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Non-linear control model for use in greenhouse climate control systems

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Abstract: In this study, a non-linear control system was designed and proposed to control the greenhouse climate conditions. This control system directly uses the information of sensors, installed inside and outside the greenhouse. To design this proposed control system, the principles of a non-linear control system and the concepts of equilibrium points and zero dynamics of system theories were used. To show the capability and applicability of the proposed control system, it was compared with an integral sliding mode controller. A greenhouse with similar climatic conditions was used to simulate the performance of the integral sliding mode controller. In this study, it was seen that the integral sliding mode control system was more accurate; however, the actuator signals sent by this control system were not smooth. It could damage and depreciate the greenhouse equipment more quickly than the proposed non-linear control system. It was also shown that the regulation of the temperature and humidity was performed very smoothly by changing the reference signals according to the weather conditions outside the greenhouse. The ability of these two control systems was graphically demonstrated for temperature and humidity responses as well as for the signals sent to the actuators.

Keywords: actuator; control; humidity; simulink; temperature

Greenhouse microclimate control is an important factor in crop growth. There are numerous environmental factors that must be carefully considered when monitoring including the temperature, relative humidity, light, and carbon dioxide. Setting the temperature in the right range can not only increase crop yields, but also prevent heat or cold stress on plants. Similarly, limiting the relative humidity reduces the likelihood of leaf mould formation, which can severely damage crops. Hence, the microclimate control of greenhouses is receiving a lot of attention today due to its excellent ability to improve the yield and quality of agricultural products (Van Straten et al. 2010), and, therefore, a variety of control techniques have been proposed by researchers (Van Henten 1994; Sigrimis et al. 1999; Tap 2000; Sigrimis et al. 2001; Pasgianos et al. 2003). Generally, many studies have focused on performance indicators to control an environmental factor, such as the indoor temperature (Setiawan et al. 2000; Coelho et al. 2005; Ghoumari et al. 2005; Kläring et al. 2007). In fact, crop growth and photosynthesis can both be attributed to the impact of several complex natural and environmental phenomena. Therefore, it is difficult to provide a one-factor control plan to meet the needs of optimal crop growth. Consequently, it is essential to develop a practical multi-factor control method. However, it should be noted that due to the inherent complexity of multi-factor controllers, their design and development is always

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a challenging task. Some of the main problems are as follows: The greenhouse controller is highly influenced by climate changes; some physical parameters of the used materials in the structure, cover and greenhouse equipment change due to long-term use; there is a great deal of uncertainty in the dynamic behaviour of the greenhouse; crop growth and consequent changes, such as the intensity of evaporation and transpiration, and the amount of plant shading significantly affect the greenhouse climate; dynamic modelling of a greenhouse climate, especially non-glass greenhouses, is a very difficult task; due to the limitations of the actuator performance, control signals must be generated based on the operating range of each actuator. Agricultural greenhouses, especially greenhouses in areas with unstable climatic conditions, are considered a complex process. In fact, they have a severe non-linear behaviour that involves several different factors such as multiple inputs and multiple outputs (MIMOs) (Gaudin 1981; Oueslati 1990; Souissi 2002). In the presence of these limitations, it is very difficult to describe greenhouse cultivation by analytical models and control their climate using conventional control methods. Researchers have used many control strategies and technologies in various fields (Coelho et al. 2005; Márquez-Vera et al. 2016; Revathi and Sivakumaran 2016), such as conventional or classical strategies, i.e. proportional integral controller (PID), artificial intelligence (AI), fuzzy control (Lafont and Balmat 2004), neural networks and genetic algorithms (Ferreira et al. 2002), advanced control techniques, predictive control, adaptive (Arvantis et al. 2000) and strong control strategies, non-linear and optimal control, which, in particular, applies to greenhouse climate control (Lees et al. 1996; Hanan 1998; Tap 2000). Due to their multivariate and non-linear behaviour, conventional control methods in greenhouse systems are difficult because the relationships between internal and external variables are complex (non-linear physical phenomena that govern the dynamics of these systems are complex). This provides an excuse to use intelligent control techniques as a viable alternative. In this regard, fuzzy logic, as part of artificial intelligence techniques, is an attractive and well-established approach to solving control problems (Lee 1990).

