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VISIÓN ELECTRÓNICA

A RESEARCH VISION

Intelligent agricultural irrigation prescription system based on sensor networks and crop modeling

Sistema inteligente de prescripción de riego agrícola basado en redes de sensores y modelado de cultivos

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ABSTRACT

The intelligent management of water in agriculture through emerging technologies is essential to increase crop yields, reduce production costs and contribute to environmental sustainability. The aim of this research work was to implement an intelligent agricultural irrigation prescription system. Nodes for the acquisition and wireless transmission of data on soil matric potential up to four depths, canopy temperature, environmental temperature and relative humidity were implemented. The inference system was implemented in a central station that receives data from the field, where the irrigation prescription is determined. The validation of results was carried out using the AquaCrop crop modeling software. The developed system allowed determining daily water prescriptions according to soil type and crop phenology, to avoid excesses and deficiencies in the application.

RESUMEN

La gestión inteligente del agua en la agricultura mediante el uso de las tecnologías emergentes es esencial para aumentar la productividad en los cultivos, disminuir costos de producción y contribuir a la sostenibilidad ambiental. El propósito de este trabajo de investigación es implementar un sistema inteligente de prescripción de riego agrícola. Se pusieron en práctica nodos de adquisición y transmisión inalámbrica de datos de potencial matricial del suelo hasta cuatro profundidades, temperatura de la cobertura vegetal, temperatura ambiente y humedad relativa. El sistema de inferencia fue implementado en una estación central que recibe los datos en campo en donde se determina la prescripción de riego. La validación de los resultados se realizó usando el software de modelamiento de cultivos AquaCrop. El sistema desarrollado permitió determinar prescripciones de agua diarias según el tipo de suelo y el estado fenológico del cultivo, con el propósito de evitar excesos y deficiencias en la aplicación.

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1. Introduction

Adequate water resources in the application of agricultural irrigation is of vital importance to achieve food security and sustainable development at a global level [1]. In several regions of the world, the depletion of this resource is evident in different seasons of the year, as a result of climate change, environmental impacts due to waste, deforestation and, especially, the inefficient use of water by humans [2]. In addition, agriculture is the largest consumer of freshwater in the world, with values close to 70% of its total availability [3], where the excessive application of the resource in the field occurs due to the inefficiency of existing irrigation systems and technologies [4].

Irrigation water use efficiency (EUAR) is a parameter that relates crop yield to the water applied during plant development. Achieving high EUAR values at the end of harvest is one of the most important challenges for modern technologies [5]. Within the so-called precision agriculture, precision irrigation is a key paradigm to manage crops by using data collected in the field, avoiding excess or deficit of water [6]. This methodology of water application in the field, hand in hand with the new digital agriculture, allows the combination of telecommunication technologies, hardware, software and data analysis techniques. The growing innovation in Internet of Things (IoT) technology platforms is expanding to agricultural applications in both research and commercial activities. In this sense, smart agriculture applies IoT and data analytics to improve the benefits of precision irrigation, with the aim of applying prescriptions according to soil conditions, plants and the environment where the crop is located, also improving the economic profitability of the farmer.

IoT systems are composed of devices that allow sensing, variable monitoring, control and action on actuators. In addition, these devices have the necessary hardware for data transmission using specific communication protocols [7]. For user interaction with an IoT-based system, information obtained from the extraction, processing and analysis of raw data can be visualized. Finally, the user has the possibility to execute control commands over actuation systems or also the autonomous operation systems can be generated [8].

In the agricultural field, emerging technologies are playing a fundamental role in process optimization. In the case of irrigation, sensor network technologies and artificial intelligence have been important for real-time monitoring of field variables, in addition to the development of applications on mobile devices and the cloud. Some reported research and developments address aspects of irrigation for smart orchards [9], soil moisture measurement [10], water resource waste management [11], development of measuring equipment [12], sensor networks for irrigation applications [13], irrigation automation [14], soil moisture monitoring and fertigation [15], data management applications and mobile devices [16], in addition to machine learning techniques for irrigation prescriptions [17-18], and the internet of things [19-21].

