Yet a Smarter Irrigation System

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Abstract. A new type of irrigation system is being developed in the context of the research project 02/SAICT/2017-28247-FCT-TO-CHAIR. The output are irrigation plans based on optimal control theory that minimize water usage and keep crops safe. In this paper, we present the main features of the system prototype. The system uses soil moisture sensors in the field, weather forecasts and parameters that the farmer provides. This data is input to an Octave/Matlab program that implements an Optimal Control algorithm to compute the irrigation plan for the crop field. The system consists of an electronic device that interfaces the sensors in the field and a server computer. The field device reads data from any analogue sensors and uses mobile communications to upload the data to the server computer. The server provides a website for users to insert data about their crops and fields and it retrieves weather forecast data from a freely available service. Once a day the server runs the Optimal Control irrigation-planning algorithm and the result is provided on the user web page using both numerical and graphical formats. Due to the diversity of irrigation infrastructures installed in crop fields and water availability for irrigation, the system does not automatically control/actuate the irrigation. That task is left on the hands of the farmer.

Keywords: Irrigation planning · Optimal control · Internet of Things

1 Introduction

Climate change is a proven fact. In the report of 2007 from IPCC [1], one can read that global warming is an issue to be dealt with urgency. Temperature will rise, longer and more frequent drought periods will occur. One of the most affected regions will be the Iberian Peninsula. In the South of Iberia, extreme drought periods are already very frequent. Our study has Portugal in mind, but

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it could easily be adapted to other parts of the world. In this scenario, it is necessary that the decision makers are able to decide on all issues related to water management.

Irrigation of crop fields consumes most of the water resources in Portugal annually. So, it becomes crucial that a proper irrigation planning is able to maximize the profits of a crop field, while spending the least water resources possible, with the highest efficiency [2]. With this paper, the authors intend to give a contribution in order to achieve such objective. A "smart irrigation" system is proposed, which is based on a mathematical model implemented in Matlab/Octave. The model uses Optimal Control theory.

Optimal control theory emerged as research topic in the 1950s, in response to problems concerning the aerospace exploration [3] of the solar system. Nowadays, optimal control is a tool acknowledged by its effectiveness, which is applied to different areas, such as robotics [4], biological systems [5], health [6], economy [7,8], agriculture [9], among many others. The goal of optimal control theory is to find a control law for a system such that a certain optimality criteria is achieved.

The proposed mathematical model is able to plan the irrigation for a given crop in such a way that water usage is minimized, while ensuring the crop is safe. The considered dynamic equation guarantees the water balance (taking into account rainfall, irrigation, humidity in the soil, evapotranspiration and losses due to infiltration), and the defined constraints ensure that crops have their water needs fulfilled. Direct methods (such as IPOPT, SQP, Active Set, etc) that guarantee a feasible solution is obtained were used in optimal control. It has been proven that mathematical models similar to the ones presented in this article obtain a solution that is a local extrema [11].

In this paper, our focus is on the integration of all the necessary technologies and know how, in order to obtain a "smart irrigation" system prototype. The paper is divided in further six sections. In Sect. 2, the mathematical model developed to generate the irrigation plan is presented. Section 3 presents the requirements of the system. Section 4 describes the proposed architecture and in Sect. 5 the behaviour of the system is presented. In Sect. 6, an initial version of the implementation of the mathematical model is shown. Section 7 presents the conclusions and future work.

2 Mathematical Model for the Irrigation Plan, and the Necessary Data

This section presents a mathematical model developed to obtain an optimal irrigation plan for a given set of data. We want to minimize the volume of water used in irrigation, knowing that the water balance equation gives the variation of water in the soil. In our optimal control problem, the trajectory is the water in the soil and the control is the amount of water introduced in the soil via its irrigation system. Our problem is formulated in its discrete version as

$$\begin{aligned}
&\min \sum_{i=1}^{N-1} u_i \\
&\text{s.t.: } x_{i+1} = x_i + h\ f(t_i, x_i, u_i), \text{ a.e. } i = 1,\ ..,\ N-1 \\
&\qquad x_i \geq x_{\min}, \qquad\qquad\quad i = 1,\ ..,\ N \\
&\qquad u_i \geq 0, \qquad\qquad\qquad \text{a.e. } i = 1,\ ..,\ N-1 \\
&\qquad x_1 = x_0,
\end{aligned} \tag{1}$$

