Water Sap flow and Soil Moisture Measurements for an Automatic Irrigation Control System

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Abstract. A sound water management requires accurate field data inquiry that can eventually allow for a proper control of the field's irrigation. This work pro-poses an automatic irrigation control system that aims at optimizing the quantity of water needed for plants' growth. The system consists of three key blocks: first, the continuous inquiry of the physical characteristics of the plant; second, the control unit to decide upon the actions to launch by the actuation unit; and third the actuation unit that sets parameters for pumps and valves. Conventional smart irrigation control systems use soil moister sensors which neglect the plant's physiology as a monitoring factor, so this paper suggests the use of a sap flow sensor that accurately evaluates the plant's condition; hence, decide upon the proper water distribution, illustrated with preliminary experimental results.

1 Introduction

More than any other factor, it is the gigantic increase of world population size that is source of anxiety about the future of the world's water resources available in the early years of the third millennium. There is no prospect of any increase in the global effective rainfall to feed lakes, rivers, and aquifers, and eventually nurture plants and animals, while the world population will increase by about one-third to some 8 billion by year 2025 [1]. The combination of rising population, rising water consumption per capita, and rising volume of domestic and industrial wastes is outstripping the geographical resources [2]. Particularly, agriculture is the sector with the largest consumption of fresh water: 70% of the total resources against 20% used in industry and 10% of domestic use [3]. This reflects the constant researchers quest to develop irrigation water-saving solutions.

Irrigation is a form of land and water management that manipulates the distribution of water in time and space for better plant growth [4]. Irrigation management dates back to ancient times in Egypt and Mesopotamia ca. 8000 years ago, with the appearance of basin irrigation [5]. With the advancement of control theory, a more sustainable and rational approach is used for optimizing irrigation controllers.

Commercially available irrigation controllers require an Irrigation Dose (ID) to be initially set, or rather estimated by the farmer. This paper introduces an Automatic Irrigation Control System (AICS) that evaluates the ID based on three recorded inputs: plant sap flow, soil moisture and water flow rate in the canalization system. These parameters are directly proportional to the plant's physiological mechanism [6]; eventually the irrigation system can compare the measured values with the values necessary for the plant. Thus far, no system fully automat-ed using the plant's sap flow readings is implemented; instead, few others based on soil moisture exist which suffer some limitations such as the high number of sensors relative to the spatial variability, and not acquiring any data on the plant condition [7]. The suggested AICS is similarly based on the intake of soil moisture values but additionally incorporates the plant sap flow sensor. This data can meticulously reflect the plant's need in water as it grows. Given all inputs, the AICS evaluates the output actions to be performed by the actuators placed in the irrigation field. It is indeed a system that closely assesses the physiology of the plant, and commands an adequate irrigation distribution; hence, controls the water intake and consumption. A much-needed feature to mitigate the global threat of water scarcity. The remainder of this paper is organized as follows: section II presents the principles of automatic irrigation system and conceptual design, section III describes the development of a prototype and results of preliminary tests; finally, section IV concludes the paper.

2 Automatic Irrigation System: Principles and Design

Irrigation scheduling is conventionally based on one of the following: (i) soil water management where soil moisture status is measured directly to determine the need of irrigation; (ii) soil water balance calculations in which

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the change in soil moisture over a period is given by the difference between the inputs (the summation of irrigation and precipitation) and the losses (the combination of runoff, drainage and evapotranspiration); (iii) plant stress sensing that relies on the plant's condition rather than the direct measurements of soil water status [8]. Each approach has its advantages and limitation (Table 1), the latter approach is more precise and reflects the plant's condition given the environment's conditions, notably soil moisture, and temperature. On the other hand, the topographical variability of soil, results in using multiple soil moisture sensors to implement the first approach which is costly. As for soil water balance, the method is governed by the following equation:

$$(P + G_{in}) - (Q + ET + G_{out}) = \Delta S, \quad (1)$$

where P is the precipitation, ET is the evapotranspiration, Q is the steam outflow, G_{in} is the groundwater inflow, Gout is the ground water outflow and ΔS is the storage change. This approach is very difficult to model accurately because the in-puts and outputs are temporally and spatially variable. Plant stress sensing represents then, the most innovative and promising approach as it reflects accurate measurements water content in plant tissues which correlates with the plant's physiology.