There are intelligent platforms used in irrigation that allow the management of information on large scales. For example, in Europe, FIGARO (Flexible and Precision Irrigation Platform for Improving Water Productivity on a Large Scale) was developed, whose purpose is to increase the efficiency of water use in agricultural fields, in addition to the development of a cost-effective technology platform for the farmer [22]. For monitoring variables in organic and precision agriculture, IoT-enabled platforms have been developed [23]. For example, for smart agriculture management, the theoretical framework for IoT-based agricultural management called Agri-IoT was developed, which also enables real-time data processing [24]. In addition, other applications for precision agriculture applications have been developed with FIWARE which is an open source technology framework for the development of smart solutions in different domains [25].

The definition of crop water requirements can be done through various technologies, such as consumptive use of the resource by determining crop evapotranspiration [26], remote sensing through aerial, satellite or ground platforms [27], measurement of variables associated with plant water stress, especially canopy temperature [28], the use of crop modeling and machine learning [29] and of course, the measurement of soil moisture, especially sensor networks [30].

Using plant measurement techniques, the time when the plant is stressed can be defined, but not the amount of water to be applied. In order to determine accurate irrigation values using climatic data, crop evapotranspiration measurements are used in conjunction with a soil water balance equation. One aspect to highlight of the methods that use environmental parameter measurements is that they do not take into account that an irrigation system or a crop is not homogeneous [31].

Volumetric water content or matrix tension sensors in the soil are used to define irrigation times and quantities, calculating the percentage of depletion with respect to the value resulting from subtracting the permanent wilting point (PMP) with respect to the field capacity (CC). In addition, these sensors can be used to determine the moment to stop water application due to the effects of water infiltration into the soil using sensors of this type at different depths. By not taking into account the evaporative demand of the crop, soil moisture sensors do not account for plant stress. On the other hand, soil moisture sensors are used to obtain point measurements that in certain cases cannot be considered representative with respect to a complete field [32].

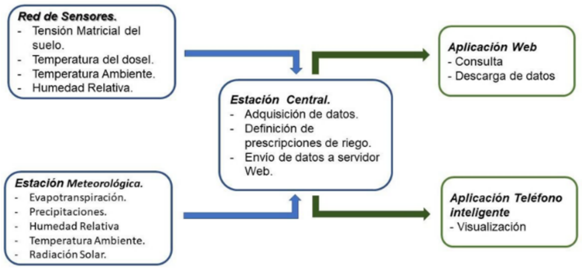
Current intelligent systems based on sensor networks, internet of things and artificial intelligence are mostly theoretical works with limited experiences showing only proof of concept. The literature references studied show that these systems are too specific, or on the contrary too generic and do not show the implementation of a system that allows replicability in implementation [33]. The system proposed in this project contributes to some challenges in the use of current technologies for precision irrigation. As a first feature, an autonomous system for intelligent irrigation prescription was developed that allows the integration of different technologies such as IoT, sensor networks and cloud computing. As a second feature, the integrated implementation of a system with heterogeneous sensors, crop models and irrigation prescription models based on artificial intelligence.

2. Methods

2.1. System requirements

The design principle of the intelligent irrigation prescription system is composed of the integration of several subsystems or modules as shown in Figure 1. The intelligent system is composed of wireless sensor nodes and a weather station, considered as the monitoring subsystem. The information is transmitted to a central station in charge of acquiring the data, determining irrigation prescriptions, which can be used by the farmer or an automatic solenoid valve opening system. All subsystems communicate with each other through a mesh network developed with Xbee Series 2 radio communicators. On the other hand, a web server application was implemented for the acquisition and visualization of the information from devices with internet access. The wireless sensor nodes and the actuation station were implemented with the ATmega328p microcontroller and the central station of the system with a Raspberry-Pi®-3B card.

Figure 1. Design principle of the intelligent irrigation prescription system.



Source: Own.

This section describes the general structure of the system and the hardware and software requirements used for system operation. Finally, the algorithms used for irrigation prescription are described.

