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

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Electronic supplementary material (ESM)

Appendix A:

The parameters of the derived control law:

$$\begin{aligned}\pi_1 = {} & S_i U_A^2 T_r \alpha + S_i U_A^2 \alpha e_{e_1} + \beta_T H_{out} \lambda U_A^2 T_r - \beta_T H_{out} \lambda U_A^2 e_{e_1} - \beta_T \lambda U_A^2 T_r H_r - \beta_T \lambda U_A^2 T_r e_{e_2} - \beta_T \lambda U_A^2 H_r e_{e_1} - \\ & - \beta_T \lambda U_A^2 e_{e_1} e_{e_2} - \beta_T C_p \lambda S_i H_r \rho - \beta_T^2 C_p \lambda S_i e_{e_2} \rho + \beta_T^2 C_p \lambda U_A T_r H_r \rho + \beta_T^2 C_p \lambda U_A T_r e_{e_2} \rho + \beta_T^2 C_p \lambda U_A H_r e_{e_1} \rho + \\ & + \beta_T^2 C_p \lambda U_A e_{e_1} e_{e_2} \rho - \beta_T C_p \lambda S_i V_H \rho V_2 + C_p S_i U_A V_T \alpha \rho V_1 + \beta_T C_p H_{out} \lambda U_A V_T \rho V_1 + \beta_T C_p \lambda U_A V_H T_r \rho V_2 - \\ & - \beta_T C_p \lambda U_A V_T H_r \rho V_1 + \beta_T C_p \lambda U_A V_H e_{e_1} \rho V_2 - \beta_T C_p \lambda U_A V_T e_{e_2} \rho V_1\end{aligned}$$

$$\pi_2 = \lambda \left(\beta_T \lambda U_A H_r - \beta_T H_{out} \lambda U_A - S_i U_A \alpha + \beta_T \lambda U_A e_{e_2} - \beta_T C_p S_i \rho + \beta_T C_p U_A T_r \rho + \beta_T C_p U_A e_{e_1} \rho \right)$$

$$\pi_3 = \beta_T U_A \left(U_A T_r + U_A e_{e_1} + \beta_T \lambda H_r + \beta_T \lambda e_{e_2} + \lambda V_H V_2 + C_p V_T \rho V_1 \right)$$

$$\pi_4 = \beta_T \lambda U_A H_r - \beta_T H_{out} \lambda U_A - S_i U_A \alpha + \beta_T \lambda U_A e_{e_2} - \beta_T C_p S_i \rho + \beta_T C_p U_A T_r \rho + \beta_T C_p U_A e_{e_1} \rho$$

where: $V_1 = G_{ET}(e_{e1}) + G_{EIT} \times \mathrm{sum}_{t\to\infty}(e_1)$ and $V_2 = G_{EH}(e_{e2}) + G_{EIH} \times \mathrm{sum}_{t\to\infty}(e_2)$ – the parameters used for the stability of the closed-loop system. The parameters G_{ET} and G_{EIT} – the control gains of the temperature error response and the temperature error integral, respectively. As well, G_{EH} and G_{EIH} – the control gains of the relative humidity error response and the relative humidity error integral, respectively.

Appendix B:

The system equations can be written as:

$$\dot{x} = F(x,v) + G(x,v)u$$

$$F(x,v) = \begin{bmatrix} -\dfrac{U_A}{\rho C_p V_T} T_{in} + \dfrac{1}{\rho C_p V_T} S_i + \dfrac{U_A}{\rho C_p V_T} T_{out} \\ \alpha S_i \end{bmatrix} \qquad G(x,v) = \begin{bmatrix} -\dfrac{1}{t_v}(T_{in} - T_{out}) & -\dfrac{\lambda Q_{fog}}{\rho C_p V_T} \\ -\dfrac{1}{t_v}(H_{in} - H_{out}) & \dfrac{1}{V_H} \end{bmatrix}$$

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$$u = \begin{bmatrix} V_r\% \\ Q_{fog}\% \end{bmatrix}^T$$

where: t_v – the inverse of the number of air changes per unit time.

The equivalent control law can be written as:

$$u = G^{-1}(x,v)\left[-F(x,v)+r\right]$$

The compensate sliding mode control law (r) can be expressed as:

$$r_i = -a_{4i}^{-1}\left(k_i s_i + \varepsilon_i\, sgn(s_i) + a_{4i}\hat{D}_{1i} - a_{4i}\dot{x}_{Ti} + a_{5i}e_i\right)$$

where: $s_i = a_{4i}e_i + a_{4i}\sigma_{0i} + \int_0^t a_{5i}e_i dt$ – the sliding surface; i – temperature, humidity.

$\hat{D}_{1i}$ can be expressed as:

$$\dot{\hat{D}}_{1i} = -L_i^{-1}\left(\dot{\sigma}_{0i} + a_{1i}\sigma_{1i} + a_{2i}\, sgn(\sigma_{1i}) + \hat{a}_{3i}\, sgn(\sigma_{1i})\right)$$

$$\sigma_{1i} = \sigma_{0i} + L_i\dot{\sigma}_{0i}$$

$$\sigma_{0i} = z - e_i$$

$$\dot{z} = r_1 + \hat{D}_{1i} - \dot{x}_{Ti}$$

$$e_i = x_i - \dot{x}_{Ti}$$

$$\dot{\hat{a}}_3 = \gamma_{0i}\left|\sigma_{1i}\right|$$

where: x and x_T – the state vector and reference vector, respectively.

The constant parameters can be written as in Table S1.

Table S1. Constant parameters of the integral sliding mode control system

i	a_1	a_2	a_4	a_5	k	ε	L	γ_0
Temperature	0.02	0.03	100	0.01	0.08	0.8	0.5	0.05
Humidity	0.01	0.01	100	0.008	0.5	2	1	0.02