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A REVIEW OF GREENHOUSE CLIMATE CONTROL AND AUTOMATION SYSTEMS BASED ON CONTROL THEORIES

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A B S T R A C T

Agriculture today is changing in light of the prerequisites of current society. Where guaranteeing sustenance supply through practices, for example, water preservation, lessening of agrochemicals and the obliged planted surface, which ensures brilliant products are popular. Greenhouses have ended up being a dependable answer for accomplishing these objectives; then again, a greenhouse as a method for ensured farming can prompt difficult issues. The greater part of these is identified with within the greenhouse atmosphere conditions where controlling the temperature, and relative humidity (RH) are the fundamental goals of engineering. Accomplishing suitable climate conditions to guarantee a high return and quality yields decreasing vitality utilization have been the objective of research for quite a while. Diverse plans in control hypotheses have been connected in this field to take care of the issues above. Hence, the point of this paper is to present a review of diverse control strategies applied in ensured farming to oversee greenhouse atmosphere conditions, showing favorable circumstances and detriments of created control stages to propose a design methodology as per results obtained from distinctive examinations.

INTRODUCTION

A greenhouse is an enclosed space that creates a different environment to that found outside due to the confinement of the air and to the absorption of short- wave solar radiation through a plastic or glass covers (El Ghoumari *et al.*, 2005). A greenhouse can be defined as a covered structure that provides plants with the optimally controlled environment for adjustment of climate growth conditions, to reduce the cost of production and increase crop yields (Badgery- Parker, 1999). That generates a new surroundings inside the greenhouse thatis better known as microclimate. The greenhouse microclimate can be manipulated by control actions, such as heating, ventilation, CO2 enrichment to name a few; to provide appropriate environmental conditions (Bennis *et al.*, 2008). These modifications imply the additional use of energy in the production process. Furthermore, it requires a control system that minimizes the energy consumption while keeping the state variables as close as possible to the optimum crop physiological reference (Coelho *et al.*, 2005). Horticulture in greenhouse conditions is a rapidly expanding interest and is consequently increasing in its economic and social importance.

A comprehensive history of green houses by Muijzenberg (1980), Woods and Warren (1988), and Vleeschouwer (2001). Earlier works in the greenhouse engineering

developments during the 1990s have been reviewed by Critten and Bailey (2002). The covering material of greenhouse structure can vary from simplesheets of selective transmission medium for different spectral frequencies which traps energy inside the greenhouse and heats both plants zone and its surroundings. The cost of growing inside a greenhouse is generally greater than growing in the field; therefore monitoring and automation control of relevant environmental parameters such as air temperature, relative humidity (RH), light level and CO2 concentration are necessary to achieve high yield at low expense and to keep the environment competitive (Bailey, 2002). It is also important that nutrients and water be delivered efficiently to the plants. Identification and modeling of different parameters in greenhouse production has been topics of numerous researchers, including Bot (1983), Hashimoto *et al.*,(1993), Zhang *et al.*,(1997), Bekkaoui, (1998) and Bakker, (2006). Controlled environment plant production systems offer the possibility to provide large numbers of high-quality crops with greater predictability.

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The increasing world population has changed food production scenario over the last decades. Developing countries, mostly in tropical and sub-tropical region, contribute and are expected to continue providing as high as about 90% of the world population increase (Soni and Salokhe, 2004). Land area in 91 developing countries, which is not in use for crop production is 2.4 times greater than the area in use (FAO, 2002). Since the available land cannot increase, greenhouse production has been employed as a solution to make more efficient use of space in hands. Several design techniques for construction of local shelters in tropical environments are available by Zabeltitz and Baudoin (1999). Many efforts have been made to develop advanced computerized greenhouse climate control systems. In particular, interesting andrelevant optimal control approaches have been proposed (Ioslovich *et al.*, 2009).

Automation Levels and Different Control Strategies in Greenhouses

Although the concept of automation and control system in the greenhouse is the same as its industrial applications, there are borders which distinct these two fields of the control. Individual environmental and biological sensors beside other control and instrumentation materials capable of working in a very humid environment and still not going out of calibration, together with an algorithm to adjust itself to diverse dynamic situations with respect to particular growing stages, microclimatic variables and crop's requirements as well as considering geographical and natural factors, are what make the greenhouse control different from industrial automation and control.

In general, automation in a tropical greenhouse environment involves automation of climate control (control air temperature, air circulation and air exchange, RH control and management), light level control and shade curtain management, Carbon dioxide (CO_2) control, irrigation, chemical treatment and nutrient supply management. The term environment refers to the plants surrounding. Greenhouse Automation is all about an efficient, accurate and modern intensiveagriculture, which judicially utilizes all available natural resources, recycles the information within the system, and claims higher productivity, higher returns, better quality while remain environment friendly. Greenhouse Automation is always associated with better management through the optimization process. Application of an integrated system for building's energy-efficient automation in the greenhouse has been discussed by Marinakis *et al*., (2013).

A very simple and classical environmental control system for tropical greenhouse consists of sensors, both inside and outside, that monitor allsignificant environmental variables which affect crop growth. These sensor data then feedback into a controller. The environmental parameters under control will be altered through pre-defined commands programmed and corresponding actuators such as fans, coolers, fogging system, lighting system and CO_2 sprayers. It should be conductedin an integrated way such that, for example, CO_2 is not injected when the ventilation system is on. In a similar way, cooling and venting should be carefully synchronized to control temperature and humidity without wasting valuable energy unnecessarily from the vents. Although utilizing two or more sets of independent sensors can alsoensure the accuracy of system monitoring and control, but in reality, plants will not necessary experience atightly controlled environment (Bailey, 2002).

Although several environmental control models are now available which correlate with input and output of a particular greenhouse for simulation or research purposes (Boulard and Baille, 1995; Rodríguez *et al*., 2002; Seginer *et al*., 1994; Sigrimis and Rerras, 1996), but a greenhouse control algorithm may be a combination of different control strategies and techniques, (such as feed forward, classical feedback with proportional-integral-derivative, self-tuning and adaptive, multivariable, step or integrated, etc.) to deal with some dynamic and complicated situations in which not a general model is available. For example, the decrease of the temperature outside the greenhouse or the increase of the wind speed will lead to the decline of inside temperature, resulting a change in the RH of greenhouse climate. In this situation, feed-forward control (or anticipatory control), can be used if the control response is predictable for a given set of conditions. Energy balance equations are usually employed to calculate the effect that the present state of the system has the controlled parameter. The actuators are then activated prior to a deviation from the set point. Predictive greenhouse models are, therefore, essential for prediction of changes so that control signals can be sent off before effects are sensed inside the glasshouse. An example of predictive control methods in greenhouse applications can be found in the works of Blasco *et al.*,(2007), Coelho *et al.*,(2005) and Piñón *et al.*,(2002). Feedforward approach can reduce input-output errors because the disturbances are measured before they have time to affect the system, for example, sensors measure the opening of vents and automatically adjust temperature control before significant deviation from set point occurs. Rodríguez *et al.*,(2001) designed a feedforward controller for greenhouse climate control based on physical models. Where feedback correction is used in conjunction with forward feed control, a high degree of precision can be achieved.

