REVIEW AND ANALYSIS OF “A MICROCLIMATE GREENHOUSE MULTIVARIABLE CONTROL: A GUIDE TO USE HARDWARE IN THE LOOP SIMULATION”

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ECE 763

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G. Cevallos, J. Pinzon, and O. Camacho, “A microclimate greenhouse multivariable control: A guide to use hardware in the Loop Simulation,” *2022 IEEE International Conference on Automation/XXV Congress of the Chilean Association of Automatic Control (ICA-ACCA)*, 2022.

STATEMENT OF INTEREST

- Groundwork for home project
  - Maintain growth of tropical plants
  - Goal is to eventually grow food plants
- Benefits of greenhouses
  - Controlled environment (temperature/humidity)
  - Protected environment (weather/pests/animals)
  - Ability to grow out of season/conditions

Picture of inside of greenhouse [2]

BACKGROUND INFORMATION

How does **Temperature** affect plants? [4]

- Plant vigor
- Leaf size
- Leaf expansion rate
- Time to fruit development

How does **Humidity** affect plants? [4]

- Transpiration
    - Calcium uptake
    - Hormonal Distribution

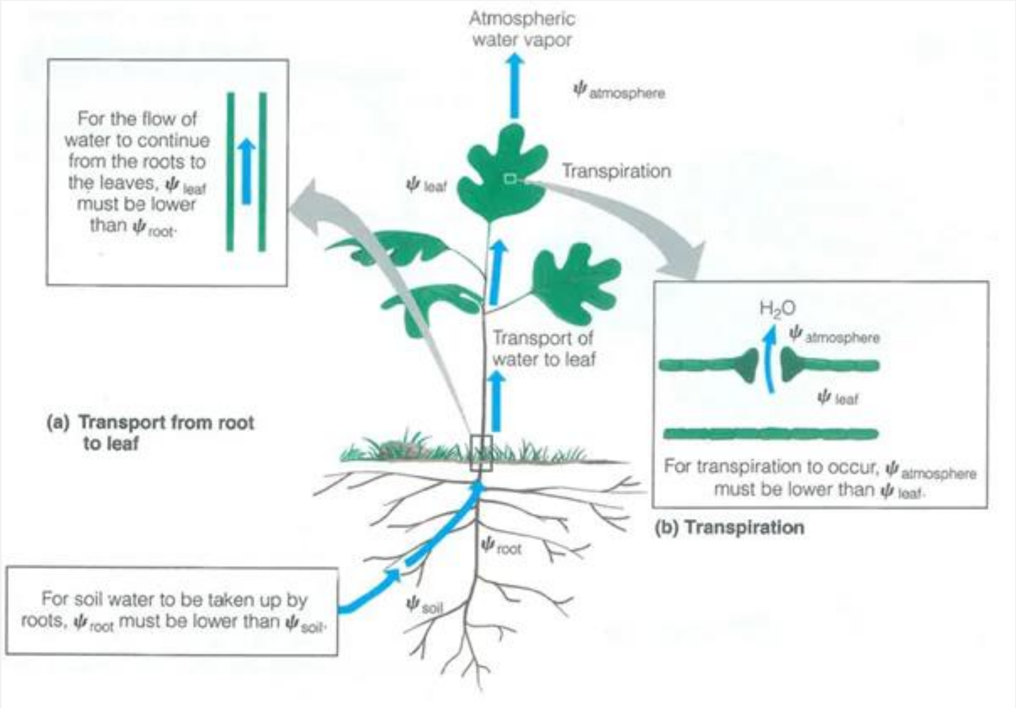


Diagram of plant transpiration process [3]

TEMPERATURE/HUMIDITY RANGES FOR PLANTS

Rule of thumb for most horticultural crops [4]:

- Temperature ranging from 70 °F - 79°F (21°C - 26°C) during the day, with temperatures ~10°F (5.5°C) lower at night.
- Relative humidity between 55% and 95%

Monstera Deliciosa
https://commons.wikimedia.org/w/index.php?curid=7094

Plant	Ideal Temperature °F	Ideal Temperature °C	Ideal Relative Humidity
Monstera Deliciosa	65 - 90	18.33 - 32.22	60% - 80%
Golden Pothos	65 - 85	18.33 - 29.44	50% - 70%
Syngonium Wendlandii	59 - 86	15 - 30	60% - 80%
Poblano	70 - 85	21 - 29.44	70% - 80%
Serrano	71 - 85	22 - 29.44	70% - 80%
Tomato	70 - 79	21 - 26	80% - 90%

TEMPERATURE AND HUMIDITY

RELATIVE HUMIDITY

$$RH = \frac{amount\ of\ water\ vapor\ in\ air}{max\ capacity\ of\ water\ vapor\ in\ air} * 100$$

