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Development of a Pilot Smart Irrigation System for Peruvian Highlands

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Abstract: With growing developments in the technology of cloud storage and the Internet of Things, smart systems have become the latest trend in major agricultural regions of the world. The Arequipa and Caylloma provinces of Peru are highly productive agricultural areas that could benefit from these technologies. This region has low precipitation, generally less than 100 mm per year. Electricity is not available in most of the agricultural fields, limiting the types of irrigation methods and technologies that can be supported. Currently, 20 ponds supplied by water runoff from the Andean glaciers are used for irrigating approximately 545 hectares of land in the Majes district (Caylloma province). In order to develop optimal techniques for water irrigation in Arequipa and improve the infrastructure, there is a need for development of a smart water irrigation system applicable to the existing conditions in the region. The current study proposes a pilot smart water irrigation framework comprised of a drip irrigation module, wireless communication module, and a sensor network for intelligently regulating water flow from the cloud. In this study, a TEROS 12 soil moisture sensor is connected to a Digi XBee wireless module for collecting measurements of volumetric water content, temperature, and electrical conductivity, which are sent through a secure IP gateway to the cloud. A user-friendly web interface is available for end-users to access and analyze real-time data. The proposed framework is easily implementable, low-cost, and is predicted to conserve water through optimization of irrigation cycles based on a set moisture threshold.

Keywords: *volumetric water content, Internet of Things, soil moisture sensor, microcontroller, irrigation efficiency*

Irrigation is crucial for the economy, poverty reduction, and food security in the Peruvian highlands, leading to a need for sustainable use of water (Davis et al. 2009; McCready et al. 2009). The recession of the Peruvian glaciers is estimated to have a significant impact on the downstream ecosystem and communities (Vuille et al. 2008). Glacier meltwater runoff buffers the water shortage caused by low precipitation during the dry season in the Peruvian highlands (Kaser et al. 2003). Water used for irrigation accounts for 80% of water usage for this region (Maos 1985). The Arequipa district of Peru benefits from high land fertility and favorable temperatures for agriculture, leading to cultivation of crops such as grapes, avocados, quinoa, onion, garlic, corn, and wheat (Gelles 2000). Until the late 1980s, a lack of effective irrigation in the Arequipa district of Peru led to poor vegetation growth (Stensrud 2016). Local farmers in the Arequipa region most commonly use flood irrigation which leads to waste of agricultural water and ineffective use of natural resources (Gurovich and Riveros 2019). The irrigation infrastructure in Peru is defined by the agricultural land and water resources, with 5.5 million hectares in use, of which 3.75 million hectares utilize rainfed agriculture and 1.75 million hectares use water reserves like lakes, ponds, and reservoirs (Huamanchumo et al. 2008). The irrigation infrastructure in Arequipa suffers from limited measurement of the actual performance, improper scheduling, low precipitation of 100 mm per year, lack of power sources, and proper logistic management (Netherly 1984; Ertsen 2010). This creates an immediate requirement for a low-cost, intelligent irrigation schedule coupled with an optimized irrigation system to manage the available water for irrigation, improve crop yield, and optimize the quality of the yield. Therefore, the goal of this work is to develop an integral solution using a microcontroller and wireless communication modules for an autonomous, low-cost smart irrigation system. Purdue University students and faculty, in collaboration with faculty from Universidad Nacional San Agustin (UNSA), Peru, under the Purdue Center for the Environment, C4E, and the Arequipa Nexus Institute, developed the testing of the pilot smart irrigation system presented in this article in order to drive forward the development of low-cost, high-tech agricultural systems for the local Arequipa region.

This paper is organized as follows: In Section 2, literature regarding the use of intelligent techniques and Internet of Things (IoT) framework in irrigation systems in the last decade is discussed. Section 3 provides details of the design and development of the proposed smart irrigation system and the collaboration between Purdue University and UNSA. Section 4 contains the details of the experiments conducted in the laboratory and Peruvian highlands for the designed smart irrigation system. As a part of this experimental validation, Section 5 contains a discussion about the outcomes from the experimental study. Section 6 summarizes the work and presents the conclusions.

Literature Review

Advancements in IoT during the last decade have led to a boom in the agricultural sector in which a combination of IoT devices, control approaches, and cloud computing has improved the effectiveness of agriculture and irrigation. Abdullah et al. (2016) conducted a study on a Smart Agriculture System (AgriSys) that could analyze an agricultural environment and intervene to maintain optimized productivity. The system dealt with general agricultural challenges such as temperature, humidity, pH, and nutrient support. Additionally, the system dealt with the desert specific challenges of dust, infertile sandy soil, constant wind, very low humidity, and extreme variations in diurnal and seasonal temperatures, using a fuzzy-logic based smart agriculture system. Nesa Sudha et al. (2011) proposed two different energy conservation mechanisms that have been analyzed based on the Time Division Multiple Accesses scheduling plan for automatic irrigation systems. Both methods provided a better performance in simulation scenarios compared to other conventional methods used in smart irrigation systems. In the last decade, ZigBee has gained a lot of popularity as a communication protocol to transfer important information, such as flow and pressure readings for use in smart irrigation decision making. This protocol may use the digicloud as a possible interface to transfer important data to and from edge to the cloud (Foster et al. 2008). Prathibha et al. (2017) proposed an IoT based smart irrigation system based on the ZigBee communication protocol to monitor and control a set of sensors and actuators assessing the water needs of crops. A similar study conducted by Usha Rani and Kamalesh (2014) used an Arduino microcontroller to monitor a smart irrigation setup. The studies proved that ZigBee has been an effective tool in optimizing labor and water costs on agricultural land. A review of the use of ZigBee communications has been conducted by Zhou et al. (2009) by investigating large scale data assimilation using a ZigBee protocol across a large field area. Valente et al. (2007) investigated multi-hop networking across a larger agricultural land using a ZigBee protocol and Multifunctional Probes (MFPz). To make the agricultural systems smarter there is a need to acquire accurate data, in addition to having an effective communication protocol. Towards this effort, a few studies (Kim et al. 2008; Gutiérrez et al. 2013; Veeramanikandasamy et al. 2014) have presented site-specific data transmission approaches for smart irrigation systems, to ensure that water use efficiency is increased through the use of intelligent approaches and automation of drip irrigation systems. The proposed approach in this study combines the communication protocol approach of ZigBee as seen in Prathibha et al. (2017) and the data transmission approach of Kim et al. (2008) to develop an IoT based smart irrigation system for the Peruvian highlands to improve productivity and conserve water in water-deprived agricultural lands.

