Switching Control Strategy for Greenhouse Temperature-Humidity System Based on Prediction Modeling: A Simulation Study

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Abstract. It is difficult to achieve coordination control of multiple facilities that are driven by on-off actuators in a greenhouse, especially when there is more than one indoor environmental factor to consider at the same time. With the consideration of indoor air temperature and relative humidity, we propose a switching control strategy based on prediction modeling. The operation of the greenhouse system was divided into several modes according to the on-off control characteristics of the available facilities. Then, a switching diagram was designed according to the relationship between the indoor air temperature and humidity and their setting ranges. When the two indoor environmental factors reach their upper or lower limits, IARX models are used to predict them over a specified horizon for each optional mode respectively. Mode switching is carried out based on prediction results. The switching control strategy was simulated based on a mechanistic model of the greenhouse microclimate. The results show that the facilities can be coordinated very well by the proposed control strategy and it is easy to implement. The control strategy is still applicative when more facilities or more indoor environmental factors need to be taken into account.

Keywords: *agricultural greenhouse; hybrid system; prediction model; relative humidity; switching control; temperature.*

1 Introduction

Many facilities are used to create a suitable microclimate for plants in modern greenhouses. In general, the facilities in different greenhouses can be very different. For facilities that are driven continuously or in multiple stages, several control methods can be adopted, such as PID control [1,2], feedforward-feedback control [3], self-adaptive control [4], fuzzy control [5,6] and predictive model control [7,8], etc. However, in many greenhouses the facilities are only driven by on-off actuators, so it is difficult to use the above control methods. For such greenhouses, the operation process can be divided into multiple modes, such as natural ventilation mode, mechanical ventilation mode, etc. Accordingly, the greenhouse system can be regarded as a hybrid dynamical

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system and the operation process, in essence, consists of switching between different modes [9].

Hybrid dynamical systems usually contain continuous variable dynamics and event-driven discrete variable dynamics, while the two dynamics interact with each other and determine each other's behaviors over time [10]. At present, hybrid systems are widely used in manufacturing systems [11], traffic management [12], automotive engine control [13], chemical processing [14], etc., but rarely in the modeling and control of greenhouse microclimates. According to the on-off control characteristics of the available facilities it is not difficult to determine the operating modes for a greenhouse system. The key issue is how to design reasonable switching rules. It is easy to design the switching rules if there is only one facility available in a greenhouse [9,15] but it is very complex when there are multiple facilities. Chu, *et al.* divided greenhouse operation into four modes for a greenhouse with three facilities, i.e. a roof window, a fan, and a wet pad [16]. They designed switching rules by considering several factors, such as the indoor and outdoor air temperature and their upper and lower limits. The resulted rules were complex but still defective. Firstly, the solar radiation was not taken into account in the rules, although it has great influence on the indoor air temperature. Secondly, only the indoor air temperature was considered while other indoor environmental factors were not. The relative humidity is an important factor: too high relative humidity tends to breed fungal diseases and damage crop flowering and pollination, while too low relative humidity leads to plant water stress [17]. Therefore it is difficult to design switching rules in accordance with the above ideas when the indoor air temperature and relative humidity are considered together.

In order to solve the above problem, we propose a switching control strategy based on prediction modeling. We constructed prediction models for indoor air temperature and relative humidity for each operating mode with outdoor environmental factors as inputs of the models. When the indoor air temperature or relative humidity reach their upper or lower limits, the models are used to predict both indoor environmental factors over a specified horizon. The prediction results reflect the influence of the outdoor environmental factors, so the design of switching rules based on the prediction results can be simplified significantly.

This rest of this paper is organized as follows. In Section 2, the proposed switching control strategy is described. Then the prediction models of indoor air temperature and humidity are introduced. Lastly, the proposed control strategy is verified by using a simulation model of a greenhouse microclimate. In Section 3, the simulation results are discussed. The paper is concluded in

Section 4. The conclusion can be used as guidance for future use of the new control strategy in practice.

2 Materials and Methods

2.1 Switching Control Strategy

The Venlo-type glass greenhouse used widely in the south of China was taken as the example in this research. Four common kinds of facilities were taken into account, i.e. roof windows, fans, a wet pad and an external shading net. It was assumed that they are all driven by on-off actuators, which is in accordance with the actual situation in many greenhouses. According to the first three kinds of facilities, the operation of the greenhouse system is divided into three modes, i.e. natural ventilation mode, mechanical ventilation mode and pad-fan cooling mode. When all the facilities do not work, the operating mode is called passive mode in this paper. The operating process of the greenhouse system can be regarded as a switching scheme between the four modes, where the greenhouse can only be in one of the four modes at any time. As the fourth facility, the state of the shading net mainly depends on the solar radiation intensity, having little containment relationship with the other operating modes. Therefore, the shading net being folded or unfolded has nothing to do with the operating modes. The switching control system of greenhouse is shown in Figure 1. Outdoor environmental factors have great influence on indoor air temperature and relative humidity, so they were inputted into the controller to facilitate the design of the switching rules.