Among the various methods, model prediction control (MPC) is a successful strategy that generates optimised control signals under certain constraints and by using system behaviour predictions (Coelho et al. 2005). At each step, the controller solves an optimisation problem based on a model that shows the relationship between the system states, control inputs, and disturbances. Only the optimised control input is executed while the others are discarded. This process is repeated at all the stages and for all the times to obtain the control signals. MPC is an ideal framework for controlling systems with slow dynamic behaviour and includes constrained inputs and outputs (Serale et al. 2018). Another advantage of using MPC in greenhouse climate control is that a greenhouse can usually be considered as a large room. In this way, the model and all the states are easily accessible, regardless of the disturbances on the system. Numerous studies have been conducted on the climate control of greenhouses that prove MPC (Zou et al. 2010; Chen et al. 2018). MPC has been proven in the real world because of its robustness, and the ability to control limitations in multivariate control programmes. Today, despite the slow computing speed of the MPC strategy, this method is widely used to control the climate in greenhouses (Ramírez-Arias et al. 2005; Van Straten et al. 2010; Gruber et al. 2011; Ramdani et al. 2015; Boughamsa and Ramdani 2018).

Recently, based on the predictive control strategy, various controllers have been proposed by researchers in which the fuzzy Takagi-Sugeno (T-S) method has been used for modelling. Hence, Xia et al. (2010) developed a predictive control method of a bound model for fuzzy discrete systems with different fuzzy membership functions. In another study (Hamza and Ramdani 2020), authors developed a predictive control method of a fuzzy time model. They exposed an interval type-2 (IT2) Takagi–Sugeno fuzzy model to the uncertainty dynamics of the plant to show the uncertainty of the parameters, which are effectively recorded by distance membership functions.

Chen et al. (2019) presented a predictive control method for a strong data-driven robust model predictive control (DDRMPC) framework to control the greenhouse temperature due to the inherent uncertainty of climate that affects the control accuracy. This dynamic model was obtained by modelling the thermal resistance capacity and the use of the building resistance-capacitance modelling (BRCM). The uncertainty set of the ambient temperature and solar radiation was recorded by the support vector clustering technique and the quality was better regulated by the training-calibration method. Although some research has been undertaken on this

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method, there is a great deal of ambiguity in creating a suitable practical model for a greenhouse control system, especially in severe disturbance conditions or when the actuators in the greenhouse are not able to meet the control needs. Therefore, it is necessary to provide a more practical control system which is more compatible with conventional cooling and heating equipment in greenhouses.

As mentioned, different controllers have been theoretically proposed for greenhouses that cannot adapt to all weather conditions. On the other hand, due to the sending of non-smooth control signals or the chattering by these controllers, some of these control systems will cause equipment damage. Therefore, this study proposes a non-linear climate control system for greenhouses that can be implemented in different environments. This control system is designed in a way that the signals sent to the actuators are generated smoothly. As a result, it will increase the actuators' life and reduce the depreciation of the greenhouse equipment.

MATERIAL AND METHODS

Non-linear controller design. The energy transfer and mass balance equations between the indoor and outdoor climate of the greenhouse and the effect of the actuators have been used to obtain the dynamic behaviour of the greenhouse (Arvantis et al. 2000; Ferreira et al. 2002). To simplify the greenhouse dynamics, it is assumed that the distribution of climatic parameters is completely homogeneous. Therefore, the temperature and humidity model based on the energy and mass conservation can be written as following Equations (1–3) (Lees et al. 1996):

$$\begin{aligned} T_{in}(k+1) = {} & \frac{1}{\rho C_p V_T}\left[Q_{heat}(k) + S_i(k) - \lambda Q_{fog}(k)\right] - \\ & - \frac{V_r(k)}{V_T}\left[T_n(k) - T_{out}(k)\right] - \\ & - \frac{U_A}{\rho C_p V_T}\left[T_{in}(k) - T_{out}(k)\right] \end{aligned} \tag{1}$$

$$\begin{aligned} H_{in}(k+1) = {} & \frac{1}{V_H} Q_{fog}(k) + \frac{1}{V_H}\left[E\left(S_i(k), H_{in}(k)\right)\right] - \\ & - \frac{V_r(k)}{V_H}\left[H_{in}(k) - H_{out}(k)\right] \end{aligned} \tag{2}$$

$$E\left[S_i(k); H_{in}(k)\right] = \alpha \ \frac{S_i(k)}{\lambda} - \beta_T \times H_{in}(k) \tag{3}$$