- Temperature dependent
- Inversely proportional

ABSOLUTE HUMIDITY

$$AH = \frac{mass\ of\ water\ vapor\ present}{unit\ volume\ of\ air}$$

- Temperature independent*

SPECIFIC HUMIDITY

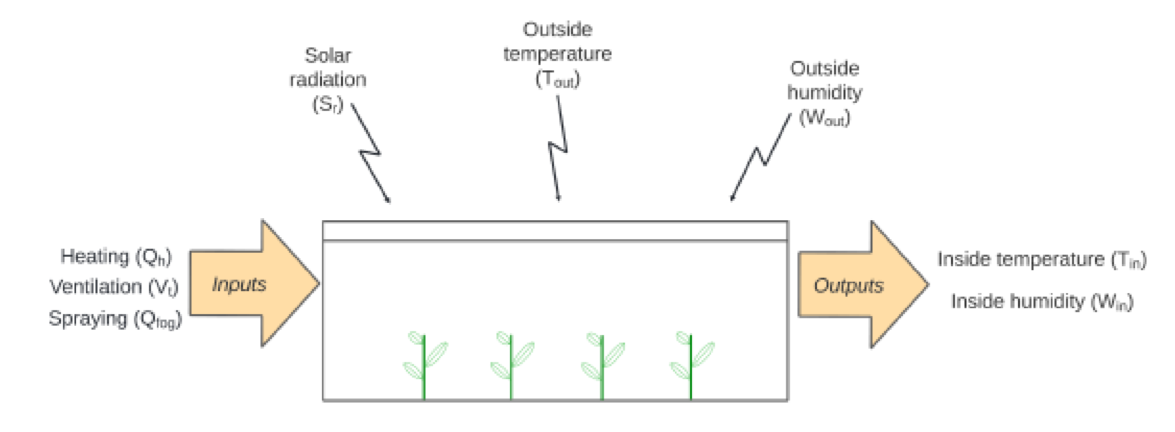
$$SH = \frac{mass\ of\ water\ vapor\ present}{mass\ of\ dry\ air}$$

- Temperature independent

*As long as the volume is kept constant

DESCRIPTION OF PHYSICAL SYSTEM

- Maintain the inside temperature and inside humidity at desired set point
  - Non-linear, coupled system
  - MIMO system; 3 input, 2 output, 3 disturbance inputs
  - Implement controller on Arduino and simulate control of greenhouse microclimate



Greenhouse Model Inputs, Outputs, and Disturbances [1]

MATHEMATICAL MODEL

$$\frac{dT_{in}}{dt} = \frac{Q_h}{\rho V C_p} + \frac{S_i}{\rho V C_p} - \frac{\gamma Q_{fog}}{\rho V C_p} - (T_{in} - T_{out})[\frac{V_t}{V} + \frac{UA}{\rho V C_p}] \quad (1)$$

$$\frac{dW_{in}}{dt} = \frac{Q_{fog}}{\rho V} + \frac{E}{\rho V} - \frac{V_t(W_{in} - W_{out})}{\rho V} \quad (2)$$

Outputs

T_{in} = Inside Temperature (°C) = x_1

W_{in} = Inside Humidity (g/m^3) = x_2

Inputs

V_t = Ventilation rate (m^3/s) = u_1

Q_{fog} = Water capacity of fog system (g/s) = u_2

Q_h = Heat provided by heater (Watts) = u_3

Disturbances

T_{out} = Outside Temperature (°C) = d_1

W_{out} = Outside Humidity (g/m^3) = d_2

S_r = Intercepted solar radiant energy (Watts/m^2) = d_3

TABLE I

CONSTANTS AND VARIABLES IN THE EQUILIBRIUM POINT. [11]

Constant	Value	Variable	Value
V	$4000\ m^3$	$\overline{S_r}$	$300\ W/m^2$
U	$25\ W/(m^2 \cdot K)$	$\overline{T_{out}}$	$25\ °C$
A	$1000\ m^2$	$\overline{W_{out}}$	$4\ g/m^3$
ρ	$1.2\ kg/m^3$	$\overline{V_t}$	$10\ m^3/s$
C_p	$1006\ J/(kg \cdot K)$	$\overline{Q_{fog}}$	$18\ g/s$
γ	$2257\ J/g$	-	-

DERIVATION OF MATHEMATICAL MODEL

Specific Heat Capacity – the amount of heat required to change the temperature of a mass by 1°C

$$Q = mC\Delta T$$

$$\Big\Downarrow \frac{d}{dt}$$

$$\dot{Q} = mC\dot{T}$$

$$\Big\Downarrow$$

$$\boxed{\dot{T} = \frac{\dot{Q}}{mC}} \quad (3)$$

Check Units:

$$J = kg * \frac{J}{kgK} * K$$

Check Units:

$$watts = \frac{J}{s} = kg * \frac{J}{kgK} * \frac{K}{s}$$

DERIVATION OF MATHEMATICAL MODEL

Conduction – transfer of heat due to temperature gradient

Check Units:

$$watts = \frac{J}{s} = \frac{W}{m^2 K} * m^2 * K$$

$$\dot{Q} = -UA(T_{in} - T_{out})$$

$$\Downarrow$$

$$mC\dot{T} = \dot{Q} = -UA(T_{in} - T_{out})$$

$$\Downarrow$$

$$\boxed{\dot{T} = \frac{-UA(T_{in} - T_{out})}{mC}} \quad (4)$$

EQUATION (1) REVISITED

$$\frac{dT_{in}}{dt} = \underbrace{\frac{Q_h}{\rho V C_p}}_{\text{Heater Term}} + \underbrace{\frac{S_i}{\rho V C_p}}_{\text{Solar Term}} - \underbrace{\frac{\gamma Q_{fog}}{\rho V C_p}}_{\text{Fog Term}} - (T_{in} - T_{out})[\underbrace{\frac{V_t}{V}}_{\text{Ventilation Term}} + \underbrace{\frac{UA}{\rho V C_p}}_{\text{Conduction Term}}]$$

Additional Discussion:

1. Solar Term
    a. Derived from Eq. (3)
    b. Heat added to system through solar radiation, watts
2. Fog Term
    a. Derived from Eq. (3)
    b. Heat removed from system due to addition of water vapor
3. Ventilation Term
    a. Temperature change due to venting out air

EVAPOTRANSPIRATION RATE, E

$$E = \alpha \frac{S_i}{\gamma} - \beta_T W_{in} \qquad (5)$$

Check Units:

$$\frac{g}{s} = \frac{\frac{W}{m^2} * m^2}{\frac{J}{g}} - \frac{g}{s}$$

Where:

$S_i = S_r * A$

α – coefficient to account for leaf shading and leaf area index

β – coefficient to account for thermodynamic constants

γ – latent heat of vaporization

EQUATION (2) REVISITED

$$\frac{dW_{in}}{dt} = \underbrace{\frac{Q_{fog}}{\rho V}}_{\text{Fog Term}} + \underbrace{\frac{E}{\rho V}}_{\text{Transpiration Term}} - \underbrace{\frac{V_t(W_{in} - W_{out})}{\rho V}}_{\text{Venting Term}}$$

Additional Discussion:

1. Fog Term
   a. Mass of water vapor added to system due to fogging
2. Transpiration Term
   a. Mass of water vapor added to system through transpiration
3. Ventilation Term
   a. Mass of water vapor removed from system through venting

LINEARIZED MODEL

$$P_{n_{(s)}} = \begin{pmatrix} G_{11(s)} & G_{12(s)} \\ G_{21(s)} & G_{22(s)} \end{pmatrix}.$$

$$P_{n_{(s)}} = \begin{pmatrix} \frac{-0.212 \cdot e^{-147.625s}}{126.892s+1} & \frac{-0.061 \cdot e^{-147.625s}}{130.829s+1} \\ \frac{-0.281 \cdot e^{-147.625s}}{435.488s+1} & \frac{0.100 \cdot e^{-147.625s}}{480.172s+1} \end{pmatrix}$$

- Authors linearized non-linear model using non-linear system identification techniques
- Delay calculated from average of delays from reference source
- Delay added to account for sensor delay in real system

Transfer Functions:

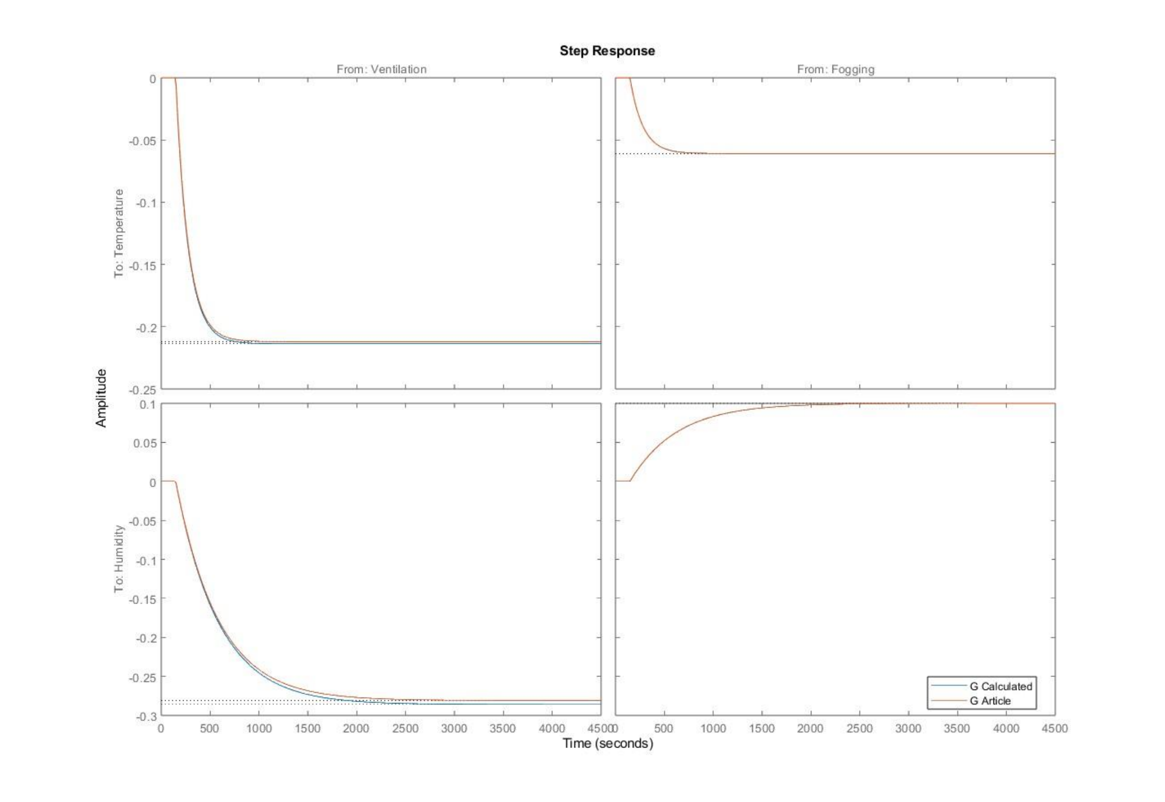
- G_{11} is Temperature response due to ventilation
- G_{12} is Temperature response due to fogging
- G_{21} is Humidity response due to ventilation
- G_{22} is Humidity response due to fogging