In a simple feedback control, the decision is based on differences between the actual measurements and the desired inputs; therefore a deviation is awaited to occur before the controller can provide any response. The resulting output will be sluggish and oscillating above and below the input. This method is useful in situations that do not demand a high degree of precision (Bailey, 2006; Albright, 2002; Serodio *et al*., 2001). In a proportional control, the response is delivered in proportion to how far away from the setpoint the measured condition is. For example, cold water mixing valve is opened between full on and full off in proportion to the error between comfortable and the actual crop zone temperature. Smaller errors produce smaller proportional control gains. In an integral control, the response is delivered in proportion to the time a measured variable has deviated from its desired value. If the feedback error is small but has been producing for some time, the integral gain causes increasing the rate of response. Proportional and integral control are usually used in conjunction to provide a dual method for returning a deviated condition to the set- point, generating control response to both the degree of deviation and the amount of time that the deviation has occurred. If the rate of change in the measured variable is rapid, derivate control can be used with proportional and integration calculation to shorten the time it takes to correct a control deviation, however, this action is seldom required for greenhouse equipment due to other process lags. Instead, step control is used to distribute control responses in a several discreet steps. In a tropical greenhouse for example, it might be desirable to provide more than one ventilation stage by utilizing several ventilation fans, so that, if temperature rises a certain degree above plant comfort point, say 3 ºC, the controller starts the first fan. In the second step, if the temperature is above six ºC, for example, another fan starts. Here, the response acts in full span operation, each fan is either on or off, but in an integrated control, response can usually be proportioned over the entire span between full on and off, providing a more accurate control response with interdependent relationships and multiple effects of the greenhouse equipment taking into account.

In a self-tuning controller, the internal parameters adjust themselves for minimizing errors in the controlled system and maximizing efficiency. This method is usually used in combination with artificial intelligence such as Fuzzy Logic and Genetic Algorithm. An application of the self-tuning method of the fuzzy system on greenhouse process can be studied in the work of Aoud *et al*., (2007). A self-tuning Fuzzy Logic Control of Greenhouse Temperature using Real-coded Genetic algorithm has been discussed by Xu *et al.*,(2006). In an adaptive controller, the characteristics of self-tuning controllers are taken a step further. If the parameters of a controlled system are uncertain or vary, the control law in an adaptive controller allows the control parameters to be adapted continuously to the changing conditions (Aström and Wittenmark, 1995). Adaptive control strategies for greenhouse temperature control have been addressed by Arvanitis (2000), Berenguel *et al.*,(2003) and Speetjens *et al.*,(2009). If only one output variable is to be controlled by only one single manipulated variable, no account needs to be taken off the interactions between other existing variables. This process is single-input, single-output. A greenhouse control process, however, do not conform to such a modest configuration, for example, the effect on temperature when controlling humidity requires a system with more than one control loop, known as multivariable control systems, which uses a model of the control environment for providing information on the interactions. Arvanitis *et al.*,(2000) designed a Multi-rate adaptive temperature control of greenhouses.

Control variables in a greenhouse

The most essential variables in a greenhouse environment that affect plant's life are temperature (air and root-zone temperatures), RH, light, CO_2, soil feeding solution PH and electrical conductivity (Bailey, 2002).A good understanding of each control parameters and their interactions with other variables of the system, such as greenhouse structure and covering materials, instrumentation properties and requirements of the crop in different growing stages need to be studied in order to design an inclusive control algorithm that can correlate between input, which is energy load, and output, which is enhanced quality.

A greenhouse structure can be either freestanding style or attached style. Freestanding styles are available in different shapes, including Quonset, slant- side, A-frame, dome, gothic arch, tri-pen and gable roof. The relatively simple structure designs of Quonset and gable roof have made them the most widely used style. Attached frames (straight-side lean-to, curved-side lean-to, and aslant- side lean-to) are used in locations where space is limited. Typical available covering materials for tropical greenhouses include 0.1 and 0.2 mm Polyethylene (PE) plastic films, the net or 2-3 mm glass panels. For financial reasons in tropical regions, where the ventilation system is active day and night, only ultraviolet (UV) stabilized PE-film are suitable for covering material (Zabeltitz and Baudoin, 1999).

Properties of covering materials and greenhouse structure along with crop growth and other environmental control variables can be represented by mathematical models for simulation and research purposes; however, the complexity of many crop growth models is under dispute for being actually implemented in this way. For example, the tomato growth model, TOMGRO version 1, has 69 state variables (Jones *et al*., 1991), and TOMGRO version 3 has 574 state variables (Kenig and Jones, 1997). Such model of this complexity should be simplified to provide a practical means for automatic simulation and control in a tropical greenhouse environment. To reduce the complexity of TOMGRO version 3 Jones *et al.*,(1999) developed a simplified tomato growth model that was reduced to 5 state variables. The simplified TOMGRO model was then designed in SIMULINK, to be used in connection with a control system in the greenhouse. It is now possible to implement the SIMULINK model with a temperature control system inside a greenhouse. The temperature sensor reading could be fed directly into the SIMULINK model. Given knowledge of the operational costs associated with greenhouse management and the value of the tomato crop being produced, the SIMULINK model could then be used to simulate the effect of the current greenhouse temperature on tomato yield and calculate whether it would be more profitable to either raise or lower the temperature in the greenhouse. Depending on the result, a signal may be sent to the mechanism responsible for cooling the greenhouse. A review of mathematical modeling of tomato plants have been addressed by Medina-Ruíz *et al.*,(2011).

Depending on the application, temperature reading in a greenhouse can be done by digital or infrared thermometers, soil temperature probes, and pipe temperature sensors. Temperature sensors in a greenhouse are exposed to the air stream and measure dry bulb temperature. The wet- bulb temperature, on the other hand, is the temperature at which air is fully saturated (RH equal to 100%); it is used as an indication of the amount of moisture in the air. A method for measuring dry-bulb temperatures during the operation of a fog system for greenhouse cooling has been described by Toida *et al.*,(2006). Relative humidity refers to the ratio of water vapor to a volume of air to the amount of water vapor that air can hold at its saturation point at the same temperature and pressure. A traditional way to measure this parameter is first to measure both wet bulb and dry bulb temperatures and then convert to RH by using the Psychometric chart. Digital RH sensors are also available; they are usually a matrix material in which a voltage is produced based on the changes of the electrical properties as water molecules diffuse into or out of the matrix material changes in response to air moisture content. According to Both and Wheeler (2002), these sensors may not tolerate conditions near saturation, so the reliability of many RH sensors is questionable when the RH rises above 95%.