Design and Methodology

The initial design of the smart irrigation system was prototyped in a laboratory with the intent that it would be replicated and expanded at Peruvian field sites, as demonstrated in this work. The proposed system incorporated three major design factors: 1) low-cost, 2) autonomy, and 3) replicability. The goal of the project was to provide a low-cost IoT architecture for irrigation leading to improved water use efficiency and improved crop yields. The proposed schematic for the IoT based smart irrigation system is shown in Figure 1. It must be noted that a filter was not required for the laboratory setup but was used for the on-site application due to low water quality in the region. The available pressure at the field sites in Arequipa (generated by gravity) was emulated at the laboratory by using an electrical pump and a pressure regulator to reduce the pressure to 6 PSI, enough pressure for the emitters (pressure compensating) to work as expected.

In order to make the proposed system shown in Figure 1 low-cost and easy to replicate, off the shelf components were specified, along with common sensors and popular microcontrollers which have open source technical support available online. The authors took into account the availability of components in the local Arequipa region to design the current setup at a cost affordable for local farmers, compared to the current off the shelf, solar powered irrigation systems (Wazed et al. 2017). Such systems are not only expensive, compared to the proposed setup, but also need better technical management of the resources required to maintain the system, primarily the communication methods. The proposed system in Figure 1 is easy to maintain, cheaper, and replicable using local resources available in Arequipa. The bill of materials of the components, microcontrollers, and sensors used in the development of the setup is presented in Table 1.

The proposed IoT system consists of three nodes: a sensor, a receiver, and a transmitter node. Node 1 was the sensing node where a TEROS 12 sensor measured 1) volumetric water content (VWC) or the ratio of the volume of water to the total volume,

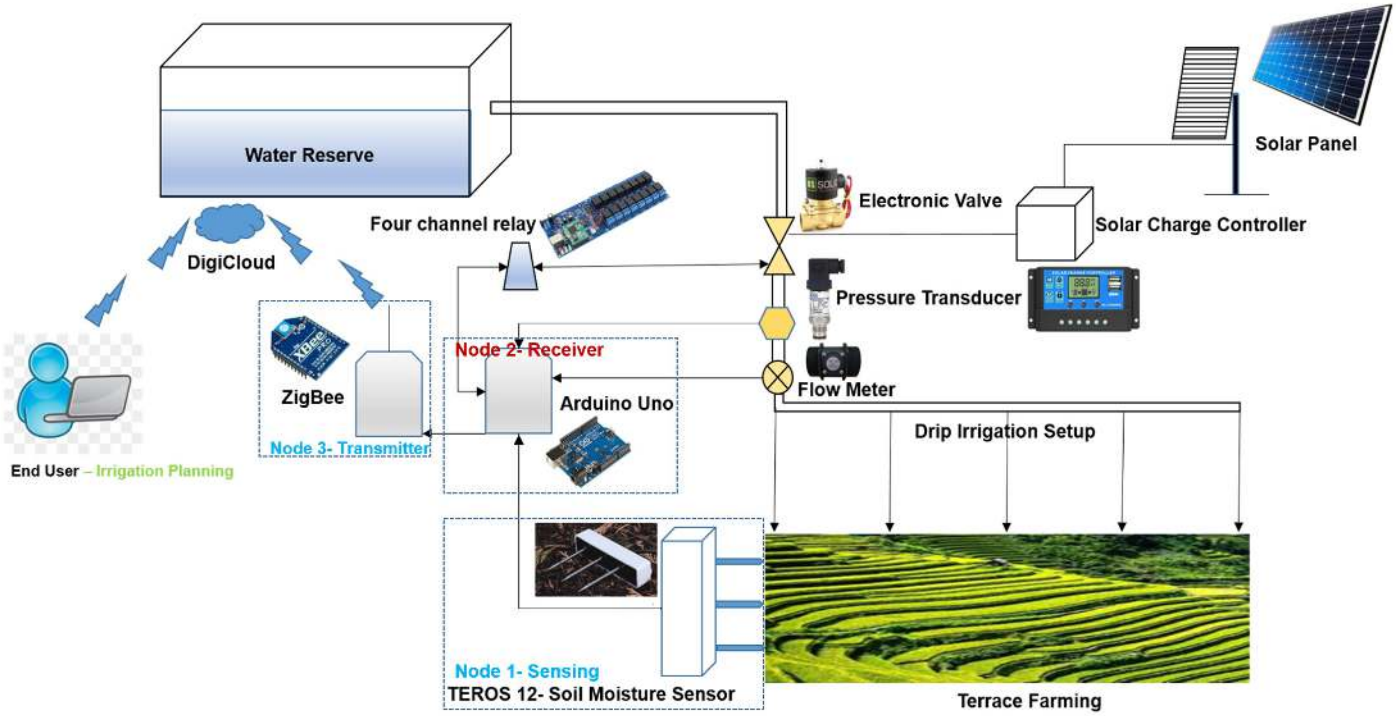

Figure 1. Schematic of the proposed IoT based smart irrigation system. The details and specifications of the sensor and microcontrollers used in this setup are described in Table 1.