2.2. Sensor nodes and weather station

The sensor nodes can be connected by wireless communication between them and the base station. Each node is connected to a 12-volt rechargeable battery and a 10-watt solar cell, and consists of an ATmega328p microcontroller (Microchip Technology Inc., Arizona, USA) used for data acquisition and communication with other devices, especially the base station via XBeeS2C modules, Arizona, USA) used for data acquisition and communication with other devices, especially the base station through XBeeS2C modules (Digi International, Minnetonka, Minn.) that operate using the Zigbee protocol, 2.4 GHz and a range of 3200 m using high-gain omnidirectional antennas (6 dBi).

Each sensor node allows data acquisition from four Watermark soil potential or matrix voltage sensors (Irrometer® Company, Riverside, CA), an RT-1 soil temperature sensor (METER Group, Pullman, WA, USA), an HDC1080 digital relative humidity and ambient temperature sensor (Texas Instruments, Dallas, Texas, USA) and a GY-906-DCI infrared sensor (Melexis, Ypres, Belgium) to measure vegetation canopy temperature. These devices were selected for their ease of acquisition on the market.

A Davis Instruments Vantage Pro2 weather station (Davis Instruments, Hayward, CA, USA) was installed, from which data on radiation, evapotranspiration, rainfall, ambient temperature and humidity, atmospheric pressure, wind direction and speed are acquired. The data are queried from the central station using an algorithm developed in Python3.

2.3. Central Station

The brain of the system was developed using a Raspberry-Pi® 3 model B. This central station is used to acquire the data from the sensor nodes and the weather station, and to define the irrigation prescriptions. It is also in charge of applying the inference algorithm for determining the best irrigation prescription based on yield prediction and efficient water use at the end of the harvest. To determine the prescriptions, the central station stores the acquired data, queries it and decides on the prescriptions and irrigation times. The software was developed using Python3TM and Qt5.

2.4. Irrigation prescription strategies

2.4.1. Irrigation prescription based on water balance

Crop evapotranspiration (Etc) is calculated as the combination of evaporation from the soil or leaves and plant transpiration through the stomata. Depletion is the amount of water withdrawn from the soil to meet plant needs while the crop is growing. Net irrigation is the water required to bring the soil to field capacity. The water balance equation (1) allows determining the depletion on the day of the prescription, taking into account the behavior of certain variables during a previous period of time, generally daily, but which can be calculated weekly, monthly or annually.

$$D = D_{-1} - R - P + ET_c$$
$$(Si\ D\ es\ negativa, colocar\ esta\ en\ 0.0) \quad (1)$$

Where:

D	Soil water deficit or net irrigation requirement.
D_{-1}	Water deficit accumulated from the previous day.
R	Amount of irrigation applied during the previous day.
P	Actual precipitation during the previous day.
ET_c	Crop evapotranspiration during the previous day.

2.4.2. Irrigation prescription based on soil moisture sensors

Irrigation prescription based on soil moisture sensors. To define the irrigation prescription, measurements from four soil moisture sensors at different depths were taken into account. The number of sensors used depends on the maximum effective root size of the crop under study. The matrix tension data are converted into volumetric water content using the water retention curve and the Van Genuchten equation (2).

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha|\psi|)^n]^{1-\frac{1}{n}}} \quad (2)$$

Where:

θ	Volumetric water content $[L^3L^{-3}]$.
$\lvert\psi\rvert$	Suction pressure ([L] or cm of water).
θ_s	Saturated water content $[L^3L^{-3}]$.
θ_r	Residual water content $[L^3L^{-3}]$.
α	Related to the inverse of the air inlet suction $10^{-3} \leq \alpha < 10^{-1}$ ($[L^{-1}]$, o cm^{-1}).
n	Measure of pore distribution, $1 \leq n \leq 10$ (dimensionless).

With these values the soil moisture depletion is determined by comparing the current moisture status with respect to the corresponding field capacity in preset layers according to the designated volume of the action cylinder of the soil moisture sensor watermark.

The start of irrigation application is programmable. If the four soil moisture sensors are used, four soil layers are generated at depths of L1 (0-100 mm), L2 (100-200 mm), L3 (200-300 mm) and L4 (300-400 mm). Sensors were located in this configuration at depths of PS1 (50 mm), PS1 (150 mm), PS1 (250 mm) and PS1 (350 mm). The depths of the sensors should coincide with the depths at which soil samples are acquired from the study field where the sensors will be installed, in order to determine the saturation point, field capacity and permanent wilting point.