where: T_{in} (°C) – inside temperature; H_{in} (%) – inside relative humidity (%); Q_{heat} – the heating control (°C); Q_{fog} – the water capacity of the fog system (g H_2OS^{-1}); V_r – the ventilation rate ($m^3 \cdot s^{-1}$); S_i – the solar radiation intercepted by the greenhouse ($W \cdot m^{-2}$); T_{out} – outside temperature (°C); H_{out} – outside relative humidity (%); U_A – the heat transfer coefficient of the enclosure ($W \cdot K^{-1}$); C_p – the specific heat of the air (1 006 $J \cdot kg^{-1} \cdot K^{-1}$); ρ – the air density (1.2 $kg \cdot m^{-3}$); E (S_i, H_{in}) – the evapotranspiration rate of the plant ($g \cdot s^{-1}$), which is affected by the given solar radiation; λ – the latent heat of vaporisation (2 257 $J \cdot g^{-1}$); α – the overall coefficient to account for the shading and leaf area index (dimensionless); β_T – the overall coefficient to account for the thermodynamic constants and other factors affecting the evapotranspiration ($kg \cdot min^{-1} \cdot m^{-2}$); V_T and V_H – the temperature and humidity active mixing air volumes of the ventilated space (m^3), respectively.

The model described by Equations (1–2) can be normalised by transforming the control variables through the following Equations (4–6):

$$Q_{heat}(\%) = 100 \times \frac{Q_{heat}}{Q_{heat\_\max}} \tag{4}$$

$$Q_{fog}(\%) = 100 \times \frac{Q_{fog}}{Q_{fog\_\max}} \tag{5}$$

$$V_r(\%) = 100 \times \frac{V_r}{V_{r\_\max}} \tag{6}$$

In Equations (1–3), we can consider the state vector and input vector as $x = [T_{in}, H_{in}]^T$ and $u = [Q_{heat}, Q_{fog}, V_r]^T$, respectively. Moreover, $d = [S_i, T_{out}, H_{out}]^T$ is the measured disturbance vector. In this model, the non-linear terms are expressed as Equations (7–8).

$$\frac{1}{V_T\left[T_{in}(k) - T_{out}(k)\right]} \tag{7}$$

$$\frac{1}{V_H\left[H_{in}(k) - H_{out}(k)\right]} \tag{8}$$

The inside temperature (T_{in}) and humidity (H_{in}) were limited by a minimum and maximum bound to have $T_{in\_\min} \leq T_{in} \leq T_{in\_\max}$ and $H_{in\_\min} \leq H_{in} \leq H_{in\_\max}$.

Non-linear control system. The equilibrium points (x_1^*, x_2^*) of the greenhouse dynamic system can be expressed as Equations (9–10):

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$$x_1^* = -C_p \cdot V_T \cdot \rho \frac{S_i - T_{out} \cdot U_A}{C_p \cdot V_T \cdot \rho \cdot U_A} \tag{9}$$

$$x_2^* = \frac{-S_i \cdot \alpha}{\beta_T \cdot \lambda} \tag{10}$$

It shows that zero is not the equilibrium point of the dynamic greenhouse system. Hence (Equations 11–12),

$$e_1 = T_{in} + C_p V_T \rho \frac{S_i - T_{out} U_A}{C_p V_T \rho U_A} \tag{11}$$

$$e_2 = H_{in} - \frac{S_i \alpha}{\beta_T \lambda} \tag{12}$$

where: e_1 and e_2 – the error equations showing the temperature error between the zero and the results of dynamic equation in the steady state.

These equations can be used to transfer the governing greenhouse equations to the centre of equilibrium. In this research, it was assumed that the greenhouse was only equipped with ventilation and humidification systems Q_{heat} = 0 and by using these two sets of actuators, the climate control of the greenhouse can be achieved. By introducing T_r and H_r as the reference command for setting the temperature and humidity of the greenhouse selected by the user, the tracking error can be written as: $e_{e1} = T_{in} - T_r$ and $e_{e2} = H_{in} - H_r$ for the temperature and humidity, respectively. Therefore, by these tracking errors, the transferred form of greenhouse dynamics with set commands can be achieved. It is observed that if Q_{fog} and V_r are selected in such a way that in $t \rightarrow \infty$, $\text{e}_{\dot{\text{e}}\text{i}}$ (the time derivatives of e_{e1} and e_{e2}) $\rightarrow 0$, $i = 1.2$, $\text{e}_{\dot{\text{e}}\text{i}}$ will also tend to be zero and the equivalence control condition will be met. As a result, the desired state variables can reach the desired value. Therefore, by setting $\text{e}_{\dot{\text{e}}\text{i}}$ = 0, the desired control rules can be expressed as following Equations (13–14):

$$Q_{fog} = -\frac{\pi_1}{\pi_2} \tag{13}$$

$$V_r = -\frac{\pi_3}{\pi_4} \tag{14}$$

where: the parameters π_i i = 1, 2, 3 and 4 are derived from Appendix A [in Electronic Supplementary Material (ESM)].