COMPARISON TO ECE763 LINEARIZATION

$$A = \begin{bmatrix} \frac{\partial F}{\partial x_1} & \frac{\partial F}{\partial x_2} \\ \frac{\partial G}{\partial x_1} & \frac{\partial G}{\partial x_2} \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{\partial F}{\partial u_1} & \frac{\partial F}{\partial u_2} \\ \frac{\partial G}{\partial u_1} & \frac{\partial G}{\partial u_2} \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \qquad (6)$$



RELATIVE GAIN ARRAY (RGA)

$$RGA(G) = \Lambda(G) \triangleq G \,.\!*\, (G^{-1})^T \qquad (7)$$

- Ratio of the open loop gain to the closed loop gain for each transfer function, ∀ω [7]
- “Measures” the amount of interaction between inputs and outputs
- All columns in the RGA sum to 1, all rows in the RGA sum to 1
- Entries ≈ 1 indicate strong interactions between input/output
- Entries ≈ 0.5 indicate strong coupling in system between inputs and outputs
- Negative entries indicate interactions in the opposite direction → instability

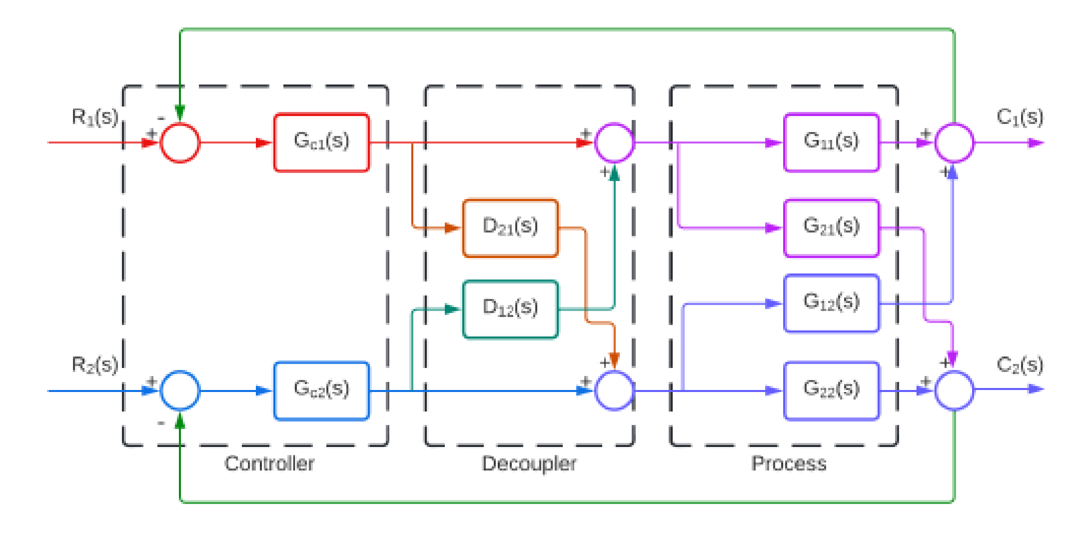
$$\Lambda = \begin{pmatrix} -0.212 & -0.061 \\ -0.281 & 0.100 \end{pmatrix} \left[\begin{pmatrix} -0.212 & -0.061 \\ -0.281 & 0.100 \end{pmatrix}^{-1} \right]^T$$

$$\Lambda = \begin{pmatrix} 0.553 & 0.447 \\ 0.447 & 0.553 \end{pmatrix}.$$

DECENTRALIZED CONTROL

- Simplest approach for multivariable controller design [7]
- Diagonal controller
- Design controllers separately, to control a single output

$$K = \begin{bmatrix} k_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & k_n \end{bmatrix}$$



DECOUPLER DESIGN

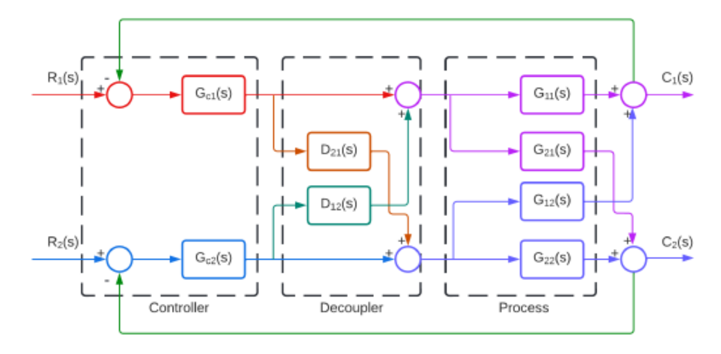
$$G^* = GW_1 = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} * \begin{bmatrix} 1 & D_{12} \\ D_{21} & 1 \end{bmatrix}$$

$$\Downarrow$$

$$G^* = \begin{bmatrix} G_{11} + G_{12}D_{21} & G_{11}D_{12} + G_{12} \\ G_{21} + G_{22}D_{21} & G_{21}D_{12} + G_{22} \end{bmatrix},$$

$$\Downarrow$$

$$G^* = \begin{bmatrix} G_{11} - \frac{G_{12}G_{21}}{G_{22}} & 0 \\ 0 & G_{22} - \frac{G_{21}G_{12}}{G_{11}} \end{bmatrix} \quad (9)$$



$$D_{12} = -\frac{G_{12}}{G_{11}} \qquad D_{21} = -\frac{G_{21}}{G_{22}} \quad (8)$$

