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GREENHOUSE ENVIRONMENT MONITORING AND CONTROL: STATE OF THE ART AND CURRENT TRENDS

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Abstract

This paper reviews the recent developments and implementations for greenhouses facilities, focusing on recent progress regarding greenhouse environment monitoring and control with many available application examples. State of the art and current trends concerning the main parts of the greenhouse environment automation are discussed: i) greenhouse climate models, ii) wireless sensor networks, iii) remote monitoring/command and supervisory control and data acquisition (SCADA) systems, iv) image processing. The greenhouse engineering covers multi-disciplinary approach, engineering and economics, and for final success and sustainability, social and political support must also be achieved. Greenhouse complex nonlinear coupled climate and biological models are discussed with high importance in greenhouse optimal control solutions. Greenhouse monitoring and control applications using Wireless Sensor Networks (WSN) ZigBee modules, GPRS data transmission, and CAN bus communication are presented and classified, highlighting the communication specific benefits. Remote monitoring/command and supervisory control and data acquisition (SCADA) systems are analyzed and classified offering to users the following advantages: local and remote visualizations of process data, access to process set-points, optimal control strategies, database data recording, report generations and alarm management. Image processing is another development direction for greenhouse facilities, with promising results for insect monitoring, chlorophyll content estimation, identification, classification and harvesting of fruits. The analysis and classification in appropriate categories of recent contributions, using significant application examples referred in the paper, offers a vision for the greenhouse environment monitoring and control based on modern solutions and technologies, ideas for new applications and relevant research opportunities to optimize the greenhouse processes.

Key words: environmental engineering, greenhouse, remote monitoring and control, SCADA, wireless sensor network

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1. Introduction

Greenhouses are part of our history for more than 2000 years. The first mention of enclosed environment usage to facilitate plant production comes from the times of the Roman Empire when Emperor Tiberius (Castilla, 2013) demanded to have cucumbers all year long. For these reasons, a new type of construction was firstly built by employing mica transparent walls.

Greenhouses are closed microclimate environments for plant growths in controlled conditions. The greenhouse microclimate is mainly controlled by adjusting of the temperature, humidity, CO_2 concentration and micro/macro nutrient concentrations (von Zabeltitz, 2011). Greenhouses reduce the risk of diseases and protect the crops from extreme weather (winds, acid rain/fog, storms, and extreme temperatures) and can offer optimal growth conditions for plants (de Gelder et al., 2012).

The high demand of greenhouse products leaded to an increased interest in developing greenhouse enclosed environments, on the first place being China with a total area of 4.6 million ha covered by greenhouses (Chen et al., 2013). In Europe, the country with the highest surface covered by

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greenhouse is Spain, where more than 53,800 ha were reported in 2005 (Aznar-Sánchez et al., 2011). The highest density of greenhouse has being observed in El Poniente region of Spain, where the greenhouse establishments counted for 16,000 ha from total area of 27,000 ha, this being one of few manmade structures visible from space (Galdeano-Gómez et al., 2011). The Netherlands is the third country in Europe with more than 10,370 ha of greenhouses, with the best greenhouse technologies.

The greenhouse engineering covers multi-disciplinary approach of the sciences, engineering and economics, and for final success and sustainability, the social and political support must also be achieved. The most effective innovations in greenhouse engineering design, operations and management, will incorporate inputs from partnerships with the academic, private and public sectors of society (Giacomelli et al., 2007).

Some important research fields, regarding bio-systems engineering for food production, develop new plant production strategies (Tey et al., 2017) with high content of beneficial compounds for human health, electronic instrumentation for monitoring production at different levels, recycling agroindustry residues, environmentally friendly approaches for food production, including greenhouses (Guevara-Gonzalez and Torres-Pacheco, 2014).

Traditionally, the greenhouse plant cultivation involves close monitoring of environmental parameters and manual actuator commands. There are three main associated activities: i) preparation of nutrient mixture, ii) irrigation, and iii) ensuring proper climate condition specific to the cultivated plants. Nutrient mixture preparations are based on the measurement of the grooving substrate pH and the electrical conductivity (EC), which ensure proper micro/macronutrients balances for the considered crop development stages. Irrigation is usually based on a daily manual irrigation schedule, with the humidity in the growing substrate determined by the soil tension measurement. The temperature and the relative humidity are controlled by using suitable sensors and actuators, heaters, ventilation and humidifiers (NaanDanJain, 2014) manually operated.

The greenhouse automation for the previously described activities using optimized process technologies is the next natural step (Oliveira et al., 2017; Soto-Zarazua et al., 2011), in order to reduce the human labor, the energy and materials, and to improve the quality and production of greenhouse facilities, i.e., to increase the performance/cost index. The optimized resources are: water, energy, materials, labor, space and capital. High scale automation of greenhouse facilities are making possible over last decades due to advances in IT, translated in high computation power at low prices (Castilla, 2013; Kacira, 2012).

The main control loops in the greenhouse automation based on computer-control with associated sensors and actuators are the following: i) *Temperature control* using inside temperature sensors, heaters to warm up the greenhouse if it gets too cold, and motors to open the windows or ventilators for fresh air from outside if it gets too warm inside; ii) *Humidity control* using air humidity sensors and foggers to rise the air humidity (and cooling) if it gets too dry inside; iii) *Light control* using light sensors and lights to illuminate the plants if it gets too dark; iv) *Irrigation control* using moisture sensors to see how wet/dry the soil is, and water pumps for the watering system; v) *Micro, macro-nutrients and* CO_2 *concentration controls* for higher greenhouse automation.

Greenhouse growing systems are composed of two distinct, but highly coupled nonlinear parts: the physical part and the biological part. The greenhouse environment can be characterized as being a highly complex distributed process with numerous parameters which can affect the crops. The greenhouse environment control is based on the *mathematical models of the physical and biological process.* The physical part of the greenhouse consists of the environmental parameters inside and outside of the greenhouse. The physical part has a high influence on the biological one, and also the biological processes highly influence the greenhouse physical environment, both parts being strong coupled. Several greenhouse climate models and biological models where developed, having different levels of complexity, varying from 2 to 300 state variables in the case of biological distributed models.

Control solutions for development and testing of greenhouse systems have benefited from the increasing number of greenhouse models. A high number of control structures have been proposed to control the greenhouse environment (López-Cruz et al., 2014; Oliveira et al., 2017; Ponce et al., 2015; Rodriguez et al., 2015).

The communication infrastructure is one important part of the greenhouse automation. Greenhouse facilities mainly rely on cabled communication. The main disadvantages are the relative high cost and vulnerability to mechanical stress, and also sensor relocations employ difficulties. One solution is to use Wireless Sensor Networks (WSN) (Ahonen et al., 2008). The ratification of ZigBee specification and high adoption rate of the ZigBee protocol for WSN modules, with cost decreasing, have leaded to development of high number of greenhouse monitoring solutions using ZigBee WSN (Zhang, 2011).

Remote monitoring/command and supervisory control and data acquisition (SCADA) systems for greenhouses add more benefits. This type of centralized system offers to users the online visualization of the process data, access to all process set-points, database data recording and alarm management (Bhutada et al., 2005).

The identification, classification and harvesting of fruits is another development direction in greenhouse automation. Robots with included image processing module are able to identify fruits with specific sensors (Dagtekin and Beyaz, 2017) and harvest the fruits (Correll et al., 2009). Satisfactory results have been obtained also in pest control by employing robots to identify different types of pests. Image processing algorithms have been used also for chlorophyll content estimations (Ali et al., 2012b).

This paper aims to present a review - state of the art and current trends in greenhouse environment monitoring and control, with great potential impact, pointing out the modern available systems with specific configurations and recent progresses using significant referred application examples. The analysis and classification of their characteristics and contributions in suitable categories, offers a vision for the greenhouse environment monitoring and control based on modern solutions and technologies, ideas for new applications and relevant research opportunities to optimize the greenhouse operations.

2. Greenhouse climate models and control

2.1. Greenhouse climate models

In order to optimize the control of the greenhouse process, two main complex mathematical models are employed: the *greenhouse climate models* and the *plant growth biological models*, with strong interconnections, nonlinearities and parameter variations, having distributed or for simplicity - concentrated parameters. The greenhouse climate models are very important to test and primary validate diverse control structures and optimization methods before implementation in real environments (Rodriguez et al., 2015).

A simplified greenhouse climate schematic suitable for control purpose is presented in Fig. 1, highlighting the input control variables, the output variables and the disturbance variables. Even if the greenhouse is a closed environment, it is highly influenced by *disturbances* as wind speed/direction, outside temperature/humidity/CO_2 air content, solar radiation and also by strong parameter variations of plant growth.

