A SYSTEM WITH PSEUDO-DERIVATIVE FEEDBACK CONTROL
FOR SHORT-TERM GREENHOUSE OPERATION

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Abstract: The efficiency of plant production in a greenhouse depends significantly on the control of climate conditions. A system has been developed to control greenhouse climate. The thermodynamic relations between system variables have been modelled into a set of differential equations and a pseudo-derivative feedback controller is applied. Varying the desired indoor air temperature and humidity ratio under various conditions of outdoor air temperature, humidity ratio and solar radiation as well as several parameter values of the system, the responses of the actuators, indoor temperature and humidity are generated by simulations. Results show reasonable behaviours of the greenhouse responses and thus the system feasibility and applicability have been proven.

Keywords: Greenhouse, Climate control, Pseudo-derivative feedback, Decoupling, Simulation, Model validation.

1. INTRODUCTION

Historically, it can be discovered that the Romans already recognized the benefits of protecting crops from unfavourable outdoor climatic conditions by means of light transmitting shelters to facilitate the cultivation of exotic crops during winter and spring. Moreover, people seemed to be aware of the fact that crop productivity could be improved by actively modifying the climate in these shelters. However, their limited qualitative knowledge of the processes involved in crop growth and production, and the poor technical status of the equipments available for climate conditioning limit the application of advanced climate control strategies (Van Henten, 1994).

Greenhouse climate control has become increasingly computerized, and currently involves many sensors located inside and outside of the greenhouse (e.g. temperature, humidity and solar radiation) and several actuators (e.g. heater, humidifier, and ventilator). The information provided by these sensors and actuators can be used to reach the desired climate goals of the greenhouse indoor climate. In this paper an efficient automatic control system of these sensors and actuators has been developed.

A schematic diagram of the greenhouse architecture is depicted in Fig. 1. Generally the greenhouse models consist of two sub-systems, namely the climate control process and the crop production process. The crop production process is a ‘slow’ response process requiring long-term studies whereas the climate control process is a ‘fast’ response process requiring short-term studies. In this paper, we consider only the short-term dynamics of variables included in the climate control process. Under the outdoor conditions of temperature, humidity and solar radiation, we control the indoor temperature and humidity to reach the desired goals by the operation of heater, humidifier and ventilator. We mention that the focus of the previous studies has been on daytime control under summer conditions, therefore heating was not considered (Albright et al., 2001, Koutb et al., 2004).

The greenhouse interior is considered to be a perfectly stirred tank consisting essentially of one homogenous component, the greenhouse air. The main purpose of the greenhouse climate model is to
predict the inside climate for the current state of the system, outside weather and control variables. The model itself is composed of coupled energy and water vapour mass balances over various components of the system. A simple greenhouse heating-cooling ventilating model is obtained by considering a set of differential equations that governs sensible heat and water vapour balances on the interior volume (Bot, 1983). The greenhouse climate model was first developed by Van Henten (1994) and later controlled by many authors, among others are Albright et al. (2001).

![Fig. 1. A schematic diagram of the greenhouse crop production process.](image)

Of course, the efficiency of the climate control system depends on its timeliness and reasonable behaviours. The failure of one of the sensors and/or actuators to function properly would impair the operation of the greenhouse, and might result in significant financial losses for the grower (Linker, 2000). We show the performance, applicability and validation of the system by simulation under various situations.

The paper is organized as follows. In section 2 a system of the greenhouse climate control is developed. A set of two coupled nonlinear differential equations are derived and a pseudo-derivative zero-feedback controller has been applied. In section 3 the response data of the system are generated by simulations. Under various situations, the behaviours of the system are presented for a full day simulation. The investigation and the interpretation of the data show the reasonable behaviours of the system variables.