For the case of short-root crops such as onion or rice, only two layers are selected, L1 (0-100 mm) and L2 (100 mm-200 mm), with a total depth of 200 mm. Homogeneous soil conditions are assumed for each interval. When the effective root of the crop is within L1, the irrigation prescription is defined by equation (3). When the root depth is within the second layer, the irrigation prescription is defined by equation (4).

$$D_{L1} = \frac{CVA_{CC1} - CVA_{sensor\ 1}}{100} * p \quad (3)$$

$$D_{L2} = \frac{CVA_{CC1} - CVA_{sensor\ 1}}{100} * L_1 + \frac{CVA_{CC2} - CVA_{sensor\ 2}}{100} * (p - L_1) \quad (4)$$

Where:

CVA_{CC1} y CVA_{CC2} volumetric water content at field capacity for layers 1 and 2 respectively.

$CVA_{sensor\ 1}$ y $CVA_{sensor\ 2}$ Volumetric water content measured by watermark 1 and 2 sensors respectively.

L_1	Soil layer 1.
p	Root depth (mm).
$D_{L1}\ y\ D_{L2}$	Soil water deficit for L_1y L_2 (mm).

2.5. Inference system

The concept of intelligent system (IS) and inference in irrigation prescription determination are explained in [34]. The conditions and rules of operation of ISs are defined by the type of architecture, either logic-based, those that implement the decision process using a direct mapping type from situation to action, Belief-Desire-Intent (BDI) based systems, and layered architectures of different levels of abstraction of the environment. In this research, a logic-based architecture was implemented. The decision on what action to perform was implemented by logical deduction by a specific language, with a defined logical theory and declarative semantics. The architecture is based on the traditional artificial intelligence approach by modeling the environment and the behavior of the intelligent system with a symbolic representation.

The developed system uses an inference mechanism based on the determination of the production yield at the end of the harvest. In this way, the system uses the calculated prescriptions and selects the one with the best future results. In other words, it seeks the best yield with the lowest water use, or to achieve the best efficient use of water at the end of the harvest. Yield prediction is calculated using AquaCrop software, which is used to model crop growth and was developed by the Food and Agriculture Organization of the United Nations (FAO). In this thesis, AquaCrop was used to simulate the yield response of the studied crop to water [35]. The configuration of AquaCrop allows establishing response to any crop that has been calibrated.

3. Results

Figure 2 shows the experimental setup of the field-installed prototype, with the electronics, sensors, solar panel, regulator and battery installed.

Figure 2. Assembly of the intelligent irrigation system prototype in the field.

Source: Own.

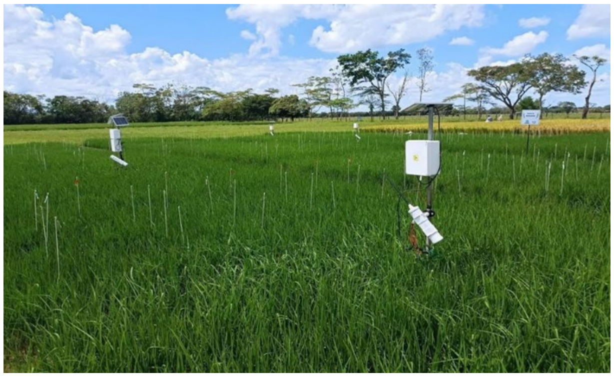
A printed circuit board (PCB) was developed for the field data acquisition system. The developed board allows the incorporation of up to four Watermark sensors by means of the signal multiplexing mechanism. The sensors are activated sequentially avoiding interference between their signals. For each Watermark sensor, two measurements are acquired by changing the power supply polarity. The resistance value measured by the sensor is determined as the average of the two acquired data. Subsequently, the resistance data are converted to matrix voltage, using equation (5), to finally find the volumetric water content using equation (2) [36].

$$SMP = \frac{-(4.093 + 3.213R_s)}{1 - 0.009733R_s - 0.01205T_s} \quad (5)$$

Each sensor node sends a data frame to the central station corresponding to: RSPMS1, RSPMS2, RSPMS3, RSPMS4, RH, TD, TA, TS, with RSPMS (Resistance of Soil Matrix Potential Sensor), RH (Relative Humidity), TD (Canopy Temperature), TA (Ambient Temperature) and TS (Soil Temperature).