Practical methods of controlling air temperature and RH in a tropical greenhouse can be categorized as ventilation (natural or mechanical), shading, evaporative cooling (if the RH of the air is suitable) and refrigeration. In a greenhouse condition with air around plants leave too hot and humid, the transpiration at the leaf surface will be ineffectual and the root and stem system may not be able to supply adequate water to the leaves.The cooling system is therefore required to reduce these stresses. With greenhouse shading, the amount of solar radiation and light intensity reaching the plants is restricted, creating a closed difference between air temperature inside and outside the greenhouse. Shading also reduces leaf surface temperature significantly. According to Glenn *et al.*,(1984), while a 20% to 80% light reduction can be expected depending on the shading materials, the sufficient light reduction for most greenhouse applications is 30% to 50%.

Both natural and mechanical ventilation can be used in the tropical greenhouse as a technique of reducing air temperature, only if the temperature of the outside air is less than inside. Ventilation also does humidity control that is crucial for the tropical greenhouse to improve plant growth, nutrient, and water uptake and for disease reduction. Natural ventilation occurs by regular air movement due to the pressure or temperature differences between the inside and the outside environment. It should be noted that in naturally ventilated greenhouse in tropical environment, inside air temperature is always greater than the outside, which can individually become a major problem during the warm season, when the maximum cooling is required, but the temperature difference is the least.In the tropical regions where solar radiation or ambient air temperatures is high, considering several design factors for optimum air exchange, such as the ratio of the area of vent opening to the ground area covered by the greenhouse, the ratio of the volume of the greenhouse and the floor area of the greenhouse, and the vertical distance between the air inlet and air outlet of the greenhouse, improves ventilation performance (Giacomelli, 2002).

Mechanical ventilation is the air movement created by inlet/outlet fans assembly. Another definition of mechanical greenhouse ventilation is "the controlled exchange of ambient air with the conditioned atmosphere within the greenhouse" (Giacomelli, 2002). Similar to natural ventilation, air temperature is not reduced by mechanical ventilation but is only exchanged. In fact, theprimary functions of greenhouse ventilation are (through ventilation inlets) and air distribution (through ventilation fans). Consequently, these two functions modify temperature, RH, and CO_2, which are required forhealthy crop production. If the RH of the outside air is less than inside, (which is usually the case in a tropical greenhouse), ventilation remove the moist air from inside and replace it with dryer outside air, until equilibrium point between inside and outside. Therefore, natural or mechanical ventilation in the best case scenario will theoretically reduce the greenhouse air temperature to the value of the outside temperature. The detailed calculations of the greenhouse energy requirements along with decision on the size of ventilation system, selection of fans and the location of the inlet(s) and outlet(s) have been provided by Wheeler and Both (2002).

In the evaporative cooling method (state change of water from liquid to gas), heat energy is absorbed from the air by the water (this energy is knownas latentheat of vaporization). Therefore, the process of evaporative cooling increases both absolute and relative humidity and decreases air temperature. As long as the RH of the greenhouse air is less than saturation point, air movements by fans in an evaporative cooler transfer water molecules into the air, causing the water in the evaporative cooling system to lose temperature and cooled down until equilibrium is reached. At this point, the amount ofheat removedfrom the evaporating water will be supplied by the air. Water evaporation in the greenhouse continues until it saturates the air. Therefore, the potential of cooling by theevaporative method depends on the RH of the air and the efficiency of the evaporative system itself.

There are three evaporative cooling techniques used in greenhouses; fan-and-pad systems, unit coolers (swamp coolers) and misting system. In the fan-and-pad system, pumps circulate water through and over a porous or cellulose pad at one end of the greenhouse. Air from outside is then pulled through the dripping wet pads by the exhaust fans operating at the other end. A drawback of the fan-and-pad system is their high maintenance and the fact that theairtemperature within the greenhouse between pad and fan is not uniform. Direct evaporative coolers, also known as swamp coolers are packed units, consisting of a metal case installed outside the greenhouse. The pads are made of cedar shavings or cellulose and are continually soaked by a re-circulating water pump. A fan draws outside air and passes through the pads on three sides and cooled air outs through a duct on the fourth side. According to Duan *et al.*,(2012), a properly operated typical swamp cooler has the potential to cool air within 3°C to 4°C of the wet-bulb temperature. These units cost less than an air conditioner and consume 60% to 80% less electricity; however, they are only practical for a small greenhouse in hot, dry regions. According to the Psychometric chart, air with lower temperature can holdless amountof moisture. This principle of removing moisture from the air using reducing its temperature is the basis of refrigeration dehumidification (air conditioners).

The electricity usage for this operating these systems are, however, high and makes them impractical for commercial application in tropical greenhouses. Misting reduces plant moisture loss and reduces leaf transpiration by reducing its temperature due to evaporative cooling. It is categorized into low-pressure and high-pressure (fog) misting. In general, evaporative cooling techniques are particularly successful in regions with RH around 60%, where a significant temperature drop can be realized. A properly designed and operated evaporative cooling system can most effectively reduce air temperature by 80% to 85% of the difference between the air temperature and the wet-bulb temperature (Giacomelli and Roberts, 1993).

Ideal Level For Temperature, Rh And Vapor Pressure Deficit (Vpd)

According to the Psychrometric chart, temperature and RHare interrelated. That means that changing temperature of a constant volume of air will change the water-holding capacity of the air and consequently changes its RH. Heating air would lower RH, and by cooling it down saturation condensation will occur. The Psychrometric chart shows that every 10ºC increase in air temperature will drop RH by a factor of 2.

Temperature and RH have optimal ranges depending on the different growth stage of the plant, different greenhouse crop, and different weather condition and whether it is night or day. For example, in the greenhouse production of tomato, five different growth stages, including germination, seedling, vegetative, early fruiting and mature fruiting, have been identified by Short *et al.*,(1998). A decision support system for the production of high-quality vegetables is available by the Ohio agricultural research and development center. Scientific methods, particularly utility theory, risk assessment, and decision support theory have been used in this program to support real crop growing recommendations that can be made from optimal values. The program is accessible in two ways, as a graphical primer and as an interactive decision support system. The definition of the successful crop in this program is a high yield high-quality produce. In the other hand, an unsuccessful plant could refer to low yield, high or low-quality crop. Using this program, the ideal values of temperature and RH for the tomato in different climate and light condition, and for aparticular growth stage.

The ideal level for humidity depends on the type of crop to be grown. The American Society of heating refrigeration and air conditioning Engineers (ASHRAE) considers RH between 40% and 60% healthy and comfortable in comfort- controlled environments (ANSI/ASHRAE, 2010). A commercial greenhouse supplier (Autogrow Systems, Ltd.; http:// www. autogrow.com /general-info/humidity-and-vpd. Accessed on: May, 20th, 2014) defines RH range between 60% and 80% to be comfortable for most greenhouse crops; however, plants exposed to higher temperature require higher humidity. This is related to the plant transpiration, for example, when the temperature is high, the plant tends to transpire more, therefore increasing RH of the airwill reduce transpiration, deferring thewilting point. In atropical environment, too much RH of the greenhouse air leads to condensation dripping from the cover, causing fungal spores besides appearing mineral deficiencies due to weaksap movement in the plant. Too much RH can also stop transpiring and lose turgor in plants.