where x is the trajectory, u is the control, f is balance water function, $x_{\min}$ is the hydrologic need of the crop, x_0 is the initial state (read from moisture sensors), h is the time step discretization and $N = 10/h$ (if we are using a $h = 1$ day, N=10). The dynamic equation implements the water balance in the soil, which is given by

$$f(t_i, x_i, u_i) = u_i + \text{rainfall}(t_i) - \text{evapotranspiration}(t_i) - \text{losses}(x_i), \tag{2}$$

where evapotranspiration is the evaporation of the soil and the transpiration of the crop, and losses are water losses due to the runoff and deep infiltration. Rainfall forecast for a specified number of days (i.e., the duration of the irrigation plan demanded by the user) is obtained from a meteorological web site. Evapotranspiration is calculated using Penman Monteith model [12] (that needs a set of tabulated values that characterize the soil, the crop, etc) and the losses parcel is described based upon the postulate of Horton's equation, which states that infiltration decreases exponentially with time [13]. That means the dynamical equation is

$$x_{i+1} = x_i + h(g(t_i, u_i) - \beta x_i, \tag{3}$$

where $g(t_i, u_i) = u_i + rainfall(t_i) - evapotranspiration(t_i)$. From (2) and (3), one may say $losses(t_i) = \beta x(t_i)$, where β depends on the type of soil.

3 System Requirements

An overview of the system is shown in Fig. 1 supporting the gathering of fundamental requirements in an informal way. The Optimal Irrigation Algorithm needs (1) weather forecast data that can be obtained from free services available on the internet, (2) soil moisture values that are obtained by soil moisture sensors, and (3) the characteristics of the field to be irrigated and the crop. An irrigation field has an irrigation system and its characterization consists of the land area, soil composition and crop identification. From this set of data the algorithm computes the irrigation plan for the given field, which consists in a list of water amount for each day, for a number of days.

Currently, the algorithm assumes infinite irrigation capacity, leaving the management of water resources entirely to the farmer. For this reason and also

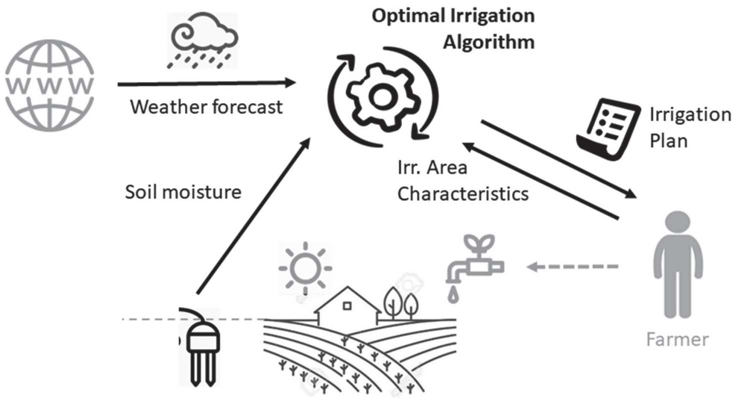

Fig. 1. Overview of system and its integration in the field.

because there are many different irrigation systems, the system does not actuate on irrigation hardware. Each irrigation area has a unique set of characteristics, most predominantly crop and soil, and naturally requires its own soil moisture sensor. To deal with variability of soil characteristics in short distances or small areas, the farmer must install the necessary sensors at appropriate places. This way the system is kept simple and flexible.

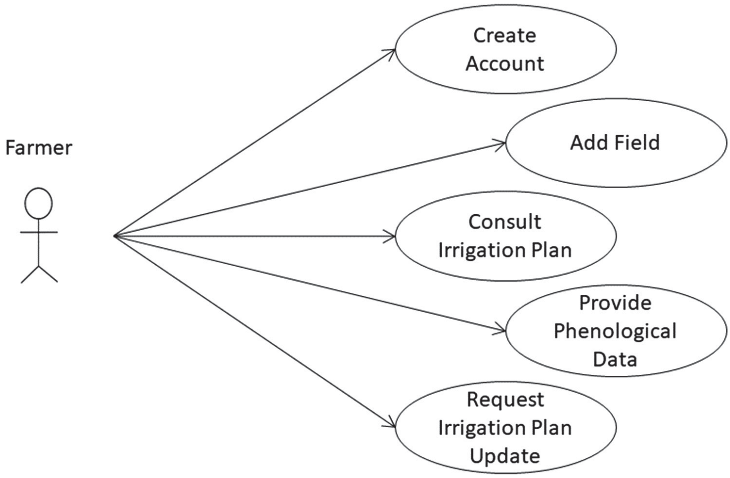

Fig. 2. UML diagram with the system's use-cases.