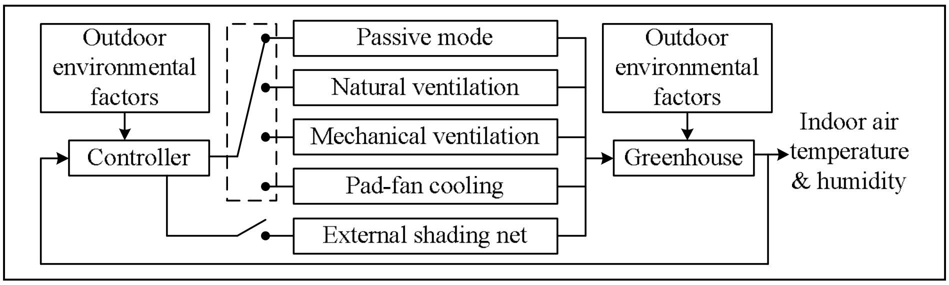

Figure 1 Switching control system for a greenhouse.

In practice, the growers set the ranges of temperature and relative humidity according to the crop species and their growth stages. When the indoor air temperature or relative humidity exceed the setting ranges, the greenhouse has to switch from the current mode to another mode in order to adjust the temperature or relative humidity so it goes back to within the setting ranges. A new control strategy is proposed to realize a reasonable switching scheme between different modes. The control strategy consists of two steps. In the first step, a switching diagram is designed according to the relationship between indoor air temperature and humidity and their setting ranges. The operating mode that will be switched to next is usually different for each mode. For example, if the system is in passive mode, the greenhouse will enter into one of the other three modes when the indoor air temperature exceeds the upper limit, while if the current mode is mechanical ventilation, the only mode that may be switched to is pad-fan cooling. Assuming that the greenhouse is in passive mode initially, the switching diagram is designed as shown in Figure 2. The switching conditions between different operating modes are marked. We use T_{in} and RH_{in} to denote the indoor air temperature and relative humidity, T_l and T_h to denote the lower limit and the upper limit of the indoor temperature, and RH_l and RH_h to denote the lower limit and the upper limit of the relative humidity.

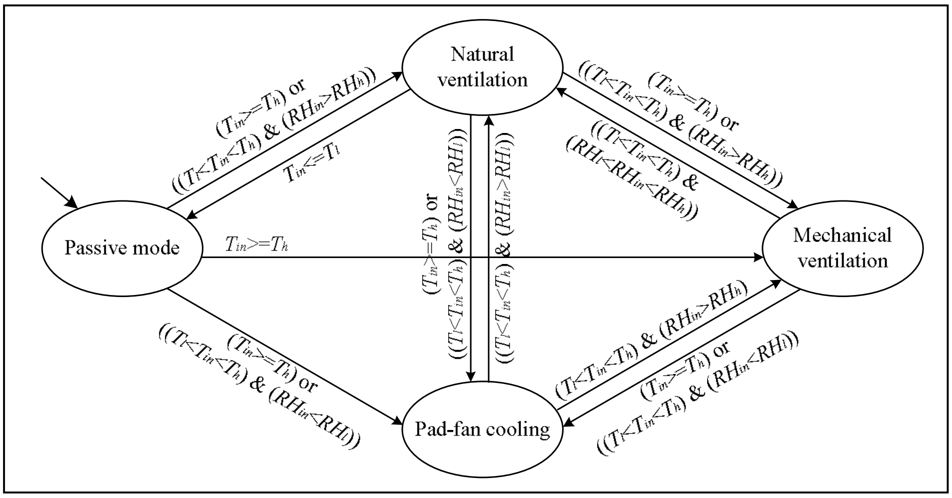

Figure 2 Switching control system of greenhouse.

Apart from the current modes, the mode switch is also related to the outdoor climate. In different weather conditions, the same operating mode may have different functions. For example, both natural ventilation and mechanical ventilation are usually used for cooling and dehumidification, but they cannot be used for cooling in hot weather and dehumidification on rainy days. The changeability of the weather makes it difficult to design the switching rules. In order to simplify the design, outdoor environmental factors were chosen as inputs in constructing the prediction models of indoor air temperature and humidity for each operating mode. The prediction results can reflect the influence of outdoor environmental factors, making it simpler to design the switching rules. The prediction models will be introduced in Section 2.2. Now we focus on the second step: the design of the switching rules.

When the indoor air temperature or the relative humidity exceeds its setting range, if the greenhouse has more than one operating mode that can be switched to, the models in each optional mode are used to make respective predictions over a specified horizon. If there is only one mode in which the prediction results are within the setting ranges, the greenhouse will immediately enter into this mode while if there are two modes, the following two principles should be followed in the mode switching process:

1. *Priority of natural ventilation mode.* Natural ventilation mode will be selected without considering other operating modes as long as the prediction results in this mode are within the setting ranges. The first reason is that little energy is consumed in natural ventilation mode, which is an advantage over mechanical ventilation mode and pad-fan cooling mode. The other reason is that the indoor environmental factors change slowly in natural ventilation mode, which is helpful to reduce switching between operating modes.