Depending on the capacity of the humidity and ventilation actuators, the saturation function can be used to limit the amount of energy consumed. Here, these changes are considered for the ventilation V_r and humidifier Q_{fog} in an interval of [0, 100]%.

RESULTS AND DISCUSSION

In Figure 1, the results of modelling the temperature and humidity inside the greenhouse were compared with the experiment. For the data collection, two sets of loggers were used inside and outside the greenhouse. The data collection time was from 15 to 18 July 2018 with a sampling time of 10 minutes. There is good agreement between the simulation and experimental values, and this depicts the performance of the selected method in controlling the greenhouse.

Figure 2 shows the closed-loop block diagram of the proposed non-linear greenhouse control system performed in the MATLAB simulator. In this control system, the user first determines the reference temperature and humidity signals. These two signals enter the control system along

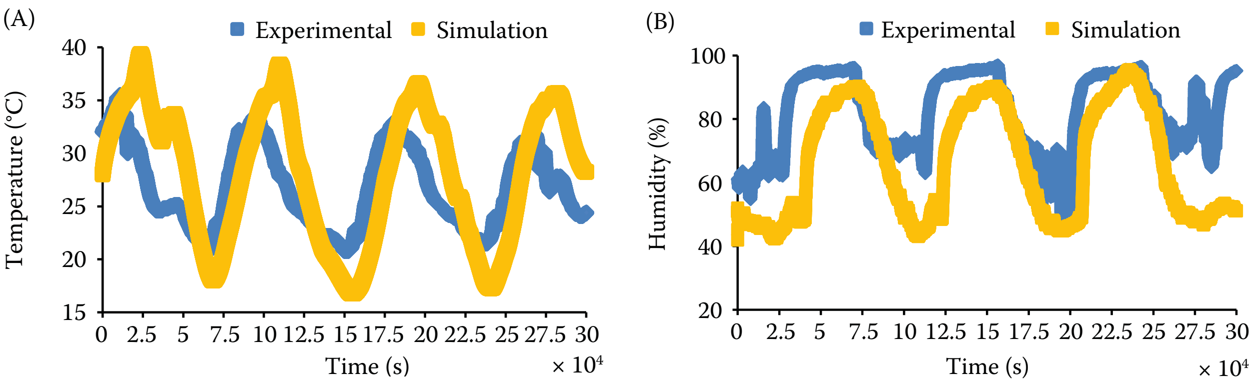

Figure 1. Comparison of simulation and experimental data inside the greenhouse; (A) temperature and (B) humidity

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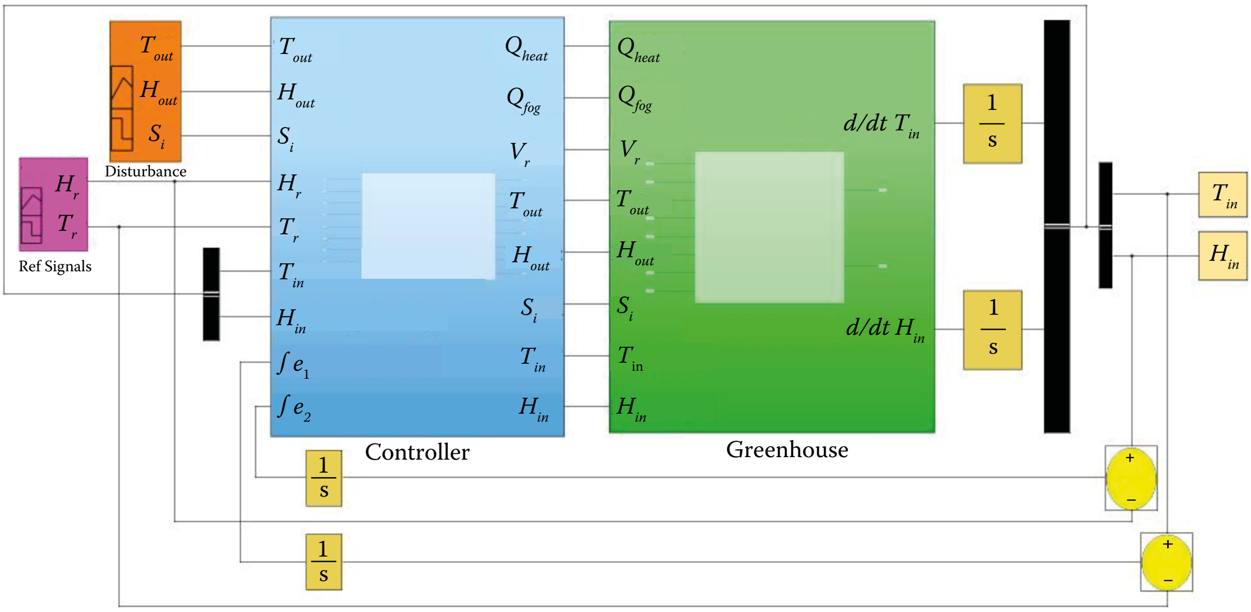

