

Figure 11. *Vout* of P4 and P5 in initial tests using samples with different water content

The data from P6 and P7 can be seen in Figure 12. The maximum *Vout* reached by P6, 24.8 V, was found at 120 kHz with a sample of 0 mL. At this frequency, the value of *Vout* decreases from 0 ml, 24.8 V, to 250 mL, 23.2 V. Then, no difference was found between a sample of 250 mL and a sample of 500 mL. This is the only frequency which can be used from all the frequencies measured. This prototype might be useful as a soil moisture sensor. On the other hand, P7 reached the maximum *Vout* (21.6 V) at 220 kHz. However, none of the evaluated frequencies with P7 might be useful. The frequencies far from the peak, 20 to 140 kHz and 300 to 500 kHz, have very low differences between samples (less than 0.1 V). At frequencies close to the peak, where there are differences between the samples greater than 0.1 V. The sample of 175 mL causes *Vout* values lower than the ones at 0 mL and at 250 mL. Thus, this prototype, at the tested frequencies, is not a promising option for a moisture sensor.

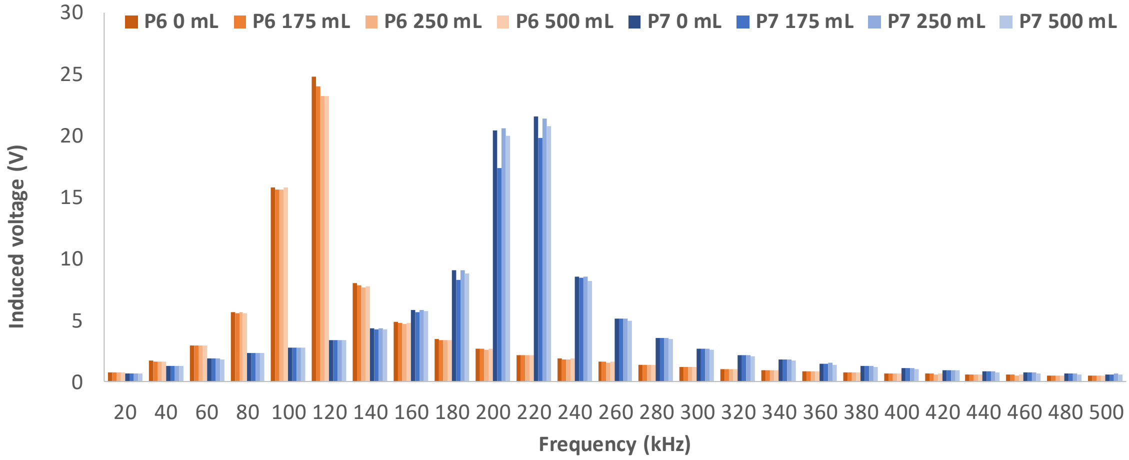

Figure 12. *Vout* of P6 and P7 in initial tests using samples with different water content

The first objective of this preliminary test was to evaluate the suitability of solenoid coils as soil moisture sensors. Some of the sensors present *Vout* values that can be perfectly related to the water content of the soil samples, like the P2, P4, and P6. Thus, we can affirm that the combination of solenoid coils can be used to determine the moisture in the soil. Moreover, it was confirmed the frequencies where the different values of *Vout* for the different samples are bigger are those close to the frequencies where the maximum *Vout* were registered. The *Vout* variations at frequencies far from these are too low and the eventual differences are lower than 0.1 V. We do not consider those differences as long as they cannot be read with the utilized equipment.

4.2. Test at peak frequencies for P1 to P15

In this subsection, the *Vout* of all the utilized prototypes in the frequencies closest to the peak frequency is shown. As each prototype has its own peak frequency, the analyzed frequencies change from one prototype to another. We consider the peak frequency the frequency where the IC has its maximum *Vout* when it is introduced in sample 1, 0ml of water and 3L of soil. First of all, in this subsection, we are going to present the results of prototypes not by sequential order, as in the previous subsection, but by similar behavior.

4.2.1. Prototypes with different peak frequencies

In the previous section, we saw that P1 presented different peak frequencies when it was introduced in different samples. This behavior, different peak frequencies, was also found in these tests with other prototypes (P1, P8, P9, and P15). In this subsection, the data from these prototypes are studied.

P1 (see Figure 13), as it was shown in preliminary tests, presents the maximum *Vout* at a higher frequency (270 kHz) with some of the samples (0, 93, and 282 mL). Meanwhile, with other samples (175 and 532 mL) the peak is reached at 267 kHz. The maximum *Vout*, 30.8 V, was found at 267 kHz with sample 3 (175 mL of water). As the results of samples 1, 2, and 4 are similar and different from samples 3 and 5, this prototype is no useful for monitoring the moisture.

This behavior, presenting two peak frequencies according to the different values of moisture in the samples, was also found in P15. P15 presents a peak frequency of 528 kHz for samples 1 and 5 and a peak frequency of 353 kHz for samples 2 to 4, see Figure

14. The peak at 528 kHz presents values of 24 V approximately for samples 1 and 5 and the values of 22 V for the rest of the samples. Otherwise, for the frequency of 353 kHz, the *Vout* for samples 1 and 5 was close to 23 V and for samples, 2 to 4 were between 23.6 and 25 V. Again, as in the case of P1, this prototype does not present an induced voltage which can be used to determine the soil moisture.

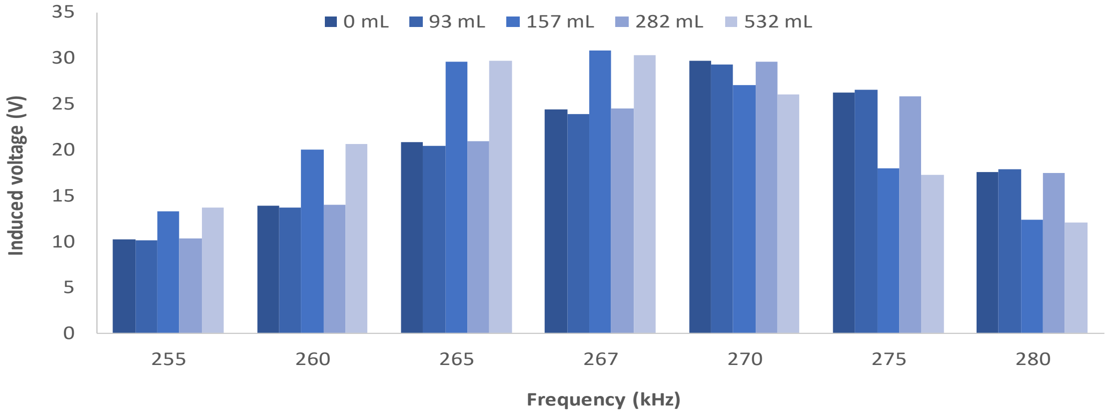

Figure 13. *Vout* of P1 in the second tests using samples with different water content

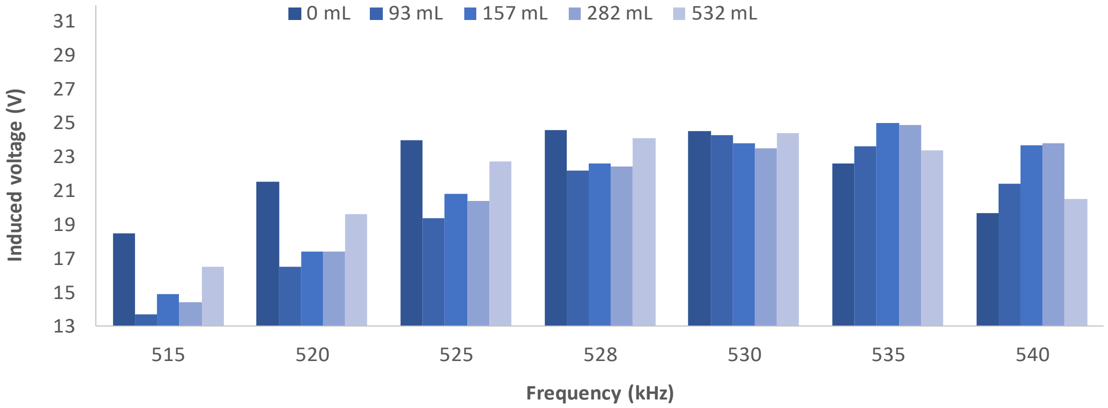

Figure 14. *Vout* of P15 in the second tests using samples with different water content

Following, we analyze the data of P8 and P9 in Figures 15 and 16, both prototypes present different peak frequencies, but unlike P1 and P15 those peaks are not so clearly associated with two or more frequencies. First, Figure 15 shows data from P8, which presents at least 3 different peak frequencies. Peak frequency for sample 1 was found at 777 kHz, but with very similar values of *Vout* at 775 and 780 kHz. For sample 2, 93 mL of water, the maximum *Vout* was registered at 780 kHz. For samples 3 and 4 the maximum registered *Vout* was found at 770 kHz and for sample 5 it was found at 765 kHz. This prototype may be interesting.

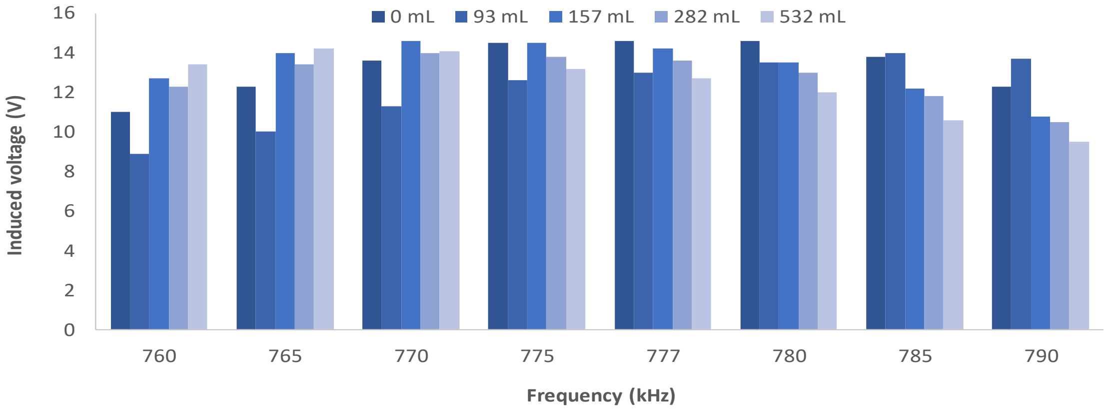

Figure 15. *Vout* of P8 in the second tests using samples with different water content

Apparently, the prototypes that present peaks of *Vout* at different frequencies are not useful; however, the results of P9 are different and can be seen in Figure 16. This prototype does not present a clear peak frequency for samples with low moisture (samples 1 to 3). The maximum *Vout*, 14.6 V approx., for samples 1 to 3 were gathered at 1225 and 1335 kHz. Besides, for sample 4 the maximum *Vout* was found at frequency 1325 kHz. The maximum *Vout* for sample 4 was 14 V. For sample 5, the peak frequency was not found in the tested frequencies. The maximum registered *Vout* for sample 5 within the evaluated frequencies was 13.5 V at 1345 kHz. With the gathered data we can affirm that at frequencies of 1320 and 1315 kHz it is possible to use this prototype to differentiate soil moisture levels. This is a promising prototype as it accomplishes many of the desired points as (i) the difference between the sample 1 and sample 5 is high, 2.3V; (ii) the *Vout* for different samples is high, 14.5 to 12.2 V; and (iii) the *Vout* for all the samples are the different. Yet, there is one missing point, the working frequency is found at a high frequency, 1520 kHz.