Table 1. Bill of materials.

Name	Type	Cost (in US$)
PVC Fittings	Hydraulic	70
Drip Tubes and Fittings	Hydraulic	90
Digi XBee Development Kit	Electronics	90
Digi Gateway	Electronics	250
Teros12 Soil Moisture Sensor	Electronics	225
Arduino Uno	Electronics	25
12 VDC Relay Module	Electronics	16
½" NPS Flow Meter – Hall Effect Sensor Switch	Electronics	13
Wika A-10 Pressure Transmitter 0-15 PSI, ¼" NPT	Electronics	175
100W Solar Panel and 10 Amp Charger Controller 12 VDC	Electronics	100
12 VDC Electric Solenoid Viton Valve – Normally Closed	Electronics and Hydraulic	30
Battery (12 VDC - 18 Ah) and Electric Accessories	Electrical	150
Total Cost		1234

2) temperature, and 3) electrical conductivity (EC). The sensed data were sent to an Arduino Uno receiver. The Arduino also took pressure and flow data from a pressure transducer and flow meter. All these data were then transferred to a Digi gateway using the ZigBee communication standard with an XBee module. The Digi gateway then transmitted the data to the cloud for analysis. The irrigation cycle time and moisture threshold were set in the Arduino controller to regulate when irrigation was needed. The Arduino produced a control signal to turn on a relay connected to an electronic solenoid valve. When a value below the moisture threshold was reached, the valve was turned on via the relay to start the irrigation cycle. The control system implemented in this design only used the minimum and maximum moisture levels to activate or de-activate the irrigation cycle. Cycle data and timing were recorded and stored on the digicloud allowing users to view the data from a remote location. The use of real-time measurements in combination with the microcontroller allows for the implementation of closed-loop control locally, and the remote collection and manipulation of data in the cloud. The system was constructed to run on local power, but because in certain locations in Arequipa there is no electrical grid, the system was also set up with a set of solar panels to charge a battery for powering the system.

Experimental Setup

Laboratory Setup

Figure 2 shows the flowchart and block diagram of the smart drip irrigation system design using IoT components. In order to benchmark the proposed schematic, a laboratory based experimental prototype was initially developed. The complete assembled experimental setup of the smart drip irrigation system is shown in Figure 3, including the electronic and hydraulic components.

Using a controlled temperature chamber with artificial light, the prototype was tested under different conditions to evaluate its performance and effectiveness with spider plants, grown in pots containing approximately three kilograms of soil. The soil used in the laboratory test was a mix of sand and silt mixed at a 76/24% ratio for all experiments. This mixture was representative of the soil conditions found in Majes and was acceptable for growing this type of plant. Cruz Chavez (2018) conducted a study to evaluate the impact of three different tillage techniques in soil structure, water retention capacity, and the presence of compacted layers at the Centro de Investigación, Enseñanza y Producción Agrícola (CIEPA), an agricultural research center in Majes. Before applying the various treatments on the different plots, a representative soil sample was