DECOUPLER DESIGN

$$D_{12(s)} = -\frac{G_{12(s)}}{G_{11(s)}} = -0.287.$$

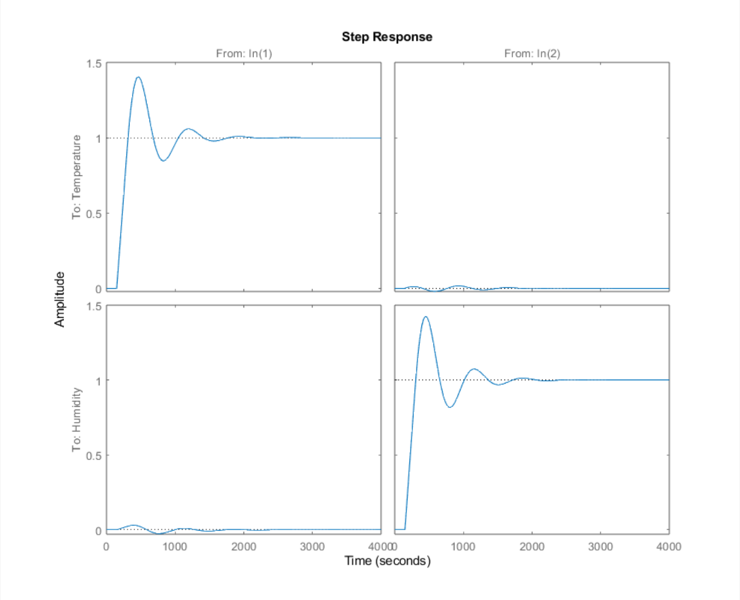
$$D_{21(s)} = -\frac{G_{21(s)}}{G_{22(s)}} = 2.813.$$

$$\Lambda(G^*) = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

CONTROLLER DESIGN

$$Gc_{1(s)} = -2.027\left[\frac{(126.892)s+1}{(126.892)s}\right]$$

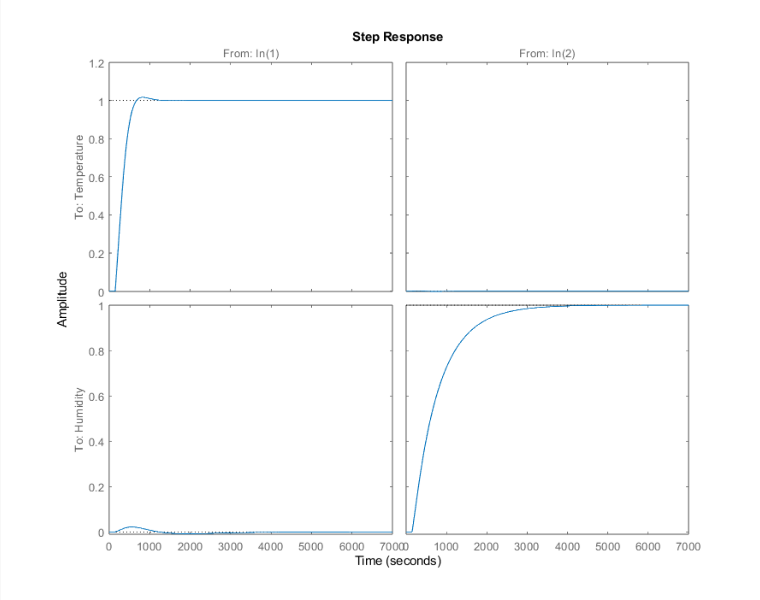
$$Gc_{2(s)} = 16.263\left[\frac{(480.172)s+1}{(480.172)s}\right]$$



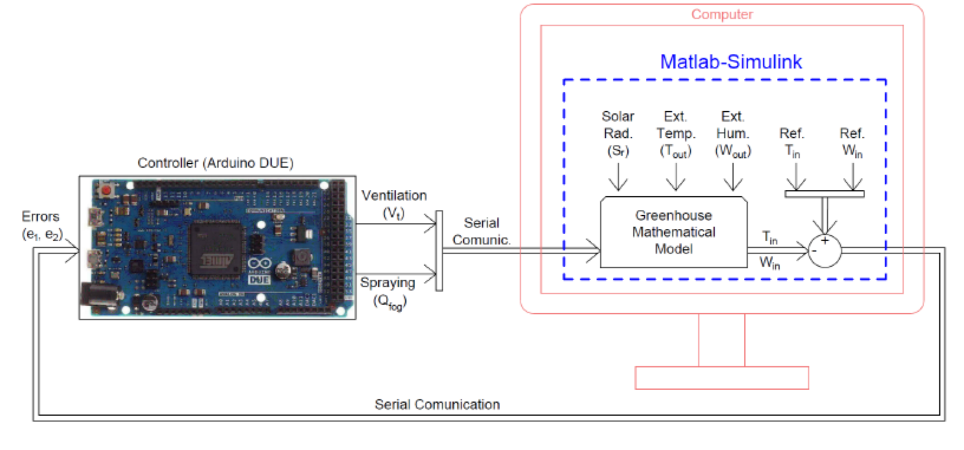
Reduce gain to improve control performance

$$Gc_{1(s)} = -1.014\left[\frac{(126.892)s+1}{(126.892)s}\right]$$

$$Gc_{2(s)} = 3.253\left[\frac{(480.172)s+1}{(480.172)s}\right].$$



CONVERSION TO DISCRETE TIME



"Tustin Approximation" [8]