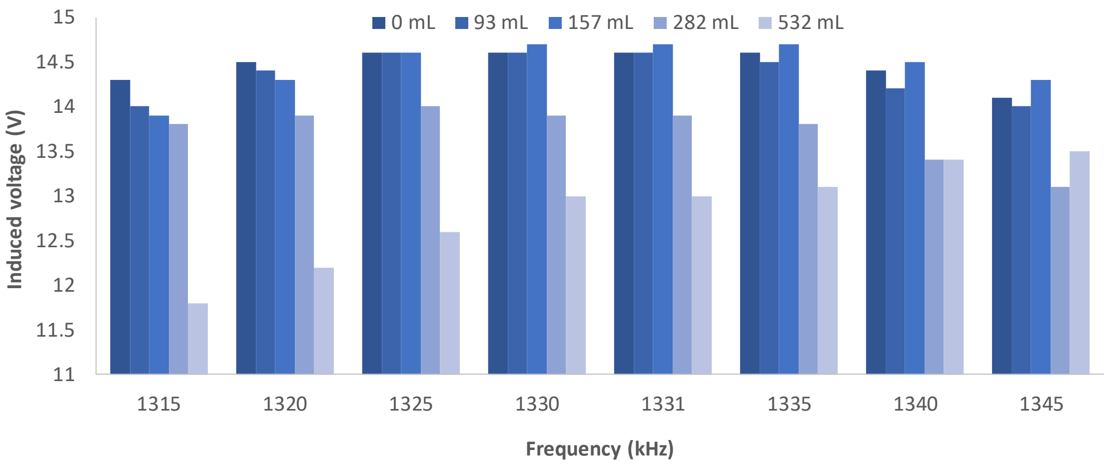

Figure 16. *Vout* of P9 in the second tests using samples with different water content

4.2.2. Prototypes with a sole peak frequency

In this subsection, the data from the prototypes with a unique peak frequency for all the samples are presented.

The first graphic, Figure 17, shows the results of P2 with different samples. This prototype presents its peak at 149 kHz, in the previous test the peak was found around 140 kHz. The maximum *Vout* was 32.8 V for both samples 1 and 5 at the peak frequency. The rest of the samples have similar induced voltage. In the initial test, at 160 kHz it was seemingly capable of distinguishing moisture levels. However, with these new values of moisture, the differences are not maintained. The samples 1 to 4 give as a result the same *Vout*, 8.72 V and the *Vout* with sample 5 is 8.56 V. Thus, this prototype cannot be used with low values of moisture. Another fact which should be mentioned is that, in the frequencies lower than the peak frequency (135 to 145 kHz), the *Vout* generally increases with the moisture. On the other hand, in frequencies higher than the peak frequency (155 and 160 kHz) the *Vout* decreases with the moisture.

Following, we analyze the data from P3. In the previous test the maximum *Vout*, 15.8 V, was found at 260 kHz. In this test, the peak frequency is found at 267 kHz with a maximum *Vout* of 25.7 V when the sensor is introduced in sample 2. In this case, as in the previous test, no relevant differences were observed in any of the evaluated frequencies. The behavior of having a higher *Vout* for the samples with high moisture levels before the peak and a lower *Vout* after the peak is also exhibited by this prototype.

Figure 18 presents the data from P4. In the initial test this prototype was the one that showed better results. The maximum *Vout*, 30.8 V, was found at 120 kHz. Now, the maximum *Vout* is found at 115 kHz with an induced voltage of 48.9 V. The observed differences on the *Vout* when the sensor is introduced in different samples are maintained in this experiment. At frequencies lower than 115 kHz, no differences on *Vout* were observed. However, after the peak frequency, the *Vout* decreases with the soil moisture, at the peak frequency the difference between the *Vout* in sample 1 and sample 5 is almost 2 V. This is a promising prototype as (i) its working frequency is low, 115 kHz; (ii) the difference between the sample 1 and sample 5 is high, 2V; and (iii) the *Vout* for different samples is high, 47 to 48.8V. Though there is one missing point, the *Vout* for two samples, sample 3 and 4, are the same. Thus, it cannot distinguish those values of soil moisture.

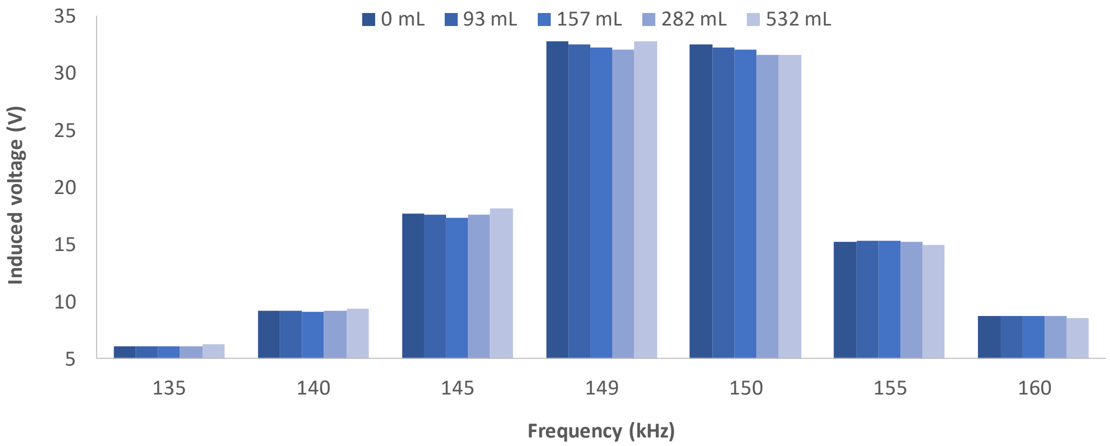

Figure 17. *Vout* of P2 in the second tests using samples with different water content

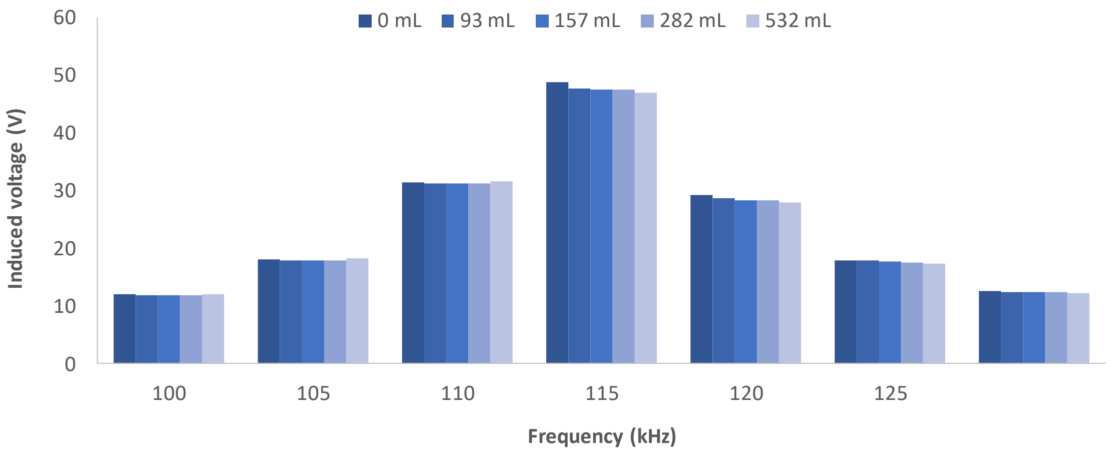

Figure 18. *Vout* of P4 in the second tests using samples with different water content

Next, we present the data from P5, see Figure 19. In the previous test, P5 presents the highest *Vout* at 220 kHz (21.8 V) and in this test the peak frequency was found at 229 kHz (31.6 V). Like the P2, this prototype follows the same pattern: at frequencies lower than the peak frequency the *Vout* increases with the moisture, and at higher frequencies, it decreases. At peak frequency, it is possible to relate the *Vout* with the soil moisture as it happens with P2 and P9. P5 meets all the desired points: (i) the difference between the sample 1 and sample 5 is high, 1.2V; (ii) the *Vout* for different samples is high, 31.6 to 30.4 V, (iii) the *Vout* for all the samples are the different, and (iv) the working frequency is found at low frequency, 229 kHz. P5 is a promising prototype as a moisture sensor.

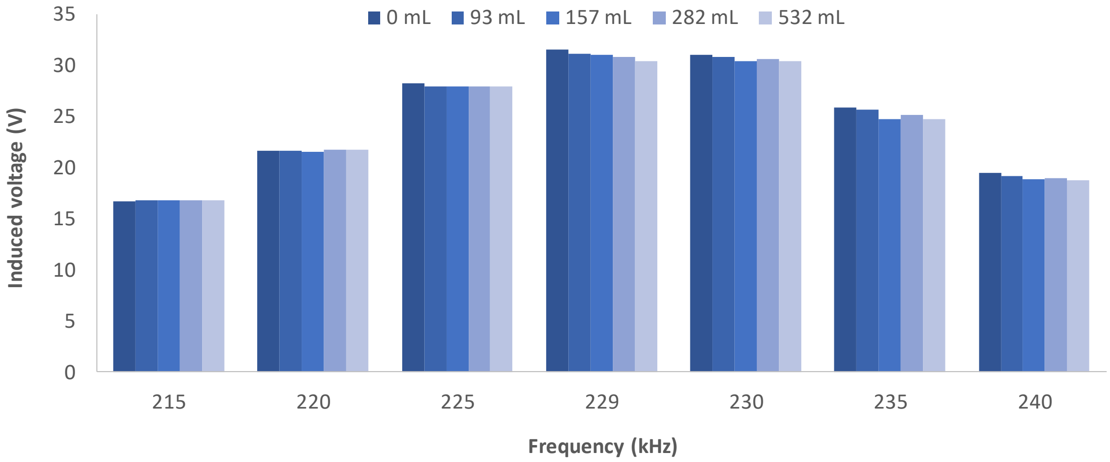

Figure 19. *Vout* of P5 in the second tests using samples with different water content

The data from P6 and P7 are analyzed in this paragraph. P6 is the prototype which presents the highest *Vout* (50.8 V) in its peak frequency, 112 kHz. Nevertheless, in no one of the measured points, a relation between soil moisture and *Vout* can be found. The maximum *Vout* of P7, 32.2 V, was registered with samples 1 and 3 at the peak frequency, 210 kHz. Besides, as P6, none of the tested frequencies seems to show a relation between soil moisture and induce a voltage. Therefore, both prototypes cannot be used as a soil moisture sensor.

Following, the data from P10 and P11 are evaluated. The peak frequency of P10 is 366 kHz and the maximum *Vout* is 30.1 V in the case of sample 3, see Figure 20. The measured *Vout* from P10 does not offer any point where the prototype can be used to distinguish values of moisture since the sample 3 or sample 4 has higher *Vout* than the rest of the samples in all the measured frequencies. Differently, P11 presents its peak frequency at 585 kHz with the maximum *Vout*, 25.5 V in the case of sample 3, see Figure 21. We can see again the aforementioned behavior of having higher *Vout* values when the moisture is higher before the peak frequency (570 to 580 kHz) and having the opposite pattern after the peak frequency (585 to 600 kHz). This prototype presents in the frequency 595 kHz a good option for measuring the moisture. The data of *Vout* at this frequency can be adjusted by a sigmoid function to the values of soil moisture. However, this type of mathematic model is not useful for us since the response of the sensor is just accurate in the vertical portion of the mathematical model, approximately between 0 and 6.21 % of water volume, after the wilting point. Therefore, we must reject P11 as a possible soil moisture sensor for our purpose. Besides, it will be a good option for application where the moisture is always within the aforementioned moisture levels.