Vapor Pressure Deficit or VPD, is the difference (deficit) between the amount of moisture in the air and how much moisture the air can hold when it is saturated. Once the air becomes saturated, water will condense out to form clouds, dew or films of water over leaves. It is this last instance that makes VPD necessary for green house regulation. If a film of water forms on a plant leaf it becomes far more susceptible to rot. On the other hand, as the VPD increases the plant needs to draw more water from its roots. In the case of cuttings, the plant may dry out and die. For this reason the ideal range for VPD in a greenhouse is from 0.45 kPa to 1.25 kPa, ideally sitting at around 0.85 kPa. As a general rule, most plants grow well at VPDs of between 0.8 to 0.95 kPa.

VPD can also be used as an indication of moisture deficit in the air; large VPD values represent more dryness of the air. The definition of VPD is based on temperature and RH, which is capable of better reflecting how a plant feels (Zolnier *et al*., 2000). Since pathogens develop and infect plants in the highly humid environment, VPD can be used to measure how close the environment is to saturation. Another important indication of VPD is to evaluate condensation potential of a greenhouse crop and to identify when it is likely to happen. A comprehensive discussion of the calculation procedure of VPD, its applications, and high or low-value indications can be found in the Ohio State University Extension Factsheet (Prenger and Ling, 2011). According to this reference, fungal pathogens and mineral deficiency symptoms appear below VPD value of 0.43 kPa and disease infection can be most damaging below VPD value of 0.2 kPa. It is therefore recommended that the VPD of greenhouse air should be kept above 0.20 kPa. The ideal range of VPD for most greenhouse crops is between 0.8 to 0.95 kPa (Argus Control Systems, 2009). Adding moisture to the air is required for values more than 1.25 kPa, and heating and dehumidification should be applied for VPDs below 0.45 kPa.

Control theories applied in greenhouse climate control systems: An analysis of advantages and disadvantages

Different research has been conducted regarding climate control for protected agriculture applications. The primary objective of these investigations is to find an accurate model that represents the greenhouse environmental dynamics and an efficient and flexible controller that adjusts the microclimates variables of interest. This problem has been the focus of many re- searchers worldwide who have analyzed, experimented and proposed many climate control systems in order to manipulate variables such as temperature, relative humidity (RH), CO_2 enrichment, radiation and many others that are necessary to generate the fundamental conditions for successful protected agriculture.

Since most control theories require the mathematical model of the system for tuning and simulating the proposed algorithms, different greenhouse models have developed. It includes simple models that only describe air temperature to detailed models that even involve crop response. The traditional greenhouse climate models are based on energy and mass balances (Setiawan *et al.*, 2000).

A model based on balances above over an elementary volume of greenhouse air was proposed by Arvanitis *et al.*,(2000). Here, air temperature is represented by a differential Eq. [1]:

$$\frac{dT_G}{dt} = \frac{1}{C}\left[K_{out,\,air}(T_o - T_G) + q_h \right] \qquad [1]$$

Where the where the $T_G$is the greenhouse internal air temperature the greenhouse thermal capacity, K is the heat loss coefficient of greenhouse air to outside air. T_O *out, air* is the external air temperature, and $c_h$is the heating power. *H* recently, more detail models have been used for control proposes (Castañeda-Miranda *et al.*, 2006). Those models involve almost all variables that influence the greenhouse behavior.

$$C\frac{dT_G}{dt} = \\ = \eta G + \alpha_a\left[A_r(T_r - T_G) + 2I_{LA}(T_c - T_G) + (T_g - T_G)\right] - \rho_a C_p(T_G - T_o) + q_h \qquad [2]$$

$$V_l\rho_a\frac{dx_i}{dt} = \\ = \frac{1}{\lambda}\left(\frac{2I_{LA}\rho_a C_p}{\gamma(rs+ra)}\left[\delta^*(T_c - T_G) + (e_i^* - e_i)\right] + \alpha_a\frac{\lambda}{C_p}(x_g^* - x_i)\right) - \frac{\phi_v}{A_g}\rho_a(x_i - x_o) \qquad [3]$$

In Eqs. [2] and [3], $T_C$is the crop temperature, $T_g$is the ground temperature, $T_r$is the roof temperature, *xi* is the absolute internal humidity, $x_O$is the absolute external humidity, $x_X$is the

Absolute Soilhumidity, *i.e.,*is the internal mean vapor pressure, C_p is the specific air heat, $V_l$is the greenhouse air to land area rate, $A_g$is the covered ground surface, $A_r$is the roof to soil rate, $r_S$is the somatic resistance,$\alpha_{Ci}$is the aerodynamic resistance, *G* is the outside short-wave radiation, $I_{LA}$is the leaf area index, αci is the convection heat transfer coefficient, δ is the leaf slope, $\rho_a$is the air density, λ is the water vaporization energy, η is the radiation conversion factor, γ is the thermodynamic constant, φ*v* is the ventilation rate and *t* is the time in *s*. The superscript * indicates that consider quantity is at saturated vapor pressure.

Finally models that consider a greenhouse- crop interaction and complex processes such as photosynthesis thesis or transpiration have been developed (Van Straten *et al.*, 2000). By this way, the greenhouse system can be represented concisely in a space state form as:

$$\dot{x}_g = f_g\left\{q_{gm}\left\{x_g, u_m, u_a\right\}, q_{ga}\left\{x_g, u_m, u_a\right\}, q_{gb}\left\{x_g, x_b, u_m\right\}, q_{gc}\left\{x_g, x_c, u_a\right\}\right\} \quad [4]$$

$$\dot{x}_b = f_b\left\{q_{gb}\left\{x_g, x_b, u_m\right\}\right\} \qquad [5]$$

$$\dot{x}_c = f_c\left\{q_{gc}\left\{x_g, x_c, u_a\right\}, q_{cc}\left\{x_g, x_c\right\}\right\} \qquad [6]$$

Here,$f\{\}$s represents vector functions of the argument between brackets; xg,x_b,$x_c$are the state vector of the greenhouse (g), the storage buffers (non-structural biomass) (b) and the crop (c), respectively; *um*, *ua*, the vectors of the manipulated control (m) and ambient (a) inputs, respectively; q_{gb}, q_{gc}, flux vectors representing fluxes between the greenhouse and the ambient environment (ga) and the operating equipment (gm), respectively; q_{gb}, q_{gc} fluxes between greenhouse and buffer (gb) and between greenhouse environment and crop (gc), respectively; q_{cc}, flux vectors related to the internal greenhouse conditions x_g and the plant states xc,but not directly on the ambient conditions outside the greenhouse. The state list typically consists of temperature,moisture content and carbon dioxide for green- house atmosphere, temperatures for the storage buffers, and various crop biomass states for the plants in the greenhouse.