Figure 2. Block diagram for the non-linear control system designed in Simulink

T_{in} (°C) – inside temperature; H_{in} (%) – inside relative humidity (%); Q_{heat} – the heating control (°C); Q_{fog} – the water capacity of the fog system (g H_2OS^{-1}); V_r – the ventilation rate ($m^3 \cdot s^{-1}$); H_r – humidity reference commands which can be set by system user; T_r – temperature reference commands which can be set by system user; S_i – the solar radiation intercepted by the greenhouse ($W \cdot m^{-2}$); T_{out} – outside temperature (°C); H_{out} – outside relative humidity (%); d/dt – the derivative time operator

with the signals containing information about the temperature, humidity, and radiation outside the greenhouse. The controller then sends the control command signals to the heater, fogger/pad-fan, and ventilation systems in the greenhouse after the calculations. The gains and control parameters along with the required information and specifications of the greenhouse and weather parameters are shown in Table 1. Figure 3 shows the proposed control system performances. Figure 3A shows that after a short time, the greenhouse temperature is set to the set values and remains stable. In this simulation, the data collection was performed for a period of nearly two days. It shows the temperature response of the proposed control system at the selected time intervals and indicates that the controller was able to give the actuators the opportunity to change the command signal. In other words, the control signals are generated in such a way that the actuators do not have to switch on with the different values very quickly, which leads to the chattering phenomenon. It was observed that the actuators need at least 500 s to change the temperature from 20 °C to 40 °C. Moreover, it showed that temperature changes of 1 to 2 degrees occur in an acceptable time frame of about 500 seconds. In addition to showing the speed of the response of the control system, this indicated that the actu-

Table 1. The system constants

λ	α	U_A	ρ	C_p	β_T	V	V_T	V_H	G_{ET}	G_{EH}	G_{EIT}	G_{EIH}
2 257	0.00332λ	25	1.2	1 006	1.5	4 000	V	ρV_T	0.3	0.3	0.04	0.01

λ – the latent heat of vaporisation; α – the overall coefficient to account for the shading and leaf area index (dimensionless); U_A – the heat transfer coefficient of the enclosure ($W \cdot K^{-1}$); ρ – the air density ($kg \cdot m^{-3}$); C_p – the specific heat of the air ($J \cdot kg^{-1} \cdot K^{-1}$); β_T – the overall coefficient to account for the thermodynamic constants and other factors affecting the evapotranspiration ($kg \cdot min^{-1} \cdot m^{-2}$); V – the greenhouse volume (m^3); V_T – the temperature active mixing air volumes of the ventilated space (m^3); V_H – the humidity active mixing air volumes of the ventilated space (m^3); G_{ET} and G_{EH} – the proportional controller gains for temperature and humidity, respectively; G_{EIT} and G_{EIH} – the integrals controller gains for temperature and humidity, respectively