The greenhouse climate model can predict the *inside climate (temperature, humidity)* by knowing the initial state and the outside climate variables (Korner et al., 2007). The greenhouse dynamic climate model can be expressed by employing two entirely different approaches. The first approach describes the process trough energy and mass flow equations (Albright et al., 2001; de Gelder et al., 2012; Pasgianos et al., 2003), while the second one is based on system identification by analyzing the process input-output data (Coelho et al., 2002; He and Ma, 2012; Patil et al., 2008; Tap, 2000; Trejo-Perea et al., 2009).

One of the heavily used greenhouse climate model was proposed by Albright et al. (2001), that is a complex nonlinear coupled MIMO state-space model. This model is a simplified one, with concentrated parameters, having the inside temperature and humidity as state variables, and taking into account only the primary disturbance variables: the outside temperature, outside humidity and solar radiation. The differential equations for coupled energy and water vapor mass balances are expressed by Eqs. (1-2):

$$\frac{dT_{in}(t)}{dt} = \frac{1}{\rho C_p V}[Q_{heater}(t) + S_i(t) - \lambda Q_{fog}] - \frac{V_r(t)}{V}[T_{in}(t) - T_{out}(t)] - \frac{UA}{\rho C_p V}[T_{in}(t) - T_{out}(t)] \quad (1)$$

$$\frac{dw_{in}(t)}{dt} = \frac{1}{\rho V} Q_{fog}(\mathrm{t}) + \frac{1}{\rho V} E(S_i(t), w_{in}(t)) - \frac{V_r(t)}{V}[w_{in}(t) - w_{out}(t)] \quad (2)$$

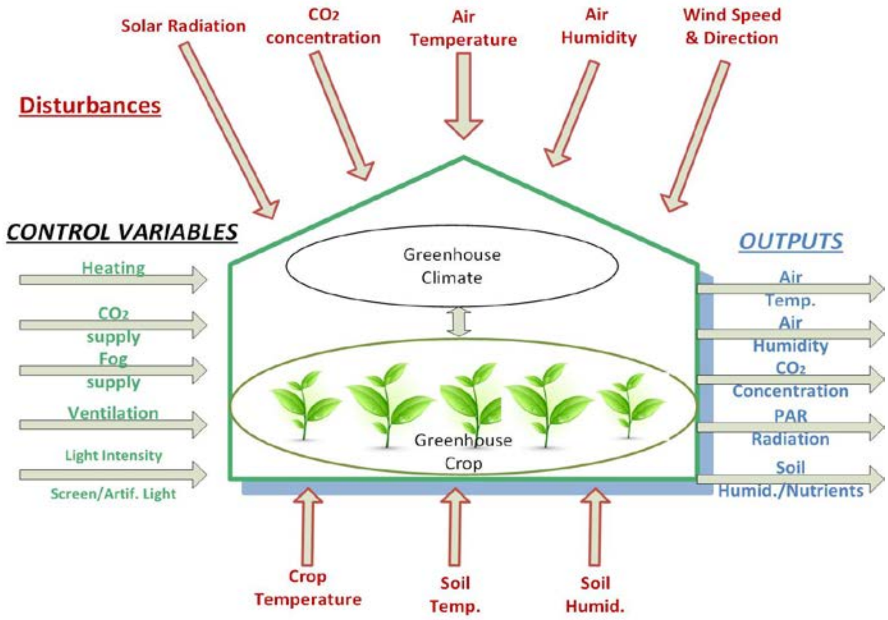

Fig. 1. Simplified greenhouse climate schematic pointing out the input control variables, output variables and disturbance variables

where: T_{in}, T_{out} are the indoor and outdoor air temperature (°C), V is the greenhouse volume (m^3), UA is the heat transfer coefficient (W/K), ρ is the air density (1.2 kg/m^3), C_p is the specific heat of air (1006 J/(kgK)), Q_{heater} is the heat provided by the greenhouse heater (W), S_i is the intercepted solar radiant energy (W), Q_{fog} is the water capacity of the fog system (g H_2O/s), λ is the latent heat of vaporization (2257 J/g), V_r is the ventilation rate (m^3/s), w_{in}, w_{out} are the interior and exterior humidity ratios (g H_2O/kg), $E(S_i, w_{in})$ is the evapotranspiration rate of the plants (g H_2O/s).

The model presented by Albright et al. (2001) can be used as a multi-season model. In the case of summer, Q_{heater} in Eq. (1) is set to zero. The main factors that determine the evapotranspiration rate of the plants $E(S_i, w_{in})$ are the intercepted solar radiation S_i and the interior humidity ratio w_{in}, being expressed through the following simplified relation (Eq. 3):

$$E(S_i(t), w_{in}(t)) = \alpha \frac{S_i(t)}{\lambda} - \beta_T w_{in}(t) \tag{3}$$

where α is an overall coefficient to account for shading and leaf area index and β_T is an overall coefficient to account for thermodynamic constants and other factors affecting evapotranspiration.

A solar heating with parabolic trough solar collectors included in the greenhouse modelling was developed by Grigoriu et al. (2015).

2.2. Greenhouse climate control system with linearization and decoupling

The complex nonlinear coupled MIMO state-space model (Eqs. 1-3) of the greenhouse climate is employed, *as a significant example*, in a greenhouse climate control system with linearization and decoupling for the temperature and humidity control developed by Gurban (2014) (Fig. 2).

The state variables are the greenhouse inside temperature (T_{in}) and the interior humidity ratio (w_{in}). The real output variables (T_{in_d} and w_{in_d}) are obtained from the corresponding state variables (T_{in} and w_{in}) adding dead times (*delay_*T_{in}, *delay_*w_{in}), taking into account the propagation delays in the real distributed process and the delays in measurements. The input variables and are the fan ventilation rate (V_r) and the water capacity rate of fog system (Q_{fog}). The disturbance variables are the intercepted solar radiant energy (S_i), the outside temperature (T_{out}) and the outside humidity ratio (w_{out}).

A *feedback-feedforward linearization and decoupling technique* based on Isidori method (Isidori, 2013) is applied (van Straten et al., 2011) and (Pasgianos et al., 2003) to the complex greenhouse climate model (Eqs. 1-3) with measurable disturbances. Finally, for the greenhouse climate process with linearization and decoupling, two decoupled Integral-Plus-Dead-Time (IPDT) equivalent simplified processes are obtained with isolated disturbances, basically used in optimized control systems for the greenhouse temperature and humidity regulations (Gurban and Andreescu, 2012).

The computation of the command variables V_r and Q_{fog}, responsible for linearization and decoupling, require the undelayed output variables T_{in} and w_{in}. The estimation of these variables ($T_{in}^{\wedge}$ and $w_{in}^{\wedge}$) can be obtained by using the process internal model, with the major drawback of losing the decoupling in dynamic regime in the case of model parameter uncertainties.

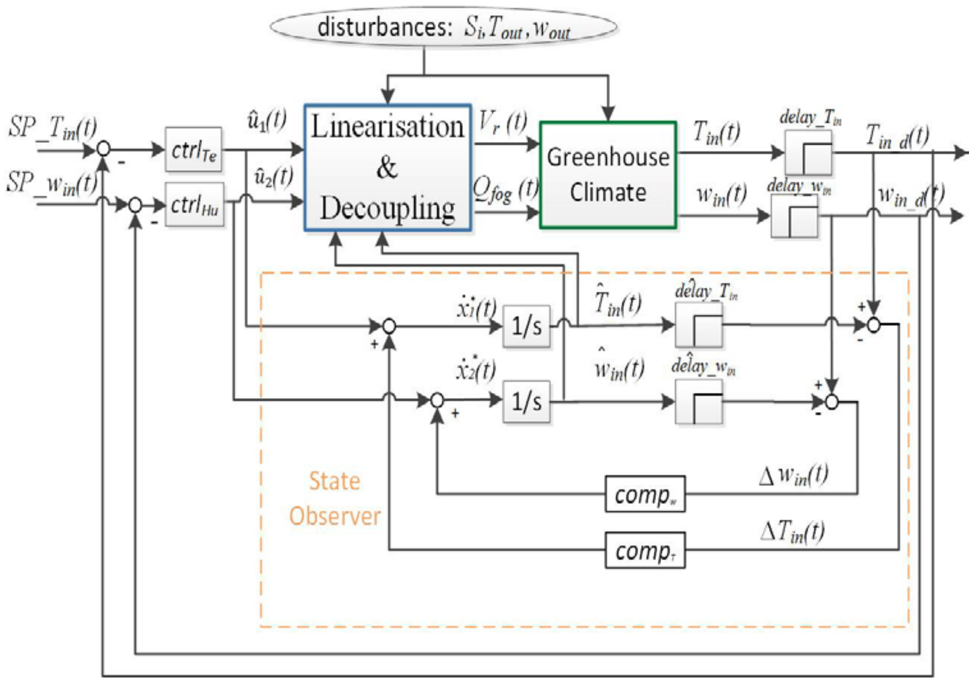

Fig. 2. Greenhouse climate control system with linearization and decoupling for temperature and humidity control using a state observer to estimate the undelayed output variables (Gurban, 2014)

A more refined solution is proposed by Gurban (2014) by employing a Luenberger state observer (Fig. 2), which was developed taking into consideration the IPDT behavior of the greenhouse climate process with linearization and decoupling for the temperature and humidity channels. The observer uses the output estimation errors between the real measured outputs T_{in_d}, w_{in_d} and the estimated delayed outputs, with proportional integral (PI) compensators providing fast and accurate estimations for $T_{in}^{\wedge}$ and $w_{in}^{\wedge}$. The advantages of this observer based estimation are low computation effort and accurate estimation in case of modeling uncertainty.