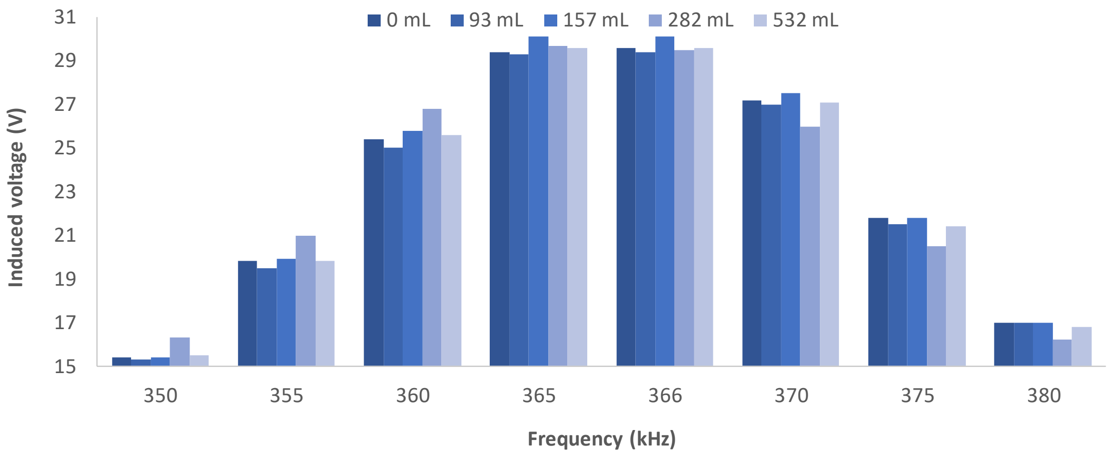

Figure 20. *Vout* of P10 in the second tests using samples with different water content

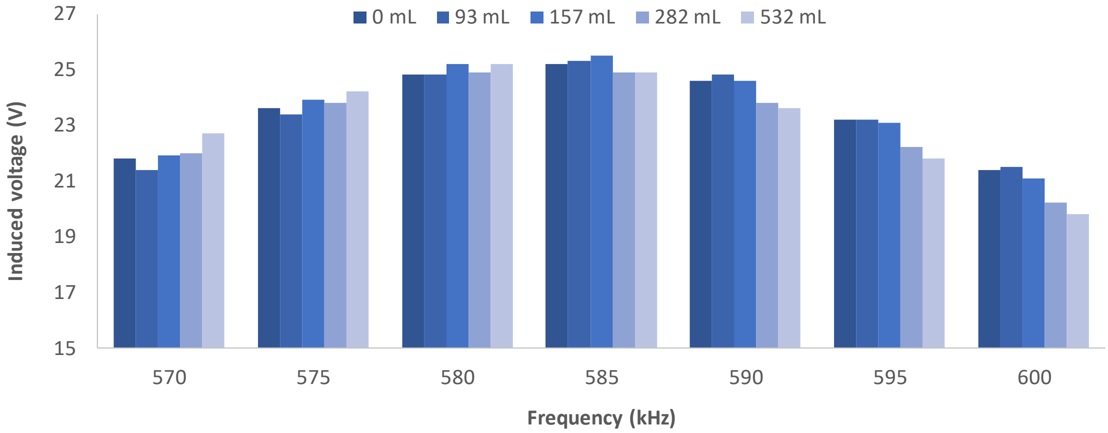

Figure 21. *Vout* of P11 in the second tests using samples with different water content

Next, we present the data from P12 and P13. The maximum *Vout* of P12 is 34.5 for 282 mL of water and its peak frequency can be found at 209 kHz, see Figure 22. The peak frequency for P13 is 340 kHz and its maximum *Vout* is 30.4 for 282 mL of water, see Figure 23. These two prototypes share the fact that their *Vout* occurs in the same water concentration. P12 shows first a decreasing with the increasing of water content and then an increasing. In several frequencies the *Vout* for 0 mL is higher than the *Vout* for 532 mL, which makes this sensor a poor choice for the monitoring of soil moisture. On the contrary, the *Vout* for P13 first increases with the water content, then decreases, increases again and decreases. Moreover, the difference between data is too small. Definitely, this sensor is not suitable for the monitoring of soil moisture. Neither of these two prototypes offers any good frequency for the desired measures. Therefore, no mathematic model has been attempted to be used in order to fit this data.

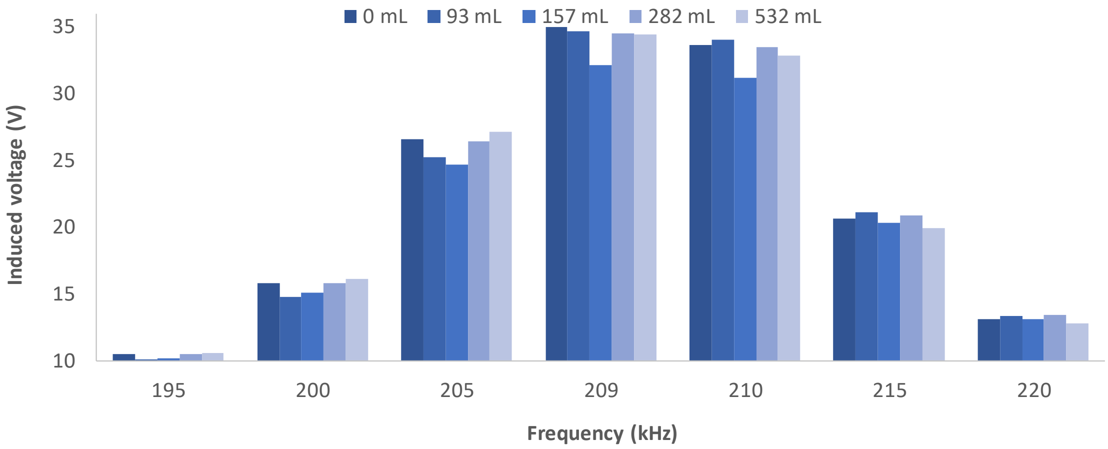

Figure 22. *Vout* of P12 in the second tests using samples with different water content

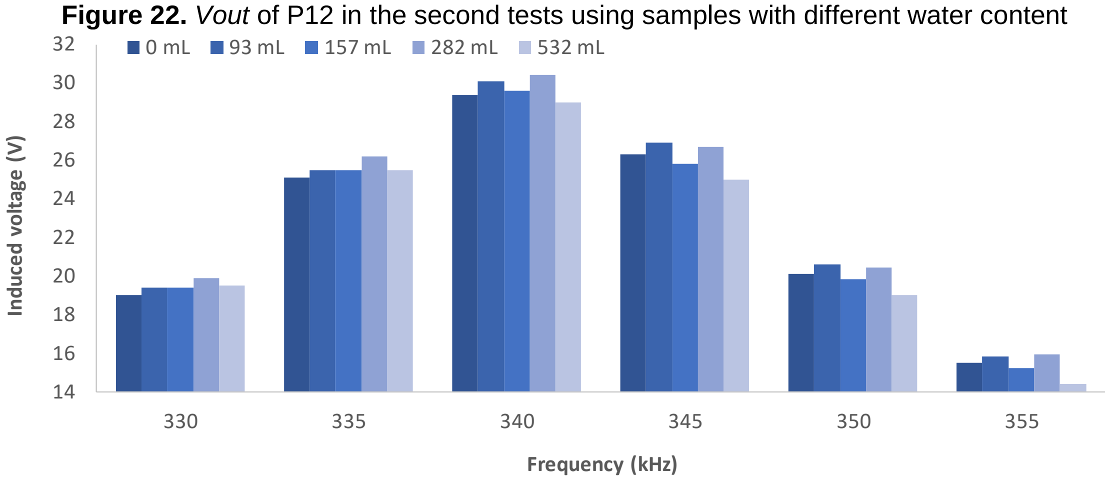

Figure 23. *Vout* of P13 in the second tests using samples with different water content

Following, the data from P14 are analyzed in Figure 24. The peak frequency for this sensor is 317 kHz, and the highest *Vout* is 24.8 V for 93 mL of water. The *Vout* behavior with the increase in water content is different for every frequency tested. For 305 kHz, 310 kHz and 315 kHz the *Vout* first decreases, increases and then decreases again. For 317 kHz, 320 kHz, 325 kHz and 330 kHz it increases, then decreases and increases again. Moreover, the differences between the *Vout* are too small to be significant. This data cannot be fit for any mathematical model due to the disparity of results and their incongruence. Therefore, this sensor is not suitable for the monitoring of soil moisture.

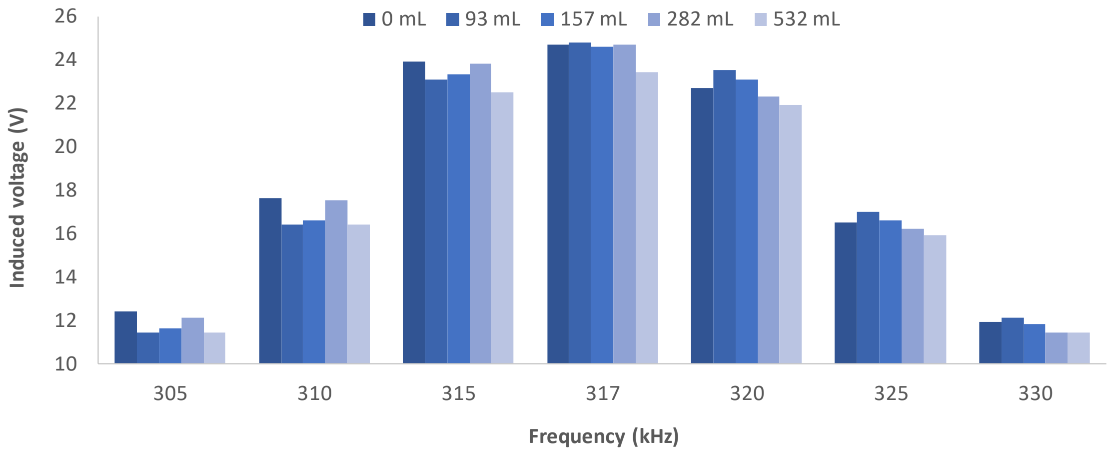

Figure 24. *Vout* of P14 in the second tests using samples with different water content

As several prototypes have been tested and different parameters have been evaluated, to facilitate the reading and comprehension of the results, a summary is shown in Table 6. The existence or absence of a relationship between the *Vout* and the soil moisture of each prototype and other relevant founds are mentioned in Table 6. Moreover, a short conclusion of each set of experiments is included.