### 2. A SYSTEM OF GREENHOUSE CLIMATE CONTROL

#### 2.1. Greenhouse dynamic model

The dynamic model of the energy and mass balance of air in the greenhouse is shown to be highly nonlinear. A simple greenhouse heating-cooling ventilating model can be presented by considering a set of differential equations which governs sensible and latent heat as well as water balances on the interior volume. These differential equations are as follows:

\[
\frac{dT_i(t)}{dt} = \frac{1}{\rho V} [\frac{q_{out}(t)}{V} + \xi \lambda S(t) - \lambda q_{in}(t)]
\]

\[
-\frac{q_{out}(t)}{V} [T_{in}(t) - T_{out}(t)] - \frac{\mu}{\rho V} [T_{in}(t) - T_{out}(t)] \quad (1a)
\]

\[
\frac{dH_i(t)}{dt} = \frac{1}{\rho V} q_{in}(t) + \frac{1}{\rho V} E(S(t), H_{in}(t))
\]

\[
-\frac{q_{out}(t)}{V} [H_{in}(t) - H_{out}(t)] \quad (1b)
\]

where \(T_{in}\) and \(T_{out}\) are the indoor and outdoor air temperature (°C), respectively, \(H_{in}\) and \(H_{out}\) are the interior and exterior humidity ratios (g[H₂O]/kg[dry air]), respectively, \(\mu\) is the heat transfer coefficient (W/K), \(\rho\) is the air density (1.2 kg[air]/m³), \(\lambda\) is the latent heat of vaporization (2257 J/g), \(\xi\) is the specific heat of air (1006 J/kg/K), \(\zeta\) is the solar heating efficiency (dimensionless), \(S\) is the intercepted solar radiant energy (W/m²), \(E(S(t), H_{in}(t))\) is the evapo-transpiration rate of the plants (g[H₂O]/s), \(q_{heat}\) is the heat provided by the greenhouse heater (W), \(q_{fog}\) is the water capacity of the fog system (g[H₂O]/sec), \(q_{vent}\) is the ventilation rate (m³[air]/s), \(A\) is the greenhouse floor area (m²) and \(V\) is the greenhouse volume (m³). It should be noted that due to short circuiting and stagnant zones exist in ventilated spaces, the active mixing volume is typically significantly less than the calculated total volume.

The active mixing volume of a ventilated space may easily be as small as 60-70% of the geometric volume. This, of course, means that indoor air temperature and humidity are unlikely to be uniform throughout the air space. The evapo-transpiration rate \(E(S(t), H_{in}(t))\) is in most part related to the intercepted solar radiant energy, through the following simplified relation:

\[
E(S(t), H_{in}(t)) = \alpha \frac{S(t)}{\lambda} - \beta H_{in}(t)
\]

where \(\alpha\) is an overall coefficient to account for shading and leaf area index, dimensionless and \(\beta\) is the overall coefficient to account for thermodynamic constants and other factors affecting evapo-transpiration (i.e., stomata, air motion, etc.) in (kg/min/m²) (Albright et al., 2001).

In this climate model, two variables have to be controlled namely the indoor air temperature and the humidity ratio through the processes of heating, cooling, humidifying, and/or dehumidifying. Since dehumidification is sometimes expensive, dehumidifiers will not be used. However, we will use a combination of heating and ventilation for the purpose of dehumidifying the greenhouse. Ventilation brings in fresh air, which is heated, allowing it to absorb some of the moist air from the inside before exhausting it to the outside. Also, when the relative humidity of the outside air is very low, only ventilation can be used to dehumidify the greenhouse air by exchanging moist inside air with drier outside air. Raising humidity levels requires some sort of evaporative devices such as misters, fog units, or roof sprinklers, all of which cool and add water vapour to the air. Evaporative cooling devices
require good ventilation rates. Fresh air must be continually brought in for warmed and humidified air to be exhausted. When humidifying is occurred under sunny conditions, ventilation is necessary since the greenhouse would soon become a steam bath without providing fresh dry air.