It is easy to find how models have been improved in response to production schemes that require more precisely methods to control the environment of the greenhouse. In this section, an analysis and classification of the different control theories is presented. Establishing a division between the controllers presented in the current literature is complicated, due to the variety and integration of diverse techniques used to solve the same problem. Fig. 1 shows a classification proposed dividing

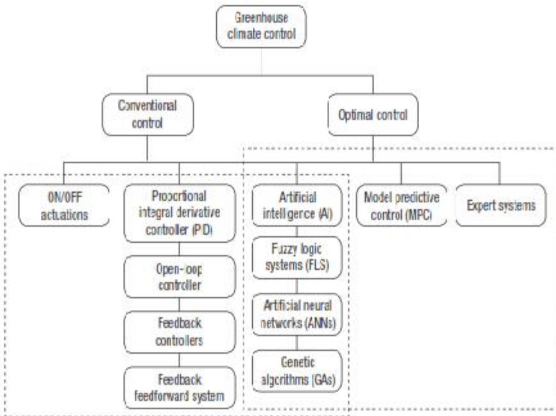

Figure 1 Greenhouse control theories classification

Greenhouse climate control task in two broad fields. The first one is usually called conventional control that consists of control theories that try to control the greenhouse environment just by reducing the deviation between set points of the interest variables and measured values to zero. As examples of conventional control, there are ON/OFF, PID, other classical controllers and Paradigms of AI such as ANNs, FLS, GAs among others. The other field is optimal control, in which the requirement is to consider aspects such as a greenhouse behavior, actuator capabilities, energy consumption and mainly crop response as input parameters of the control process. Here, expert systems and Model Predictive Control (MPC) are the most common techniques. However, techniques above can be also considered as optimal control when they consider input parameters such as crop responses among others.

Conventional greenhouse climate control

The most representative component of this theory is the

PID (Ang *et al*., 2005); which is a feedback mechanism commonly used in industrial control systems (Fig. 2).

Therefore, it is necessary to explain each component and action of the PID controller.

- Proportional (P) control: In certain cases having a smooth control and an error that is almost zero in the steady state is desired, where the proportional controller is suitable for this type of plant since that a proportional controller provides a control signal that is proportional to the error, that is, it returns its input multiplied by the proportional gain (Kp), thus, the control signal is given as:

$$u(t) = K_p e(t) \quad [7]$$

$$e(t) = y_d(t) - y(t) \quad [8]$$

- Moreover, the transfer function is obtained using the Laplace transform as:

$$\frac{U(s)}{E(s)} = K_p \quad [9]$$

- Integral action: When an integral action is implemented, the integral of the error is added to the control signal. If the error signal is large, then the control signal increases quickly, but if the error signal is small, then the control signal increases slowly. It is a remark- able that if the error approaches zero then the controller output would remain constant. Due to this feature, integral action can be used when a constant load is present in the plant; even when no error is present, the controller will keep on providing an output signal for compensation.
- Proportional integral (PI) control: Since a proportional control is not capable of compensating a load in the plant without error, the integral action is necessary. Integral action can compensate and provide a zero error; the PI controller is given as:

$$u(t) = K_p e(t) + K_i \int e(t)dt = K_p \left[e(t) + \frac{1}{T_i} \int e(t)dt \right] \quad [1$$

- Where *Ti* adjusts, the integral action and *Kp* adjusts both the integral and proportional actions. Its transfer function is given as:

$$\frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} = \frac{K_p s + K_i}{s} = \frac{K_p(T_i s + 1)}{T_i s} \quad [11]$$

$$T_i = \frac{K_p}{K_i} \quad [12]$$

- Proportional Derivative (PD) control: The goal of a derivative controller is to provide a signal proportional to the signal error change rate, causing derivative action to be present only when there is a change in the error signal. In other words, the derivative action introduces damping to the system. The PD controller is given as:

$$u(t) = K_p e(t) + K_d \frac{de(t)}{dt} = K_p \left[e(t) + T_d \frac{de(t)}{dt} \right] \quad [13]$$

- Moreover, whose transfer function is:

$$\frac{U(s)}{E(s)} = K_p + K_d s = K_p(T_d s + 1) \quad [14]$$

$$T_d = \frac{K_d}{K_p} \quad [15]$$

- Proportional Integral Derivative (PID) control. By combining the three different control actions a PID controller is obtained by:

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt} \quad [16]$$

The PID controller is a complete controller available and the most resorted to since it provides a quick response, a control signal that tends to provide stability to the system and a minimum steady state error. The PID controller is an important control tool for industrial processes, and only three gains have to tune (Ogata, 2003; Dorf & Bishop, 2005).

Although the PID is the most utilized controller in the industry, and it is widely accepted for agricultural applications, it is not the only solution to agricultural problems. Occasionally it is not a good choice due to the absence of a reliable mathematical model within the system. Taking this into account, a climate control system basedon ON/OFF operation has been proposed when the mathematical model is unknown, and this complicates the tuning of the controllers. It manages the times when actuators are turned on and prevents external climatic changes issues based on recorded data (Ali &Abdalla, 1993). Thetechnique above was studied by Hooper & Davis (1988), who implemented a controller based on an algorithm that modifies the greenhouse heating setpoints depending on previously achieved temperatures. This technique has shown good performance managing deviations in the setpoints through soft changes. Hooper (1988) also presented an integral greenhouse climate control by applying a mixture of controllers, a PI controller used to heating and ventilation, and ON/OFF control applied for irrigation, pH, electrical conductivity, and nutrients management.However, Setiawan *et al.*,(2000) reported that a Pseudo-Derivative-Feedback (PDF) control presents better performance than a PI for agriculturalapplicationbecause PDF controls have better load handling capability than PI controls. PDF control was better than PI for systems without time delay and significantly better for systems with time delay.

It is easy to find current investigative work regarding the field of greenhouse microclimate control; however, reported results reveal thattechniques above are not the most adequate to solve the problems inherent in greenhouses. The reason lies in the fact that the model of a greenhouse is very complex and it has many non-linearities; consequently, this has encouraged the development of new control techniques that do not require the greenhouse mathematical model (Sigrimis *et al.*, 2002).

In the past, the application of new and advanced techniques for control was limited because of the limited computational power that was then available. Controllers based on FLS, ANNs or GAs, could not be implemented in the former technological platforms due to their high complexity. These unconventional techniques based on soft computing and computational intelligence is now gaining popularity in the field of agriculture. Several soft-computing, such as ANNs and knowledge-based systems have been implemented with significant success (Soto-Zarazua *et al.*, 2010).

FLS controllers are conceptually very simple; they consist of an input stage, a processing stage, and an output stage. The firstphase maps sensors and other inputs to the appropriate membership functions and truth values. The processing stage invokes the appropriate rules and generates a result for each. Finally, the output stage converts the combined results into an accurate control output value. Furthermore, ANNs is a knowledge paradigm and automatic processing system that attempts to imitate how the nervous system of animals works. The principal advantage of this technique is that it does not require a model of the system. The system is composed of neurons with propagation, activation, and transfer functions that are interconnected with them to reduce the error to zero. GAs is a heuristic research that mimics the process of natural evolution. This heuristic is routinely utilized to generate solutions to optimization and search problems. Gas produces solutions to optimize problems using techniques inspired by natural evolution such as inheritance, mutation, selection and crossover.