2. *Minimum deviation.* When the prediction results of indoor air temperature and relative humidity under natural ventilation mode cannot meet the control requirements, if the prediction results under mechanical ventilation mode and pad-fan cooling mode are within the setting ranges, it is necessary to make further judgment on the choice between the two modes. Assuming that the outdoor environment factors do not change, the steady-state prediction results can be obtained by the models. Eq. (1) is defined to determine the extent to which the steady-state prediction results deviate from the averages of the setting ranges of temperature and humidity.

$$J = a\left(\frac{T_{pred}(k+N\,|\,k)-T_a}{T_h-T_a}\right)^2 + (1-a)\times\left(\frac{RH_{pred}(k+N\,|\,k)-RH_a}{RH_h-RH_a}\right)^2 \qquad (1)$$

where the letter k denotes the current time instant; N is the length of prediction horizon; $T_{pred}(k+N|k)$ and $RH_{pred}(k+N|k)$ are the predicted values of temperature and relative humidity at time instant $k+N$; T_h and RH_h are the upper limits; T_a and RH_a are the set averages; a is a weight coefficient with the value range (0-1) and is set to 0.5 in this research. The prediction deviations of indoor air temperature and humidity under each optional mode can be calculated by Eq. (1). The operating mode with the smallest deviation will be chosen. If the prediction results in all optional modes are not within the setting ranges, the above minimum-deviation principle is used to select the most suitable mode.

When the indoor air temperature or the relative humidity exceeds its setting range, if the greenhouse has only one optional mode, the switching rules are as follows. If the optional mode is passive mode, the greenhouse will enter into this mode as soon as the indoor air temperature is reduced to the lower limit. If the optional mode is not passive mode, whether or not the greenhouse enters into the optional mode depends on the prediction results. If the prediction sequences of indoor air temperature and relative humidity, i.e. $\{T_{pred}(k+i|k), i=1,\ldots, N\}$ and $\{RH_{pred}(k+N|k), i=1,\ldots, N\}$, exceed the set ranges very soon, it is not necessary to switch operating modes. In all other cases it should be effectuated.

2.2 Prediction Models of Indoor Air Temperature and Humidity

It is important to construct the prediction models of indoor air temperature and relative humidity for all operating modes. At present, there are three kinds of prediction models, i.e. mechanistic [18,19], ARX [20,21] and neural network [22]. The ARX model is the simplest and has a smaller computational burden than the other two models. We have constructed the temperature prediction models in different operating modes based on the analysis of mechanistic models, called IARX models (incremental auto regressive prediction model with external variables) [23]. IARX models have fewer coefficients than typical ARX models, so they are more suitable for real-time online identification. The IARX prediction models of indoor air temperature in passive mode, natural ventilation mode and mechanical ventilation mode have the same form, as expressed by Eq. (2), while the model in pad-fan cooling mode is expressed by Eq. (3).

$$\Delta T_i(k+1) = \alpha_1 \Delta T_{oi}(k) + \beta_1 Q_{rad}(k) + \varepsilon \tag{2}$$

$$\Delta T_i(k+1) = \alpha_1 \Delta T_{oi}(k) + \beta_1 Q_{rad}(k) + \gamma_1 \Delta T_{pi}(k) + \varepsilon \tag{3}$$

where $\Delta T_i(k+1)$ denotes the difference of indoor air temperature at time instants $k+1$ and k; $\Delta T_{oi}(k)$ is the difference between outdoor and indoor air temperature at time instant k; $\Delta T_{pi}(k)$ the difference between indoor air temperature and that of wet air that passes through the pad at time instant k; $Q_{rad}(k)$ is the solar radiation intensity at time instant k; α_1, β_1, γ_1 and ε are coefficients.

The prediction models for indoor air humidity were constructed in the same way. The models in passive mode, natural ventilation mode and mechanical ventilation mode also have the same form, as expressed by Eq. (4), while the model in pad-fan cooling mode is expressed by Eq. (5).

$$\Delta \rho_{iwv}(k+1) = \alpha_2 \Delta \rho_{oi}(k) + \beta_2 Q_{rad}(k) \tag{4}$$

$$\Delta \rho_{iwv}(k+1) = \alpha_2 \Delta \rho_{oi}(k) + \beta_2 Q_{rad}(k) + \gamma_2 \tag{5}$$

where $\Delta\rho_{iwv}(k+1)$ denotes the difference of indoor water vapor density at time instants $k+1$ and k; $\Delta\rho_{oi}(k)$ is the difference between outdoor and indoor water vapor density at time instant k; α_2, β_2 and γ_2 are coefficients. The coefficient γ_2 is related to the slow-changing physical quantities such as long wave radiation, etc. Recursive identification is adopted to update the model coefficients regularly so as to keep good predictive accuracy and, hence, coefficient γ_2 is regarded as a constant.