$$z = e^{sT_s} \approx \frac{1 + sT_s/2}{1 - sT_s/2}. \qquad (10)$$

$$H_d(z) = H(s'), \qquad s' = \frac{2}{T_s}\frac{z-1}{z+1} \qquad (11)$$

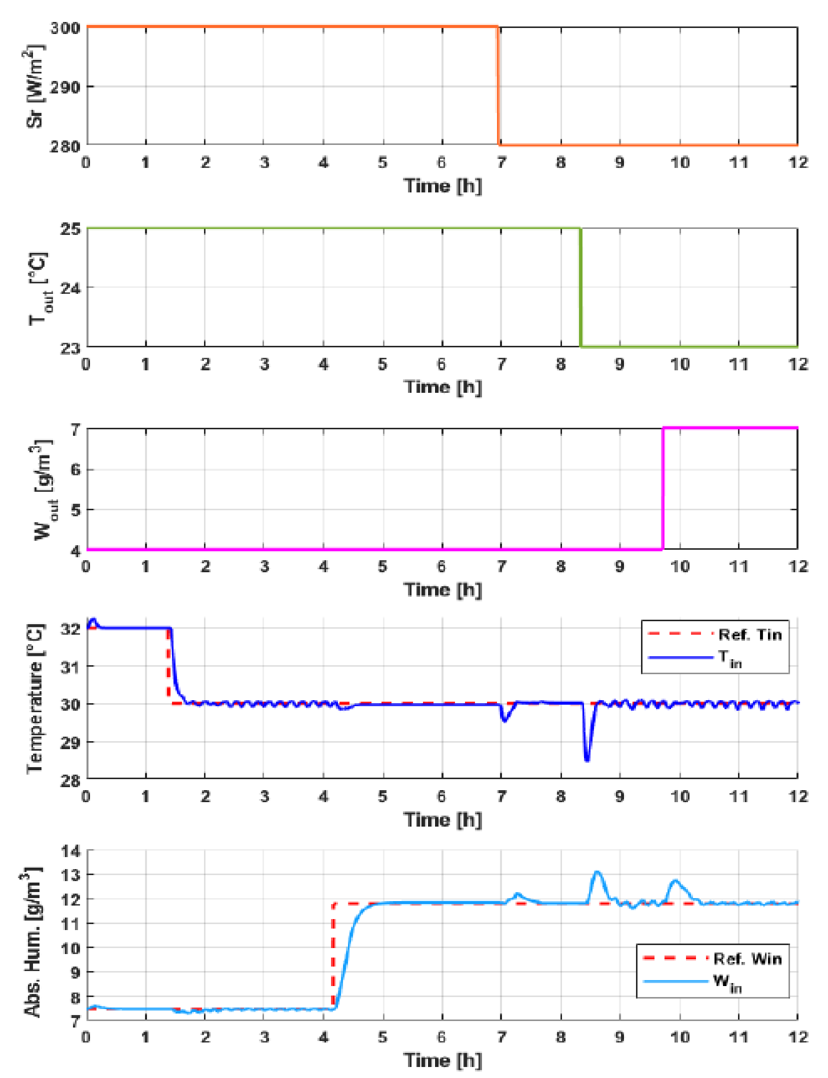
$$Gc_{1(z)} = -1.092 \cdot \left(\frac{z - 0.856}{z - 1}\right)$$

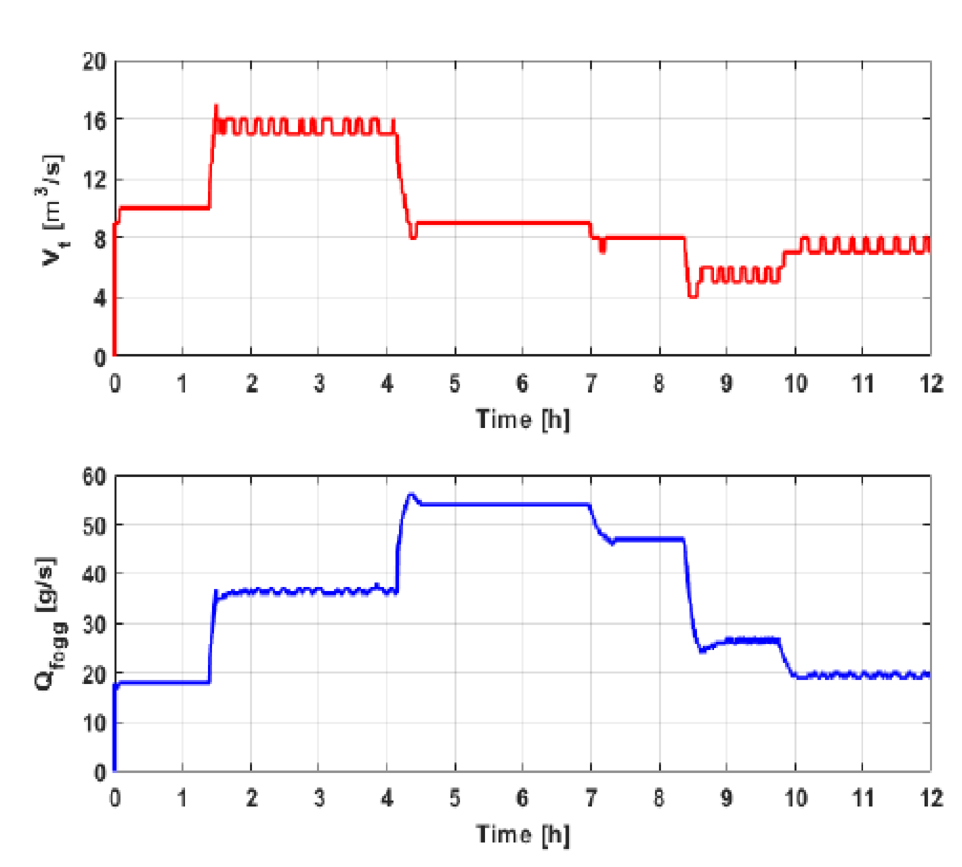
$$Gc_{2(z)} = 3.320 \cdot \left(\frac{z - 0.960}{z - 1}\right).$$