The relatively new field of evolutionary computing has become increasingly popular in recent years due to the development of robust and low-cost computational systems. Because AI based systems have been updated and improved, these techniques solve the main problem of classic controls that being the identification of the system which is commonly nonlinear (Caponet- to *et al.*, 2002).

The classical solutions proposed are based on the linearization of the process behavior regarding the operating points. Other research has been carried out on this technique of linearization, not only dealing with the operating points, but also by taking into consideration all the input-output space to obtain several local linear models. The primary difficulty with this technique is the model transition. Indeed, many methods of modeling and identification based on FLS are often used for these types of systems (Trabelsi *et al.*, 2007). Some controllers base their operation on the aforementioned paradigm, as proposed by Castañeda-Miranda *et al.*,(2006) who implemented a FLS on a field programmable gate array (FPGA) to control the temperature of the greenhouse microclimate or Kurata & Eguchi (1990) who applied this theory in crop management for protected agriculture.

Other systems thatare classified in AI techniques are knowledge-based systems, like the one proposed by Gauthier & Guay (1990) which manages the climate control and production. This system supports dynamic optimization and continuous greenhouse monitoring. The proposed prototype was designed using an object- oriented programming, obtaining good performance in the problem area. These expert systems have proven to be a reliable alternative in greenhouse control applications. Jacobson *et al.*,(1989) reported an expert system to control misting. This system was based on a strategy of an experienced grower. Gauthier (1992) reported changes to this scheme in a system that sup- ports various types of digital process controllers as well as the creation and deployment of knowledge-based control strategies with the goal of being able to intervene in a wide number of areas such as crop protection, climate control, plantnutrition, operational and strategic planning. This scheme received additional improvements such as changing the heuristic knowledge of the growers for data routinely collected in a commercial greenhouse (Seginer *et al.*, 1996).

Fuzzy systems achieved remarkable results in the field of climate control for protected agriculture. Moreover, it is necessary to have reliable information about the system behavior, and that is not sufficient for this requirement a correct abstraction to create rules based on heuristic and empiric knowledge of the grower's experience is also necessary. ANNs have proven their strengths and flexibility to adapt to non-linearities and unexpected parameters of the system. Their main disadvantage is that their proper training requires extensive multi-dimensional sets of data to reduce the risk of extrapolation and the un-certainty about their response to inputs that differ about the training information. Therefore, minimizing the dimensionality of the problem, both input and state vectors become of paramount importance (Seginer, 1997).

GAs as FLS and ANNs offer the ability to control the system with a good performance without the requirement to base their operation on plant identification of the system. Although GAs represents a solution for the control of nonlinear regimes, the computational requirements have limited its use *in situ* applications until recently. The conclusion is that the use of AI-based systems is justified in control problems where the system plant is highly nonlinear or when the model is not reliable or has not been identified. Each control technique offers solutions forparticular problems. Unfortunately, a special controller that deals with the different characteristics and limitations presented in highly non-linear and complex systems of greenhouse microclimate has not yet been found. Consequently, hybrid models that combine different control schemes have begun to appear. Combinations of classical control theory with AI and considerations of crop process have been demonstratedas promising. A demonstration of this was reported by Pinon *et al.*,(2005); he proposed a scheme for green- house temperature control using the advantages of combining Feedback Linearization (FL) and standard linear MPC. The discussed hybrid control structure, MPC + FL, offers a reliable solution of nonlinear con- tool problems, transforming a non-linear greenhouse system subject to input constraints, to an optimized problem for a linear greenhouse system.

Optimal control

The advantages of using optimal instead of conventional greenhouse climate control can be summarized as follows. An optimal control approach to greenhouse climate control fully exploits scientific quantitative knowledge concerning the greenhouse, the greenhouse equipment and the crop, captured all in a mathematical dynamic model that deals with the problem of maximizing the profit, achieving welfare of the harvest through practices that minimizes production costs (Van Straten *et al.*, 2011). In this section, climate controllers based on sophisticated algorithms are discussed. An analysis of MPC, real-time controllers, robust and nonlinear control, feed- forward and systems that take into consideration decision support tools to gain efficient temperature integration are presented. Also, a survey of reported methods that considers morphological and physiological characteristics of the crops is given.

The need for guaranteed yield and quality of greenhouse crops has demanded stricter control of plant climate; previously, controllers were utilized for the sole purpose of adjusting the microclimate variables, but with recently increasing costs of energy, an appropriate controller that also considers the energy consumptions is necessary. One example of this was reported by Nielsen (1995) who presented a computer algorithm design to distribute the energy demands of greenhouses, reducing the peaksdisplayed in the actuator in the day-to-night and night-to-day transitions. Other authors, proposed more complex systems (Arvanitis *et al.*, 2000; Davis & Hooper, 2002). These methods operate by considering that greenhouse parameters varied with operating conditions and applied a new pole- placement scheme. It estimates the unknown parameters of the greenhouse on-line from sequential data of the greenhouse temperature and the heating power which is recursively updated to obtain a slightly soft control.

Sigrimis & Rerras (1996) reported a controller based on a linear model structure to track and predict green- house behavior as a Multiple-Input-Multiple-Output (MIMO) system. This method takes into consideration disturbances like uncontrollable inputs. ClimateControllerssystems have been improvedin order to con- sider external disturbances and have the ability to compensate for them; even they take into account plant responses such as crop growth. Reports regarding feed- forward controllers indicate that they are reliable and achieve good performance for greenhouse heating (Jewett & Short, 1992; Takakura *et al*., 1994). On the other hand, real-time systems have also been utilized in greenhouse applications, improving the systems to the point where Operator intervention is only required to define the constraints of the heating setpoints.

Another real-time control algorithm for generating optimal heating setpoints was presented by Chalabi *et al.*,(1996). This method adjusts greenhouse temperature setpoints over a period of time to achieve energy savings for a tomato crop, justifying these control actions by using the results of physiological studies showing that for some crops it is sufficient to maintain an average temperature in a greenhouse over a given period (Hurd & Graves, 1983; De Koning, 1990). the algorithm is based on a model of greenhouse energy requirements and on a numerical method for optimization, where the optimal control problem is converted into a non-linear programming problem solved by sequential quadratic programming.

AI was also applied combined with the crop process knowledge to generate paradigmsemployed in protected agriculture. Fitz-Rodriguez & Giacomelli (2009) made use of FLS combined with ANNs to propose a better control strategy for agriculture under greenhouse conditions taking into account models of crop growth. However, one disadvantage of ANNs is that it requires getting a considerable set of data to train the net. This problem was addressed by Linker *et al.*,(1998) using previously acquired data over a two-month period in a commercial greenhouse to train the net. The resulting model not only fit with data, but also seemed qualitatively correct and produced reasonable optimization results in a scheme of CO2 enrichment control. Hybrid controllers which fuse FLS and GAs were presented by Goggos & King (2000) in a research project that applies qualitative reasoning and evolutionary computing in the design of optimal set points and control strategies for greenhouses. This fusion of different intelligent control techniques was also implemented in an intelligent environment control for plant production systems. The author used a decision-making system based on ANNs and GAs in order to optimize plant growth under hydroponics conditions and also identified the response of plant growth to the nutrient concentration (Hashimoto *et al.*, 2002).