The following presents the block of the proposed automatic irrigation system:

2.1 Measurement unit

It is important to consider key measurements for irrigation scheduling, notably plant sap flow, soil moisture and water flow rate. The values vary according to the nature of the plant terrain and seasons and reflect the plant water demand. Once these measurements are acquired, the adequate water volume is calculated to meet the demand of plant growth and avoid excessive irrigation which can not only hinder plant's well-being but cause a waste of water resources [9].

2.1.1 Soil Moisture Sensor

It is used extensively to measure soil moisture in a variety of land management applications. Currently, the most commonly favored techniques are either time domain reflectometry (TDR) or capacitance, to measure soil moisture, as they can both be automated and have excellent spatial and temporal resolution [10]. The considered soil moisture is a connector-type TDR sensor that consists of two stainless steel waveguides (a tube conveying microwaves) of 6 mm diameter. The TDR sensor is vertically inserted to provide measurements over depths of 0-10, 0-15, 0-20, 0-25 or 0-30. It can provide the volumetric water constant from the apparent soil dielectric constant independently of soil type, density or temperature and salt content. the connector-type TDR sensor is the most soil moisture sensor of a strong agreement with the thermogravimetric measurements compared to the other soil moister sensors available in the market (Campbel Scientific wa-ter content reflectometer, Virrib® soil moister sensor and burial-type TDR sensor) [11].

2.1.2 Sap Flow Sensor

The sap flow sensor employs heat balance principle to measure the sap flow in the plant: the stem is heated electrically, and the heat balance is solved for the quantity of heat taken up by the moving sap stream, which is then used to calculate the flow of sap in the stem [12]. The heat balance of stem is defined as:

$$P = q_v + q_r + q_f, \quad (2)$$

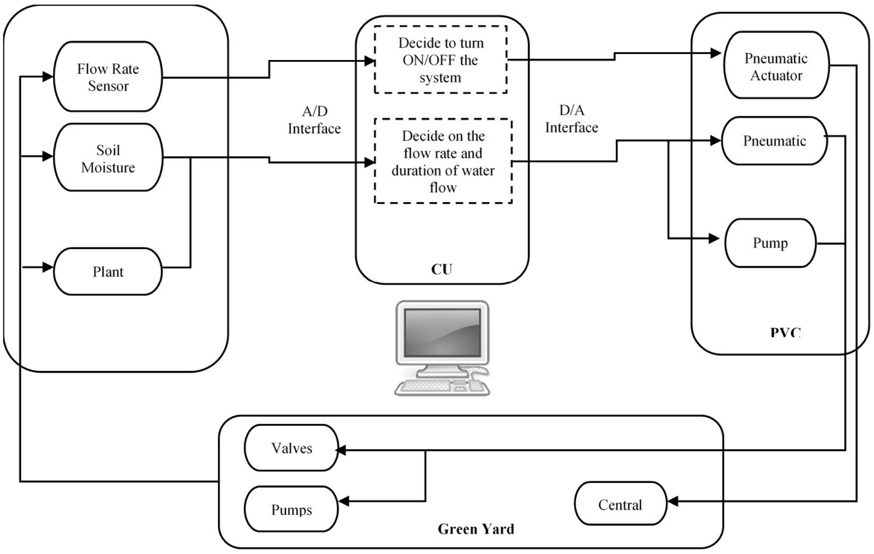

Fig. 1. Block diagram of the automatic irrigation system.