The central station, through the communication protocol used, recognizes the transmitter sending the data frame. The weather station is consulted when information is needed for irrigation prescription based on the water balance equation.

Figure 3. Final field assembly of the intelligent field irrigation system.

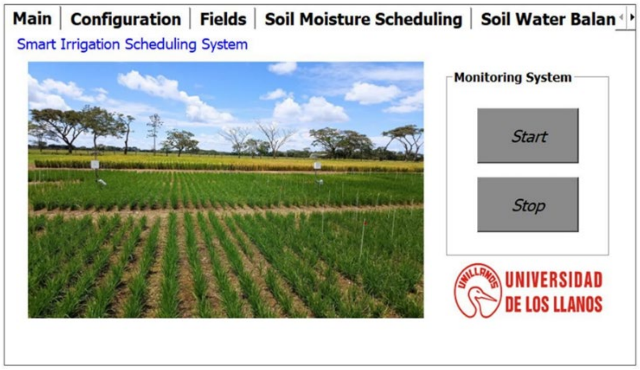


Source: Own.

For the development of the final assembly, the incorporation of materials such as boxes, cables and connectors that could withstand the climatic conditions associated with high solar radiation, high temperatures and precipitation, especially rains with electrical discharges, was taken into account. Figure 3 shows the installation of the sensor nodes in the field for a real experimental crop, highlighting the robustness of the system.

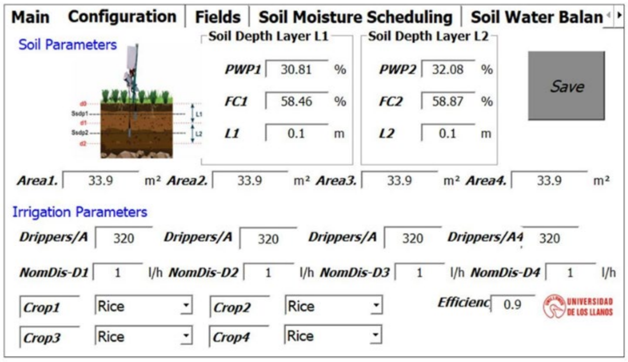
A graphical user interface (GUI) was developed for the visualization of field data at the central station. Figure 4 shows the main window of the GUI. Once the program is started, the central station starts acquiring field data. On the other hand, there is a configuration window of the characteristics of the studied plots, related to soil, crop and other measurements of the plots monitored by each sensor station (Figure 5). In addition, the last data sent by each sensor can be visualized and plotted (Figure 6).

Figure 4. Main tab graphical user interface - Central Station.



Source: Own.

Figure 5. Configuration of batch parameters - Central Station.



Soil Depth Layer L1
PWP1 30.81 %
FC1 58.46 %
L1 0.1 m

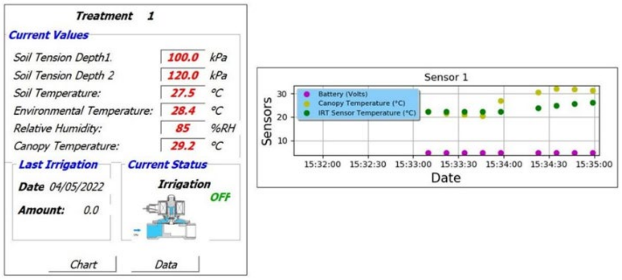
Soil Depth Layer L2
PWP2 32.08 %
FC2 58.87 %
L2 0.1 m

Area1. 33.9 m² Area2. 33.9 m² Area3. 33.9 m² Area4. 33.9 m²

Irrigation Parameters
Drippers/A 320 Drippers/A 320 Drippers/A 320 Drippers/A4 320
NomDis-D1 1 l/h NomDis-D2 1 l/h NomDis-D3 1 l/h NomDis-D4 1 l/h
Crop1 Rice Crop2 Rice
Crop3 Rice Crop4 Rice
Efficienc 0.9

Source: Own.