Relative humidity is a variable that can be directly measured. Water vapor density cannot, so it is necessary to achieve a conversion between the two physical quantities. The related calculation equation is described in Eq. (6) as follows [24]:

$$\rho_{wv} = RH \cdot e_{zero} \cdot \exp\left(17.4T/(239+T)\right)M\big/\left(R\left(273.15+T\right)\right) \tag{6}$$

where RH denotes the relative humidity (%); e_{zero} the saturated water vapor pressure at 0 °C (610.7Pa); M the molar mass of water (18 g/mol); R the perfect gas constant (8.314 J/(mol °C)); T the air temperature (°C).

When the indoor air temperature and relative humidity are predicted at time instant $k+i$ (i>1), it is necessary to provide the data of the relevant environment factors at time $k+i$-1. However, the environmental data at future time instants are unknown in practice. The lazy man weather prediction method [25] was adopted, in which the outdoor environmental factors remain unchanged over a specified horizon. This prediction method is effective when the horizon is not too long.

2.3 Simulation Experiment

A mechanistic model of a Venlo-type glass greenhouse microclimate [26] was constructed and used to simulate the proposed control strategy. The mechanistic model is described as follows:

$$\begin{cases} \rho_a V_g C_a \dfrac{dT_{in}(t)}{dt} = Q_{radin}(t) - x_1 Q_{nv}(t) - x_2 Q_{mv}(t) - x_3 Q_{pf}(t) - Q_{exch}(t) - Q_{tran}(t) \\ s.t.\ \sum x_j \le 1,\ \ x_j = 0,1\left(j = 1,2,3\right) \end{cases} \tag{7}$$

$$\begin{cases} V_g \dfrac{d\rho_{iwv}(t)}{dt} = E_{tran}(t) - x_1 E_{nv}(t) - x_2 E_{mv}(t) - x_3 E_{pf}(t) - E_{cond}(t) \\ s.t.\ \sum x_j \le 1,\ \ x_j = 0,1\left(j = 1,2,3\right) \end{cases} \tag{8}$$

where ρ_a denotes the air density(g/m^3); V_g is the greenhouse volume (m^3); C_a is the air specific heat (J/(g°C)); $T_{in}(t)$ is the indoor air temperature (°C); t is time (s); $Q_{radin}(t)$ is the solar radiation power received in the greenhouse (W); $Q_{nv}(t)$ is the power loss by natural ventilation (W); $Q_{mv}(t)$ is the same loss by mechanical ventilation (W); $Q_{pf}(t)$ is the same loss by pad-fan cooling (W); $Q_{exch}(t)$ is the same loss caused by the energy exchange through a cover layer (W); $Q_{tran}(t)$ is the same loss through crop transpiration (W); $\rho_{iwv}(t)$ is the water vapor density in the greenhouse (g/m^3); $E_{tran}(t)$ is the water vapor density produced by crop transpiration (g/s); $E_{nv}(t)$ is the loss of water vapor density caused by natural ventilation (g/s); $E_{mv}(t)$ is the same loss caused by mechanical ventilation (g/s); $E_{pf}(t)$ is the same loss caused by pad-fan cooling (g/s); $E_{cond}(t)$ is the same loss caused by water vapor condensation on the inner surface of the cover layer (g/s); x_j (j = 1, 2, 3) are decision variables and have a value of either 0 or 1 (0 denotes OFF and 1 ON). There is at most one decision variable with value 1 at any time according to the operating process of the greenhouse described in Section 2.1.

It has been found that a bandwidth of 8 °C has little effect on indoor rose crops [27], so the temperature range was set to 22-30°C in this simulation. Because the indoor relative humidity was not high when the mechanistic model was verified [26], the range was set to 40-70%. The thresholds were also set for the shading net. The net is unfolded when the solar radiation intensity exceeds 420 W/m^2 and folded when it is reduced to 400 W/m^2. The light transmission of the shading net was set to 50%. It has been found that indoor temperature and humidity stabilize after the greenhouse enters into another operating mode for ten minutes [23], so the prediction horizon was set to ten minutes. A sunny day, April 22, 2014 in the Nanjing area was selected and the simulation period was set to 7:30-16:30.

The data of four environmental factors are needed for the simulation, i.e. outdoor air temperature, relative humidity, solar radiation, and wind speed. Because the sampling period was 30 minutes, the environmental data were fitted and interpolated by using RBF neural network. Only the wind level values were available, so it was necessary to convert them to wind speeds. There is a wind level table on the China Meteorological Administration website [28]. The minimum wind speed value for each wind level was selected in order to reduce the influence of other factors on wind speed, such as wind direction. Huang, *et al.* provided the data of solar radiation intensity [29]. The outdoor environmental factors are shown in Figure 3.