One of the main problems with climate control is the greenhouse dynamic model that is highly not- linear. Consequently, many researchers have applied simplified models for the non-linear problem, such as Ioslovich *et al.*,(1996), who designed a controller based on a simplified model of the crop growth with constraints on the control signals. The objective of this optimization was to take into account the cost of energy used by heating and ventilation systems.

When it is necessary to control non-linear systems where the plant model is unknown, the use of feedback-feedforward control is an alternative. In this configuration, unexpected events are considered in the control model, and the controller attempts to reduce the error to zero no matter the disturbances. These system characteristics were used to design a nonlinear controller for coupled air temperature and humidity (Albright *et al.*, 2002). A feedback-feed forward combination was also utilized by Pasgianos *et al.*,(2003) in a system linearization and decoupling of a greenhouse, maintaining control of ventilation/cooling and moisture. This technique also served to compensate for external disturbances. Finally, the controller was designed to consider the actuators capabilities and saturation set points.

In this section, applied strategies in climate controller systems with the objective of saving energy are discussed. Nevertheless control techniques that consider physiological plant processes are also studied and described in this section. Horticultural research has indicated that for the majority of plants, crop growth responds to long-term average temperatures rather than distinct day and night temperature profiles (Langhans *et al.*, 1980; Miller *et al.*, 1985). Based on this research it has been suggested that the heating set-point can be adjusted to ensure that a desired average temperature over a given period can be achieved, and thereby energy savings obtained. This knowledge was applied by Sigrimis & King (2000) in the design of a tool available to exploit the interaction between photosynthesis and growth According to the intuition of the grower because this interaction is not well known for most plants. The method is based on varying heating set points using previously recorded information to achieve the desired average for any user-defined period. The proposed system does not require weather information, and the grower can also set safety limits as the ultimate minimum and maximum temperatures permitted.

These control schemes were exploited by authors like Gauthier *et al.*,(1995), who presented control strategies applied to heat, cool and dry greenhouse air, and also in the regulation of CO_2, light and irrigation. Considering that plant processes vary with the day and vegetative state of the crop, they do not require strict control of the microclimate all the time. With this in mind, temperature integration systems for greenhouse cultivation were developed by Körner & Challa (2003a). The concept considers different crop processes, and a decoupled process with fast temperature response (*e.g.* photosynthesis or stress) from a process with a slow response time. The objective was to improve the heat integration concept by introducing dynamic temperature constraints; these flexible boundaries depend on the underlying crop process while increasing the potential for energy saving in greenhouses.

A different approach was proposed as a decision support tool that assists in choosing the most appropriate climate according to the week of the year in order to obtain the optimal gains in sustainability and plant quality. The greenhouse climate and crop model are studied separately and jointly considering the effects of six different regimes with increasing degrees of freedom for various climate variables (Körner & Van Straten, 2008) which include: crop model, temperature integration, dynamic humidity control and negative DIF regimes (DIF = the difference between average day temperature and average night temperature, and there- fore reduces the use of chemical growth regulators). MPC is an advanced control technique applied in the field of protected agriculture. The objective was to predict the greenhouse variables behavior. Developments in MPC algorithms for greenhouse operation which takes into account weather predictions to generate new optimal control problems for each update of forecasted weather information as solved numerically by linear programming were also developed (Gutman *et al.*, 1993). A contribution to this scheme was offered by Van Straten *et al.*,(2000) where information about crop growth simplifies the design of greenhouse control strategies to obtain agenuine economic control strategy. This approach leads to the concept of selecting processes by time response where the short-term effects of photosynthesis and evapotranspiration are dealt with by an automated model-predictive optimal controller while the long-term impact tis left to the grower

Aiming energy saving proposes, MPC algorithm has seen advances that take into account constraintson both manipulated and controlled variables, using on-line linearization for a real-time application. This proposal was applied in greenhouse temperature regulation, achieving excellent performance and energy savings. The results were compared with a PID solution. MPC based controllers solve the problems commonly presented in PID systems (El Ghoumari *et al.*, 2005). Due to the advantagesgiven by MPC, different strategies have been applied to design optimal MPC controllers. The Particle Swarm Optimization (PSO) was used to de- sign a model-based predictive greenhouse air temperature controller subject to restrictions; the model employs data from the climate inside and outside the greenhouse, as well as the control inputs and controller outputs. The operation principle ensures set-point tracking and minimizes control efforts. The conclusions presented show better efficiency over GAs and sequential quadratic programming methods (Coelho *et al.*, 2005).

MPC with GAs facilitating the incorporation of energy and water consumption to adjust non-linear models parameters have been suggested. The combination of MPC and GAs permits the control of the green- house microclimate while achieving energy and water savings (Blasco *et al.*, 2007). GAs in annealing form (AGAs) has also been applied for calibrating classical controllers such as PID, where the AGAs play a role in the parameter identification, demonstrating advantages over traditional GAs like premature convergence and low computing efficiency that are required to implemented these (Fan & Zuo-hua, 2006). Feed-forward neural networks have been applied in conjunction with simple neural models to drive the system outputs to desired values (Fourati& Chtourou, 2007). Robust control also contributed to systems in protected agriculture because of its ability to deal with uncertain parameters, disturbances or modeling errors. It was applied focusing on managing the high correlations between air temperature and hygrometry (Bennis *et al.*, 2008). Different methods have been used at- tempting to find a reliable, optimal control solution for greenhouse environment, utilizing concepts from advanced sequential control search (SCS) or Pontryagin's maximum principle (PMP) (Seginer & McClendon, 1992), to systems that consider the crop model and its effects on greenhouse behavior (Jones *et al.*, 1990). The objective of these approaches was to include weather and greenhouse plant characteristics such as ventilation and stomatal resistance in the control actions (Baptista *et al.*, 2010). Humidity control regimes were also proposed by using information about the vegetative state of the plant (Körner & Challa, 2003b).

Authors worldwide have dedicated time and substantial effort to develop not only control systems, but they have also been working to create strategies to ensure reliable measurements through the use of filters and signal processing techniques to guarantee good performance of controller systems (Ibrahim & Sø- Jensen, 2010). One of the main objectives of the developments above is energy savings; however, all require knowledge of plant processes which is limited and usually empiric or heuristic. Consequently, advanced smart sensors are being developed in order to measure crop specific characteristics such as plant transpiration dynamics and photosynthesis in order to understand how physiological processes occur in the plants and how they affect and modify their surroundings (Millan- Almaraz *et al*., 2010).