Figure 6. Visualization of last acquired data - Central Station.



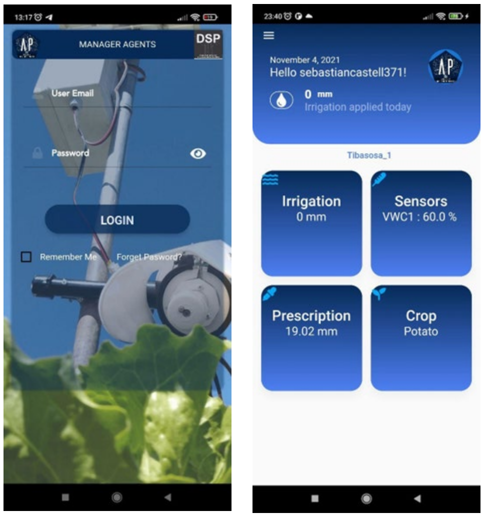
Treatment 1
Soil Tension Depth1. 100.0 kPa
Soil Tension Depth 2 120.0 kPa
Soil Temperature: 27.5 °C
Environmental Temperature: 28.4 °C
Relative Humidity: 85 %RH
Canopy Temperature: 29.2 °C
Date 04/05/2022
Amount: 0.0
Irrigation OFF

Source: Own.

If the central station is located in a place with internet access, the data is automatically transmitted to a server, where it is stored and the behavior of the sensors in the field can be visualized.

The mobile application developed by Juan Sebastian Castellanos Patiño meets certain conditions that allow the user a dynamic interaction with the smart system for irrigation management in crops (Figure 7). The mobile application for visualization and control of intelligent systems allows the user the following actions: secure authentication of multiple users, creation and registration of new intelligent systems, for subsequent management and observation through the same application; editing of irrigation prescription and application schedules; visualization of the most important states of the system, opening of valves, times and amounts of prescribed and/or applied irrigation; graphic representation of the change of states in the sensors of the intelligent system for irrigation prescription and application. For the development of the application, the Flutter framework was used, which allows the development of applications for different platforms. Flutter is mainly used to develop Android and IoS applications without the need to write its own code base for each of the systems.

Figure 7. Application on mobile device.



November 4, 2021
Hello sebastiancastell371!
0 mm
Irrigation applied today

Irrigation
0 mm

Sensors
VWC1 : 60.0 %

Prescription
19.02 mm

Crop
Potato

Source: own.

4. Discussion

Historical data from the weather station and field sensors were used to validate the results of the inference system, based on the heuristic of selecting the method with the best response in yield and efficient water use. Prediction results for the bulb onion crop were evaluated using AquaCrop crop modeling software. The inference system was evaluated for the previous version of the system shown in this paper. The previous version was based on the use of volumetric soil moisture sensors, in which Vegetronix and Spectrum sensors were tested, in addition to the use of an Arduino Nano in the monitoring stations [34]. Volumetric water content sensors have the need for calibration for each soil type, in addition to being affected by conductivity generated by soils with high salinity levels. In the version presented in this paper, matrix tension sensors (Watermark) are used, which require greater hardware and data processing needs, but do not require calibration and are more related to the behavior of moisture in the soil and the response of the roots to this moisture.

5. Conclusions

An intelligent system for irrigation scheduling in agricultural crops was designed and implemented. A wireless sensor network was developed for soil matrix tension at four depths, ambient, canopy and soil temperature, and relative humidity. The data from the sensor network and the weather station allowed the definition of agronomic prescriptions based on the data and not on thresholds or farmers' organoleptic perception.

The contribution of this work is to develop a system based on current technologies for data acquisition through plant, soil and climate sensors, and a reasoning mechanism based on crop yield heuristics and water use efficiency to support decisions. The system was developed to withstand inclement weather, which is important, because most similar systems have been developed for gardens, but in real agricultural crop conditions they do not have the robustness for proper operation. For future research, the intelligent system will include canopy temperature information for irrigation prescription, as well as automatic learning strategies. The system can be adapted to any crop, soil and irrigation infrastructure.

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