Table 6. Summary of the accomplished requisites up to iv

	Test 1	Test 2
P1	Does not accomplish requisites ii and iii	Does not accomplish requisites ii and iii
P2	Does not accomplish requisites i, ii and iii	Does not accomplish requisites ii and iii
P3	Does not accomplish requisites ii and iii	Does not accomplish requisites ii and iii
P4	Acomplishes all requisites	Does not accomplish requisite iii
P5	Does not accomplish requisites ii and iii	Acomplishes all the requisites
P6	Does not accomplish requisites ii and iii	Does not accomplish requisites ii and iii
P7	Does not accomplish requisites ii and iii	Does not accomplish requisites ii and iii
P8		Does not accomplish requisites iii
P9		Does not accomplish requisites iii and iv
P10		Does not accomplish requisites ii and iii
P11		Does not accomplish requisites ii and iii
P12		Does not accomplish requisites ii and iii
P13		Does not accomplish requisites ii and iii
P14		Does not accomplish requisites ii and iii
P15		Does not accomplish requisites ii and iii
Summary	Solenoid coils can be used in order to measure soil moisture. Moreover, the best frequencies for these tests are those where the *Vout* is at its peak.	P5 shows a trend in the data that can be fitted to a mathematical model. P8 and P9 should be further studied. The other prototypes are not suitable for this purpose.

4.3. Soil samples characterization

In this sub-section the results for the soil moisture measures are presented, as well as the analysis on the effect of temperature on the *Vout*. This information will help understand the following sub-sections.

Table 7 presents the soil volume, the initial and final water volume and percentage and the variation. S1 to S3 could be measured for the duration of the experiment. Meanwhile S4 and S5 could only be tested for eight and seven days each. This is because S4 was completely dried and the last three measures for S5 gave the same reading, 16.23 %.

Due to the high content of organic matter, S1 retained more water than the other samples. This made it impossible for the WP to be reached during the test. The lowest soil moisture percentage measured on this soil was a 51.61 %.

On the contrary, both S2 and S4 have been tested from FC to WP. S2, composed of a soil made of about a 60 % sand and a 30 % of silt, may very well have its WP around a 15 % soil moisture. In the case of S4, being a sandy soil, the FC should be at around 24 % and the WP at around 7 %. Taking into account that both these limits have been surpassed, we can conclude that the analysis considered both points.

S3 and S5 are in a similar condition to S1. The final soil moisture is higher than the WP, although in the case of S5 we could assume it is the WP due to the water being strongly retained in the soil.

Table 7. Summary of the soil moisture variations on each soil

	S1	S2	S3	S4	S5
Soil volume (cm^3)	2246	1103	1363	882	1023
Initial water volume (cm^3)	1689	479	698	321	334
Final water volume (cm^3)	1159	161	310	0	168
Initial water percentage (%)	75.21	43.45	51.19	36.36	32.66
Final water percentage (%)	51.61	14.60	22.74	0.00	16.43
Soil moisture variation (%)	23.60	28.84	28.46	36.36	16.23

Next, the results for the temperature changes affecting the *Vout* are displayed. The three selected prototypes were tested on soils 1 and 2. Table 6 presents the initial temperature the soil presented at room temperature and the *Vout* obtained for each prototype on S1 and S2. It also presents the lowest temperature achieved after cooling the samples at temperatures between 11 and 16 °C and its corresponding *Vout*. We can observe the temperature variation as well as the *Vout* vatiation on Table 8. These variations are supposed to represent temperature changes on an average spring day. Where during the day the average could be around 25 °C and at night it would fall about 10 °C.

To better asses the effect of temperature on the *Vout* a comparison between the measures taken at room temperature and several measures done at the same temperature on each soil and prototype combination is done. The temperatures repeated on every test were 15.9 °C, 17.6 °C, 19.5 °C, 20.4 °C and 21.2 °C. To contrast the data, the relative error was calculated using its pertinent formula (Eq. 8), as seen in Table 9.

Table 8. Summary of the temperature variations on S1 and S2

		Initial temperature (°C)	Initial *Vout* (V)	Lowest temperature (°C)	Lowest temperature *Vout* (V)	Temperature variation (°C)	*Vout variation* (V)
S1	P9	25.2	12.6	14.2	13.8	11.0	-1.2
	P8	25.5	12.5	14.5	12.3	11.0	0.2
	P5	25.6	17.8	11.6	17.6	14.0	0.2
S2	P9	26.3	13.9	11.6	13.4	14.7	0.5
	P8	26.3	12.1	15.3	12.7	11.0	-0.6
	P5	26.7	29.6	11.7	29.2	15.0	0.4

Table 9. Relative errors for the temperature variations on S1 and S2

		Relative error at each temperature in %				
		15.9 °C	17.6 °C	19.5 °C	20.4 °C	21.2 °C
S1	P9	9.52	9.52	7.94	7.94	7.14
	P8	1.60	1.60	0.00	2.40	2.40
	P5	1.12	1.12	1.12	1.12	1.12
S2	P9	3.60	2.88	2.88	2.88	2.88
	P8	4.96	4.96	4.13	4.13	4.13
	P5	1.35	1.35	1.35	1.35	0.68

$$\text{Relative error (\%)} = \frac{|\text{Initial } Vout \text{ (V)} - \text{Temperature } Vout \text{ (V)}|}{\text{Initial } Vout \text{ (V)}} \cdot 100 \quad \text{(Eq. 8)}$$

What we observe from these values is that P5, being cased, has a very low relative error, lesser than 1.5 % in each and every test. Meanwhile, P9 and P8 seem to behave worse. Nevertheless, taking into account that the final prototype would be cased, we can assume that temperature does not affect greatly the measures. Due to this data being enough for the purpose of the test, soils 3 to 5 were not tested.

4.4. Study of the *Vout* on different sorts of soils

In this subsection, the results from the tests performed with the prototypes P5, P8 and P9 on S1 to S5 are shown. The *Vout* from the IC was measured every 5 kHz around the peak frequency and on the peak frequency itself.

The results from the P5 on S1 show a peak *Vout* of 31.2 V on several levels of soil moisture. This was obtained on the peak frequency, 229 kHz. This frequency shows a decreasing trend that could be further analyzed, as seen in Figure 25. Therefore, this prototype may be useful for S1.

The data from P5 on S2 show an increasing trend up to the peak frequency, and a decreasing trend afterwards. The peak *Vout* observed with this prototype is of 30.8 V, on different soil moistures for the peak frequency. This prototype shows big differences between two contiguous frequencies, which makes the changes between different water percentages look small. The frequency 220 kHz seems to show an uninterrupted increasing trend, as seen in Figure 26. This frequency should be further studied to fit a mathematical model.

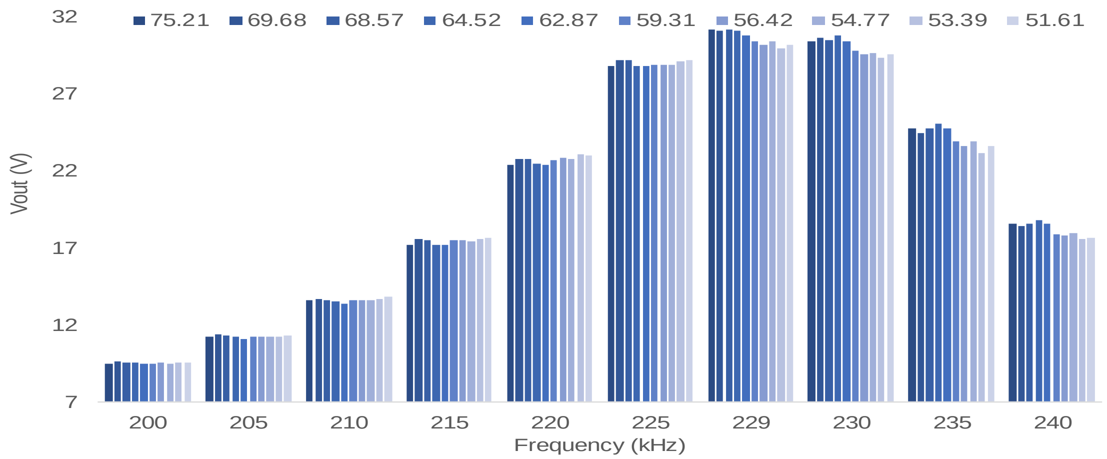

Figure 25. *Vout* of P5 using S1

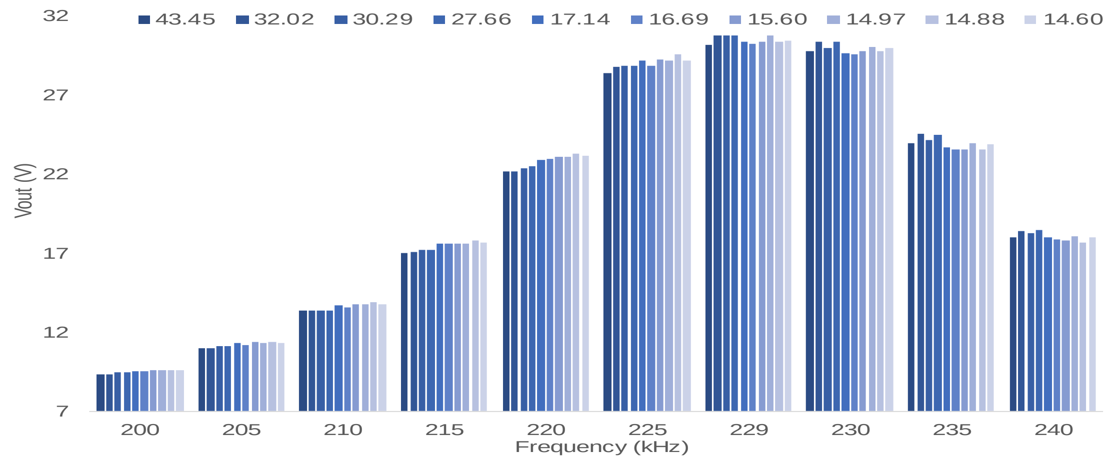

Figure 26. *Vout* of P5 using S2

P5 on S3 shows a peak *Vout* of 30.7 V for a 38.95 % soil moisture obtained on the peak frequency, 229 kHz. The *Vout* seems to decrease and then increase with the decreasing in soil moisture until the peak frequency. This behavior is reversed afterwards, first increasing and then decreasing. The measures do not seem to show a pattern, as seen in Figure 27. Therefore, this prototype is not useful for S3.

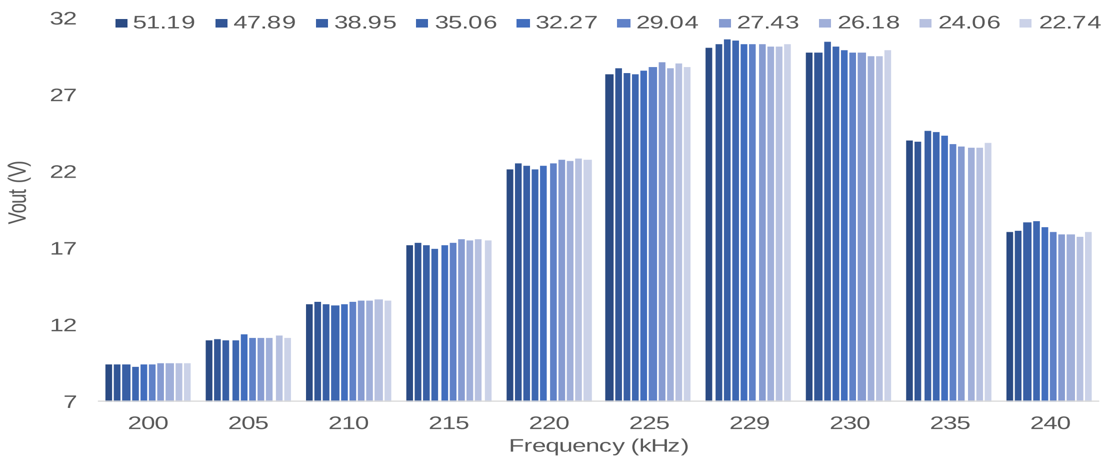

Figure 27. *Vout* of P5 using S3

The results from P5 on S4 shows little to no differences for most of the contiguous measures. The peak *Vout* observed with this prototype is of 30.8 V, on the peak frequency for a 0 % soil moisture. Adding to the too small differences, this prototype shows no pattern for this sort of soil, as seen in Figure 28. Thus, this prototype is not suitable for this sort of soil.