The prediction models should be validated before used, so the following settings were made. Initially, the greenhouse was in passive mode. When the indoor air temperature exceeded the upper limit for the first time, the greenhouse entered into natural ventilation mode; for the second time and the third time, the greenhouse entered into mechanical ventilation mode and pad-fan cooling mode, respectively. The data of the environmental factors were obtained in the four operating modes and used to validate the IARX models. Then, the identified models were used in the next simulation experiment. Recursive identification was adopted to update the model coefficients in time. The sampling period was set to 30 seconds in order to obtain sufficient environmental data in a short time for model validation. The simulation of the control strategy was programmed in MATLAB software.

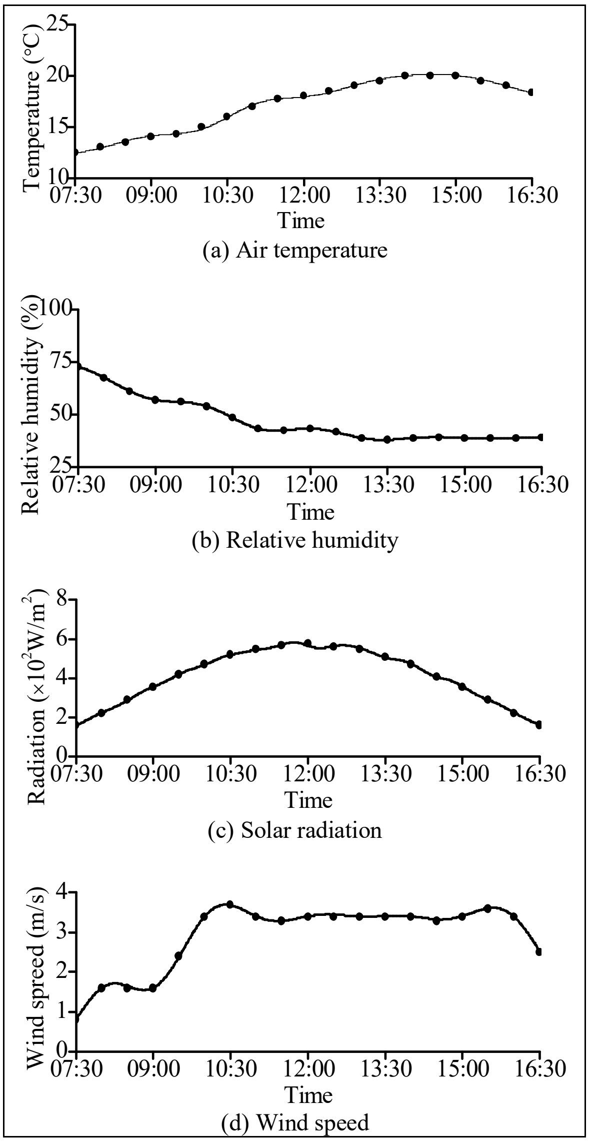

Figure 3 Outdoor environmental factors.

3 Results and Discussion

The switching process of the four operating modes is shown in Figure 4. In this figure, the four operating modes, i.e. passive mode, natural ventilation mode, mechanical ventilation mode and pad-fan cooling mode, are abbreviated to PM, NV, MV and PF. The time frame that the shading net was unfolded is also plotted in the figure.

The dynamic behaviors of indoor air temperature and relative humidity are shown in Figures 5 and 6, respectively. When the indoor air temperature reached the upper limit for the first three times, the greenhouse experienced natural ventilation mode, mechanical ventilation mode and pad-fan cooling mode in turn in order to obtain enough environmental data for model validation, like those used in the simulation. The simulation results indicate that operating modes switching was done reasonably well by the proposed control strategy and the indoor air temperature and relative humidity were controlled very well.

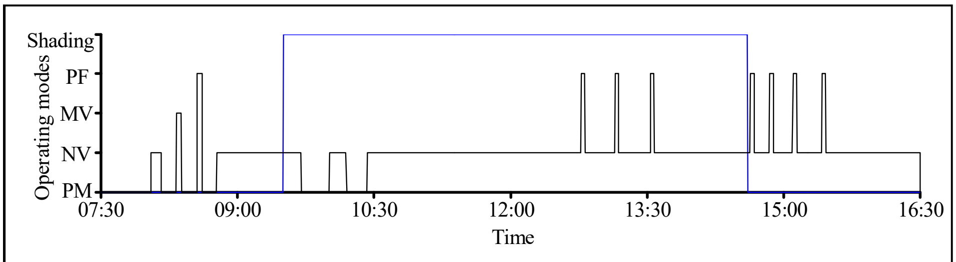

Figure 4 Switching process of operating modes.