3. Biological growth models

The other main part of the greenhouse model is the biological growth model. The biological growth process is very complex, having parameters that need to be particularized for each culture type. TOMGRO model (Jones et al., 1991), describing *the tomato culture* evolution, has 71 state variables (69 plant state variables) and 50 parameters. A more detailed tomato model is described by Koning (1994) having more than 300 state variables. A simplified one, and two state lettuce growth model to present the dry matter evolution, is shown in (Van Henten, 1994; Van Straten et al., 2011).

Furthermore, Van Straten et al. (2011) present a tomato model that describes the evolution of leaf and fruit biomass from anthesis to the first fruit. The main state variables can be categorized based on biomass type into non-structural and structural states. The model has three main states: the structural biomass in leaves and fruits, and the non-structural biomass that can be seen as an assimilator buffer.

Vanthoor et al. (2011) present a tomato model with the plant development stage divided in two phases, i.e., vegetative and generative phase. The model is based on the carbohydrates flow in the leaves, steams, roots and fruits for both development stages (Vanthoor, 2011).

A generalized greenhouse model, where the greenhouse states variables are categorized into the plant state variables and the climate state variable, is described by the generalized differential equations (Eqs. 4-5) (Challa and van Straten, 1993):

$$\frac{dX_p}{dt} = g(X_p, X_c, U_e) \quad (4)$$

$$\frac{dX_c}{dt} = f(X_p, X_c, U_e, U_c) \quad (5)$$

where X_p are the plant state variables (biomass distribution in the plant constituent parts: root/strain/leaf biomass), X_c are the climate state variables (greenhouse air temperature, humidity and carbon dioxide concentration), U_e are the external inputs (outside greenhouse temperature, humidity, carbon dioxide concentration, solar radiation and wind speed and direction) and U_c are the control inputs (ventilation rate, fogger debit, supplemental light intensity).

Van Henten (1994) proposed a *lettuce growth model* considering structural and non-structural biomass accumulations that is described by differential equations (Eqs. 6-7):

$$\frac{dX_n}{dt} = c_\alpha \Phi_{phot} - r_{gr} X_s - \Phi_{resp} - \frac{1-c_\beta}{c_\beta} r_{gr} X_s \quad (6)$$

$$\frac{dX_s}{dt} = r_{gr} X_s \quad (7)$$

where X_s and X_n are the structural and non-structural biomass, Φ_{phot} is the plant CO_2 uptake considering the photosynthesis process, r_{gr} is the conversion rate from nonstructural to structural biomass, Φ_{resp} is the amount of biomass (carbohydrates) used during respiratory process, c_β coefficient accounts for nonstructural biomass losses due to nonstructural to structural conversion process.

The gross carbon dioxide uptake due to photosynthesis of the canopy can be expressed by Eq. (8) (Goudriaan and Monteith, 1990):

$$\Phi_{phot} = \Phi_{phot,max}[1 - exp(-c_k c_{lar,s}(1-c_t)X_s)] \quad (8)$$

where Φ_{phot} is the gross CO_2 assimilation, $c_{lar,s}$ is the leaf area to strain structural biomass ration, $(1-c_t)$ is the green dry mass to total crop dry mass ratio and c_k is the canopy extinction coefficient.

The methane is a greenhouse gas with a very high capacity of heat trapping, which also results from wastewater treatment plants (Manea et al., 2013). The usage of treated-wastewater for greenhouse crops was studied and short term usage is feasible, with the remark that a strict heavy metals monitoring is necessary (Marofi et al., 2013).

4. Wireless sensor network in greenhouse monitoring and control

In the last period, high number of greenhouse environment control systems benefit from Wireless Sensor Network (WSN) usage (Lakshmi, 2016; Mechalikh and Bouafia, 2017; Ojha et al., 2015; ur-Rehman, 2014; Srbinovska et al., 2015). A WSN is composed of several wireless sensor nodes that encapsulate mainly the following modules: sensors, microcontrollers, radio frequency transceivers and power sources. Recent advances in electronics implying miniaturization, increased computation capabilities, decreased consumption power, leaded to the development of low cost, low power consumption, multifunctional sensor nodes that are able to measure and process the environment variables, and most important are able to network with other sensor systems and exchange data with other data processing devices (Sohraby et al., 2007).

4.1. Wireless transmission protocols: ZigBee and Bluetooth

Two protocols are mainly used for wireless transmission of information from sensors: ZigBee and Bluetooth. Although *Bluetooth* was designed for high data rates, the higher power consumption of nodes discourages it usage in monitoring of greenhouse environment.

ZigBee is based on the IEEE 802.15.4 standard (Di Francesco, 2012; Stevanovic, 2007) with added network and application layer functionality. ZigBee allows the usage of different topologies (tree, star, mesh), and it also supports a high number of nodes (65.536). ZigBee has the lowest current consumption, typically of 30 mA in RX mode, compared with Bluetooth devices with a consumption of 65-170 mA. In most cases, the ZigBee nodes are powered by batteries, thus special attention have been taken for the power consumption in sleep mode, at this point current consumption below 1uA is achieved. A feature of the ZigBee WSN is the ability of moving, adding or removing sensor nodes without disrupting the communication due to its auto configuring capability (Ruiz-Garcia et al., 2009). Taking into consideration all these aspects, the usage of ZigBee has been imposed in large applications of greenhouse monitoring and control (Zhang, 2011).

Modifying the type of cultivation, or moving the cultivated plants to a different lot, is difficult when employing a wired system. Usage of wireless sensor networks in greenhouse environments adds the flexibility of wireless data transmission.

4.2. WSN greenhouse applications

One of the first usages of WSN in greenhouse monitoring and control systems is presented by Liu and Ying (2003) being based on Bluetooth protocol.

A greenhouse monitoring system based on ZigBee nodes, used for collecting the environment and crop information, is presented by Lee et al. (2010). By using WSN, the following parameters are monitored: fruit temperature, leaf temperature, leaf wetness, greenhouse inside temperature, humidity, luminance, root zone environment information (pH and electrical conductivity), wind velocity and direction, precipitations. The proposed solution (Fig. 3) covers three layers: *physical, middle and application layer*. i) The physical layer contains sensors, actuators and PLC devices. The following actuators are used: window openers, fans and heaters, and LED lamps to provide artificial light. ii) The middle layer contains the following modules: data management, artificial light manager, PLC control, data analysis, database and sensor management. iii) The third layer, application layer is the web based Human Machine Interface (HMI).

The data filtering module processes the raw data from the sensors, correcting the overlapping and incorrect data, and writing all information in the database. The environment control module transmits the control signal to the PLC. The artificial light control module transmits the control signal to the artificial light controller.