2.2 Feedback-feedforward linearization and decoupling

In this section, the feedback-feedforward linearization and decoupling (FFLD) control method is applied (Pasgianos et al., 2003). Eq. 1 can be rewritten in the following form:

\[
\frac{dT}{dt} = -\frac{\mu}{\rho \xi V} T(t) - \frac{1}{V} \dot{T}_o(t) q_{\text{vent}}(t) - \frac{\lambda}{\rho \xi V} q_{\text{heat}}(t) + \frac{1}{\rho \xi V} q_{\text{vent}}(t) + \frac{1}{\rho \xi V} T(t) T_{\text{o}}(t) \tag{3a}
\]

\[
\frac{dH}{dt} = -\frac{\beta}{\rho V} H(t) + \frac{1}{\rho V} q_{\text{fog}}(t) + \frac{\alpha \xi A}{\lambda \rho V} S(t) - \frac{1}{\rho V} H(t) q_{\text{vent}}(t) + \frac{1}{\rho V} q_{\text{vent}}(t) H_{\text{o}}(t) \tag{3b}
\]

Due to the complexity appearing as the cross-product terms between control and disturbance variables Eqs. (3a) and (3b) are obviously coupled nonlinear equations, which cannot be put into the rather familiar form of an affine analytic nonlinear system. Therefore, a combined scheme of feedback with simultaneous feedforward linearization is plausible. For the system to be I/O linearized, decoupled, and disturbance isolated the closed-loop system should take the form:

\[
\frac{dT}{dt} = -\frac{\mu}{\rho \xi V} T(t) + \tilde{K}_T \tilde{u}_T(t) \tag{4a}
\]

\[
\frac{dH}{dt} = -\frac{\beta}{\rho V} H(t) + \tilde{K}_H \tilde{u}_H(t) \tag{4b}
\]

where \(\tilde{u}_T, \tilde{u}_H\) are new external control signals and \(\tilde{K}_T, \tilde{K}_H\) are process gains. By comparing Eqs. 3 and 4 and solving for \(q_{\text{vent}}, q_{\text{fog}}\) and \(q_{\text{heat}}\) we obtain the relations:

\[
q_{\text{vent}}(t) = \frac{1}{\rho \xi V} \left[ \frac{1}{\rho \xi V} q_{\text{vent}}(t) \right.
\]

\[
+ \frac{\mu}{\rho \xi V} T_{\text{o}}(t) - \tilde{K}_T \tilde{u}_T(t) - \frac{\lambda}{\tilde{K}_H \tilde{u}_H(t)} \right] \tag{5a}
\]

\[
q_{\text{fog}}(t) = -\frac{\alpha \xi AS(t) + \rho q_{\text{vent}}(t) \left( T_{\text{i}}(t) - T_{\text{o}}(t) \right)}{\lambda} + \rho V \tilde{K}_H \tilde{u}_H(t) \tag{5b}
\]

\[
q_{\text{heat}}(t) = -\frac{\xi AS(t) + \lambda q_{\text{fog}}(t)}{\lambda} + \rho \xi q_{\text{vent}}(t) \left( T_{\text{i}}(t) - T_{\text{o}}(t) \right) - \mu T_{\text{o}}(t) + \rho \xi V \tilde{K}_H \tilde{u}_H(t) \tag{5c}
\]

By applying the above control law, the closed-loop system takes in the form of Eq. 4. This is just the scheme of inverse dynamic control. The control system structure is depicted in Fig. 2 where the heater control signal will only be used when the desired indoor air temperature is higher than the outdoor temperature.

2.3 Pseudo-Derivative Feedback Controller

Pseudo-Derivative Feedback (PDF) Controller was first developed by Phelan (1977) and later expanded and applied to greenhouse temperature control by Setiawan et al. (1998). It is a modification of integral control with a derivative-feedback algorithm (I-DF). This structure provides all the control aspects of proportional integral derivative (PID) control but without system zeros that are normally introduced by a PID compensator. Phelan (1977) named this structure PDF control from the fact that the rate of the measured parameter is fed back without having to calculate a derivative. In the present application, we focus our attention on the simplest possible case of the general PDF control structure, depicted in Fig. 3. This feedback scheme is called the Pseudo derivative zero feedback (PD-0F) control structure. The only performance ‘design’ criterion used is the assignment of the time constants of the two decoupled subsystems (Koubt et al., 2004).

2.4. Failure detection

In the absence of automatic failure diagnosis, the bias or drift of sensors and actuators affects the greenhouse’s operation until the changes become sufficient enough to be noticed by the grower. Therefore, the grower himself is solely responsible
for noticing the abnormal behaviour of the crop. Providing automatic detection of failures occurring in the greenhouse would free the grower from these time consuming activities. Moreover, if failures could be detected at an early stage, it would enable early repair and reconfiguration of the control policy, such that the resulting damage could be minimized.