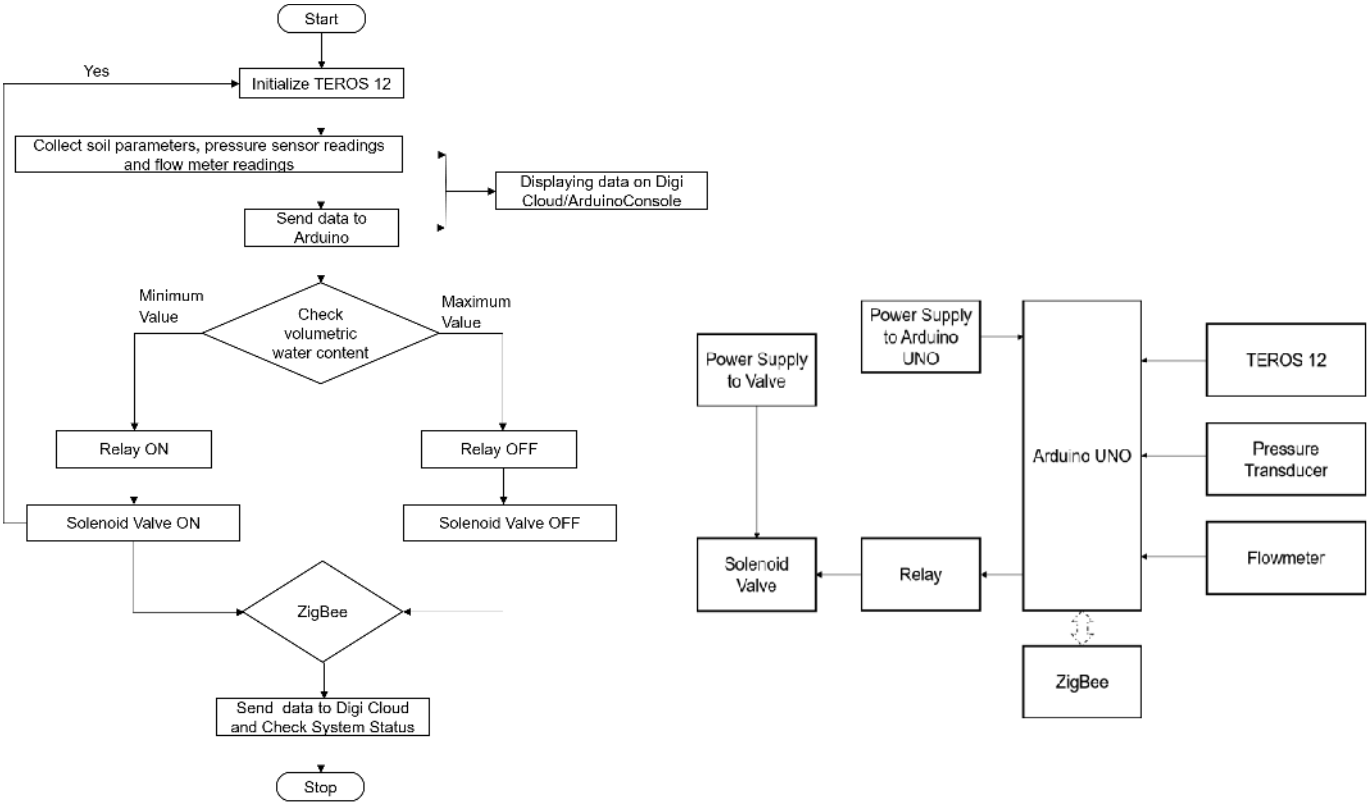

Figure 2. Flowchart and block diagram of the developed smart drip irrigation system using IoT.

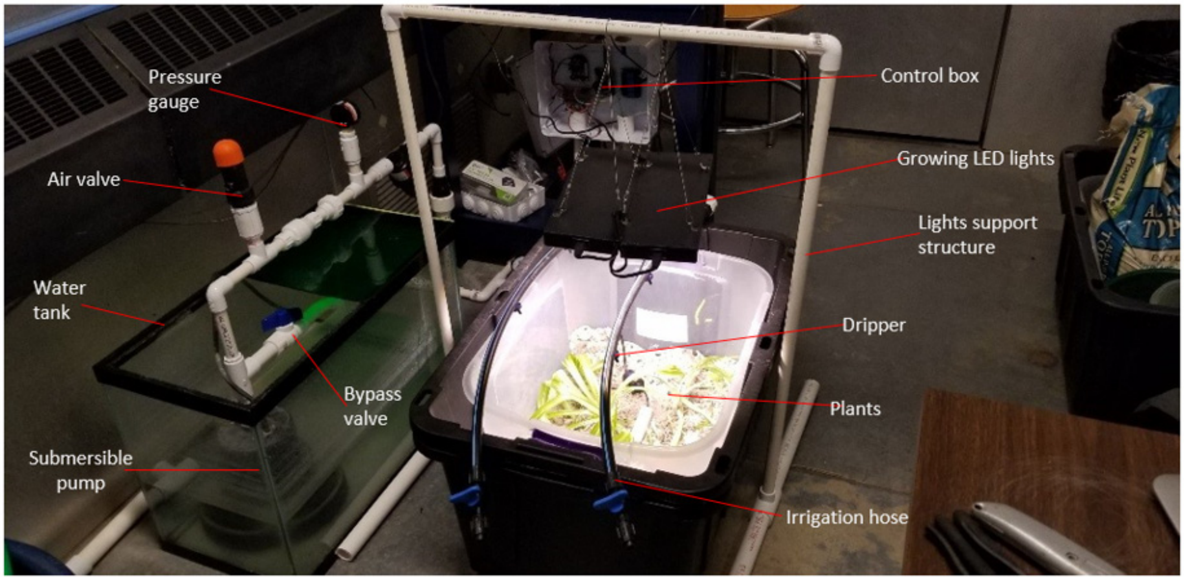

Figure 3. Assembled experimental setup of the smart irrigation system in laboratory.

analyzed. The laboratory results showed a sandy loam soil texture, with 76% of sand, 19.2 % of silt, and 4.9% of clay.

The spider plant (*Chlorophytum comosum*), native to South Africa, has been proven to thrive well in a wide range of soils, and to be drought and heavy-metal tolerant (Wang et al. 2011; Sanchez-Lizarraga et al. 2018). Due to its easy cultivation, spider plants are readily available (Sanchez-Lizarraga et al. 2018). Sandy soils such as the one proposed for the laboratory tests offer a well-drained substrate for growing spider plants, which is key for their development (Lattoo et al. 2006).

The setpoints were defined by taking soil samples to the saturation point and then after releasing excess water, field capacity was achieved. It was found that the field capacity corresponds to a VWC close to 30% (m^3/m^3). The field capacity was chosen as the upper setpoint, to avoid water waste. On the other hand, the lower setpoint was determined based on the soil texture. Sandy soils have a small water holding capacity of around 10% (Sharma 2019) and considering how well the water is drained and that the spider plant root zone is just four inches from the surface, a VWC of 27.5% was chosen as the irrigation triggering condition.

Once the VWC is below 27.5%, the controller will start irrigating for a pre-set amount of time (1.5 or 3 minutes, see Table 2). After finishing the irrigation cycle, the controller will take a new measurement, if the VWC is equal to or larger than 27.5%, the controller will not irrigate and will wait until water is consumed by the plant or it evaporates.