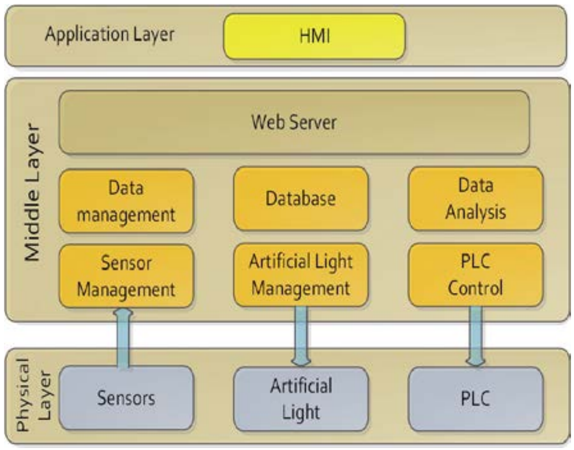

Fig. 3. Greenhouse system structure with three layers (Lee et al., 2010)

A diurnal and nocturnal temperature control system is presented by Matijevics (2009). Sun SPOT WSN modules are used to acquire temperature and humidity information. By day, the natural ventilation is employed to control the inside greenhouse temperature, primary, and secondly to vary the inside humidity. The ventilation is controlled by proper adjustment of the greenhouse vent openings. Under diurnal conditions, a heating system is designed with a control algorithm using gain scheduling PI controller. The tuning parameter adjustments are based on the external disturbances: wind speed and outside temperature. For nocturnal conditions, an on/off hysteresis controller is used to command the forced air heaters.

A greenhouse modular irrigation system using ZigBee nodes is presented by Beckmann and Gupta (2007). Mica2 sensor nodes are used for monitoring the environment (soil moisture, air temperature and humidity) and for controlling the irrigation cycle. The greenhouse cultivated area is split into different irrigation sections, each section having its own irrigation control implemented on a ZigBee node that collects data from the adjacent wireless sensors. One important aspect is the option of relocating the sensor node, in which case the WSN node will be automatically reconfigured to communicate to the proper irrigation node.

Monitoring of multiple greenhouses in farms employing WSN and Controller Area Network (CAN) bus (Fig. 4) is studied by Mirabella and Brischetto (2011). In each greenhouse, the monitored parameters are transmitted to the supervisory and control unit located near the greenhouse. The Supervisory Control and Data Acquisition (SCADA) system processes the environmental information and sends commands to the actuators in each greenhouse. This solution is based on a CAN type network backbone, which connects the supervisory and control system to sensors and actuators by the CAN/ZigBee bridge. The Smart

Distributed System (SDS) application layer, defined by Honeywell, is chosen due to its implementation simplicity and good suitability for small resources devices. It offers all the necessary services for greenhouse automation. In order to provide a uniform service set, the SDS-CAN application layer is ported to ZigBee which bears the name ZSDS. In doing this, the device physical network independence is guaranteed, making possible for all devices to access both CAN and ZigBee network resources regardless of the physical network connectivity.

A low cost acquisition system using ZigBee WSN for greenhouse environmental variables is developed by Zhang (2011). A simple system structure is adopted; the system core is a SPCE3200 microcontroller for monitoring the terminals and data processing with capabilities of receiving commands from a supervisory PC, and locally, of storing data records. The sensor nodes are based on CC2420 ZigBee transceiver modules.

A large scale tomato greenhouse based on WSN solution for monitoring the environmental variables is presented by Mancuso and Bustaff (2006). The workload implied for the installation and maintenance of a wired infrastructure in a large greenhouse is very high.

The proposed system uses Sensicast RTD204 nodes that measures air temperature, relative humidity and soil temperature. The used protocol is SensiNet, which is based on IEEE 802.15.4 with frequency hopping modulation technique. A bridge node acquires the monitored information from sensors and transmits it through LAN to the base station that has a data acquisition system developed in LabVIEW.

A self-configuration multi-hop WSN for a greenhouse environment monitoring system to monitoring the temperature, electrical conductivity, measure substrate water, daily photosynthetic radiation and leaf wetness, is developed by Lea-Cox et al. (2009). Other WSN system for monitoring the solar radiation is proposed by Cotfas et al. (2011).

A two-part framework based WSN prototype is proposed by Liu et al. (2007). The first level contains wireless sensors for measuring the temperature, light intensity and the soil moisture, plus a sync node that is connected to a Global System for Mobile Communications (GSM) module. The second level contains GSM modules for transmitting the information from sensors, and the management software running on a remote PC.

Remote control, distant monitoring and diagnosis are some crucial features for greenhouse automation. Janos and Martinović (2009) present a WSN integrated solution for distant monitoring and command based on a microcontroller with embedded Ethernet controller running a web server. The environmental parameters are monitored by using Sun SPOT WSN; this information, and also a log of the monitored information and the live video stream from the greenhouse, are displayed on the web page. The same authors propose a *mobile climate measuring station* based on Waspmote ZigBee WSN implemented on a Boe-Bot robot kit (Janos and Matijevics, 2011).

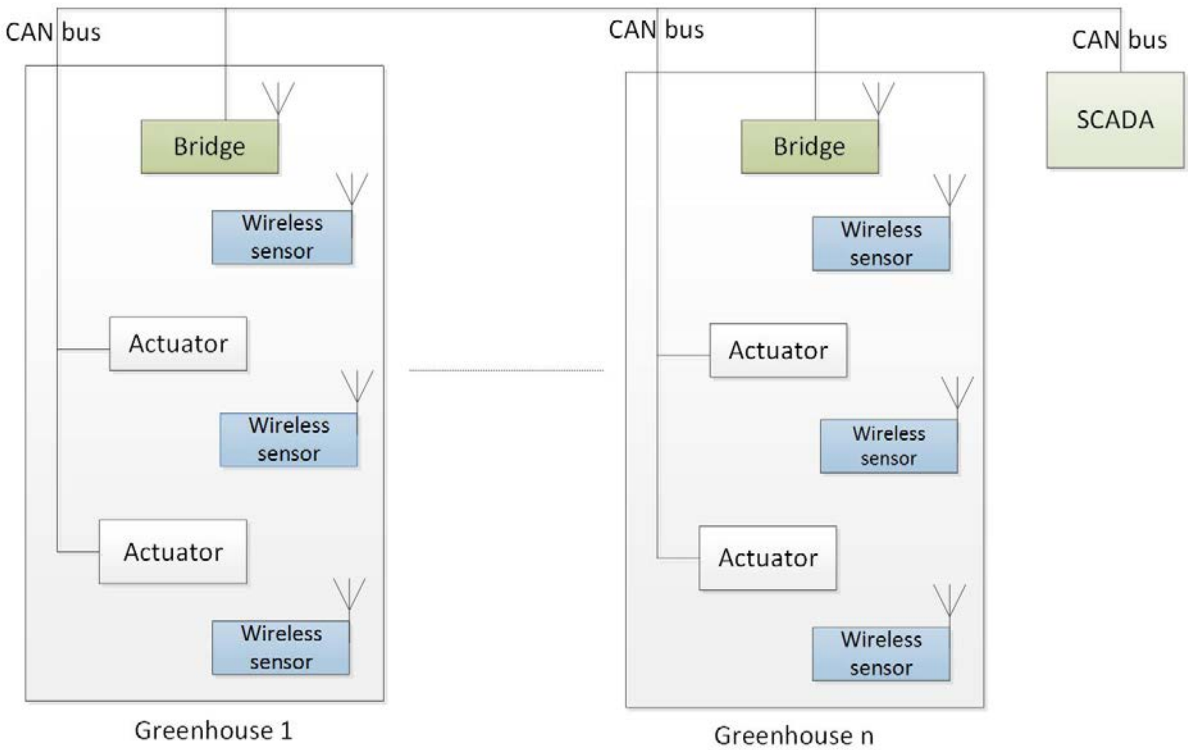

Fig. 4. CAN/WSN hybrid infrastructure for greenhouse farms (Mirabella and Brischetto, 2011)

An event-based control system for greenhouse climate using a ZigBee WSN is proposed by Pawlowski et al. (2009). Due to nonlinearity of the climate model, a PI gain scheduling technique is employed with the PI tuning parameters dynamically modified based on external disturbances. The management of level crossing sampling is based on the testing of control performance using 3% and 5% difference between the last transmitted measurement and the new one. Comparing with the time-based sampling, this event-based sapling ensures 90% traffic decrease on WSN, and 80% reduction of control output signals, which have a positive effect on the actuator lifetime. The performance comparison of the classical control and the event based control system (using different levels crossing sampling) leads to the conclusion: the best compromise between performance and state changes is obtained for delta of 3%.

4.3. Plant diseases, insects monitoring and prevention

One important problem in greenhouse environment is the dew condensation on the leaves, which creates a perfect habitat for fungus or bacteria, leading to various plant diseases. A solution to solve this problem is a *WSN based control system for dew condensation prevention* proposed by Park et al. (2010). This solution uses WSN for collecting environmental data, process data, commands the actuators, and also employs a server for data storage and processing. The dew point is calculated by applying the Barenbrug formula, the system using five sensors for air and leaf temperature and humidity. A scale down greenhouse model is used to test the automatic control system for dew condensation prevention, showing good results.