where P is the power supplied to the heater, q_v is the rate of vertical heat loss, q_r is the radial heat loss by conduction and q_f is the heat uptake by the moving sap stream. The considered sap flow sensor adheres to the Thermal Dissipation Method (TDM). Both methods use three probes. It consists of a temperature probe, a constant heat probe and gives a steady power output. To retrieve the sap flow rate of the plant, the cross-sectional area of the plant is multiplied by eqn. (4) [13].

$$Qs = 0.00019\left(\frac{\Delta T_0 - \Delta T}{\Delta T}\right)^{1.231}, \qquad (4)$$

where Qs is the sap flux density ($m^3.m^{-2}.s^{-1}$), ΔT_0 is the maximum daily value of ΔT (°C) and ΔT is the temperature difference between the upper and lower probes (°C).

2.2 Analog/ digital Interface

The analog to digital interface converts the electrical signal resulting from sensors into digital format – either 0 or 1, while the digital to analog interface con-verts the digital format of data resulting from sensors into an electrical signal (voltage) applied to the solenoid per which the valves function as well as the pump motor. The accuracy of the conversion is affected by the resolution of the equipment.

2.3 Control unit (CU)

Electronic controllers use solid state and integrated circuits. They provide a clock/ timer, have memory to store data acquired from sensors and can control all devices connected to the automated system (valves and pumps), with relatively low cost. Breaking a single irrigation event into a series of a brief period of operation followed by a brief period of rest can be added as a feature to guarantee lateral movement of water. However, they are sensitive to powerline quality, i.e., they are affected by spikes in the power, so electrical suppression devices are used to boost their reliability.

2.4 Pump and valve controllers (PVC)

The hydraulic actuators are the equipment on the terrain that act on water flow rate and the duration of each flow rate cycle. Flow rate is defined as

$$Q=V/\Delta t, \qquad (3)$$

where Q is the flow rate, V is the volume of water and Δt the duration/time inter-val. The pneumatic actuator is simple and cost-effective solution for the solenoid valve automation. It has a high duty cycle life (up to 106 cycles) and a visual position indicator. It is also characterized by a permanent lubrication and a corrosion resistant coating. As for the pump actuator, it combines linear output force with precise position control and can send the regulated electric signal that controls the volume in the variable-volume pump.

3 Case study

As a real-world deployment of the previously described system, an experiment was conducted to feature the soil moisture sensor.

3.1 General architecture

In this setup, the following components were used (Fig. 2): Wireless Sensor Network, a network of sensors in charge of retrieving and sending data related to plant and atmosphere (soil and humidity); Wireless Actuator Network, devices that receive decisions from the control unit and translate them into actions such as switching ON/ OFF pumps; Big Data Analytics Platform (BDAP) that is responsible for storing and processing sensed data, then supplies and forwards processed data to its control unit that takes the decision, and send it to the WAN in real-time; Renewable energy sources or PV panels that feed the pumps and the battery with electrical energy; Storage unit, which are batteries that store excess energy for later