In the system developed a simple failure detection algorithm has been built. When the system can be validated, the signal readings of sensors and actuators from the system become ideal ones. Thus, we set a specific threshold value for each of sensors and actuators, and the system releases the corresponding alarm when actual reading and system reading show difference greater than their threshold value. As expected, small threshold values lead to a large number of false alarms and a small number of missed failures (and short detection times), and vice-versa for large threshold values. The proper threshold values can be determined considering the costs of false and missed alarms.

3. SYSTEM VALIDATION

We validate the system developed. Varying the parameter values of the system such as volume of the greenhouse $V$, heat transfer coefficient $\mu$, ventilation rate $q_{\text{vent}}$, etc., we investigated the corresponding behaviours of the sensors and actuators. The simulation results which are not presented here show the reasonable responses to the changes.

We present here one of the most complex situations simulated. Outdoor temperature $T_{\text{out}}$, humidity ratio $H_{\text{out}}$ and solar radiation $S$ change in sinusoidal ways as shown in Fig. 4 to represent real measurements. Outdoor temperature changes from a minimum value of 15 °C at 6 AM to a maximum value of 30 °C at 4 PM. Outdoor humidity ratio can be inferred from air temperature and dew point temperature through Clausius-Clapeyron equation, it takes values from about 6 and up to 15 g[H2O]/kg[air]. It is worth noting that when both air and dew point temperatures are very close, the air has a high relative humidity while the opposite is true when there is a large difference between air and dew point temperatures which indicates air with lower humidity ratio (Kittel and Kroemer, 1985). Solar radiation increases from zero W/m2 at sunrise up to 300 W/m2 at noon and then it decreases to zero W/m2 at sunset and during the whole night until the next sunrise and so on.

We used a greenhouse of a surface area of $A=1000$ m2 and a height of 4 m. The greenhouse has a shading screen which reduces the incident solar radiant energy by 60%. The maximum capacity of the humidifier system is 26 g[H2O]/min/kg[air]. Maximum ventilation rate corresponds to 20 air changes per hour (22.2 m3/sec). We simulated for 2 days (2880 minutes) and investigated the system behaviour in every minute. The followings are the analysis of the results during the last day.

Fig. 4. Changes of outdoor air temperature, humidity ratio and solar radiation in a sinusoidal way.

In the first experiment, indoor air temperature is required to hold constant at 25 °C and humidity ratio at 18 g[H2O]/kg[air]. Fig 5 shows that both the required and actual indoor air temperatures and humidity ratios which are perfectly coincided whereas the climate controller response is shown in Fig. 6. The heater starts to work when the desired indoor air temperature is lower than the outdoor temperature, as sunrises, the greenhouse air temperature starts to increase due to absorbed solar energy and due to increasing the outdoor air temperature, therefore the heater decreases its rate and then stops providing heat to the greenhouse air. As sun rises in the sky, ventilator increases its rate to keep a constant indoor air temperature and humidity ratio.

Fig. 5. Greenhouse climate for a setpoint of 25 °C for temperature and 18 g[H2O]/kg[air] for humidity ratio.
4. CONCLUSION

We developed a control system for greenhouse operation. A model for nonlinear thermodynamic laws between numerous system variables affecting the greenhouse climate has been formulated and PD-OF controller is devised. The system has been validated by simulation. The sensors and actuators in the system behaved in reasonable manners and responded quickly to the changes of conditions such as predetermined outdoor climate and the indoor climate goals. Thus the signal readings from the system could be used as criteria for failures of actual sensors and actuators. The proper and timely control and failure detections of sensors and actuators will contribute to the efficient and effective greenhouse operation.

The approach is not limited to greenhouse applications, but could easily be extended to a broader range of applications where heating, ventilation and humidification are used, especially in livestock houses, growth chambers, poultry houses as well as industrial applications. The optimal operation of greenhouse and the long-term crop production process will be further studies.

REFERENCES


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