Insect monitoring is an important aspect of greenhouse management, because the insect pests are developed often more rapidly in greenhouses than in filed cultures, due to high levels of humidity and lack of natural enemies. Adhesive traps for monitoring insect evolution are used, with the downside of being a time consuming task, as the inspection has to be done periodically. Tirelli et al. (2011) present a solution based on *distributed imaging devices of traps using WSN* that are able to acquire and send the trap images to a remote host station. This master station evaluates the insect density and activates an alarm when a certain threshold is reached. The proposed solution for insect monitoring was tested during a four weeks period inside a greenhouse, showing very good results.

4.4. Factors affecting communication quality

One issue encountered while using the WSN in the greenhouse environment is *the drop in communication range due to dense flora cultures and high humidity*. A tomato greenhouse culture was monitored by using Sensinode sensor platform achieving just a 10 meters communication range, representing one third of the communication range for open spaces (Ahonen et al., 2008). *Pollen sedimentation* on sensors is another common problem in greenhouse systems with negative impact on measurements. *The relative humidity* influence is studied also by Haneveld (2007): if the relative humidity is high, then the gateway receives around 60% of the expected messages, growing back to more than 70% when the relative humidity is low.

5. Greenhouse remote monitoring and SCADA implementations

The remote monitoring, remote command and system alarm handling play an important role for greenhouse management. A high number of control systems are used in greenhouse automation, but a more unified approach is achieved by using supervisory control and data acquisition (SCADA) systems. This type of systems benefit from integrating remote monitoring and command telematics systems, alarm notifications, process data visualizations, and setpoint modifications. The SCADA communication infrastructure for greenhouses is developed using mainly the wireless ZigBee protocol and the CAN protocol. The communication with the supervisory levels and the communication that allows the remote monitoring and command mainly relies on the TCP/IP protocol.

This chapter presents and discusses solutions for greenhouse *SCADA implementation with associated technologies*, and also implementations of remote monitoring and command systems (i.e., SCADA components) based on *web based interface by using Networked Embedded System Technology (NEST)*. Due to the high number of interacting control systems used in the greenhouse environment (temperature, humidity, CO_2 concentration, light, micro macro nutrients), and due to high coupling of the process variables, new control solutions have been developed using *multi-agent system*, which solve the conflict between the interacting control systems by offering optimized solutions to this multi-objective problem.

5.1. Web based remote monitoring and command

Networked embedded systems have gained popularity for monitoring and control operations due to their continually increasing computation power, small form factor and reduced cost. Microcontrollers with standalone or integrated Ethernet controllers made possible the usage of embedded web servers for remote monitoring and command. This type of systems allows the user to remotely monitor the environmental factors affecting plant growth, to modify the set points, to be informed in case of actuator or sensor malfunctions.

A networked embedded greenhouse monitoring and control, based on embedded web servers and 1-wire protocol for connecting the sensors and the actuators, is developed by Stipanicev and Marasovic (2003). The system employs a Tiny InterNet Interface (TINI), which is a Dallas Semiconductor development platform where the chipset has three components: DS80C390 microcontroller, firmware FLASH ROM and an Ethernet controller. The programming is done using JAVA, which is recommended due to its high portability, allowing the usage of the developed application on different microcontrollers without recompiling the source code. The code portability is very important because it ensures the system scalability, provides an efficient way for stepping up to a more powerful microcontroller to add new functionalities.

The system monitors the temperature and the humidity inside of the experimental greenhouse model, and the temperature, wind speed and wind direction outside of the greenhouse. Three types of actuators are used: ventilators, heaters and humidifiers. The inside temperature is measured by two distributed groups of three 1-wire sensors: in the ground (5 cm deep), at the ground surface and in the air. Another 1-wire sensor is used to measure the temperature and humidity in the greenhouse center. Based on a microcontroller hosted webpage, the developed software allows the user the following actions: i) to remotely monitor the inside temperature and humidity, the actuator states, the outside temperature and humidity, the wind speed/directions; ii) to command the actuators; and iii) to modify the control algorithm parameters. All the process variables values are recorded in an xml file, and can be accessed by the user through the developed webpage. The proposed networked embedded systems distinguishes itself through low dimensions and cost in comparison with PC based system, preserving the full system functionality.

A modular greenhouse remote monitor system based on embedded network and wireless transmission technology is presented by Wang et al. (2011). The system has three main components: embedded server, main control module and acquisition/executive secondary node modules. i) The embedded server is based on an ARM architecture processor (ARM920T), i.e., a Samsung microprocessors S3C2440 that uses embedded Linux OS. For wireless data transmission it uses an RF transceiver nRF905 connected through SPI interface, which is recommended due to its low power consumption. The embedded server acquires data from the process through wireless communication with the main control module, and makes data available to the client through the hosted webpage. ii) The main control module uses an ATMEL ATmega128 microcontroller and a wireless communication module. The main control module is responsible: for collecting and processing environmental data from the sensors nodes, for computing and sending the control commands to the execution nodes, and also for sending the necessary data to the embedded server. iii) Secondary node modules are based on an ATMEL ATmega16 microcontroller and a wireless communication module. Two types of secondary node modules are used: data acquisition secondary node and executive secondary node. Each data acquisition node has the following sensors: temperature sensor (DS18b20), humidity sensors (AH11), light intensity sensor (On9658) and carbon dioxide concentration sensor module (B-530). The entire system has high applicability and reliability, the operation of remote monitoring is simple, and it can have good prospects in greenhouse monitoring and control.

A remote monitoring system for greenhouse environment is proposed by Li et al. (2006). This is based on microcontroller system that sends the greenhouse monitored parameters to a remote server by using a *General Packet Radio Service (GPRS)* and Code Division Multiple Access (CDMA) wireless module. The remote server employs a (Structured Query Language) SQL server for data recordings, and a web server for hosting a web page, that displays real-time data and also the history evolution.

The Short Message Service (SMS) can also be used for remote command and monitoring. Research regarding the SMS usage for greenhouse parameters remote monitoring indicates that the remote system shows good performance and reliability (Aziz et al., 2009). The SMS based on GPRS or GSM can meet the communication requirements taking into consideration the distance and the coverage, but on the other hand, it fails to do so after there are considered the costs, possible delays in transmission, and small transmitted data frames (just 140 characters / SMS).

Android based devices for implementing human machine interfaces (HMI) show good characteristics for a variety of processes due to high resolution screens, increased processing power and unified user interface. The significant increased popularity of SmartPhones with Android operating system offers a viable option for greenhouse remote monitoring and command as following: i) *An environment remote monitoring system using an Android SmartPhone* as terminalis implemented by Gao et al. (2013). The graphical user interface (GUI) provides information from temperature, humidity and light intensity sensors, relay states, and also displays a video stream from a wireless camera placed at the process location. ii) *A low cost Android based greenhouse remote monitoring system* using a Samsung S3C2440 microprocessor and a GPRS module is proposed by Ai and Chen (2011). For measuring the greenhouse air temperature and humidity are used DB171 temperature and humidity sensors that are connected through a 2-wire, I^2C serial interface. The developed remote monitoring interface can be installed on any Android based device offering a low cost remote monitoring solution.

5.2. SCADA systems

The demand of SCADA systems in high-complexity industrial control systems leaded to a multitude of hardware and software solution being developed by multiple specialized vendors.

A typical SCADA schematic structure pointing out the main levels is presented in Fig. 5.

i) *The SCADA lower level contains several field devices* connected to sensors and actuators for process control: Remote terminal units (RTUs) (e.g., from Siemens, Schneider Electric, Motorola), Programmable Automation Controllers (PACs) (e.g., from National Instruments, Allen-Bradley, Advantech) and Programmable Logic Controllers (PLCs) (e.g., from Siemens, Allen-Bradley, Schneider Electric, Mitsubishi, ABB, Omron).

ii) *The common communication protocols* used in SCADA are: RS485, RS422, Profibus, Modbus, Ethernet, ZigBee and IEEE 802.11.

iii) *The SCADA upper level* contains: OPC Server, SCADA Supervisory Server, Historical Server, Human Machine Interface (HMI), and Web Server, with the following functions:

- OPC Server (e.g., Matrikon, KEPServerEX, NI OPC Server) achieves the communication between the field devices and the upper SCADA level. The OPC servers/client technology is an open standard that allows accessing the field devices (I/O and memory), achieving interoperability between different vendor software and hardware products.

- Several software platforms are used to implement the SCADA upper level, e.g., Rockwell RSView32, Siemens Simatic WinCC, Vijeo Citect, Wonderware Intouch HMI.