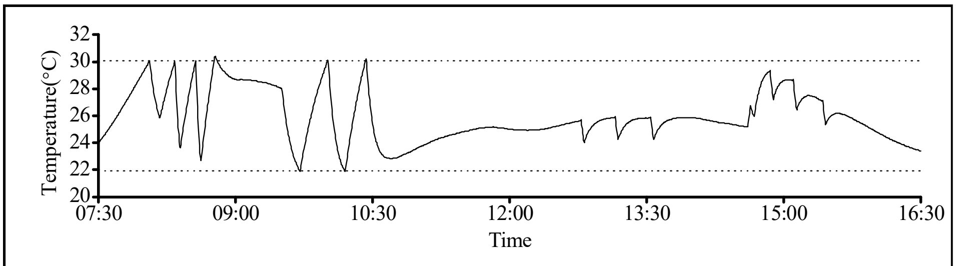

Figure 5 Dynamic behavior of indoor air temperature.

The prediction models reflect the influence of outdoor environmental factors on indoor air temperature and humidity, so the prediction results change with the outdoor environmental factors. The mode switch is realized based on real-time prediction results, so the control strategy has good adaptive ability. Because the outdoor relative humidity was too low in the afternoon, the indoor relative humidity reached the lower limit several times in natural ventilation mode, which caused the greenhouse to enter into the pad-fan cooling mode several times. This shows that the outdoor relative humidity has great influence on the indoor relative humidity.

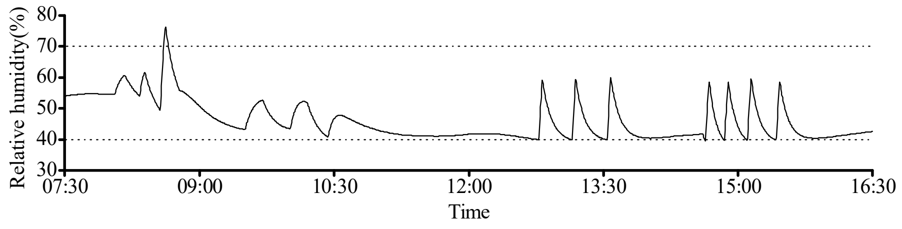

Figure 6 Dynamic behavior of indoor relative humidity.

Although both the indoor air temperature and relative humidity are considered together, the proposed control strategy is still simple to implement. If more indoor environmental factors are considered, for example CO_2, the proposed control strategy is still applicable as long as the prediction models of all environmental factors in each operating mode are constructed.

Generally, the more indoor environment factors are considered, the more frequently the operating mode will be switched. Conversely, the fewer indoor environment factors are considered, the fewer mode switch take place. For example, if only the indoor air temperature is considered, it is not necessary for the greenhouse to enter into pad-fan cooling mode when the shading net is unfolded.

In this simulation, the pad-fan cooling mode is the only way to increase the indoor relative humidity. However, when the mode is used to increase the indoor relative humidity, the indoor air temperature is reduced significantly, which may increase the operating mode switching frequency. It would be better if a humidifier were installed in the greenhouse. This shows that the simulation results can provide a reference for the installation of new facilities. If there are other facilities in the greenhouse apart from those adopted in the simulation, the proposed control strategy is also applicable as long as the operating modes are correctly re-divided and the prediction models of the indoor environmental factors in each mode are constructed.

The simulation result shows that the indoor air temperature decreased rapidly when the shading net was unfolded, which shows that solar radiation has great influence on the indoor air temperature. On the other hand, it also shows that shading is an effective way of cooling. Although both solar radiation and outdoor air temperature increased later, the natural ventilation mode combined with shading net could meet the cooling requirements. Because both shading and natural ventilation consume very little energy, it is necessary to take full use of them.

In order to protect the facilities, the operating modes should not be switched too frequently. Except for the indoor environmental factors and facilities considered above, the setting ranges of indoor air temperature and relative humidity also have a great influence on the operating mode switching frequency. We changed the range of indoor relative humidity from 40-70% to 50-80%, and repeated the above simulation. The results are shown in Figures 7-9.

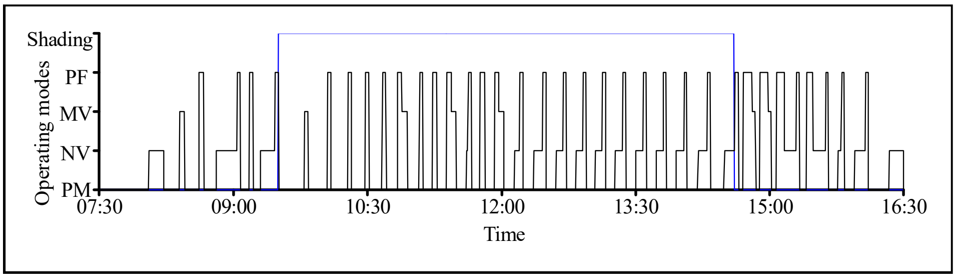

Figure 7 Operating-mode switching process.