The usage of the system is described in the UML use-case diagram of Fig. 2, whose actors for now are farmers only. First, they need to create an user account, with usual information, and then they can add irrigation areas, including their characteristics. Afterwards, they can consult the irrigation plan that the system computes daily for each of its fields. The farmer can also provide phenological data, such as bud break and flowering date, to fine-tune the output of the system. All other inputs to the Optimal Irrigation Algorithm are either obtained automatically (e.g., soil moisture reading) or fixed parameters (e.g., soil characteristics) introduced only once. The idea is to make the system practical to use on the daily farming life.

Besides the daily plan that is scheduled, the system allows the farmer to request an update of the irrigation plan at any moment. This is important to deal with situations in which any input variable changes significantly and unexpectedly within a day. This is called re-planning (see [10] for more details) and it is likely to be useful when weather conditions deviate from the forecast.

4 System Architecture

The system is composed of Soil Moisture Measuring Devices (SMMDs), one for each field, and an Irrigation Planning Server. The hardware architecture of the former and software architecture of the latter are shown in Fig. 3. The farmer interacts with the system through a web application, which is appropriate for usage both on a smartphone in the field and on a larger computer screen at the office. The farmer web application provides the functionalities identified in Fig. 2.

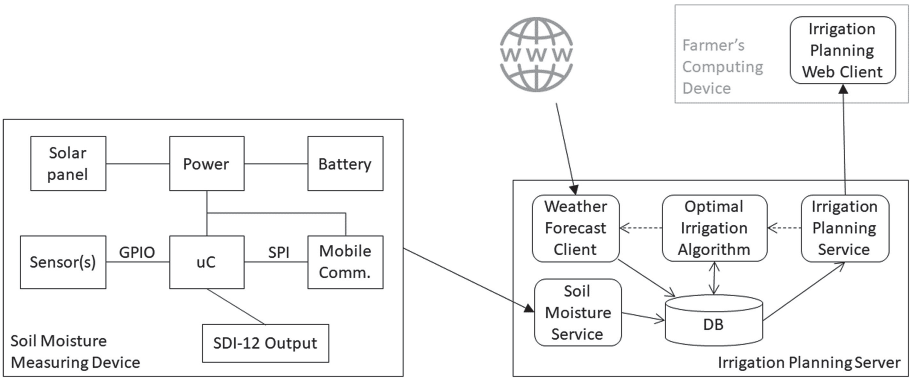

Fig. 3. System architecture

The SMMDs at the field are low power devices offering several months of operation on a battery, and a solar panel for longer power autonomy. They read the values of a set of soil moisture sensors at different depths and send the readings to the central server using mobile data communications (through a GPRS/UMTS module), following the Internet-of-Things concept. The SMMDs processing is done by a low-power micro-controller, that puts the device to sleep almost all of the time. To be compatible with standard environmental data loggers, SMMDs will also feature an SDI-12 interface. SMMDs software consists of: (1) a very simple configuration routine; and, (2) a main routine that makes moisture sensor readings and sends them to the server.

The software architecture of the Irrigation Planning Server consists of: (1) a Database storing all the data, present and historic data for analysis; (2) a Soil Moisture Service that receives the data from SMMDs and stores it in the database; (3) a client to retrieve weather forecast data from an internet service; (4) the Optimal Irrigation Algorithm; and, (5) an Irrigation planning service that serves the farmer's web client. The implementation will use modern approaches, such as REST interfaces for services, single-page application based on a framework such as Angular, and a NoSQL database (since data is mostly collections). The programming language will either be Javascript on node.js or python.

5 System Behaviour

Although the Optimal Irrigation Algorithm is executed on the server once a day by default, the SMMDs main routine sends data to the Soil Moisture Service hourly. This mechanism is important for further research analysis and also to support sporadic planning requested by the farmer.