Six soil samples were used to test the accuracy of the chosen soil moisture sensor. Each soil sample was watered until saturation was attained, and the weight was measured and compared with the dry weight. The TEROS 12 sensor was installed in the soil sample before the watering process. Once the sample released the excess water, the sensor reading was captured. The calibration equation provided by the sensor's manufacturer for mineral soils (any soil different than artificial substrates) was employed to convert the raw data into VWC values. A 5% error was found when comparing the VWC calculated based on dry and saturated weights and the VWC provided by the sensor, proving its effectiveness and easy setup.

Field Testing in CIEPA-Majes

The prototype developed at Purdue University was taken to two different field test sites in Peru. The first tests took place in a plot planted with grass inside the CIEPA agricultural research center. The test was adapted to the hydraulic connections of the system. The plot used received water by gravity from a nearby water pond which was filled daily from a main channel.

The solar array was replicated with local components because there was no electric grid on the plot, simulating the conditions of a traditional farm. Hose laterals were installed over the area to be irrigated and emitters were inserted using a punch tool every 20 cm, producing flows of two liters per hour each. Finally, the gateway was placed in the research center's main building at the highest accessible point, powered by a battery and sending data to the cloud using a 3G-SIM card from a local provider. The main objective of performing this test was to prove the effectiveness of the prototype in the real environment by letting the system work during the irrigation time window (when water is provided from the water pond), running the closed-loop program, and sending information to the cloud.

Field Test in Moquegua

A farm growing avocados and other fruit trees, located in the Moquegua State next to Arequipa, was used to test the prototype in a different agricultural setup. The farm had a hilly topology and the lines of trees were aligned with topographic curves, conditions challenging for common flood irrigation practice. A similar approach to the Majes test took place. Hoses with emitters were connected to a tank which was filled using an electrical pump installed in a nearby channel and powered by a solar energy array. In this case, taking advantage of Wi-Fi availability over the weak 3G signal in the area, the microcontroller sent the data to the Ubidots platform.

Results and Discussion

The laboratory prototype of the experimental setup was able to communicate data to the cloud effectively. This is evident from the relay data recorded in binary format on the cloud shown in

Figure 4. The data from the soil moisture sensor, pressure transducer, and flow meter were also recorded on the cloud and retrieved from the digicloud web interface.

The irrigation time, system pressure, and time between measurements were changed as described in Table 2, to test variations in irrigation cycles. The prototype was tested under steady environmental conditions of 22°C and relative humidity of 60%, which represent the maximum monthly average temperature and average humidity (Cruz Chavez 2018) in the Majes region. The experimental parameters for producing the various experimental cases were changed in the software. The initial soil moisture was also specified for each case. The flexibility of the system becomes a strength when installing the setup in different regions. Different soil types and plants will require a short calibration process to then determine the irrigation setpoints.

The results demonstrate the closed loop effectiveness of keeping the VWC of the soil within a small threshold, providing the plants with favorable growing conditions. The VWC was recorded over 19 hours for cases one to four. Figure 5 presents these results. System pressure was adjusted beforehand using a manual bypass valve installed on the system to prevent over pressurization. A pressure of 6 PSI was set to emulate the water head pressure created by the height difference between the water pond and the field.

Cases number one and two exhibit similar behavior. Once irrigation is triggered, the VWC increases over the setpoint due to the lag caused while the water infiltrates. Then evapotranspiration takes away part of the available water. Once the water content goes below the setpoint, the system turns on the irrigation mechanism. Case number three involves an irrigation time two times larger than cases one and two, creating higher peak values for the soil moisture level after each irrigation cycle, therefore, reducing the system's start times. Case number four uses the same irrigation time as in cases one and two, but the system pressure is increased up to 10 PSI compared to the 6 PSI of the other experiments. This increase in pressure has a similar effect when compared to the increase of irrigation time, higher peak values, and lower start times.