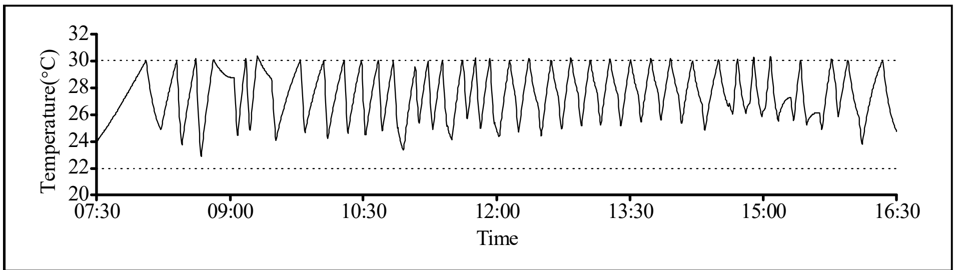

Figure 8 Dynamic behavior of indoor air temperature.

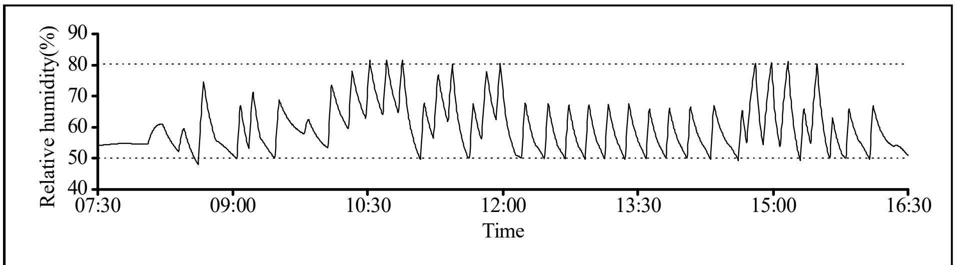

Figure 9 Dynamic behavior of indoor relative humidity.

The operating mode switching frequency increased significantly because the greenhouse had to enter into pad-fan cooling mode to increase the indoor relative humidity many times, which also led to frequent fluctuations of indoor air temperature and relative humidity. Therefore, it is necessary to consider many factors, such as facilities, crop species, etc., in order to set the appropriate ranges of temperature and humidity.

4 Conclusion

When more than one indoor environmental factor is considered together, it is difficult to achieve coordinated control of multiple facilities driven by on-off actuators in a greenhouse. In this study, the greenhouse system was considered as a hybrid system and a switching control strategy was proposed based on prediction models of indoor air temperature and humidity. The simulation results indicate that the proposed control strategy has good adaptive ability and can achieve coordinated control of multiple facilities very well. The proposed control strategy is still applicable if more indoor environmental factors are considered or more facilities are installed in the greenhouse. Therefore, the proposed control strategy has a good universality.

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References

[1] Setiawan, A., Albright, L.D. & Phelan, R.M., *Application of Pseudo-derivative-feedback Algorithm in Greenhouse Air Temperature Control*, Computers and Electronics in Agriculture, **26**(3), pp. 283-302, 2000.

[2] Zeng, S., Hu, H., Xu, L. & Li, G., *Nonlinear Adaptive PID Control for Greenhouse Environment based on RBF Network*, Sensors, **12**(4), pp. 5328-5348, 2012.

[3] Pasgianos, G.D., Arvanitis, K.G., Polycarpou, P. & Sigrimis, N., *A Nonlinear Feedback Technique for Greenhouse Environmental Control*, Computers and Electronics in Agriculture, **40**(1), pp. 153-177, 2003.

[4] Arvanitis, K.G., Paraskevopoulos, P.N. & Vernardos, A.A., *Multirate Adaptive Temperature Control of Greenhouses*, Computers and Electronics in Agriculture, **26**(3), pp. 303-320, 2000.

[5] Sriraman, A. & Mayorga, R.V., *Climate Control Inside a Greenhouse: An Intelligence System Approach using Fuzzy Logic Programming*, Journal of Environmental Informatics, **10**(2), pp. 68-74, 2007.

[6] Castañeda-Miranda, R., Ventura-Ramos, E. Peniche-Vera, R.D.R. & Herrera-Ruiz, G., *Fuzzy Greenhouse Climate Control System based on a Field Programmable Gate Array*, Biosystems Engineering, **94**(2), pp. 165-177, 2006.

[7] Piñón, S., Camacho, E.F., Kuchen, B. & Peña, M., *Constrained Predictive Control of a Greenhouse*, Computers and Electronics in Agriculture, **49**(3), pp. 317-329, 2005.

[8] Coelho, J.P., Oliveira, P.B.D.M. & Cunha, J.B., *Greenhouse Air Temperature Predictive Control using the Particle Swarm Optimisation Algorithm*, Computers and Electronics in Agriculture, **49**(3), pp. 330-344, 2005.

[9] Yang, B., Qin, L.L. & Gang, W., *Modeling and Control for Greenhouse Temperature System based on Hybrid Automata*, In Proceedings of the 30th Chinese Control Conference (CCC), pp. 1627-1631, 2011.