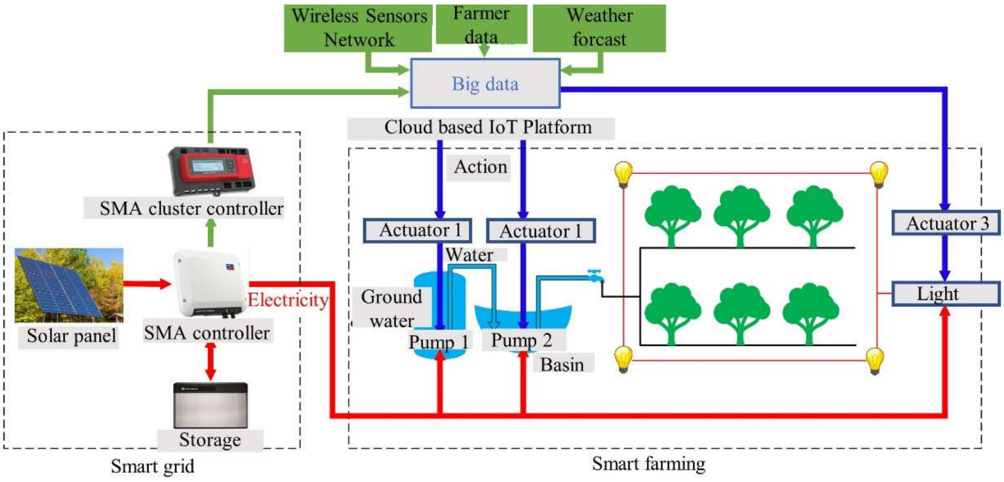

Fig. 2. General architecture [13-14].

use when the sun goes down; Energy Control Unit that decides whether to pass the electric energy directly to the electrical devices, store it in batteries, or feed in the grid based on real-time data of the power production/consumption; SMA cluster controller, the device that send all the data relat-ed to the solar system to the sunny portal Cloud of SMA for real-time monitoring and storage.

3.1 General architecture

MiEach wireless sensor node (Fig.3) is composed of three main components: (i) sensors that measures the environment parameters such as soil moisture, temperature, humidity and sap flow. (ii) Microcontroller, this is an Arduino nano that connects all the components together. (iii) Communication module, this is a ZigBee module that sends all the data measured by the sensors in real-time to the gateway device which in its turn forward it to the big data analytics platform.

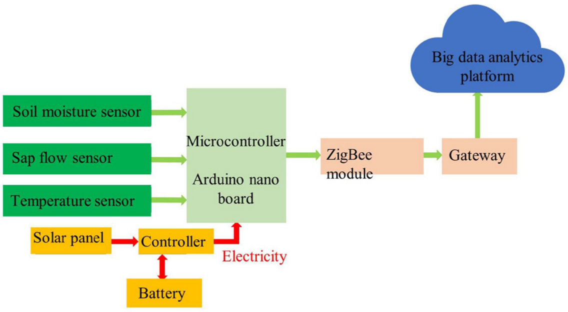

Fig. 3. WSN Architecture.

3.2 Wireless Sensor Network

Due to its reliability and its ability to make each wireless sensor node able to simultaneously function as a sensor and a router, a ZigBee wireless mesh network is implemented. In this study, four wireless sensor nodes and a gateway device were used (Fig.4).

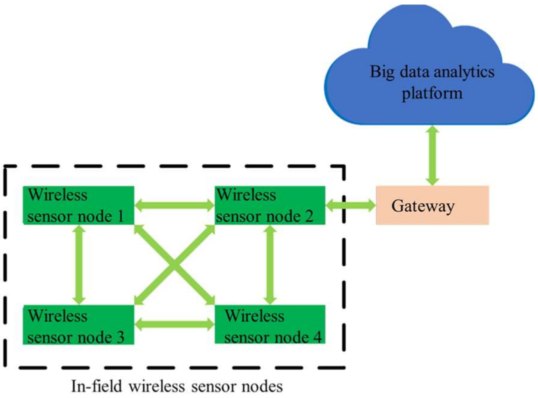

Fig. 4. Zigbee Mesh Network Architecture.

3.3 Irrigation control using soil moisture sensor

A control algorithm (Fig.5), based on the soil moisture sensor, was employed to control the irrigation of the field. The algorithm starts by reading the soil moisture average then compares it to 50%. If the average moisture is below 50%, the water pumps are automatically switched on to irrigate the field.

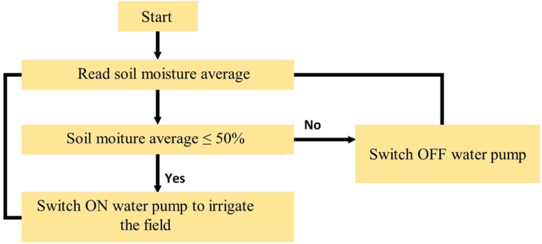

Fig. 5. Control algorithm flowchart.