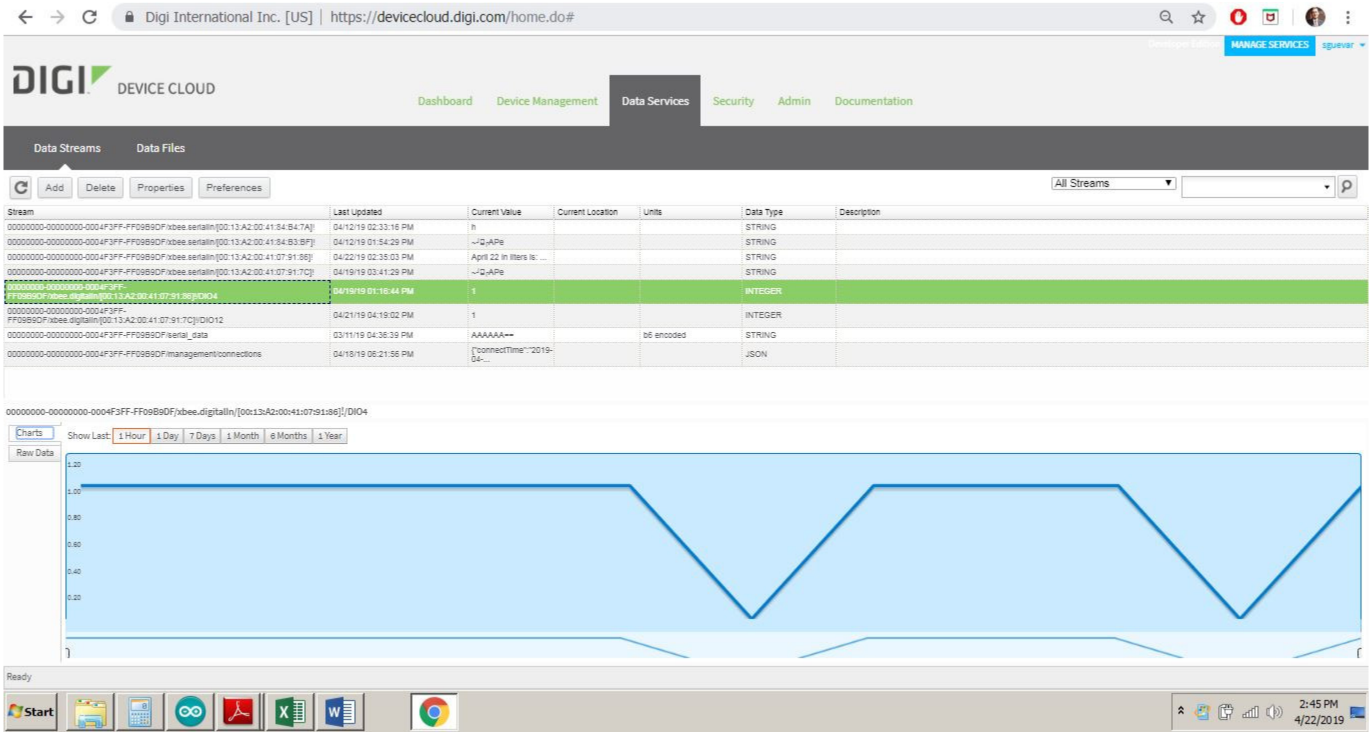

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Figure 4. Data on the cloud from the laboratory test of the experimental setup showing ON/OFF switching of relays in binary format. Sensor data from different on-board sensors are recorded on the cloud.

Table 2. Laboratory tests.

Case number	Time between measurements (min)	Irrigation time (min)	System pressure (PSI)	Soil initial moisture level
1	3	1.5	6	Dry
2	3	1.5	6	Slightly dry
3	3	3	6	Dry
4	3	1.5	10	Dry
5	30	1.5	6	Dry

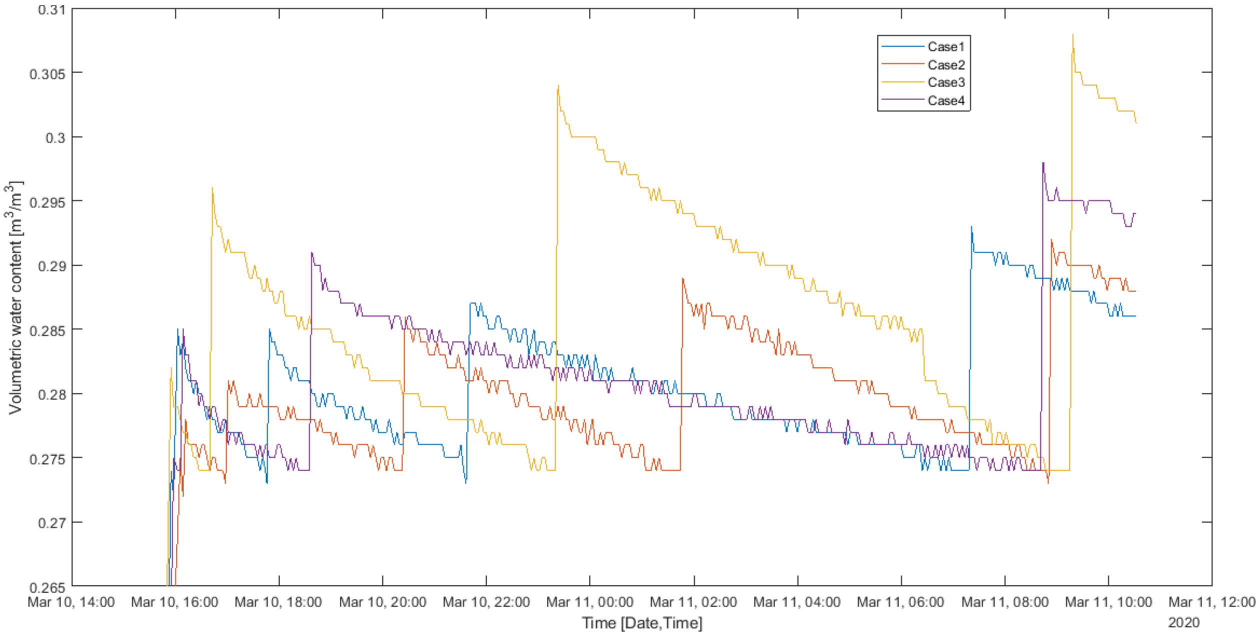

Figure 5. Volumetric water content through time for cases one to four.

Test case five was carried out for 73 hours; the VWC, soil temperature, and soil EC were recorded. A plot containing the three variables was generated along with the irrigation trigger (black line) to visualize its effect as seen in Figure 6.

Figure 6 presents the behavior of the VWC initially increasing after the first irrigation event. From that point, a consistent pattern between water consumption from the plant and irrigation triggering is displayed for the 73-hour irrigation cycle. Soil temperature (Temp.) tends to remain around a steady value, affected by the cooling effect of irrigation as seen in Figure 6.

The soil EC shown in Figure 6 decreases through time as the plant consumes the available minerals of the soil. When the irrigation cycle takes place, a peak on the EC is generated as a result of the momentary increased ability of the soil to conduct electricity due to the water. To display the values on the plot, a multiplier of ten was applied to increase the scale of the axis.