- SCADA Supervisory Server acquires data, manages alarms, records the time-stamped data and alarms in a database, processes and sends command to the field devices.

- Historical Server makes periodical backup of the SCADA Server databases.

- HMI delivers information, which are made available by the SCADA Supervisory Server to the user/operator, offering the possibility to visualize the trends of the monitored parameters, to monitor the alarms, to modify the setpoints or to manually command the actuators.

- Web Server allows remote monitoring and command through web based interface on various Internet-enabled devices like cellphones, tablets or PCs.

A hierarchic National Instruments (NI) LabVIEW SCADA system implementation for greenhouse environment is proposed by Bhutada et al. (2005). The supervisory and control is implemented by using a three hierarchic level models. The 1st level contains sensors and actuators, the 2nd one contains field point modules, and the 3rd one is represented by the main host computer. The benefit of using a hierarchic approach is the lack of disturbance in the field point modules for process control operations in the failure case of main host computer. The implementation is based on NI LabVIEW VIs running on the main host computer and on the field point modules. The SCADA system is responsible for temperature, humidity, lighting and irrigation controls.

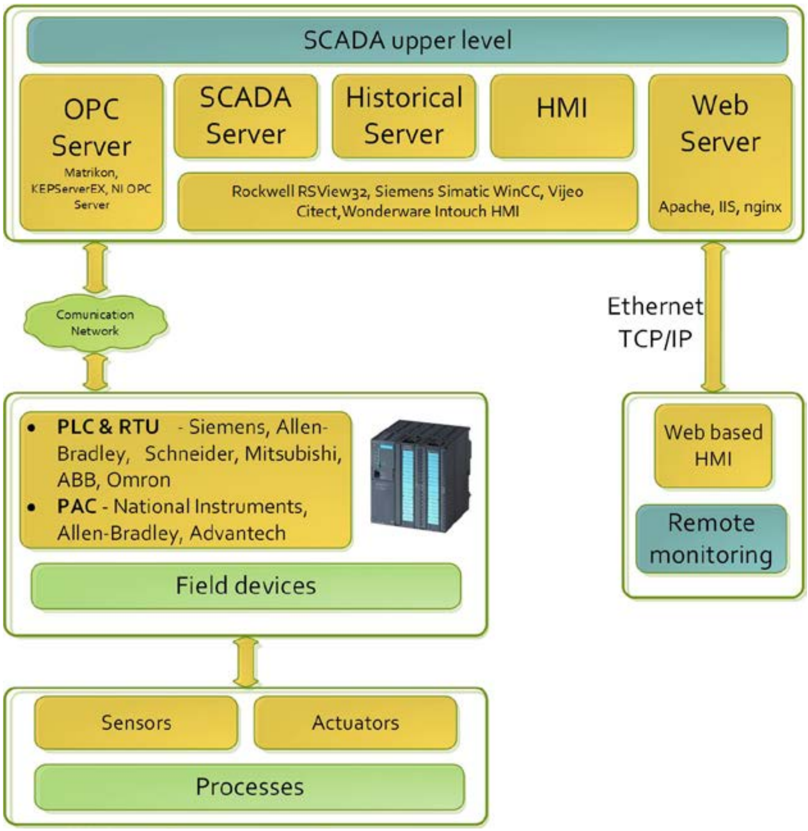

Fig. 5. SCADA schematic structure pointing out the main levels

A SCADA system for temperature, humidity and illumination control in greenhouse, based on LabVIEW and NI technology is developed by Fang and Wang (2011). ZigBee WSN is used to acquire temperature, humidity, CO_2 and light intensity data by employing NI WSN-3202 modules with four analog channels, which send data to a PLC (OMRON CPM2AH). The HMI is implemented using LabVIEW and can be accessed on the local PC, or remotely by using the LabVIEW Remote Front Panels functionality. LabVIEW offers the facility to visualize and control the virtual instrument (VI) front panel remotely by using a web browser, where the web based interface is in fact the main VI front panel. The communication between LabVIEW and the PLC is established using NI OPC server.

A SCADA system for three control subsystems: temperature and humidity, irrigation and fertilization, lighting and CO_2 is proposed by Mirinejad et al. (2008). The process control and the Human Machine Interfaces (HMI) are implemented by using NI LabVIEW. A microcontroller is employed for acquiring data from sensors by monitoring the soil nitrate, phosphate, sulphate, calcium levels, and also the soil moisture, CO_2 concentration, light intensity, air temperature and humidity. The microcontroller is connected to a PC that hosts the NI LabVIEW application by using the RS-232 serial communication. The LabVIEW application processes the measurement data, and takes regulatory actions by using on/off dead-band control. The control actions are sent to the microcontroller that commands the actuators.

A distributed SCADA irrigation control system with WSN, with quickly made and economical structure is proposed by Dumitrascu et al. (2013), and is presented in Fig. 6.

There are three interconnected subsystems implemented with specific technologies: i) An environmental monitoring subsystem, employing Memsic eKo wireless sensor network (WSN), collects data from distributed level sensors for irrigation tanks. Six wireless eKo sensor nodes are connected, each of them allowing four sensor connections. The data from the sensors is gathered by using a Radio base station connected to the eKo Server using the USB interface, and is stored using a SQLite database. The eKo Server provides sensor network management, data visualization and recording functionalities. ii) The central control device is a Siemens S7-1200 PLC, which communicates with the eKo Server by using SiriusTCP protocol, and is connected by PROFINET bus to a LOGO BA7 PLC, and to a KTP600 HMI touch panel. iii) The irrigation system actuators, i.e., one water pump and three on/off electro-valves are controlled by LOGO BA7 PLC.

A SCADA architecture for distributed greenhouses with low cost telematics system is developed by Moga et al. (2012) and is presented in Fig. 7.

The system architecture contains the following main elements: i) the field devices in three greenhouses, with specific sensors and actuators, ii) the supervisor system for monitoring and control on PC with remote HMI, and iii) the communication on inter-bus by using wired RS-485 protocol between supervisor system and greenhouses.

i) In each greenhouse there is a wireless USB sensor network for temperature, light, relative humidity, which transmit data to a bridge that converts wireless USB protocol to RS-485 for inter-bus. An intra-bus connects controllers and smart actuators, and a gateway device ensures the interface between intra-bus with RS-485 inter-bus. ii) A PC-HMI software package is installed on a remote machine and made possible the monitoring of greenhouse environment variables, the adjustment of controller setpoints and network parameters. A total of 18 sensor nodes, 5 controllers and 4 actuators are used. The key features of the proposed telematics system are flexibility, scalability, remote operation, low cost, and easiness in deployment.

A hybrid SCADA telematics system implementation based on the GSM and Ethernet is developed by (Gurban and Andreescu, 2011). The microcontroller-based telematics system hosts a web server and a GSM hardware modem with AT command capabilities. The remote commands and monitoring are accomplished by using the GSM/3G Short Message Service (SMS)/phone calling, or using the web page hosted by the microcontroller.

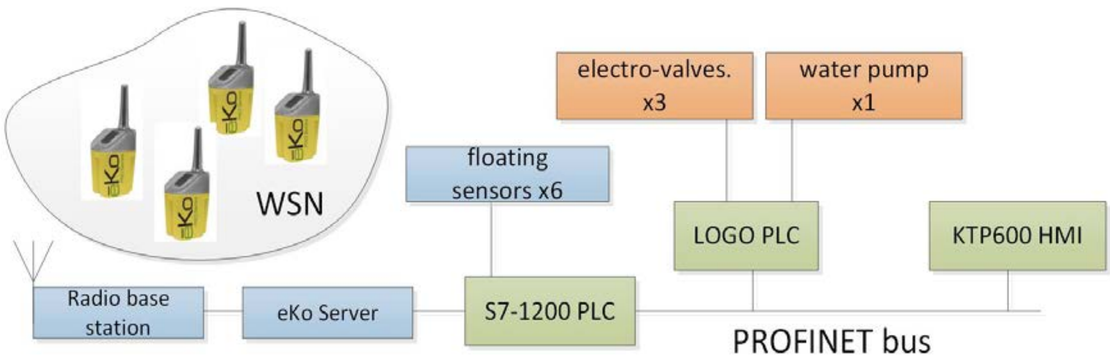

Fig. 6. SCADA irrigation control system (Dumitrascu et al., 2013)