3.4 Results and discussion

The variation of soil moisture throughout the day goes way beyond the necessary value (Fig.6). This shows the importance of efficient water distribution both for the crops' wellbeing and water consumption, hence the environment. Similarly, the variation of temperature throughout the day (Fig.7) asserts the necessity to combine the input of different parameters such as temperature, soil moisture and humidity to decide upon the best output to offer to the agricultural land in terms of water flow rate, fertilizers, and others.

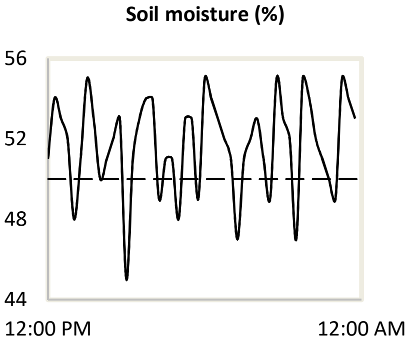

Fig. 6. Real-time soil moisture, desired soil moisture, i.e., 50% (dashed line).

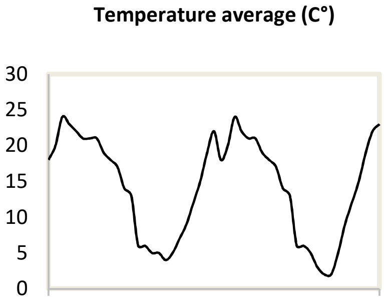

Fig. 7. Real-time average temperature.

The economic feasibility of any system is worth discussing to gain a perspective on its implementation. A thorough evaluation covering assets and liabilities, cash flows and expenses —direct and indirect, is beyond the scope of this paper. Instead, an overview of the key factors that have been used in recent economic studies of smart irrigation systems, is discussed herein.

First, and particularly in the countryside, electricity can be unstable, which can freeze the system including the pumping power to provide water. Thereof, one emerging cost is the back-up energy storage which can be done for example with solar panels [15-16].

Second, the greatest interest of a farmer is the crops' production yield. This has a major impact on the value of implementing a smart irrigation system. Such systems have proven to have decreased the amount of water used, provided a uniform water distribution and have decrease the amount of fertilizer needed. This correlates directly with the reduction of operational costs on the long run while covering gradually for the capital costs initially invested [17-18].

Finally, the hesitation of farmers to implement smart irrigation systems come mainly from two reasons, either the non-familiarity with the technology, or the costs of implementation of both hardware and software. One way to overcome the latter problem is to boost the scalability of the software so that less investment is made on the sensors [19].

Different aspects are considered when dealing with the economic viability of an irrigation system. The estimation of design's cost is far from sufficient. The increase of yield, the resulting crops quality, the variability of rainfall, and others help in avoiding misleading or irresponsible characterization of the feasibility/ profitability of a new design. Additionally, one special case that needs extra attention when considering the costs, is source of water: while some parts of the world have abundant ground or surface water, others have very limited resources as it is the case in the middle east, so investing in a water produced by cost-efficient technologies such as water desalination instead of distillation is crucial for keeping the irrigation system sustainable [20].

4 Conclusion

In this paper, an automatic irrigation control system was proposed to offer an optimized usage of sensors and better water management in agricultural fields. Compared to conventional irrigation systems, this one adds a crucial feature into the control unit which is to correct the error generated by soil moisture sensor using the readings of the sap flow sensor that reflects the plant's physiological condition. The latter is affected by the watering applied to the plant, and sur-rounding temperature; thus, the system facilitates production of healthier crops along their optimum lifespan. The paper also presented preliminary results of lab-made prototype that shows the use of real-time data of temperature and soil moisture to decide upon the conditions required for plant's growth. Future work of this paper would be to further develop the prototype to allow for the system to perform under different physical conditions and plant types.

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