[10] Lin, H. & Antsaklis, P.J., *Hybrid Dynamical Systems: An Introduction to Control and Verification*, Foundations & Trends in Systems & Control, **1**(1), pp. 1-172, 2014.

[11] Pepyne, D.L. & Cassandras, C.G., *Optimal control of hybrid systems in manufacturing*, In Proceedings of the IEEE, **88**(7), pp. 1108-1123, 2000.

[12] Febbraro, A.D., Giglio, D. & Sacco, N., *A Deterministic and Stochastic Petri Net Model for Traffic-responsive Signaling Control in Urban Areas*, IEEE Transactions on Intelligent Transportation Systems, **17**(2), pp. 510-524, 2016.

[13] Balluchi, A., Benvenuti, L., Benedetto, M.D.D. & Sangiovanni-Vincentelli, A., *The Design of Dynamical Observers for Hybrid Systems: Theory and Application to an Automotive Control Problem*, Automatica, **49**(4), pp. 915-925, 2013.

[14] EI-Farra, N.H., Mhaskar, P., Christofides, P.D., *Hybrid Predictive Control of Nonlinear Systems: Method and Applications to Chemical Processes*, International Journal of Robust and Nonlinear Control, **14**(2), pp. 199-225, 2004.

[15] Ma, G., Qin, L., Liu, X. & Wu, G., *Modeling and Predictive Control of Greenhouse Temperature-humidity System based on MLD and Time-series*, In Proceedings of the 34th Chinese Control Conference (CCC), pp. 2234-2239, 2015.

[16] Chu, Z., Qin, L., Lu, L., Ma, G. & Wu, G., *Hybrid Controller Design and Analysis for Experimental Greenhouse Temperature System*, Journal of University of Science and Technology of China, **45**(4), pp. 268-274, 2015.

[17] He, F. & Ma, C., *Modeling Greenhouse Air Humidity by Means of Artificial Neural Network and Principal Component Analysis*, Computers and Electronics in Agriculture, **71**(S), pp. 19-23, 2010.
[18] Singh, G., Singh, P.P., Lubana, P.P.S. & Singh, K.G., *Formulation and Validation of a Mathematical Model of the Microclimate of a Greenhouse*, Renew Energy, **31**(10), pp. 1541-1560, 2006.
[19] Briceno-Medina, L.Y., Avila-Marroquin, M.V. & Jaimez-Arellano, R.E., *SIMICROC: Greenhouse Microclimate Simulation Model*, Agrociencia, **45**(7), pp. 801-813, 2011.
[20] Frausto, H.U., Pieters, J.G. & Deltour, J.M., *Modelling Greenhouse Temperature by Means of Auto Regressive Models*, Biosystems Engineering, **84**(2), pp. 147-157, 2003.
[21] Patil, S.L., Tantau, H.J. & Salokhe, V.M., *Modelling of Tropical Greenhouse Temperature by Auto Regressive and Neural Network Models*, Biosystems Engineering, **99**(3), pp. 423-431, 2008.
[22] Frausto, H.U. & Pieters, J.G., *Modelling Greenhouse Temperature using System Identification by Means of Neural Networks*, Neurocomputing, **56**, pp. 423-428, 2004.
[23] Xu, Z., Chen, J., Zhang, J., Liu, Y. & Zhang, Q., *Incremental Auto Regressive Prediction Models with External Variables of Greenhouse Air Temperature for Control Purposes*, International journal of smart home, **10**(9), pp. 45-58, 2016.
[24] Jiang, Y., Qin, L., Shi, C. & Wu, G., *Modern Greenhouse Humidity System Modeling based on Mechanism Model*, Journal of Jiangnan University (Natural Science Edition), **12**(5), pp. 535-540, 2013.
[25] Tap, R.F., Willigenburg, L.G. & Straten, G.V., *Receding Horizon Optimal Control of Greenhouse Climate based on the Lazy Man Weather Prediction*, In Proceedings of the 13th IFAC World Congress, pp. 387-392, 1996.
[26] Xu, Z., Chen, J., Zhang, Q. & Gu, Y., *Dynamic Mechanistic Modeling of Air Temperature and Humidity in the Greenhouses with On-Off Actuators*, TELKOMNIKA (Telecommunication Computing Electronics and Control), **14**(2A), pp. 248-256, 2016.
[27] Rijsdijk, A.A. & Vogelezang, J.V.M., *Temperature Integration on a 24-Hour base: A More Efficient Climate Control Strategy*, Acta Horticulturae, **519**, pp. 163-169, 2000.
[28] China Meteorological Administration, *The Classification of Wind.* http://www.cma.gov.cn/2011xzt/20120816/2012081601/201208160101/201407/t20140717_252607.html, (Accessed on July 17, 2014).
[29] Huang, J., Chen, Z., Li, C., Lou, Q., Tang, F. & Wang, P., *Characteristics of Solar Radiation in Nanjing*, Power and Energy, **34**(1), pp. 82-84, 2013.