The effectiveness of the system was demonstrated under laboratory conditions. The prototype was able to respond to different VWC levels assuring the plants' wellbeing while conserving water through drip irrigation at optimized times. Since the laboratory setup was designed to be replicated in the Peruvian environment, after the experimental lab testing was completed, the experimental prototype was installed in an agricultural farm,

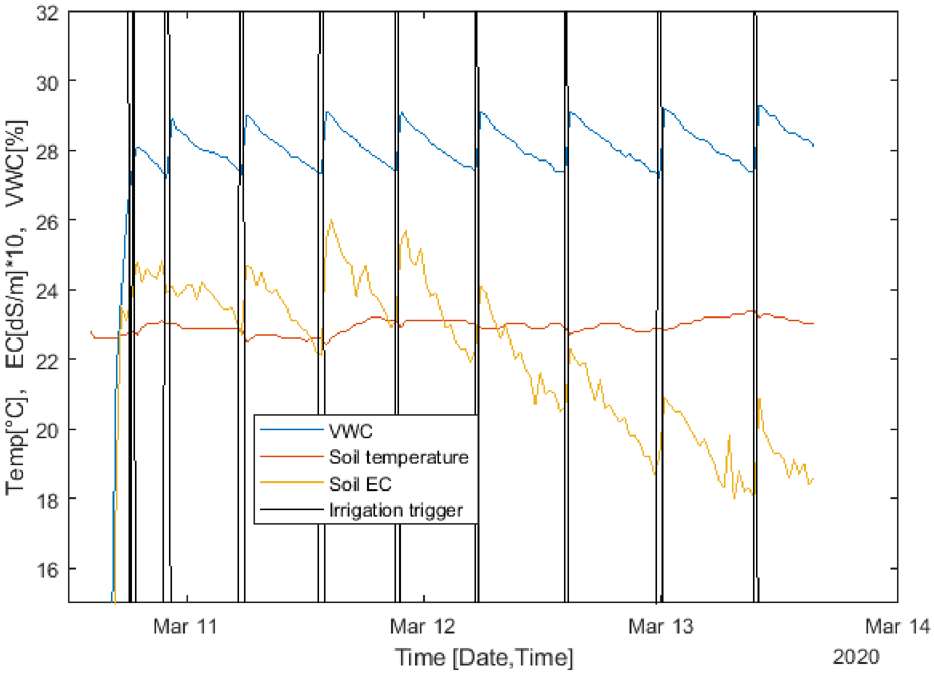

Figure 6. Volumetric water content through time for case five.

CIEPA-Majes at UNSA and a field site in the neighboring state, Moquegua. The major objective of the replication experiment was to determine the effectiveness of the developed laboratory setup in a real environment. Figure 7 (top) shows the implementation of the experimental prototype at CIEPA-Majes.

Six cases were measured in Moquegua, for three zones with 15 trees planted in rows in each zone. The approximated full irrigation area was 330 m^2. The soil moisture sensor was installed at approximately 20 cm below the surface at the end of each row of trees, and the system was set so that the irrigation control valve would turn on when the soil moisture value was below 40%. The picture in Figure 8 (left) shows the hardware used in the field. Since the test area was located on land previously inaccessible for agriculture, due to its hilly topology and non-optimal topographical features for flood irrigation, growing these trees is a remarkable improvement. Moreover, water saved by implementing the smart irrigation setup is an important step towards the region's sustainability. If the trees had been placed next to the water ditch, 5,000 liters of water would have been used to flood a zone of similar size (15 trees in a row) by letting a pump work for five minutes with a flow rate of 1,000 liters per minute. Flood irrigation has a reported efficiency of 40% in the region (The World Bank 2013), meaning that from those 5,000 liters, just 2,000 liters would have been delivered to the trees. On the other hand, the smart irrigation setup used 362.3 liters to bring the soil to field capacity in zone 1, employing drip irrigation with an efficiency in the range of 75% to 95% (Howell 2003). Assuming an efficiency of 85% for the smart irrigation setup, 308 liters were estimated to be delivered to the trees in one and a half hours compared to the application of 2,000 liters in five minutes offered by flood irrigation. Considering the soil in the Arequipa region is well known for its high drainage capabilities, the use of the proposed smart irrigation system allows farmers to effectively provide water to the root zone in a constant manner, saving water and as demonstrated in past work, maintaining yield (Miller et al. 2018).

The plots shown in Figure 8 (right) portray the results captured by the smart irrigation system implemented at the field site in Moquegua. This setup measured six cases, where cases 1 and 2 refer to node 1 row of trees. Similarly, cases 3 and 4, refer to node 2 for the second row of trees on the same days, and cases 5 and 6 refer to the third row of trees. In all cases the solenoid-controlled

Control box installed.

TEROS 12 located at a soil depth of 20 cm.

Assembled smart drip irrigation setup.

DIGI Gateway installed on building roof.

Waterhead for the assembled smart drip irrigation setup.

Installed drip lines with drippers.