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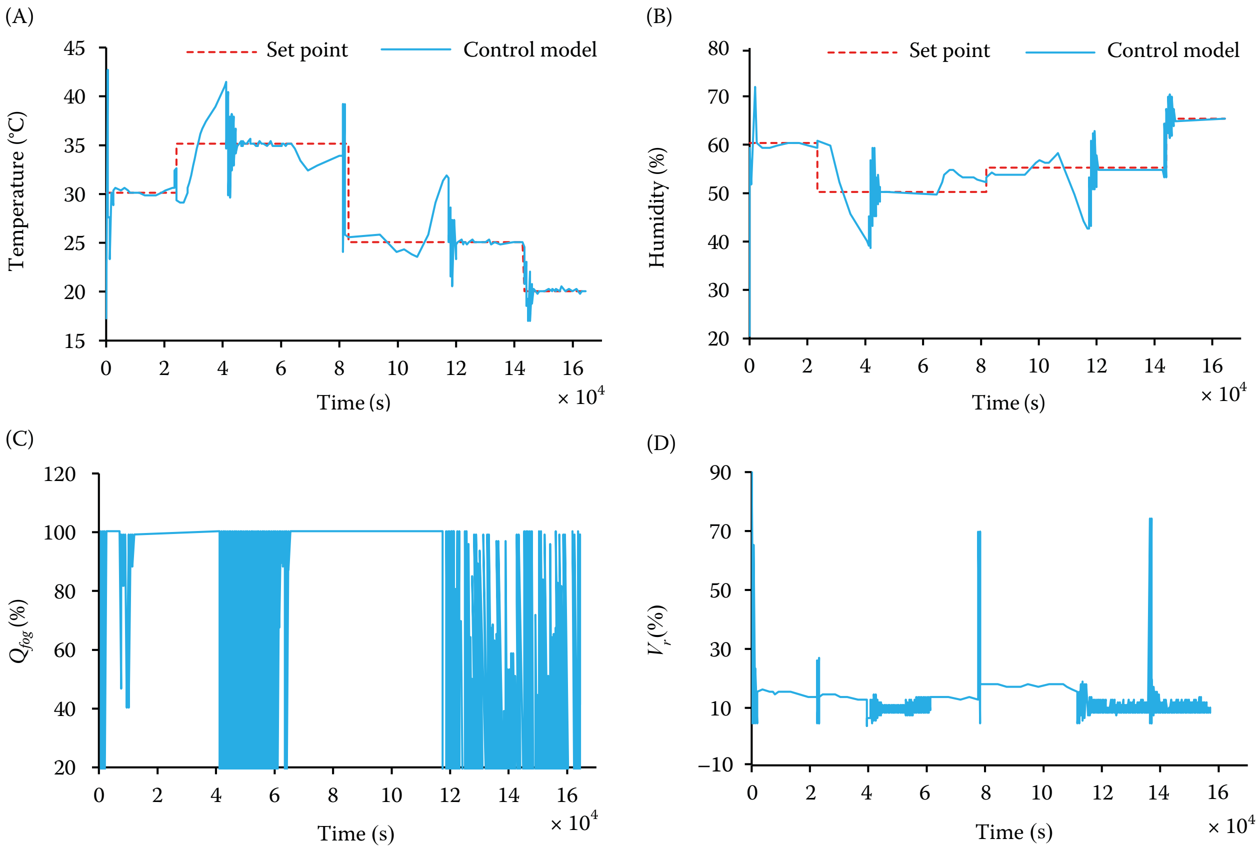

Figure 3. The performance of the control system; (A) temperature, (B) humidity, (C) Q_{fog} and (D) V_r

ators had enough time to create the desired temperature in the greenhouse. It should be noted that the climatic conditions outside the greenhouse play an important role in controlling the greenhouses. If the set points of the control system are appropriately selected according to the weather conditions outside the greenhouse and the capacity of the equipment of the greenhouse systems, the controller can perform the control operation more quickly and accurately. In this study, the weather conditions out side the greenhouse is depicted in Figure 4.

Figure 3B shows the proposed controller responses to set the relative humidity inside the greenhouse. Since the relative humidity can be directly increased by using the foggers/pad-fan and can be directly reduced by the ventilation, the response of the relative humidity to the changing commands was faster than the temperature