$$u1_{(k)} = u1_{(k-1)} - (1.092)e1_{(k)} + (1.092)(0.856)e1_{(k-1)}$$

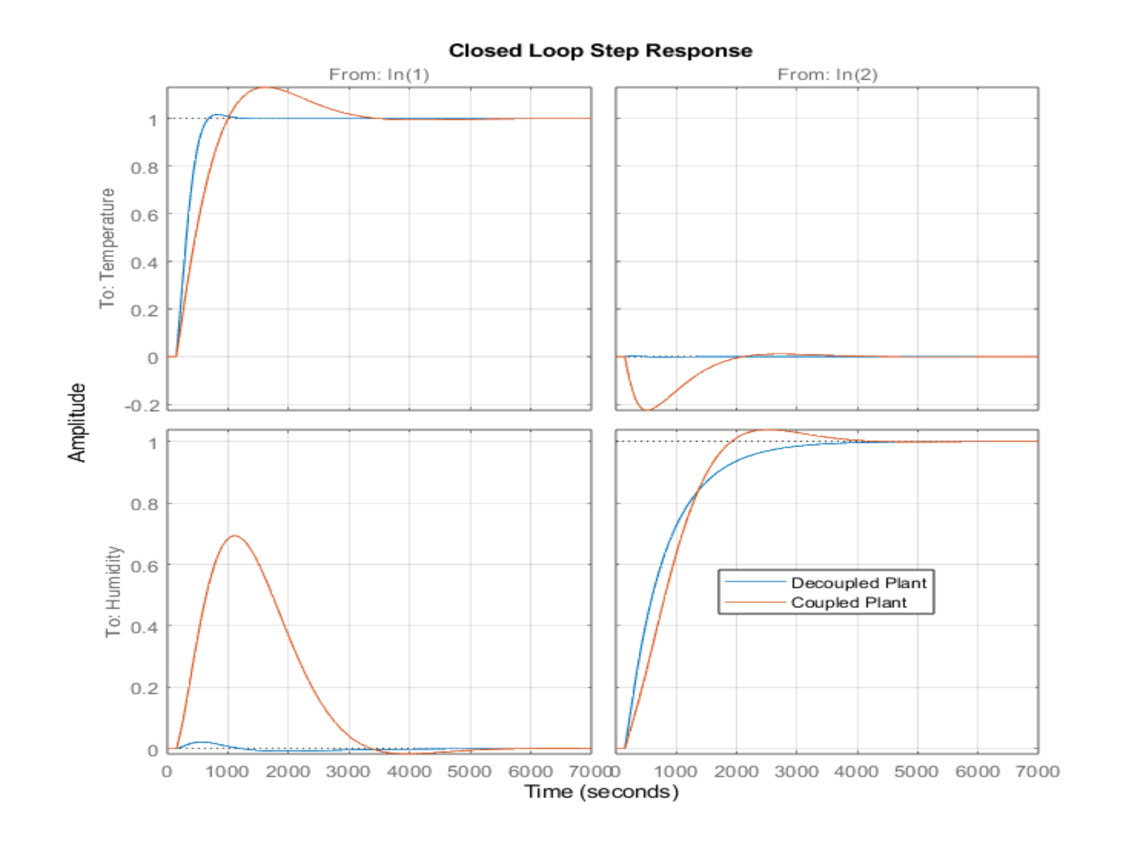
$$u2_{(k)} = u2_{(k-1)} + (3.320)e2_{(k)} - (3.320)(0.960)e2_{(k-1)}$$