The peak *Vout* for P5 on S5, which is 30.9, is found on the peak frequency, 229 kHz, at a soil moisture of 22.79 %. It is possible that this value is a threshold, thus explaining why 30.8 is repeated so many times around it. The measures do not seem to show a pattern, as seen in Figure 29. Which means this prototype is not useful to estimate the soil moisture on S5.

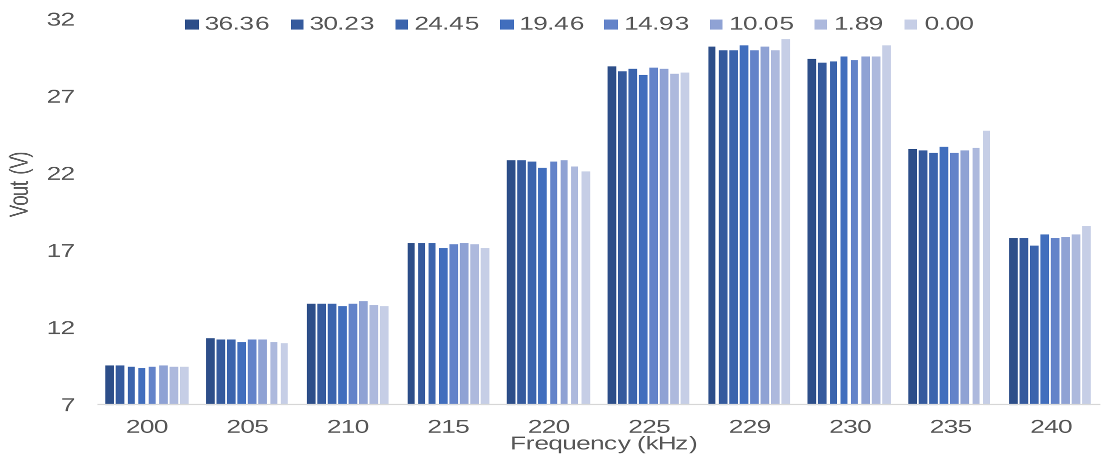

Figure 28. *Vout* of P5 using S4

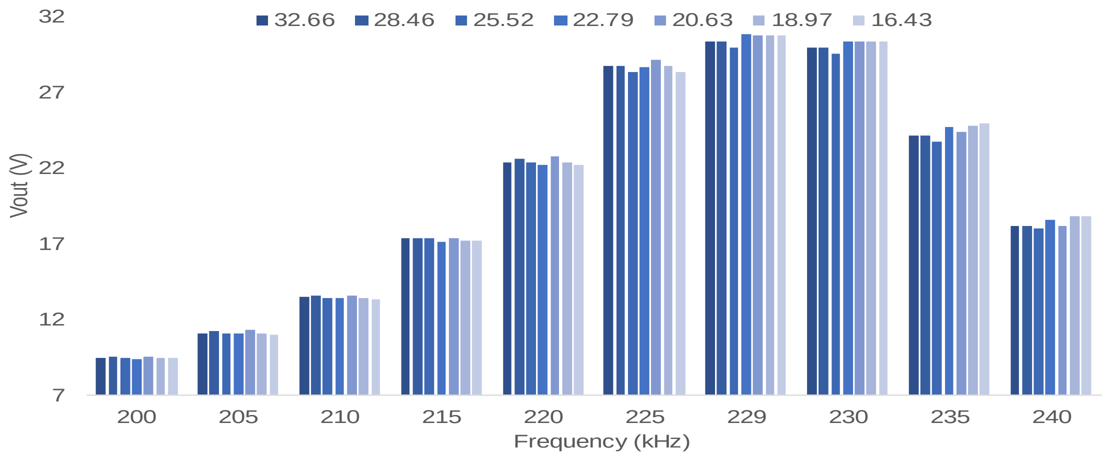

Figure 29. *Vout* of P5 using S5

Out of the five sorts of soils tested on P5, S1 and S2 were the ones which presented a frequency which could be useful for the purpose of this study. They are further studied on the next sub-section in an attempt to model an equation to calculate the soil moisture depending on the *Vout*.

The second prototype tested on different sorts of soil, P8, does not show any trend for S1. The peak *Vout* is reached at a 69.68 % soil moisture on a frequency of 770 kHz. Said peak *Vout* is 14.6 V. Neither of the tested frequencies present a discernible trend, the data seem inconsistent, as seen in Figure 30. Therefore, this prototype is not suitable for the study of S1.

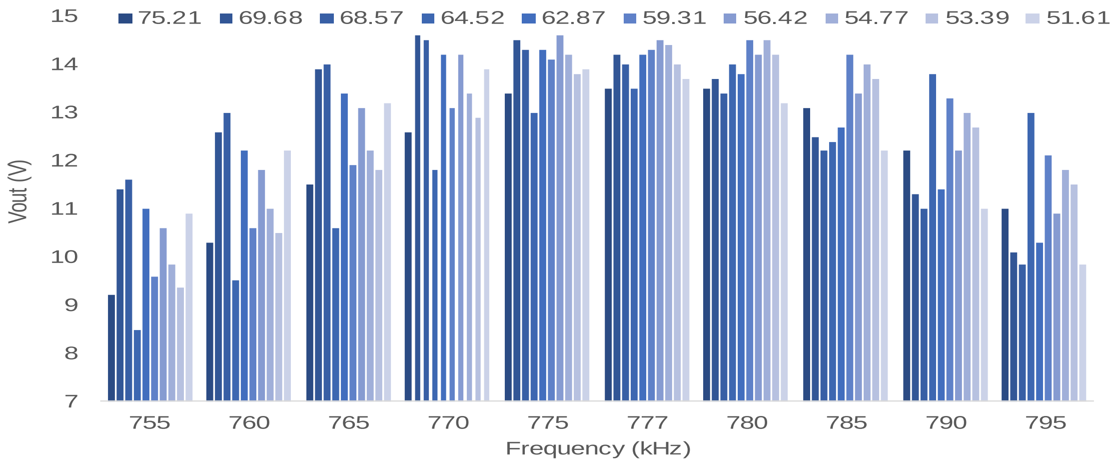

Figure 30. *Vout* of P8 using S1

The same prototype when tested on S2 showed similar results. The *Vout* seems to increase and decrease arbitrarily. The peak *Vout*, 14.7 V, is reached at 777 kHz, the peak frequency, for a 32.02 % of water content. The inconsistency on the trend of this data makes it unsuitable for the purpose of this experiment, as seen in Figure 31.

When tested on S3, the peak *Vout*, 14.6 V, is repeated throughout several frequencies and soil moisture levels. Although some of the frequencies show irregularities, we can observe a clear increasing trend for the frequency 775 kHz, as seen in Figure 32. This frequency should be further studied.

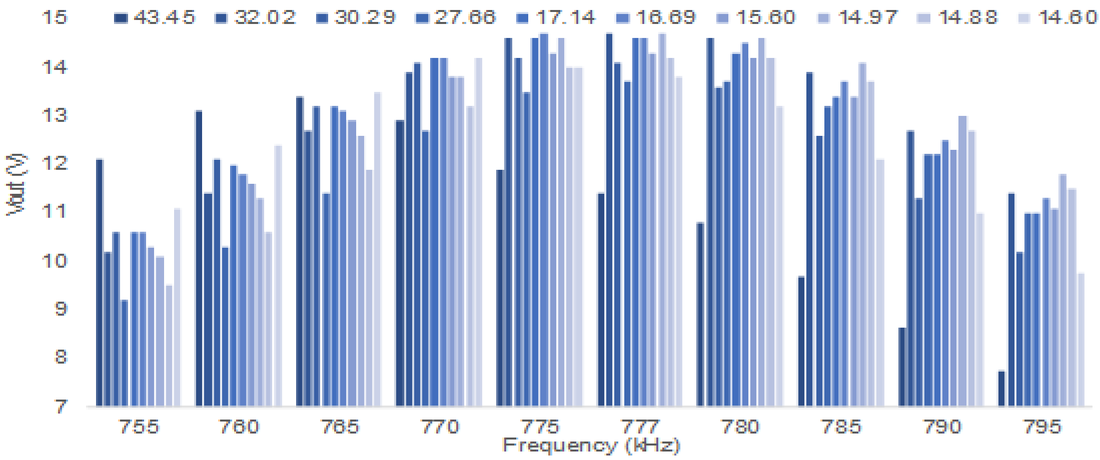

Figure 31. *Vout* of P8 using S2

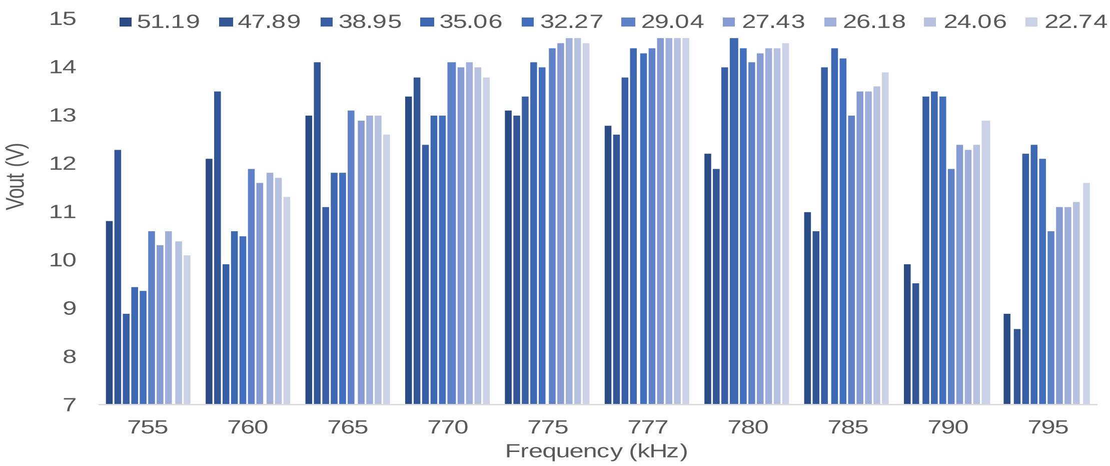

Figure 32. *Vout* of P8 using S3

A seen in Figure 33, the response to this prototype to S4 shows a clear increasing trend up to the peak frequency. The frequencies higher than 777 kHz do not seem to follow a trend. The peak *Vout*, 14.6 V, is repeated on both 775 kHz and 777 kHz for a 0 % soil moisture. Even though it does not present the peak *Vout*, 770 kHz should be studied due to the regular decreasing of its *Vout* measures.

Decreasing and increasing trends are seen on each side of the peak frequency for S5. The peak *Vout*, 14.6 V, is found at 777 kHz for a 22.79 % soil moisture. This soil presents big differences between two contiguous measures, as seen in Figure 34. This makes it suitable for the purpose of this experiment. It should be further studied to determine which frequency works best.