SMMDs configuration routine is executed when the configuration button is pressed, and sends a message to the server announcing a new SMMD is available to be configured. When this happens, the farmer's web application display a new device (ID) on the view for adding new fields. Then, the farmer has only a few tens of seconds to select the device and start configuring it. After that time the new field is no longer available for configuration. Besides the introduction of the fixed parameters mentioned in Sect. 3, the configuration involves giving the field a meaningful name. If the farmer is using a device with GPS, the application automatically fills-in the coordinates of the new field, simplifying the process. Otherwise, the farmer must choose the location on a map.

The time during which a new field is available for configuration is short, but still there is a chance that two or more fields might appear at the same time. When that happens the farmer must retry until a single field appears to be positively sure that the field is hers/his. This process reassures the farmer about the correct linking between SMMDs and irrigation field in the web app.

The fields are shown on a map and on a list, respectively making them easily identifiable geographically and by name. When a field is selected, the respective most recent irrigation plan is shown. If the system does not receive data from a given sensor, the farmer is alerted that the device has failed and the respective irrigation plan is not updated.

6 Implementation and Results

Currently, the system is not yet fully implemented. We have implemented the Optimal Irrigation Algorithm in Octave/Matlab. The weather forecast data is automatically downloaded from a meteorological web site (https://www.apixu.com/) using a phyton script and it is converted to text files stored on a dropbox folder. The data consists of temperature (maximum and minimum), average wind speed and average humidity in the air, for seven days. Soil moisture data is obtained manually using a data logger and analog sensors. The tabulated values that characterize soil (ThetaFC and ThetaWP, which affect hydrologic need of the crop, $x_{\min}$ in Eq. 1, see [15]) and crop (Root height that affects $x_{\min}$ and crop's evapotranspiration, and crop ET coefficient that affects the crop's evapotranspiration, see Eq. 2) are provided by the user via a simple application developed with GUIDE from Matlab. The interface, shown in Fig. 4, allows the user to perform a new execution of the algorithm, either by changing soil or crop data, or by feeding in a new weather forecast and sensor data file. Once the plan is ready, the user may use it on the irrigation system.

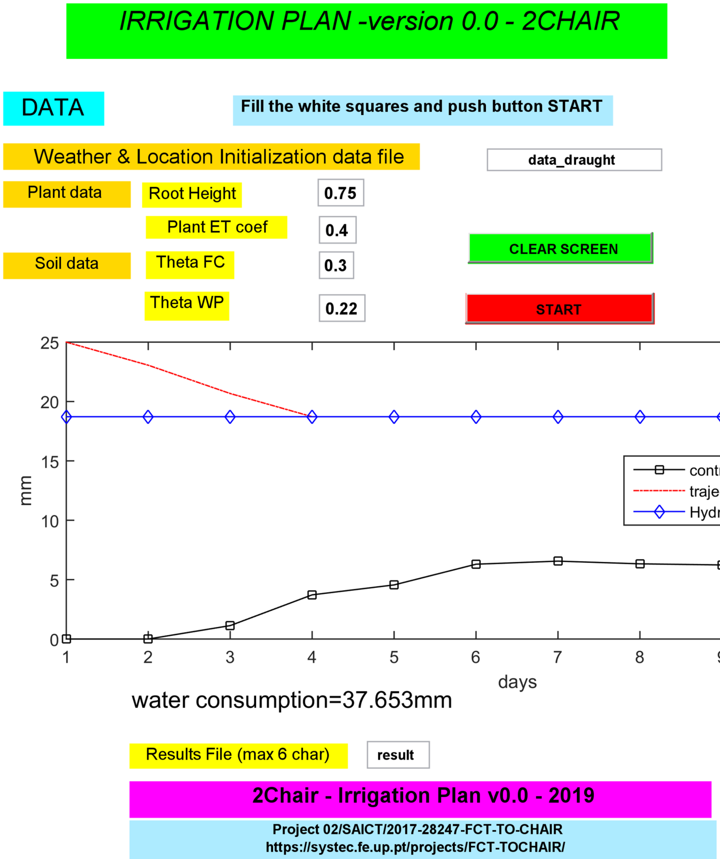

Fig. 4. Irrigation plan for a grass field in Oporto on a dry period (summer).

