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Water content virtual sensor for tomatoes in coconut coir substrate for irrigation control design

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ABSTRACT

The main objective of this work has been the development of a virtual sensor (VS) based on the water balance dynamics of tomato crops in greenhouses, using coconut coir substrate as an example in this case. Such sensors are used to provide a viable and economical alternative to expensive or impractical sensors. The final virtual sensor is the result of combining: crop growth, where the water is distributed in structural and non-structural plant biomass (storage); the substrate, which is considered to be composed of a single layer; and the water loss caused by transpiration and drainage. In this work, two ECH2O-EC-5 sensors (Decagon Devices) were calibrated and then used to determine the substrate water content; and a microlysimeter was installed to continuously sample the water supplied, the drainage, and the crop water loss values. The VS took into account the water supplied, the amount of water in three stores (the substrate, the root, and the aerial part of the crop), the climate, and the water loss. The water dynamic was determined by system identification techniques and by physical virtual sensors, which considered the water balance from a holistic point of view – as a sub-model for a customizable interface between crop growth and the plant ecosystem. The influence of both the crop and the climate conditions on the water balance was analysed and the virtual sensors were evaluated giving good final results.

1. Introduction

Water is a limited resource in many agricultural areas. Furthermore, this resource limitation is made worse due to the recent rapid expansion of the surface area occupied by greenhouses in the Mediterranean Basin. This expansion has enabled substantial economic development whilst, at the same time, it has increased the use of resources such as land and water. Consequently, this has also led to water becoming a more important consideration in the sustainability of the greenhouse-based system in Almería (south-eastern Spain). Several institutions have worked to improve water use in irrigation, reducing the environmental problems associated with irrigation in order to mitigate the severe structural water deficit. This deficit has been progressively depleting the aquifers in the area (Sánchez-Martos et al., 2007; Carvajal et al., 2014). Eighty percent of the irrigation water used comes from underground sources leading to localized overexploitation of aquifers (Fernández et al., 2007). Over the last few years, as in other arid and semi-arid areas of the world, Almería has promoted the use of alternative water sources such as purified water, desalination, rain and condensed water collection as a secondary source, the reuse of drainage water, and the development of new technologies related to water-use efficiency such as advanced irrigation controllers.

For these reasons, the water needs to be supplied precisely, given that too much leads to excessive washing out of fertilizers. In turn, this might result in radicular asphyxiation, substrate flooding, or subterranean water contamination. Conversely, a hydric deficit may be provoked if irrigation fails to provide enough water. This can lead to a decrease in production and might even be dangerous to crop growth. Hence, automatic irrigation control systems are fundamental tools in supplying water to the crop at the required amount and frequency.

In recent years, various irrigation control techniques have been developed with the aim of avoiding such problems – techniques based on PLC with on-off actuators; accumulated solar radiation (Shin et al., 2014); or based on water consumption (van Vosselen et al., 2005). Furthermore, some authors have tried advanced control algorithms. Kläring et al. (1997) and Sigrimis et al. (2001) carried out a water supply feedforward control. In Gieling (2001), the feedback control was via drainage whilst water absorption was

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treated as a system disturbance. Zhang and Wu (1996) and Ruiz et al. (2000) determined when and how much to water by developing a fuzzy control from soil humidity and drainage measurements applied to ornamental plant irrigation. Ruiz et al. (2000) used the substrate water content and the estimated evapotranspiration from climatic data as input variables, and then constructed decision rules for irrigation applications on tomatoes grown directly in soil. In soilless systems, irrigation water control is closely linked to nutrient supply control. Therefore, many of the works carried out are aimed at controlling water and nutrients, as are the cases in Kläring et al. (1997) and Sigrimis et al. (2001).

Consequently, virtual sensors have become very efficient and powerful tools which have been successfully used in other fields as support to control techniques (Ponsart et al., 2010; Thies et al., 2006). Virtual sensors are useful in replacing physical sensors, thus reducing hardware redundancy and acquisition costs; or as part of fault detection methodologies by having their output compared with the corresponding sensor. Ideally, the virtual sensors should be simple and obtainable from the collected data. Using them should not require extensive training. These sensors utilize mathematical models in order to estimate features from low-cost measurements, obtained directly from first principles. In many cases, where mathematical models are unavailable, the virtual sensors have to be developed based on system identification (black-box; Ljung, 1999).

This work proposes two groups of virtual sensors to estimate the hydric balance in crop growth – climatic data and the water supplied: (1) based on first principles and (2) based on linear and non-linear black-box, as shown in the scheme proposal in Fig. 1. In this scheme, the different inputs are represented: (1) climate conditions – vapour pressure deficit (V_{VPD}) and solar radiation (V_{SR}), (2) microlysimeter data, and (3) the TOMGRO model – leaf area index (X_{LAI}), total dry weight (X_{PS}), and root dry weight (X_{PR}); whilst also including the possibility of another virtual sensor that estimates crop water loss through transpiration – as developed by the research group members (Sánchez et al., 2012).

Thus, the aim of this paper is to provide several alternatives of virtual sensors that help in the design of irrigation controllers based on the substrate water content. Additionally, this work informs us of the water balance, since the water forms a continuous liquid phase between the substrate and the crop. This phase is extended into the substrate, through the root surface, forming the so-called continuous substrate-plant-atmosphere. So, if the soil is dry, the crop is unable to take up water and nutrients – when this happens, an irrigation process is necessary.