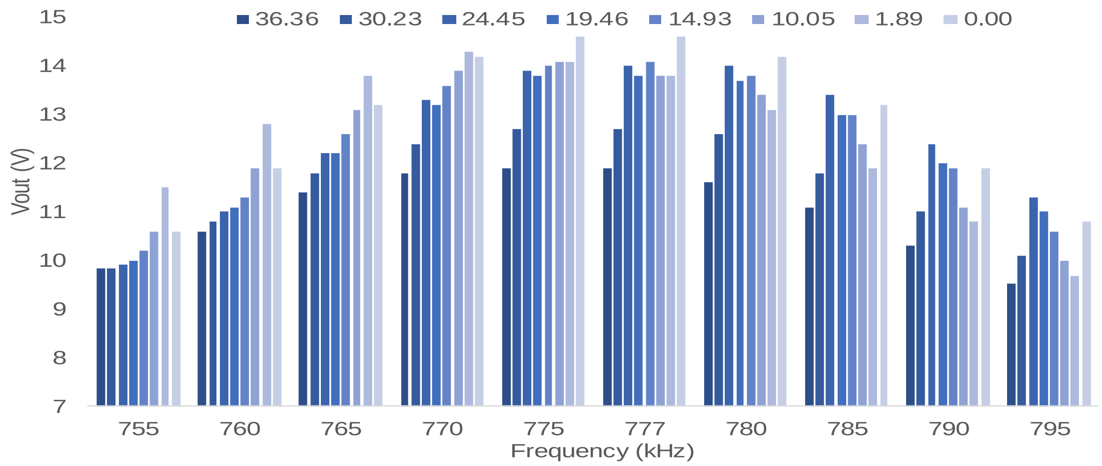

Figure 33. *Vout* of P8 using S4

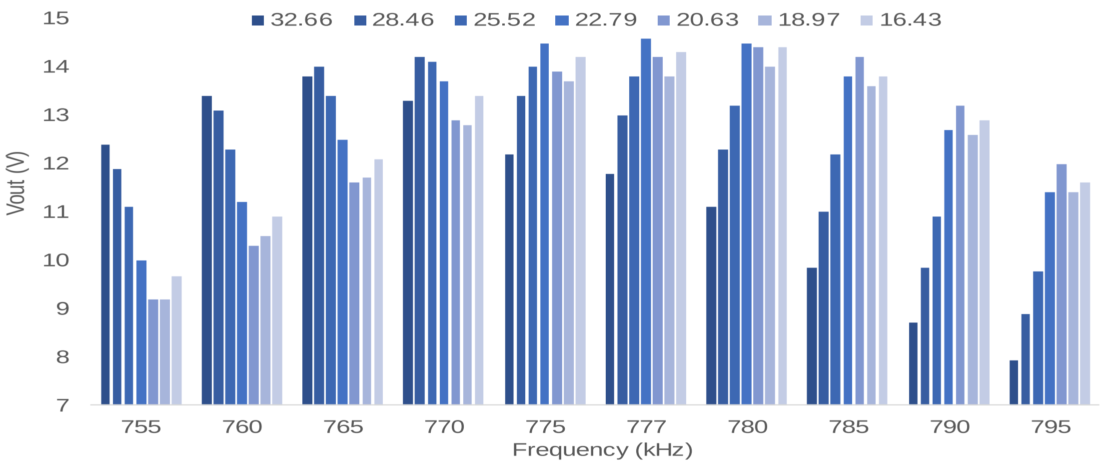

Figure 34. *Vout* of P8 using S5

P8 showed a good response to S3, S4 and S5. Several frequencies, most of them around the peak frequency, present interesting points for the use of mathematical models. This is dealt in the next sub-section, where the data from this prototype on those soils is fitted on the frequency that shows the best results.

The data obtained from P9 when testing S1 shows a clear decreasing trend for most of the frequencies, as seen in Figure 35. For this prototype only one side of the peak frequency was studied due to it being too high. The peak *Vout* is 13.8 V, and it is found on the highest frequency for a 56.33 % soil moisture. The frequency 1315 kHz should be further studied due to the regular decreasing trend it shows.

The results from P9 on S2 are completely random. The *Vout* increases and decreases every other frequency, as seen in Figure 36. The peak *Vout* is 13.8 V, obtained on the frequency 1340 kHz for a 27.66 % water content. The absence of a trend presented by this prototype makes it unfit for the purpose of this experiment.

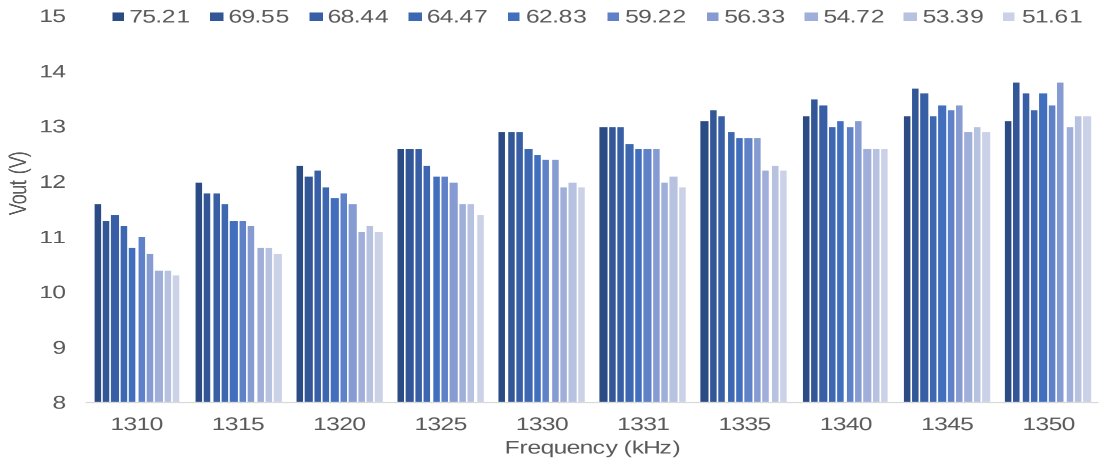

Figure 35. *Vout* of P9 using S1

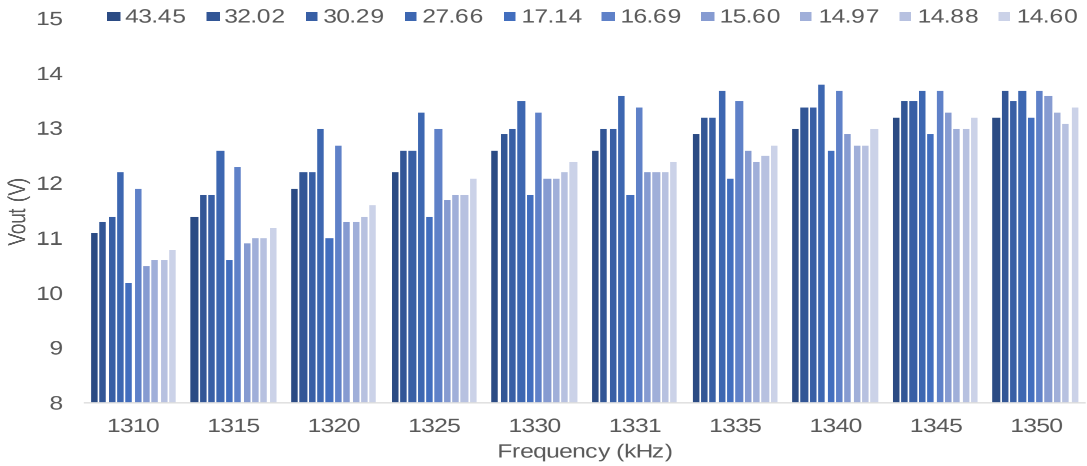

Figure 36. *Vout* of P9 using S2

Figure 37 presents the results of P9 when tested on S3. Similar to the results shown for S2, these data show no discernible trend. The peak *Vout*, 13.8, is present for the last two frequencies for a 35.06 % soil moisture. The arbitrariness of the data makes this prototype not suitable for our purpose.

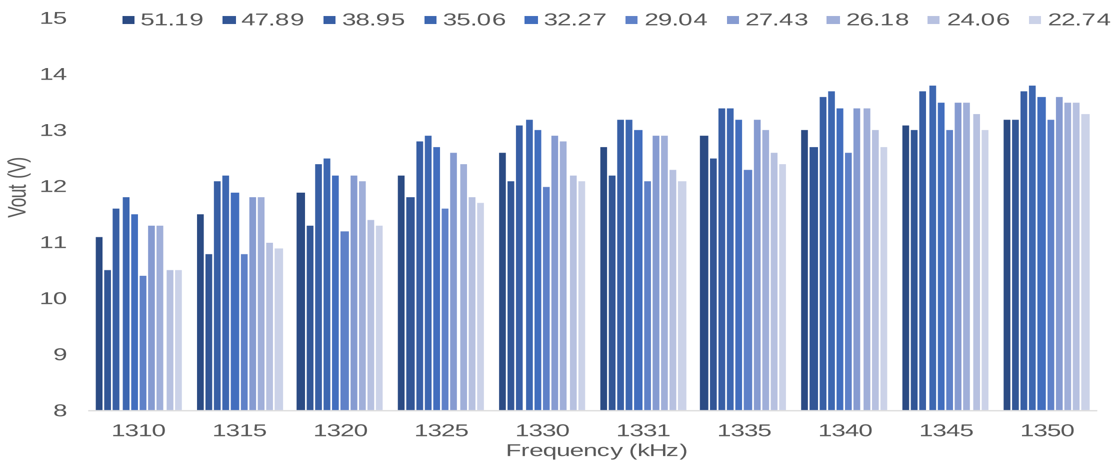

Figure 37. *Vout* of P9 using S3

The results of P9 when tested on S4 and S5 are shown on Figures 38 and 39 respectively. Both these soils are rich in sand. Both peak *Vout* for these samples are obtained at the highest tested frequency, 1350 kHz. For S4, the peak *Vout* is 13.9 V and is obtained for a 24.45 % soil moisture. In the case of S5, the peak *Vout*, 13.8 V, is obtained at a soil moisture level of 18.97 %. Measures on the higher end of the tested frequencies show no changes for contiguous measures, which make both these prototypes unfit.