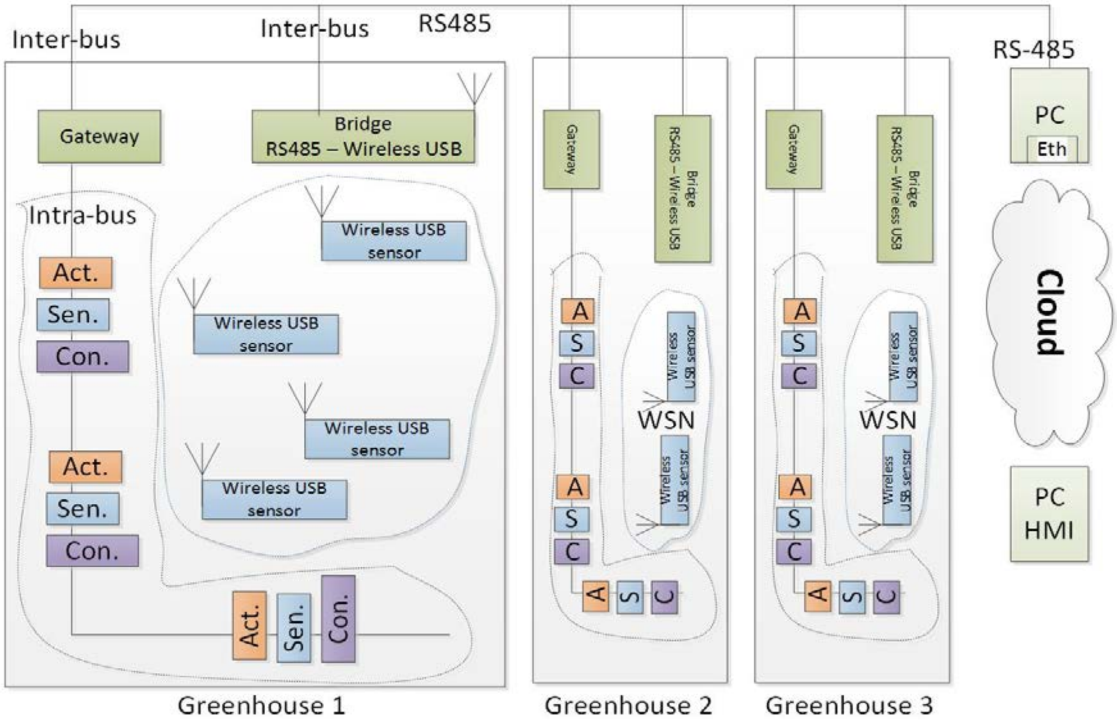

Fig. 7. SCADA architecture for distributed greenhouses using WSN and RS-485 devices (Moga et al., 2012)

5.3. CAN bus communication systems

The Controller Area Network (CAN) communication protocol is gaining popularity in greenhouse communication infrastructures. This is a Carrier Sense Multiple Access with Collision Detection (CSMA/CD) communication protocol, showing to the sender that it has to check if there is activity on the bus before sending a CAN frame. Multiple controllers can start sending frames, but after sending the identifier message only the controller with the highest priority will continue to transmit data. CAN bus uses differential data transmission allowing data transmission in high noise environments, and in most cases, the communication can continue even if one of the two bus wires is broken. Currently, there are two CAN specifications in use: 2.0A - low speed CAN with maximum data transfer rate of 125 Kbits/sec, and 2.0B - high speed CAN with maximum data transfer rate of 1 Mbit/sec.

An irrigation control system to cover multiple greenhouses using Programmable System on Chip (PSoC) and CAN bus is presented by Puri and Nayse (2013). The system implementation is based on a PC core that centralizes data from the field devices, offering a centralized way for the greenhouse monitoring. The PC is connected by a PSoC module to the CAN backbone bus, which connects all greenhouses by employing individual master modules responsible for setting the soil moisture setpoints. For each greenhouse, the own master module is connected also to the local CAN bus linking the irrigation control modules, which uses two moisture sensors and a solid state relay to drive the solenoid valve. Each greenhouse has two irrigation control modules extended with temperature and humidity sensors for two climatic parameters used by the irrigation algorithm. By partitioning the greenhouse area in several blocks, a more precise irrigation is achieved by providing optimal soil moisture conditions for each zone. If one or both CAN buses are physically damaged, the irrigation modules continue to function with the remark that moisture setpoint changes and centralized monitoring of the greenhouses are not possible.

A greenhouse temperature and humidity control system based on CAN bus infrastructure is proposed by Pengzhan and Baifen (2010). The greenhouse climate control system structure has two main layers: the coordination management and the distributed monitoring and control layer, with specific implementation technologies. The distributed monitoring and control layer consists of several STM32F103CBT6 MCU that monitor the temperature and humidity in their proximity location by using DS 18B20 1-wire digital temperature sensors, and SHT10 2-wire digital temperature and humidity integrated sensor. The main control unit is an ARM STM32VBT6 with a built-in controller compatible with CAN 2.0B frames. It interrogates the distributed monitoring for temperature and humidity measurements, applies linearization corrections, and sends commands to the actuators based on the implemented control strategy.

Other greenhouse temperature and humidity control system using CAN bus to connect monitoring and control modules is proposed by Song et al. (2012). This is based on a three level hierarchical model. The supervisory 1st level consists on a PC that has HMI, database recording and remote monitoring using a web based interface. The 2nd level contains the monitoring and control modules connected to the PC by using

CAN bus. The 3rd level consists on sensors and actuators connected to the monitoring and control modules. Because the greenhouse zone has assigned one monitoring and control module, it is very easy to extend/reduce the greenhouse cultivation area by adding/removing the CAN bus connected modules.

5.4. Multi-agent systems

Multi-agent systems have emerged as a recent methodology to address the issues in organizing large-scale software systems, providing a conceptual model for imposing and maintaining constraints in continuous evolving environment (Lin, 2007). Wooldridge (2009) define an agent as a computer system that is capable of independent (autonomous) action on behalf of its user or owner (figuring out what needs to be done to satisfy design objectives, rather than constantly being told). A multi-agent systems is composed of several autonomous interacting agents that are able to cooperate, coordinate and negotiate, the final goal of the multi-agent systems being to take the necessary actions to fulfill the agent's interests/goals.

The greenhouse automation systems are used to control highly nonlinear and coupled processes containing several control subsystems: climate control (air temperature, humidity, CO_2 concentration), lighting control, fertigation control. Due to the high interaction of the process variables, the control requirements or desiderates can be achieved by implementing them through autonomous agents.

A multi-agent system for greenhouse climate control and for remote monitoring and command is developed by Stipanicev et al. (2005). The implemented multi-agent system is detailed, emphasizing the formalization of the implemented multi-agent system. The implementation reuses the previously developed software for temperature and humidity control, sensor monitoring, power control, video image capturing and video camera pan/tilt operations. The multi-agent architecture is implemented using Java Agent Template Lite (JATLITE) and KAPI (KQML Application Programmer Interface), where the Agent Communication Language (ACL), Knowledge Query and Manipulation Language is used. The multi-agent system is composed of five agents: user interface agent, greenhouse agent, greenhouse control executioner agent, video agent and video control executer agent. The multi-agent system implementation for greenhouse climate control and remote monitoring and command was successfully used as didactic material for control course laboratory activity. The proposed and implemented multi-agent architecture is a simple and an effective solution showing good results.

A complex multi-agents system for integrated management of hydroponic greenhouse production is proposed by Ferentinos et al. (2005). The multi-agent system consists of two types of agents: environmental agents (air temperature/humidity/CO_2 concentration, light intensity), and hydroponics agents (PH, electrical conductivity, temperature, dissolved O_2, salinity), where the agents correspond to the controlled variables. Each agent has its own goal, but also global goals for the system are set. Conflicts between agents can appear when the action of an agent influences the internal state of another agent, in this case negotiation between agents has to be achieved. To prevent some conflicts between agents, an agent discussion area is proposed, where the agents exchange information about their state and they inform the other agents about the actions that they have to take to achieve their goals. The final actions are imposed by the optimization algorithm that take into consideration the user goals, the agent goals and their proposed actions to achieve the desired state. The optimization algorithm uses the process model, plant diseases and pest control models by estimating possible consequences and results of several scenarios. For resolving the conflicts between the agents, several methodologies are used: fuzzy logic, descent methods and evolutionary algorithms. The result of the optimization can modify the actuators commands but can also modify the agent setpoints.