2. Materials and methods

2.1. Water content for tomatoes in coconut coir substrate

Water balance has been studied and described in terms of the energy state of water, which allows one to describe the flow rate through the soil (Burés, 1997) or substrate (Kramer and Boyer, 1995). In this kind of flow, water velocity is proportional to the potential gradient (Burés, 1997), where the proportionality constant is a substrate characteristic; thus, the same potential gradient will produce different flows in different substrates (Burés, 1997). Hence, the water potential in the substrate ($\psi_{h,s}$) is the sum of the potential:

$$\psi_{h,s} = \psi_{m,s} + \psi_{g,s} + \psi_{os,s} \quad (1)$$

where $\psi_{m,s}$ is the matric potential, $\psi_{g,s}$ is the gravitational potential, and $\psi_{os,s}$ is the osmotic potential. In this work, the gravitational potential ($\psi_{g,s}$) can be ignored given that the substrate height is less than 7 cm (Burés, 1997). The water potential remains as a function of the matric potential and osmotic potential:

$$\psi_{h,s} = \psi_{m,s} + \psi_{os,s} \quad (2)$$

In addition, for substrate characterization, one of the important factors is the water retention capacity (Kirda et al., 2004), which depends on physical characteristics: porosity, structure, particle size, and distribution (Ansorena, 1994; Burés, 1997). Substrates with a particle size between 1 mm and 10 mm have little variation in the amount of water stored but this capacity increases when the particle size is less than 1 mm (Ansorena, 1994). The water retained in the substrate has a nonlinear relationship to the matric potential and also presents the hysteresis phenomenon (Burés, 1997). Knowledge of this relationship has been the subject of many studies (da Silva et al., 1995; Burés, 1997; Domeño et al., 2009; Urrestarazu et al., 2008) and is useful in formulating water balance virtual sensors.

2.1.1. Physical water content virtual sensor

The proposed model is a generic one, which considers the water balance from a holistic point of view. It is dynamic, explanatory, and simple. It takes into account the amount of water in three stores: the substrate, the root, and the aerial part of the crop (including leaves, stems, and fruit). The state variables are the substrate ($X_{AG,s}$), root ($X_{AG,r}$), and the water content of the aerial part ($X_{AG,d}$). This virtual sensor (VS) can be changed to accommodate different conditions (Thornley, 1996).

$$dX_{AG,s}/dt = F_{AG,s} - X_{AG,d}/dt - X_{AG,r}/dt \quad (3)$$

$$F_{AG,s} = F_{AG,I} - F_{AG,dr} \quad (4)$$

where $F_{AG,I}$ is the water supplied by irrigation, $F_{AG,dr}$ is the drainage, and $F_{AG,s}$ is the substrate water flow. The state variables $X_{AG,r}$ and $X_{AG,d}$ are defined by (Thornley, 1996):

$$dX_{AG,d}/dt = F_{AG,r\text{-}d} - F_{AG,atm} \quad (5)$$

$$dX_{AG,r}/dt = F_{AG,s\text{-}r} - F_{AG,r\text{-}d} \quad (6)$$

where $F_{AG,r–d}$ is the root to crop water flow, $F_{AG,d–atm}$ the water flow from crop to atmosphere, and $F_{AG,s–r}$ from substrate to root:

$$dX_{AG,s}/dt = F_{AG,I} - F_{AG,s\text{-}r} - F_{AG,atm} - F_{AG,dr} \quad (7)$$

The water flow is described by (Thornley, 1996):

$$F_{AG,s\text{-}r} = (\psi_{h,s} - \psi_{h,r})/r_{AG,s\text{-}r} \quad (8)$$

$$F_{AG,s\text{-}d} = g_{AG,r\text{-}d}(\psi_{h,r} - \psi_{h,d}) \quad (9)$$

where $\psi_{h,s}$, $\psi_{h,r}$, and $\psi_{h,d}$ are the substrate, root, and aerial part of the plant potentials, respectively. $r_{AG,s–r}$ is the flow resistance of the substrate to the root, and $g_{AG,r–d}$ is the root to crop conductivity. $r_{AG,s–r}$ is defined by Eq. (19), in which C_{sors} and C_{rsr} are parameters that define the resistance between the substrate and the root, C_{kwrsr} is a root resistance parameter, K_{se} is the substrate hydraulic conductivity, and ρ_r is the root density.

$$r_{AG,s\text{-}r} = (C_{sors}\,\rho_r)/(K_{se}\,X_{pr}) + C_{rsr}/\rho_r\,((X_{pr} + C_{kwrsr})X_{pr}) \quad (10)$$

The hydraulic conductivity of a canopy root is determined by the following equation, where C_{cndag} is the parameter conductivity of the soil water.

$$g_{Ag,r\text{-}s} = C_{cndag}\,X_{AG,r}\,X_{AG,d}/(X_{AG,r} + X_{AG,d}) \quad (11)$$

The substrate hydraulic conductivity was calculated from the equation given in (Mualem, 1976):

$$K_{rSe} = S_e^{1/2}(1 - (1 - S_e^{1/Cagm})^{Cagm})^2 \quad (12)$$