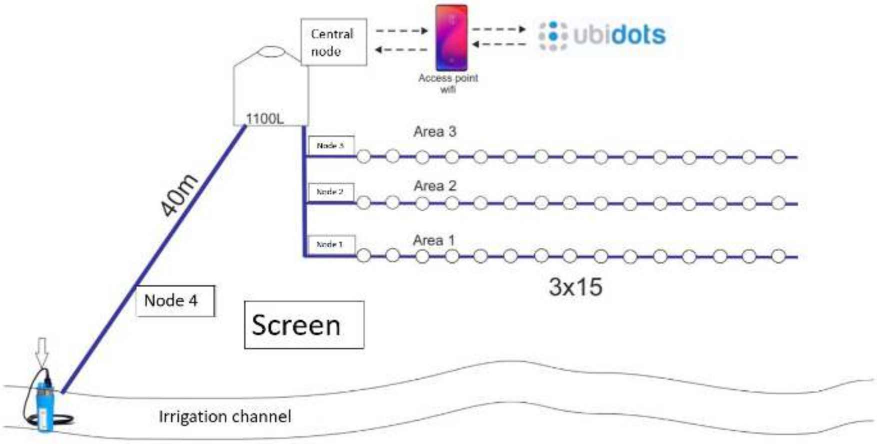

Figure 7. Replication of the smart irrigation setup at CIEPA-Majes (top) and Schematic representation of the measurement setup used in Moquegua (bottom).

irrigation valve was turned on until the humidity threshold (40%) was reached. Due to the larger area of the field, it was observed that attaining the desired humidity at the sensor took an approximate time of 1 hour and 30 minutes for node 1, 2 hours and 30 minutes for node 2, and 3 hours and 45 minutes for node 3. While the reason for the discrepancies between the nodes is unknown, it is believed that the differences in measurement may be due to the sensors' locations and the unevenness of the terrain. As drip irrigation does not wet the entire soil surface, irrigation uniformity is both hard to estimate and usually low (Howell 2003). In cases 1 and 2, the soil moisture sensor was installed close to the emitter, which exposed it to a higher moisture content than surrounding areas. Soil topography and infiltration variations within the same farm negatively affect the generalization of the sensors' measurements (Howell 2003). It is also noted that adding more sensors in each irrigation node would improve the performance of the irrigation control system.

Conclusion

The current study developed a closed-loop, autonomous smart drip irrigation system based on

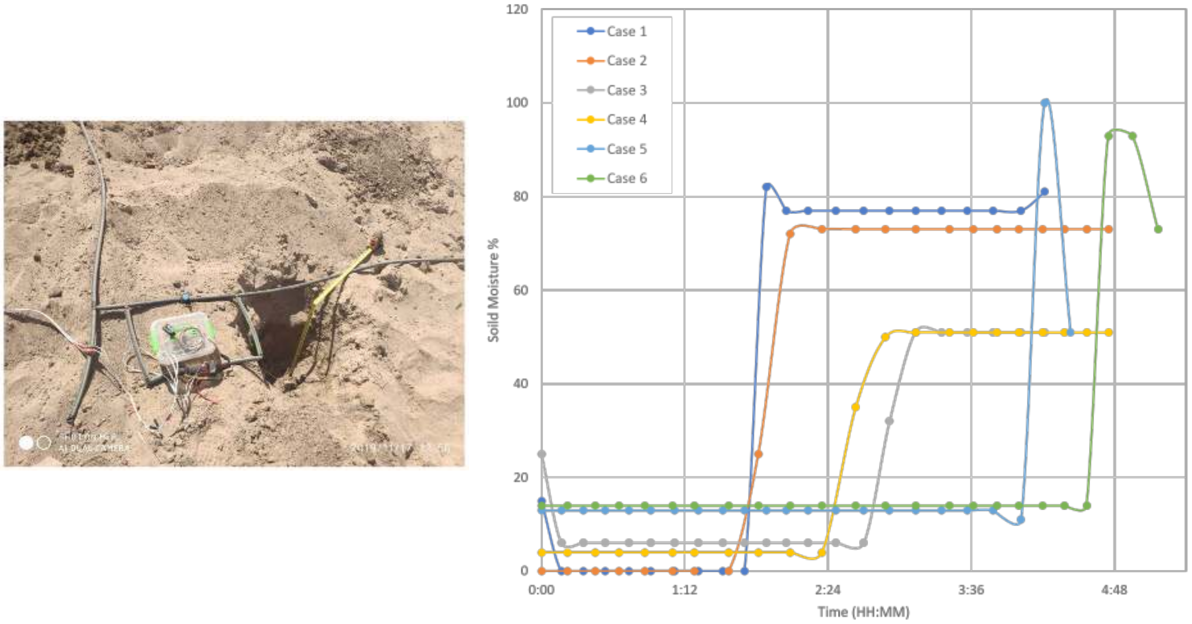

Figure 8. Hardware setup at the Moquegua test site.

concepts of IoT. A low-cost, autonomous smart drip irrigation system was initially designed and tested in a laboratory setting with replicability in mind and later tested in agricultural farms in Peru. This system was found to be effective in providing reliable measurements of soil moisture, temperature, and conductivity along with optimization of the irrigation cycles based on a set moisture threshold. This design provides a simple, low-cost, autonomous solution for the irrigation needs in Peru and addresses issues like lack of electrical power by using solar panels, and the Digi module for communication. The working prototype was designed and built at around U.S. $1,000 using readily available components, and was demonstrated to operate consistently overnight and in varying temperature, moisture, and soil conditions.

The field tests proved that the cellular network availability and poor signal quality impose a challenge in remote areas for the prototype to effectively send the information to the cloud. Similarly, in remote areas, additional attention must be paid to securing the components from theft. Another drawback of the system is the lack of synchronization between the water supply from the irrigation district and the operating hours of the prototype. Irrigation might be triggered when there is no water supply from the water pond or the determined reservoir, wasting energy on operating the electro valve and depressurizing the system.

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