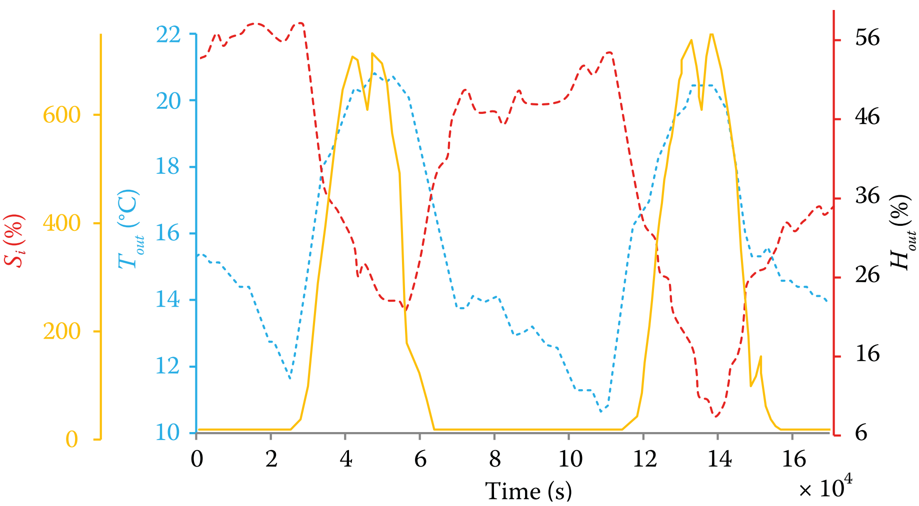

Figure 4. Climate conditions outside the greenhouse; the solar radiation (S_i), the outside temperature (T_{out}) and the outside relative humidity (H_{out})

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response. As expected, it is observed that the behaviour of the temperature and relative humidity changes are opposite to each other, and where the humidity decreases, the temperature increases and *vice versa*. It was observed that the relative humidity changes in the greenhouse caused by the proposed control system changed smoothly. These humidity changes occurred over a period of at least more than 100 seconds; therefore, the actuators had enough time to generate the required humidity in the greenhouse.

Figure 3C shows the signal sent to the fogger and also shows that this actuator was sometimes active at its maximum value. For the fogger signal to behave according to the ability of the actuators in the greenhouse, a saturation value was used to set the actuators so that the signal sent to the foggers was in the range of [0, 100]%. It was observed that the signals sent from the controller to the actuator were generated in such a way that due to the size and time of its effect, so the system does not suffer from the chattering phenomenon. Therefore, the fogger actuator can easily supply the required humidity of the greenhouse with this control system.

Figure 3D shows the signal sent to the ventilation actuator in which the operator signal variation was limited to 0% to 100%. It shows that there is enough time for this signal to change the commands of the actuator. The ventilation signal takes more than 100 s for the opening to open and close or for the fans to turn on and off. The simulation results show that at intervals with high signal densities, more than 100 s were required for changes in the ventilation actuator. Moreover, the timing of the ventilation signal changes was not extremely fast due to their magnitude and could be easily created by the system actuators. Therefore, by selecting the appropriate set points and creating appropriate reference signals, this control system can be successfully used in a greenhouse with openings, fans, heaters, and foggers.

Climate changes outside the greenhouse can help the ventilation to regulate the humidity and temperature inside the greenhouse. However, it can also be considered as a disturbance that prevents proper control operations. Comparing Figure 3A–D with Figure 5A–D, we can see that at the peak times of the temperature, humidity and radiation outside