A complex multi-agents for controlling the greenhouse variables: inside air temperature, humidity, CO_2 concentration, light intensity and also the soil temperature, humidity, nutrient concentration is proposed by Kasaei et al. (2011) using the results from Ferentinos et al. (2005). A star topology WSN to measure the environmental variables is used, where the gateway node is connected to PC. The greenhouse is segmented in several zones, and each zones has nodes deployed at predefined heights for a better understanding of greenhouse microclimate layers. For implementing the multi-agent architecture the JADE 4.1.1 (Java Agent Development Framework) is employed.

A multi-agent-based climate control system that allows new control strategies to be adopted without the need to solve conflicts in advance is presented by Sørensen et al. (2011). The climate control requirements are represented as separated autonomous agents. The artificial lighting control subsystem is employed for achieving an optimal photosynthesis gain of the plants, taking into consideration the CO_2 concentration levels, energy consumption, energy cost and weather forecast. Five agents are developed, corresponding to the five requirements that are considered for artificial lighting. Each control cycle of actuator output is negotiated by the agents before the cycle start and is maintained throughout the cycle duration. A novel multi-objective negotiation protocol is proposed and implemented by using genetic algorithms to obtain an optimized solution. A negotiator generates random option sets that are evaluated by agents. For each option set a fitness value is calculated and just the fittest solution are keep, the discarded population being rebuild using mutation and crossover of the fittest solutions. The solution with the best fitness value is selected to be used in the following control cycle. In the case when the optimized global solution was not accepted by all the agents, the human supervisor is notified, allowing him to fine tune the system or to relax the agent goals. The proposed multi-agent-based control system is tested trough empirical evaluation in an ornamental floriculture research facility with good results. The multi-agent-based control system can be easily expanded to control to other greenhouse environmental factors.

5.5. Data reliability, validity and availability

The measurement data reliability is one important aspect in acquisition systems. The eliminating of measurement noises, the detecting and replacing invalid data, have to be fulfilled by implementing a *data cleaning module*. This plays a crucial role for the greenhouse climate control and for the climate system black box modelling.

The data validity and availability is other important aspect in cases when black-box system identification techniques are used, requiring large sets of data during the learning phase. Some solutions, in case of measurement errors or missing values, are presented in (Eredics and Dobrowiecki, 2011; Eredics et al., 2012). In the case of a single incorrect value, a simple replacement with the previous value is performed. When blocks of missing measurement values are found, the proposed solutions are based on spatial interpolation or regression methods. These solutions increase the usable measurements records by 50%. The authors look at yet another solution based on Bayesian networks, showing good performance results for data cleaning.

6. Robotics and image processing in greenhouses

6.1. Robotic applications in greenhouses

Another development direction in greenhouse automation by using robots is the *identification, classification and harvesting of the fruits*. A recent state of the art on robots in agriculture is given by Roldán et al. (2018). A multi-robot system for mapping environmental variables of greenhouses is presented in Roldán et al. (2016).

A complex distributed autonomous gardening system is presented by Correll et al. (2009). The project was developed at MIT for determining the position of the plants, watering, identifying and harvesting of the fruits. The system has two main components: the IRobot Create (mobile robot platform for developers) and the wireless sensors attached to each growing pot. IRobot is controlled by using a laptop, with the communication done using an USB to Serial connection. It is equipped with 4 degrees of freedom arm controlled by a servo board, a water pump/reservoir, and a webcam. The wireless communication between the IRobot and plant sensor nodes is established using IEEE 802.11b Wi-Fi communications protocol. Each plant pot is equipped with a wireless sensor node which monitors the soil humidity, and makes request to the IRobot if the humidity is under a defined threshold. When the IRobot receives a request, it travels to the plant pot (that is unique identified by its IP address), waters the plant and makes a plant inventory by identifying the plant fruits. The identification procedure uses a filter based identification using color, shape, size and spectral highlights information. Finally, the location and color for each fruit are recorded and synched with the plant wireless sensor. Another developed feature is the fruit harvesting, implemented by using an image based algorithm.

A picking robot for sweet pepper cultures, where the main problem is the fruit identification by image processing, is developed by Kitamura et al. (2008). In the case of eggplant and tomato, the identification algorithm is based on the fruit color, but in the case of sweet peppers, the plant foliage and the fruits have the same color. Therefore, the image acquisition is based on a *stereovision system* using two color CCD cameras and a capture board to compute the distance from camera to plant. White LED lighting is used, providing similar brightness levels for all acquired images. One identification step is the processing of the HSI (Hue, Saturation and Intensity) histograms based on the differences that appear on the hue channel between foliage and fruits. Due to different texture of foliage and fruits, an identification method based on reflection of LED lightning is used. There was determined that the fruits have an increase reflective behavior, which translates to areas with high values for intensity and low values for saturation of HSI histograms. An 80% identification rate is obtained with no wrong identification of leaves as fruits.

6.2. Image processing in greenhouse

Pesticides are highly used in agriculture to protect the crop from pests (bugs, fungi, bacteria etc.). On the other hand, the consumer demand for products labelled organic or natural has led to an increased interest to reduce the pesticide usage, but in the same time to keep high production levels. One solution would be an early identification of contaminated area and extermination of pests by using a minimum required dosage of pesticide.

An optimized solution for pesticide plant disease treatment using a spraying robot is proposed by Geng et al. (2012). The system consists of three modules: image acquisition and processing module, mechanical module (mobile platform, manipulator and nozzles), and motion control module. The system can identify the cucumber downy mildew based on leaf color and texture. The proposed classification algorithm was tested considering different illumination levels and proves a very high accuracy of 90%.

The plant health and nutrient assimilation can be monitored trough destructive and nondestructive methods. One important indicator of the plant health is the *chlorophyll content*. The foliar chlorophyll concentration can be measured in laboratory by organic extraction using mass spectrometry analysis.

The image processing algorithms for chlorophyll content estimation comprises another method. Vollmann et al. (2011) use a commercial digital camera for capturing the leaves images. To ensure the equivalent illumination condition, incandescent lamps are used. After selection of the leaves from the background, the average green tones of the leaves are used to estimate the chlorophyll content. Inconsistent results can be obtained due to different illuminating conditions.

Other solution using a Pico Life hand-held digital scanner is proposed by Ali et al. (2012a, 2012b). An algorithm is developed in Matlab for measuring the following leaves dimensions: area, height, width and perimeter. The chlorophyll content is estimated by using a logarithmic sigmoid function with normalized values of green component with respect to red and blue components.

7. Conclusions

This paper reviews the recent developments and implementations for greenhouse facilities, focusing on recent progress regarding greenhouse environment monitoring and control based on many available application examples. The highlighted novel contributions lead to optimized plant growth technologies in order to reduce the human labor, energy and materials, and to improve the quality and production level of greenhouse facilities, i.e., to increase the greenhouse performance/cost index.

The paper presents the state of the art and current trends of the greenhouse environment automation, monitoring and control, covered multidisciplinary areas: i) greenhouse climate models, ii) Wireless Sensor Network (WSN), iii) remote monitoring/command and supervisory control and data acquisition (SCADA) systems, iv) image processing. Greenhouse climate models and biological models have high importance in development and testing of optimal control solutions.

Wireless Sensor Networks (WSN) ZigBee modules, GPRS data transmission and CAN bus communications represent new approach techniques for implementing the greenhouse network communication infrastructure. Nowadays, cabled (wired) communication standard systems are mainly used in greenhouses having the following disadvantages: relative high cost, vulnerable to mechanical stress, low reliability, and sensors relocation is difficulty to do. One viable economic solution to replace the old wired infrastructure is the usage of wireless sensor network *WSN ZigBee* modules infrastructure due to: continue decreasing costs, low current consumption with long periods without the need of battery changing, the auto-configuring capabilities making possible the relocating/adding/removing nodes. A high number of greenhouse monitoring and control applications using ZigBee modules were presented and classified in this paper, underlining the benefits of WSN usage. Hybrid CAN and ZigBee networks are also proven to be viable solutions.

Significant *remote monitoring/command and supervisory control and data acquisition (SCADA)* systems are described and classified to obtain optimal plant growth, implying high volumes of data to be acquired, processed and recorded. The highly desired features of the greenhouse operators are: online real time process visualization, historical data visualization, automate on demand report generation. SCADA systems offer to users the local and remote monitoring and visualizations of the process data, access to the process setpoints, optimal control strategies, database data recording, report generations, and alarm management.

The image processing is another developed direction for greenhouse facilities with promising results for: insect monitoring, chlorophyll content estimation, identification, classification and harvesting of the fruits.

The analysis and classification in appropriate categories of recent contributions, using many application examples referred in the paper, provide a vision for the greenhouse environment monitoring and control based on modern solutions and technologies, and also ideas for new applications and relevant research opportunities to optimize the greenhouse processes.

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