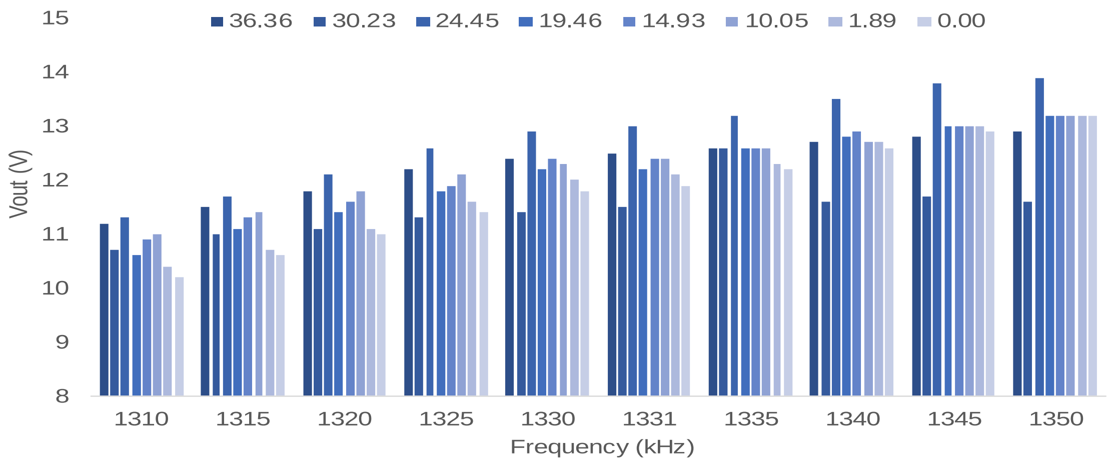

Figure 38. *Vout* of P9 using S4

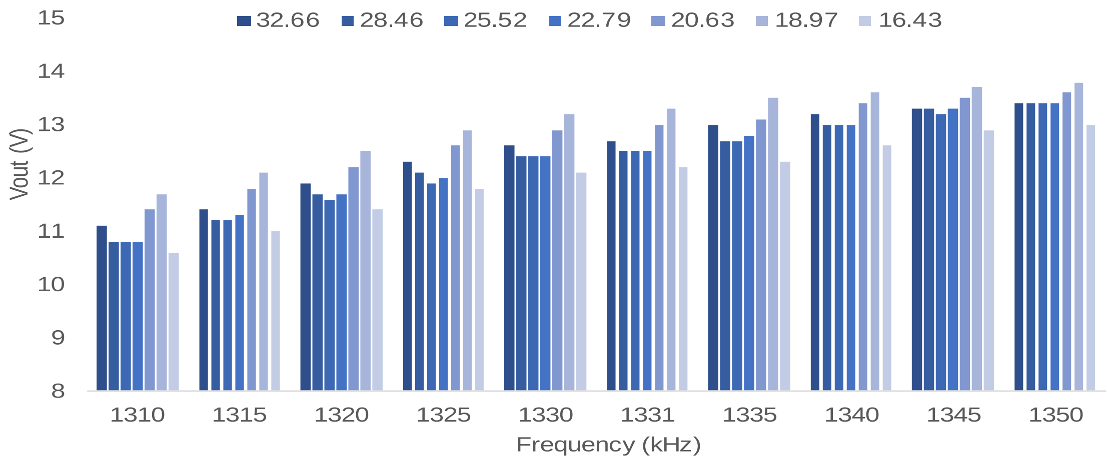

Figure 39. *Vout* of P9 using S5

The only soil tested with P9 which shows a link between soil moisture and *Vout* seems to be S1. This correlation is put to the test in the next sub-section, where the data is fit to a mathematical model.

4.5. Calibration of the sensors

In this subsection, we try to determine whether one sensor can be used for the determination of the soil moisture in different sorts of soils. We present the graphs with the calibrated data from the frequencies and prototypes of interest. All calibrations will be shown along their R2. It is a statistic parameter to estimate the correlation degree between the formula and the data, the higher it is to 1 the more accurate correlation is. Unless stated otherwise, the mathematical model used to calibrate the data is a linear regression.

As proven by the previous graphs, P5 shows good results for S1 and S2. Nonetheless, it is useless for the other sorts of soil. The contrary is true for P8, which works for S2, S4 and S5. Unfortunately, P3 seems perform well only for S1.

The data for the calibration of P5 with S1 is the *Vout* from the peak frequency itself, 229 kHz. We can see a representation of this data along with the calibration equation (Eq. 9) and the R2, see Figure 40. The difference in soil moisture is a 23.60 % and the variation of *Vout* is of 1 V. This means a change of 0.1 V every 0.24 %.

The other prototype useful for S1 is P9. The data used for the calibration is from the frequency 1315 kHz. For the same difference of 23.60 % soil moisture, this prototype shows a variation of *Vout* of 1.3 V. Which means a little over a change of 0.1 V for every 2 %. As seen in Figure 41, the R2 for this calibration is significantly bigger than the one obtained with P5. The equation (Eq. 10) is presented as well.

Due to the soil being rich in organic matter, the water was retained, and the wilting point could not be tested.

$$\text{Soil moisture (\%)} = 15.577 \cdot Vout\ (\text{V}) - 415.96 \qquad \text{(Eq. 9)}$$

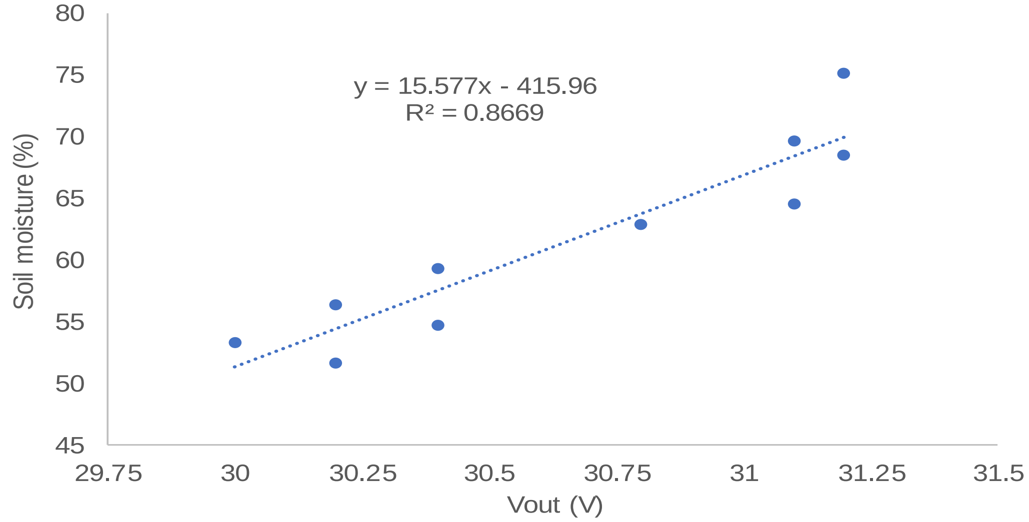

Figure 40. *Vout* of P5 using S1 and its mathematical model

$$\text{Soil moisture (\%)} = 16.412 \cdot Vout - 124.37 \qquad \text{(Eq. 10)}$$

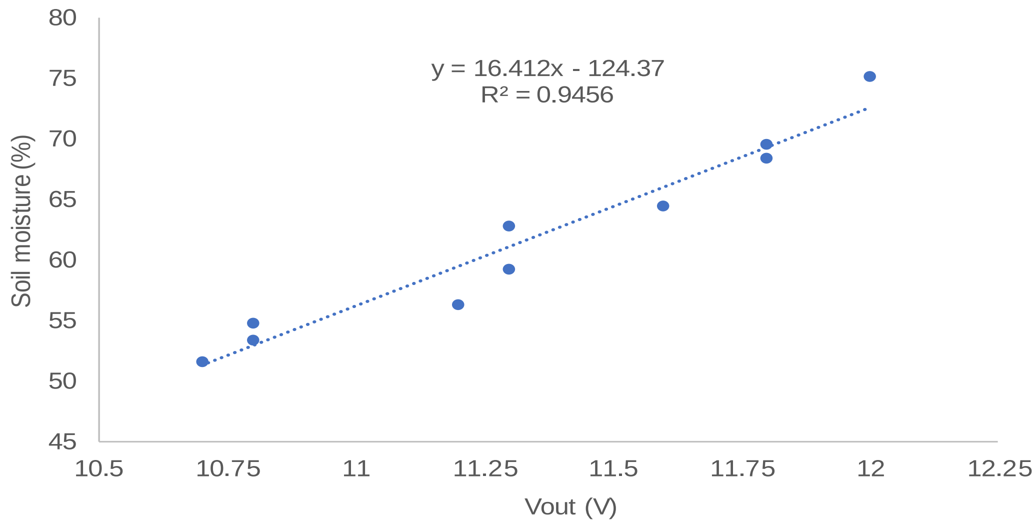

Figure 41. *Vout* of P9 using S1 and its mathematical model

The only prototype which shows a relation between the *Vout* and soil moisture on S2 is P5. The data used to model an equation is from the frequency 220 kHz. This is a different frequency to the one used for S1. Nevertheless, for the final sensor, the frequency used could be specified after determining the sort of soil. This frequency shows a variation of 1 V for the difference of 28.84 % of soil moisture. This gives a rough change of 0.1 V for every 3 %. The data fitted to a mathematical model, as well as its corresponding equation (Eq. 11) and the R2 value can be seen in Figure 42.

$$\text{Soil moisture } (\%) = 9 \cdot 10^{29} \cdot \, Vout \text{ (V)}^{\,-21.1} \qquad \text{(Eq. 11)}$$

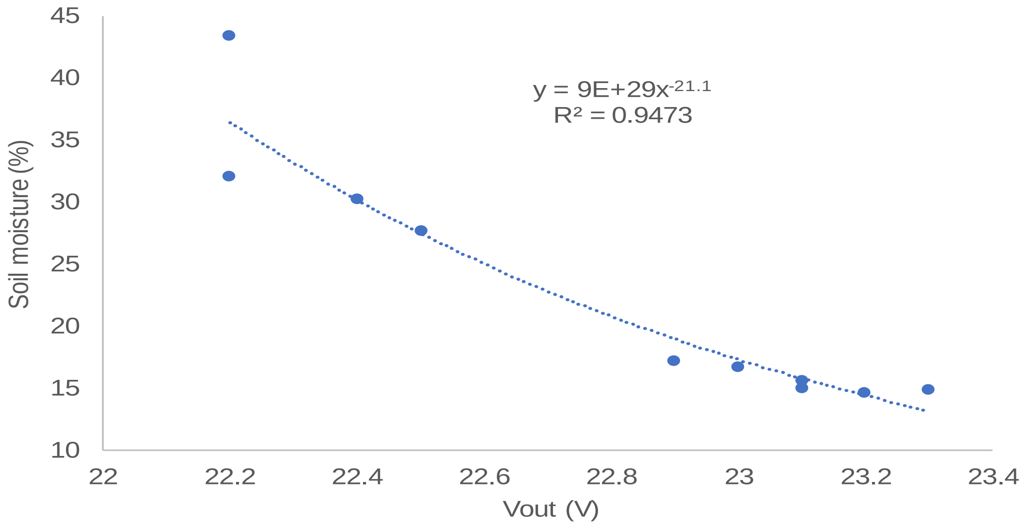

Figure 42. *Vout* of P5 using S2 and its mathematical model

The prototype which works on more sorts of soils is P8. This sensor works for S3, S4 and S5. These are the soils with the highest proportion of sand. Although there are other parameters which could affect the measures (mostly salinity) it is to be noted that this prototype worked best for these three soils.

