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Research Paper

Wireless sensor networks for greenhouse climate and plant condition assessment

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Spatially distributed environmental measurements at plant level can be used to create a precise and detailed representation of the climate at various regions inside a greenhouse. Climatic heterogeneity can cause significant differences in terms of yield, productivity, quantitative and qualitative characteristics of the plants, as well as the development of various diseases. This work presents: i) the assessment of wireless sensor networks (WSNs) operation reliability and accuracy in actual greenhouse conditions, ii) the development of a distributed monitoring system using a WSN in a commercial greenhouse, and iii) the analysis of the collected spatially distributed data for the investigation of possible problematic situations for the growing plants caused by climatic heterogeneity inside the greenhouse. A prototype WSN was initially developed in order to investigate the effects of the environmental conditions to the operation reliability of the network and assess its performance and the feasibility of its operation in a commercial greenhouse. The enhanced WSN was then installed in a commercial greenhouse to investigate the spatial variation of the existing environmental conditions. Analysis based on WSN measurements showed significant spatial variability in temperature and humidity with average differences up to 3.3 °C and 9% relative humidity and transpiration, with the greatest variability occurring during daytime in the summer period. There were conditions that favoured condensation on leaf surfaces and other problematic situations.

1. Introduction

The existence of strongly coupled factors affecting the greenhouse environmental conditions makes climate control a complex task. In addition, spatial heterogeneity which is inherent to the biological and physical aspects of the involved processes and systems, makes the optimal control task even more challenging. In modern greenhouses, several measurement points at plant level are required to create an objective and detailed view of the climate at various regions in the entire greenhouse space. Specific climatic gradients can cause significant differences in terms of yield, and quantitative and qualitative characteristics of the plants, as well as the development of various diseases. To be able to eliminate these

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Nomenclature

a	Constant defined in Eq. (2), dimensionless
b	Constant defined in Eq. (2), W m^{-2} kPa^{-1}
BS	Base-station
CEA	Controlled environment agriculture
MRD	Mean relative deviation
N	Number of measurements
PA	Precision agriculture
R	Radiation intensity, W m^{-2}
R^2	Determination coefficient
RMSE	Root mean squared errors
Std	Standard deviation
Tr	Transpiration, W m^{-2}
VPD	Vapour pressure deficit, kPa
WSN	Wireless sensor network

differences, a precise and accurate distributed monitoring system is required.

With the relatively recent advancement of wireless sensor networks (WSNs), such distributed monitoring is technically and economically feasible. These networks usually consist of battery-powered nodes equipped with specific sensors that collect appropriate information and transmit it wirelessly to a central base-station (BS), which stores the received data for future processing or uses it dynamically for monitoring, control and other purposes, e.g., data analysis, forecasting (Akyildiz, Su, Sankarasubramaniam, & Cayirci, 2002; Li, Sha, & Lin, 2014; López; Riquelme et al., 2009; Matese, Di Gennaro, Zaldei, Genesio, & Vaccari, 2009; Vox et al., 2014). The main properties that are crucial to the proper operation of a WSN are: i) sufficient accuracy of measurements, ii) reliable network connectivity and iii) low power consumption. The importance of other aspects of proper WSN operation, like data security, depends on each specific application. Several network architectures, communication protocols and energy-management algorithms have been applied to WSNs to maximise sensing coverage of the network as well as life-duration of the battery-powered sensor nodes (Ghiasi, Srivastava, Yang, & Sarrafzadeh, 2002; Krishnamachari & Ordonez, 2003). These properties are affected not only by the characteristics of the sensors and the design parameters and communication algorithms of the network, but also by the environmental and physical conditions that the WSN operates in.

Precision agriculture (PA) and controlled environment agriculture (CEA) introduce several application-specific parameters that have to be considered alongside communication-specific and energy-specific properties, when designing a WSN (Baggio, 2005; Ferentinos & Tsiligiridis, 2007; Garcia-Sanchez, Garcia-Sanchez, & Garcia-Haro, 2011; Mancuso & Bustaffa, 2006). The use of WSNs in such applications provides valuable information about the spatial distribution of the monitored variables, which constitutes a very important tool for precise control mainly in PA, but also in large-scale CEA (Balendonck, Van Os, & Schoor). Especially in the case of CEA, which mainly involves the monitoring and control of greenhouse environment, several issues can arise in relation to the sensing quality of the WSNs used, mainly because of the extreme environmental conditions inside a greenhouse (Ferentinos, Katsoulas, Tzounis, Kittas, & Bartzanas, 2015). Such conditions can make the WSN measurements noisy and usually associated with some measure of uncertainty (Katsoulas, Ferentinos, Tzounis, Bartzanas, & Kittas, 2015a; Wen, Xiao, Markham, & Trigoni, 2015). Ahonen, Virrankoski, and Elmusrati (2008) developed a WSN specifically for a commercial greenhouse facility, measuring temperature, humidity, solar radiation and CO_2 concentration. They performed several tests and concluded on the specific issues that arise in a greenhouse WSN application. Similarly, Balendonck et al. (2014) reported limitations of WSNs sensing accuracy in greenhouse environments in relation to measurement errors introduced by the effect of direct radiation exposure on the sensor nodes.

Kittas and Bartzanas (2007) reported that many researchers in greenhouse environment have considered the climate inside a greenhouse as uniform during development of climate control methodologies. However, several studies investigated the heterogeneity of greenhouse conditions (Soni, Salokhe, & Tantau, 2005; Teitel, Atias, & Barak, 2010). With the capability of multiple measuring points in a practical and cost-effective way with the WSN technology, the exploitation of climatic variability is now feasible. Several recent works have investigated the use of WSNs for the estimation of climatic variability in the greenhouse (Balendonck et al., 2014; Bojacá, Gil, & Cooman, 2009; Castillo, 2007). In addition, efforts have been made to introduce such analyses in the development of distributed greenhouse environmental control (Chaudhary, Nayse, & Waghamare, 2011; Gomes, Brito, Abreu, Gomes, & Cabral, 2015; Gonda & Cugnasca, 2006; Pawlowski et al., 2009).

The current work first investigated the operation reliability and accuracy of WSNs installed in experimental greenhouses. Specific greenhouse environmental conditions in relation to solar radiation exposure of the sensor nodes that affect the quality of measured variables in terms of accuracy were identified, and their role in the accuracy of measurements was explored and analysed. Consequently, relevant preliminary work presented in Katsoulas, Ferentinos, Tzounis, Bartzanas, and Kittas (2015b) was expanded, with a primary goal to use a fully operational WSN to detect and analyse the spatial variability of environmental and plant-related conditions inside a commercial greenhouse. This can potentially increase the possibility of detecting problematic situations for the cultivated plants, leading to environmental control methodologies capable of minimising the occurrence of problems associated with crop production. Issues relevant to energy consumption of the battery-powered sensor nodes, as well as network communication issues in greenhouse WSNs, have been addressed in our previous work (Ferentinos et al., 2015) and were not part of the current study. Finally, security of data communications for the specific greenhouse application under investigation, was not considered as a crucial factor and was not considered, mainly because no environmental control was involved and the WSNs usage was restricted to measurements reliability analysis and greenhouse climate assessment.