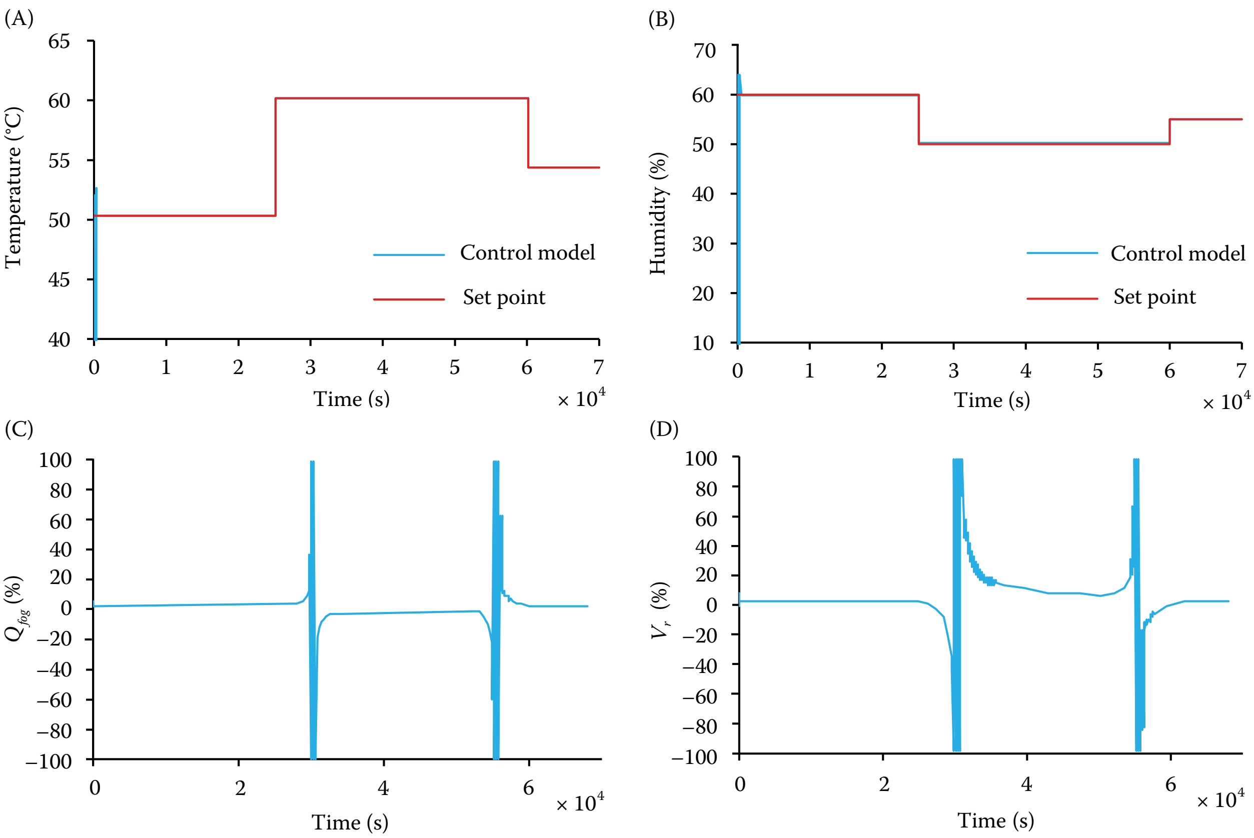

Figure 5. The performance of the interval type-2 (IT2) Takagi–Sugeno fuzzy model predictive control system in the responses of the (A) temperature, (B) humidity, (C) Q_{fog} and (D) V_r

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the greenhouse, the changes related to the actuator signals oscillate more and they have a significant effect on the control response. To demonstrate the efficiency of this proposed control system, we compared it with an integral sliding mode control system (Appendix B – see ESM). This comparison was performed for 70 000 seconds. Figure 5 shows the response of the integral sliding mode control system according to the measured weather conditions outside the greenhouse and the selected set points. As can be seen, the humidity command signal was tracked very quickly. However, Figures 5C and 5D show that this control system requires much more powerful actuators to perform the desired commands than the actuators of the real greenhouse. It can be observed that this system takes less than 100 s to track the reference signal. Figure 5A shows the system response has an overshoot of less than 20 seconds. It was observed that the system rapidly sets the humidity inside the greenhouse to the predetermined values and has a short settling time. Therefore, the signal magnitude of the foggers and ventilation have changed from –100% to +100%. It also shows that these changes occurred very quickly. As a result, the greenhouse actuators will not have enough time to create the desired humidity in the greenhouse. This not only impairs the operation of the control system, but also destroys the greenhouse fogger system.

Figure 5A shows the temperature response of this integral sliding mode control system, which can also be seen here, the control commands changed rapidly. Moreover, the system overshoot was less than 10 seconds. It was observed that the signal density of the actuators occurred in a way that the system experienced severe temperature fluctuations. It can be seen that temperature changes in the greenhouse were fast and not very smooth. Figure 5D shows the signal of the ventilation actuator that endured a large load to control and stabilise the greenhouse climate. It shows that the ventilation actuator should make ventilation changes from zero to more than 80% in less than 10 seconds. It should be noted that the greenhouse system actuators are not able to make such changes to the greenhouse ventilation. Therefore, it was found that because of its speed and accuracy, the integral sliding mode controller cannot control the greenhouse in practice. This control system causes damage to the greenhouse equipment, which is generally expensive, and their repairs are costly.

CONCLUSION

In this study, a non-linear climate control system was designed in such a way to use different sensor information installed inside and outside a greenhouse. Moreover, in this study, an integral sliding mode control system was used for comparison and evaluation. This system was able to set the temperature and humidity inside the greenhouse with high accuracy using information about the sensors and dynamic system parameters. It was shown that for high accuracy, the integral sliding mode control system can cause the intensive depreciation in the system actuators. However, it was shown that the command signals from the proposed nonlinear control system were quite smooth and, due to its action time, could be easily generated by the greenhouse actuators. However, it was shown that by changing the set points, the control system held its stability and slowly changed the greenhouse climatic conditions. Therefore, this control system can be used in greenhouses that have different cooling, heating, and ventilation systems. It was found that when the differences between the outside and inside greenhouse climate parameters were large, the actuators signals fluctuated to maintain the stability of the climate inside the greenhouse. Moreover, it was shown that the set points can have a direct effect on the control response and load on the actuators.

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