For S3 the data used to fit the model comes from the frequency 775 kHz, close to the peak frequency. The *Vout* changed 1.4 V and the soil moisture changed a 28.46 %, which is roughly a 0.1 V change for each 2 %. The accuracy of this change is acceptable. Although the WP may not be included in these measures, we can assume it could be interpolated due to the high value of R2. This value, along with the equation (Eq. 12) and the model, can be seen in Figure 43.

$$\text{Soil moisture } (\%) = -15.096 \cdot Vout \text{ (V)} - 245.12 \qquad \text{(Eq. 12)}$$

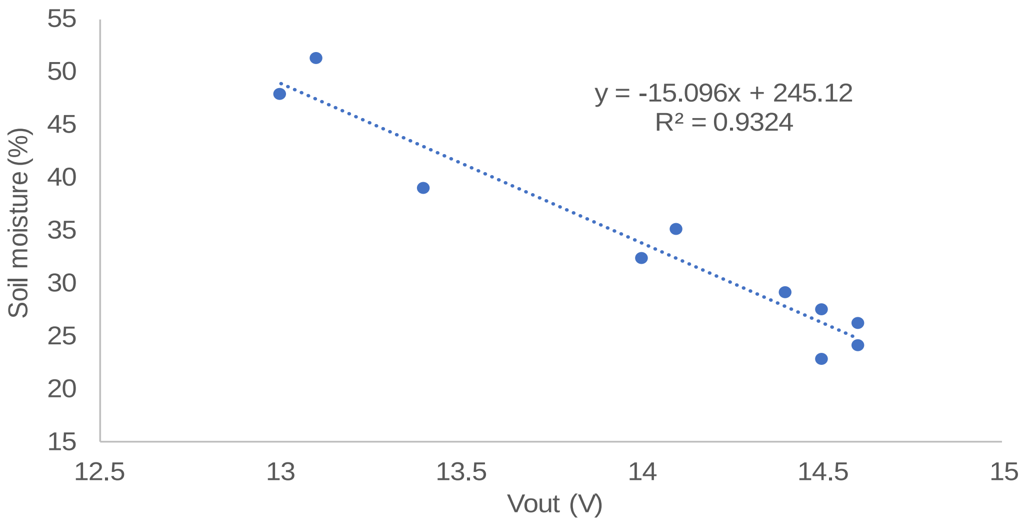

Figure 43. *Vout* of P8 using S3 and its mathematical model

S4 was tested until it was completely dried up. For S4 the data from frequency 770 kHz are the one used for the fitting of the model. This data present a difference of 2.4 V for a soil moisture variation of 36.36 %. This means an increase of about 0.2 V every 3 % soil moisture. The R2, along with the equation (Eq. 13) and the mathematical model can be seen in Figure 44.

The frequency chosen for S5 is 755 kHz. The difference presented by the data is even bigger than for S4. The change in soil moisture presented was of 16.23 % and the corresponding *Vout* variation was 2.72 V. This means a change of over 0.3 V for each variation of 1 %. The equation (Eq. 14) for this model, as well as its R2 can be seen in Figure 45. Similar to the case of S3, the high value of R2 serves to assume the equation can be used until the WP.

$$\text{Soil moisture } (\%) = -15.096 \cdot Vout \text{ (V)} - 245.12 \qquad \text{(Eq. 13)}$$

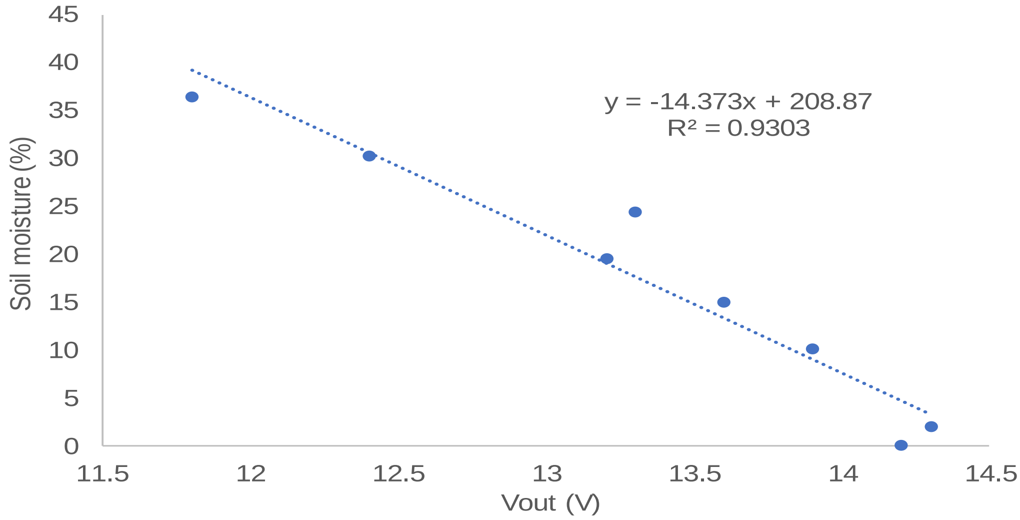

Figure 44. *Vout* of P8 using S4 and its mathematical model

$$\text{Soil moisture } (\%) = -15.096 \cdot Vout \text{ (V)} - 245.12 \qquad \text{(Eq. 14)}$$

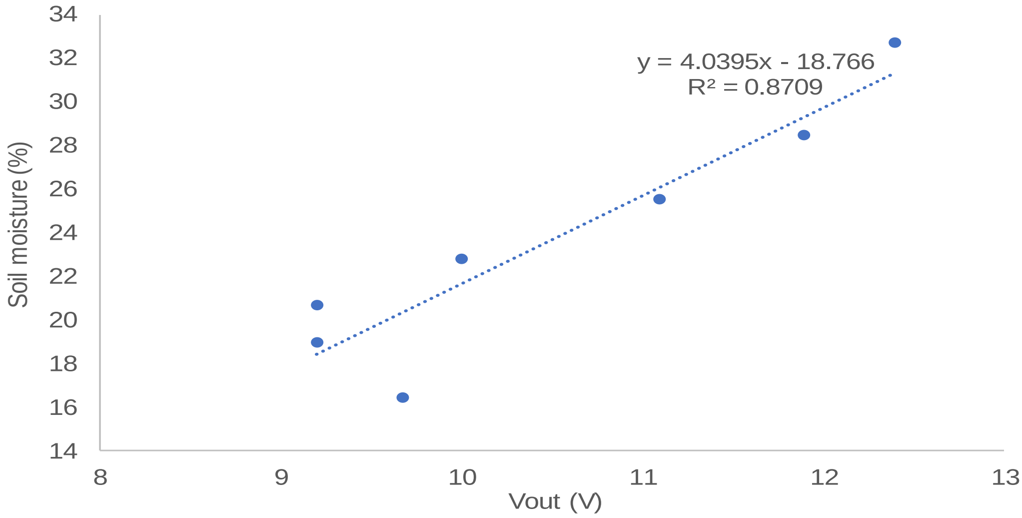

Figure 45. *Vout* of P8 using S5 and its mathematical model

5. Conclusion and future work

5.1. Fulfillment of the objective

What we have attempted to achieve is the design and development of a low-cost conductivity-based soil moisture sensor which could be integrated into a WSN. These sort of systems of smart irrigation are only used nowadays in some greenhouses and other specific places where precision agriculture is applied. Precision agriculture has become one of the most important tools in order to better manage the resources. Nevertheless, solutions that come from precision agriculture and the use of IoT are often too expensive.

In this study, a novel low-cost soil moisture sensor design and development were presented. The sensor is based on the mutual inductance effect and is composed of two solenoids. A total of fifteen different prototypes were tested with the aim of finding a prototype that has a high *Vout*, high Δ of *Vout* between different moisture, different *Vout* for all the tested moisture samples, a low working frequency and can be used on several sorts of soil. From the first set of tests we concluded that the *Vout* presents bigger changes close to the peak frequency. Moreover, some of the prototypes presented more than one peak frequency depending on the soil moisture.

Three out of the fifteen tested prototypes were selected to be further studied on different sort of soils. These prototypes were P5, P8 and P9. P5 has 40 spires in the IC and 80 spires in the PC both distributed over 8 layers and is one of the tested cased prototypes. Both P8 and P9 do not present casing, the first has 5 spires in the PC and 10 spires in the IC while the later has 10 spires in the PC and 5 spires in the IC. The first tested soil was an organic matter rich substrate used in gardening, with a high content of nutrients and sand. A fallow land was the second soil, with a high percentage of sand (about a 60%), a substantial quantity of silt (about 30%) and a low percentage of nutrients and organic matter. The third soil was obtained from the hillside of a mountain, its main component being sand (about a 70%) with the second most present component being silt. The last two soils used were collected near the beach, from cultures, they were composed mostly of sand (about 95% and 90% respectively).

Nowadays, the principal limitation of our sensor is the fact that it is powered with a high voltage, and the miniaturized systems are not able to power a sensor with this Vpp. However, as the *Vout* is high, we can expect that when the sensor is powered at 3.3Vpp the *Vout* will still be high enough.

Moreover, out of the three selected prototypes, P5 and P8 complement each other. P8 was useful for S3, S4 and S5. Whereas P5 was good for S1 and S2. Therefore, they could be combined into one sensor useful for different sort of soils. The prototype used for each soil, as well as the frequency, could be specified for each soil. Moreover, it is always recommended to do a calibration of the soil moisture sensors when using them on different soil types, in order to adjust them to the characteristics of each soil.

5.2. Difficulties found during the process

Some difficulties were encountered during this study. The main one being the difficulty on making sure the not cased prototypes were completely cleaned and dried between two tests. In order to avoid the possible error due to the sensor not being completely dried, the measures were taken from driest to moistest soil.

Moreover, the constant extraction and introduction of the sensors in the soils difficulted the task and could have caused errors. This issue could be mended using a copy of the same prototype for each pot.

5.3. Personal opinion

When I studied *Sensores para la medida de campo* I decided I wanted to do my project on something that had to do with sensors. I was worried about the subject being too complicated for my background, but instead I learnt a lot. Not only about IoT, WSN, smart cities, the use of sensors for environmental monitoring; also, about how to do research work. I know my project is slightly peculiar for an Environmental Sciences student, but I think technology is an important tool for the environment monitoring. The world is not doing great lately, we need to use every resource we have to try to save it. So why not use technology? Even if it means having to learn things you never thought you would.

5.4. Publications

The author worked on two papers using the data obtained from the tests performed for this study. Those papers can be seen cited below with the APA format. They were conceived within the framework of a European Project directed by one of the tutors ERANETMED (Euromediterranean Cooperation through ERANET joint activities and beyond) project ERANETMED3-227 SMARTWATIR.

Parra, M., Parra, L., Rocher, J., Lloret, J., Mauri, P. V. & Llinares, J. V. (2019, July). A Novel Low-Cost Conductivity Based Soil Moisture Sensor. In *The 2nd International Conference on Advanced Intelligent Systems for Sustainable Development*, Maarrakec, Morocco, 8-11 July, (Vol. 2, ID: 261)

Parra, M., Parra, L., Rocher, J., Lloret, J., Mauri, P. V. & Llinares, J. V. (2019, September). Low-cost Soil Moisture Sensors Based on Inductive Coils Tested on Different Sorts of Soils. In *1st International Workshop on Technology for Precision Agriculture and Crops* (TeCrop 2019), Granada, Spain, 22-25 October 2019

Parra, M., Parra, L., Rocher, J., Lloret, J., Mauri, P. V. & Llinares, J. V. (2019, September). Design and Calibration of Moisture Sensor for Irrigation Monitoring. Pending finding the most suitable journal for publishing

5.5. Future research and applications

The future work will be focused on evaluating the effect soils with a higher concentration of salts will have on the *Vout* since this will affect the dielectric constant of the medium. Moreover, as in some cases the irrigation is complemented with fertigation the resultant water has higher conductivity than the regular water (as it has the fertilizers needed by the plants). Therefore, a calibration must be done including water with different amounts of fertilizer. However, even in the commercial sensors some type of adjustment or even a full recalibration must be carried out before its implementation in a specific soil to adjust the response to the soil and water properties.

The prototypes will be tested in more soils, in order to search for a pattern. Moreover, the prototypes will also be tested under different temperatures to test their sensibility to the changes in the environment. Besides, the efficiency of P8 when cased has yet to be tested, as well as the efficiency of combining it with P5. Further tests will be done without extracting the sensor from the soil between measures, this will be accomplished making several copies of the same prototype.

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