This enables us to experiment with the model. For example, we have executed the optimal irrigation algorithm for the same soil/location during a dry period, for two different crops, and during a rainy period. For the dry period, the resulting irrigation plan for ten days is shown in the graph of Fig. 4, showing irrigation is necessary almost everyday. The x-axis is the days ahead, "trajectory-IS" curve is the moisture in the soil, "control-IS" curve is the amount of water to be supplied by the irrigation system, and "hydric needs" is the minimum moisture the soil must have such that the crop does not die. Next, we increased the evapotranspiration coefficient of the plant. It will need more water, thus the algorithm should provide an irrigation plan with more water. Results can be seen in Fig. 5, and follow what is expected. Considering a period of rainy days, there is no need to irrigate, as shown in Fig. 6. The interface developed is easy to use and constitutes a reasonably good prototype for testing different scenarios.

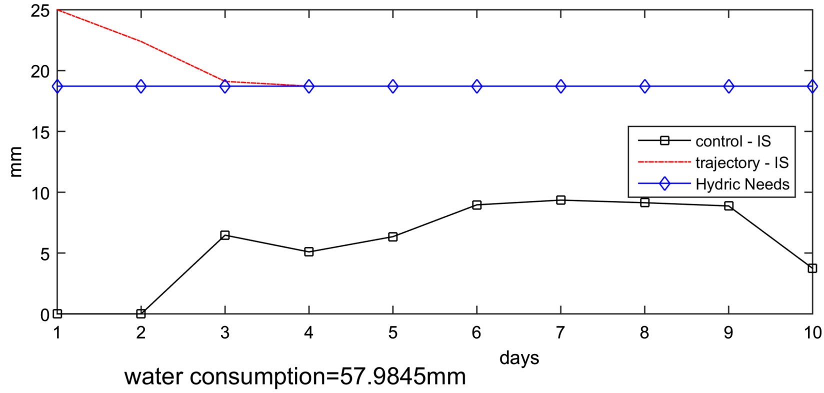

Fig. 5. Irrigation plan for a crop with higher evapotranspiration (ET coef.= 0.6) in Oporto on a dry period. The crop needs more water, consumption increases.

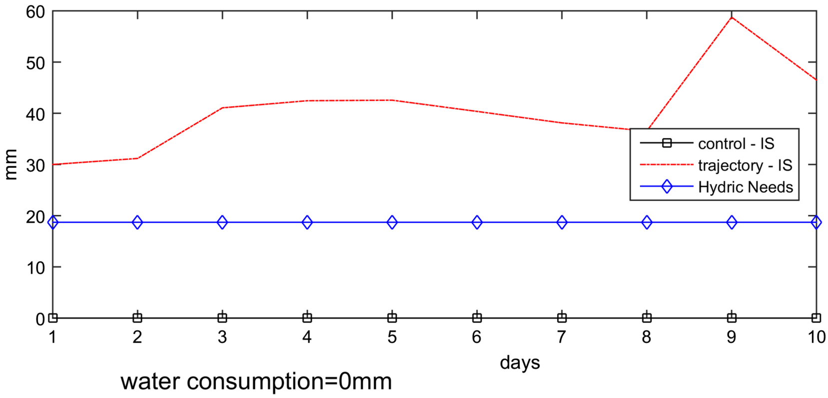

Fig. 6. Irrigation plan for a grass field in Oporto on a wet period (early spring). No irrigation is needed.

7 Conclusion and Future Work

We were able to integrate a smart irrigation system that provides the farmer with an optimized irrigation plan for a period of up to 10 days. Weather data is imported from https://www.apixu.com/, the moisture sensor provides the soil moisture that is manually uploaded to a server. This data is collected to a file that is the input to the optimization program. The rest of the data, crop and soil characteristics, is provided by the farmer. The prototype is an application developed using GUIDE (from Matlab). It is easy to use and allows a farmer to easily create scenarios by changing the input data. The output is the irrigation plan, which can be seen graphically and also in the form of a text file generated by the application.

We have also designed a system architecture to offer optimal irrigation planning to multiple users in a friendly way, namely through a web application with minimal input. Future work includes the next development stage, which is the implementation of the architecture described in this paper, and the introduction of an additional mathematical model. This model, based on Richards equation [14], is in development, and it will be able to estimate soil moisture given a reduced number of sensors. There is also the possibility to search for irrigation systems that offer an interface for external command, and include some hardware modules on the field devices to automatically actuate them.

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