Throughout this review, particular attention has been directed to demonstrate that not only the controller is necessary to guarantee appropriate microclimate conditions, but a fundamental part of the design is the use of reliable systems that take into consideration the importance of failure detection tools.By applying a hybrid of physical/neural network models with robust fault detection, failures are correctly detected and identified, leading to a significant reduction of losses caused by failures (Linker *et al.*, 2000).

Technological platforms appliedto climate control theories implementation

Technological platforms are also important when a system is being developed to solve particular problems; protected agriculture is not an exception to this rule. Agronomy field imposed hard operating conditions and found it is necessary toconsider these restrictions strictly. Despite the fact that greenhouse climate is not a fast response system, robust platforms that guarantee uninterrupted operation are required, flexibility is crucial to improving changes in the system in order to solve emerging needs and lower cost is also necessary to ensure success of a newly emerging crop production industry (Fang & Zhen-xiao, 2008). The first and most popular platform chosen for greenhouse control applications has been the personal computer (PC). The use of PCs in greenhouse operations has created possibilities to implement sophisticated algorithms that were impossible to apply in the past (Fang & Zhen-xiao, 2008). Consequently, the integration of new task modules, sensor, and communication devices becomes easier (Ali &Abdalla, 1993). Different configurations of PCs and networks have been proposed to achieve more efficient greenhouse management (Hooper, 1988).

Commercial climate control computers and proprietary data-logger were also applied (Nielsen, 1995; Linker *et al.*, 1998). These systems offer solutions for protected agriculture problems. However, PCs are not the most appropriate platforms for heavy duty field applications and are characterized to be a noisy and harsh environment with high humidity rates that are subject to constant temperature changes. Consequently, PCs are susceptible to failures and damage caused by the harsh greenhouse environment. Another consideration when discussing the use of PCs is the high cost to integrate PC networks or property systems. Other technological platforms should be proposed to ensure reliable sustainability. Microcontroller and Digital Signal Processors (DSP) based systems have attempted to solve the aforementioned problems with promising results; however, their limited capacities have proven to be difficult in the application of advanced algorithms with considerable computational demands (Coelho *et al.*, 2005).

The development of embedded systems for a particular application has been demonstrated to be the best choice for industrial applications. This idea was translated into precision agriculture field, designing plat- forms that consider hardware requirements and the conditions where the system will be placed to ensure robustness in the operation and low cost of the developed embedded platform. Field Programmable Gate Arrays (FPGAs) have been demonstrated to be a solution with a high performance, flexibility, and robustness for greenhouse embedded applications (Castañeda- Miranda *et al.*, 2006).

New Tendenciesin Greenhouse Climate Control Systems

This review clearly shows that there is a trend towards utilizing climate controllers for protected agriculture applications where they are based on very simple control theories, like ON/OFF, PID controllers or some variation because of that. This tendency has been caused by the low computational power availability in the past. Consequently, the control was limited to basic operations and real-time processing was unreachable because of the absence of adequate processing devices. Because of this, recent mathematical algorithms and control theories evolved faster than computing technologies. Consequently, sophisticated algorithms were not available to be implemented in any technological platforms at an affordable cost a few years ago.

This scenario changed when computers cost de- creased and the processing capabilities became considerably higher, at least to the point to make it possible to implement sophisticated algorithms. Soon after that, modern control theories based on real-time control process, adaptive schemes or intelligent techniques were applied to achieve a more accurate, efficient and strict manipulation of the interesting green- house variables. Considerations regarding quality, yield, water and energy savings were also studied and integrated in the control models (Vazquez-Cruz *et al*., 2010). These low cost platforms also make it possible to design and implement sensor networks, mobile robots for agricultural proposes, image processing for early diseases and pest detection as well as many other contributions to agriculture (Sigrimis *et al*., 2000; Contreras-Medina *et al*., 2009).

Despite the excellent results obtained with the high performances low-cost computers, and advanced algorithms, tendencies are changing again; recently investigations and reports lead to the development of controllersthatalso consider plant physiology and morphology. Phenomena such as transpiration and photosynthesis have been studied for better under- standing of plant behaviors to control climatic and nutritional requirements, according with real plant needs. New energy savings strategies have been proposed considering the available information regarding plant processes, manipulating weather conditions when it is necessary for plant growth and the establishment of adaptive operating ranges for actuators with more degrees of freedom where strategies are helpful and when the reduction of energy consumption is essential.Nevertheless, the information about plant processes is limited. More investigation is necessary to establish correlations between physiological processes and plant growth in regards to temperature, humidity, nutrition and others controllable variables of the greenhouse, with the objective of reaching a sustainable protected agriculture industry (Millan- Almaraz *et al*., 2009).

CONCLUSIONS

Greenhouse climate control is currently one of the main objectives of engineering in precision agriculture. Temperature and humidity are variables that have a direct relationship with the plant production. Moreover, recent investigations have shown that is not enough to adjust temperature and humidity ratings to maximum and minimum setpoints that are affordable for plant needs.

Because of this, many control theories have emerged in the years such as conventional control techniques and optimal control. Conventional control is based mainly on the proportional-integral-derivative controller and some variants. Furthermore, optimal control techniques relyprimarily on AI algorithms and adaptive control theory thatproposes an alternative way to solve the climate control problem when greenhouse mathematical model is unknown or often very complex. Another important fact that has limited the development of the more advanced climate control system was the technological limitations a few years ago. However, the relatively new computational technologies such as microprocessors, digital signal processors and field programmable gate arrays are allowing continuing the implementation of more sophisticated control systems. According to some authors, the application of advanced controllers capable of following particular variable setpoints has not yet proven to be an optimal solution. Because of this, new tendencies are appearing in greenhouse climate control based on gathering extra information about physiological and morphological processes in the plant such and transpiration, stomatal conductance and photosynthesis. These new control theories report that it is not necessary to have strict temperature and humidity set points. Instead of this, more flexible thresholds are proposed to save unnecessary energy consumptionthat is consumed when the controller tries to follow the set point in a strict way. Photocontrol is the new theory that suggests the use of the plant physiological responses as an input sensor to establish the set point in the climate controller. Also, this has not proved to be a stable and reliable method because it is necessary to gather much information to demonstrate the reliability of this. Nevertheless, different types of controllers have emerged showing advantages and disadvantages among them, better performance for some actions among other characteristics. Researchers need to analyze variouscontrol theories to determine which one is the most proper for their projects, according to their specific requirements of greenhouse climate control systems.

This paper provided a relatively detailed discussion of the different control variable, their ideal levels and interaction with the environment in a tropical greenhouse. The automation levels and different control strategiesthatare either in the research and experiment phases or have been already commercialized to use in real greenhouses were also discussed. It can be concluded that understanding plant physiology and environmental changes in tropical greenhouse together with analyzing the control parameters and their interactions with environment, engineering modeling, simulation concepts and control hardware/ software materials, support a more efficient and successful designing of the automation control software/ hardware system that can adequately control and monitor environmental parameters for data analysis and evaluating performance.

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