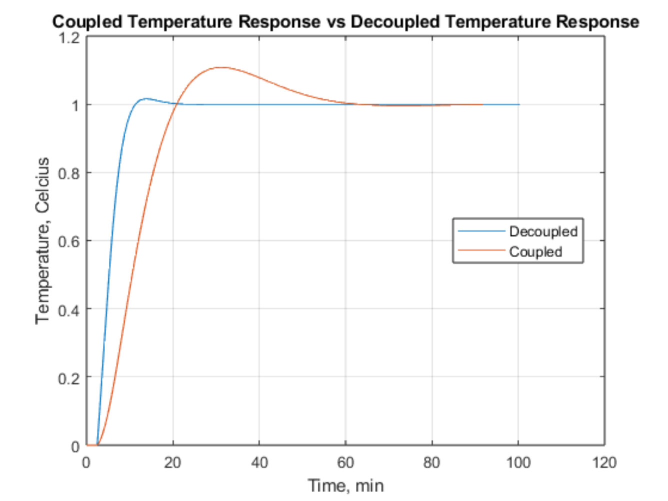
ARTICLE RESULTS

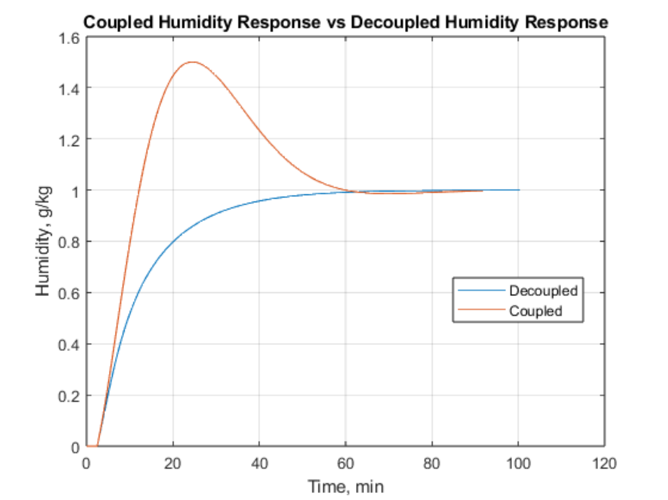




SYSTEM INSIGHTS: DECOUPLING VS COUPLING



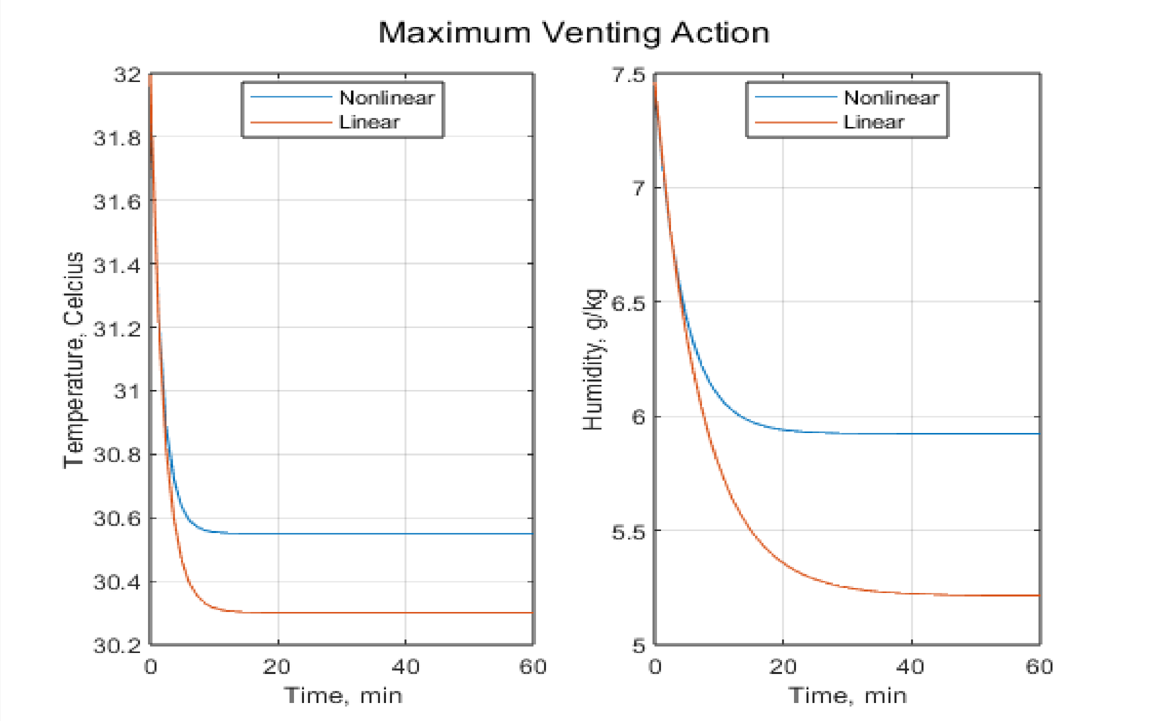


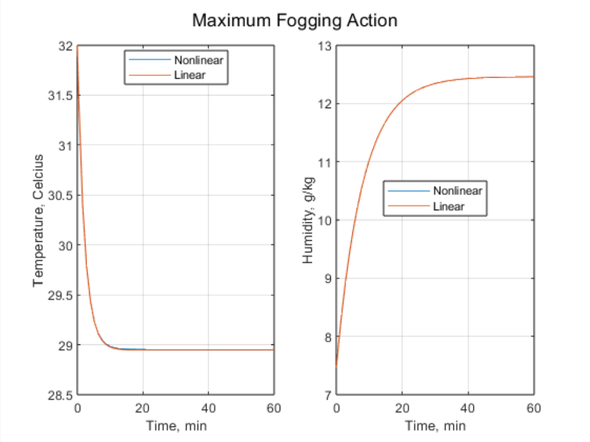


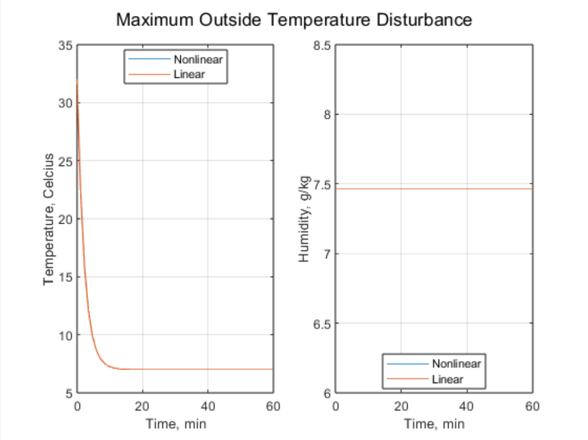
SYSTEM INSIGHTS: VALIDITY OF LINEAR MODEL

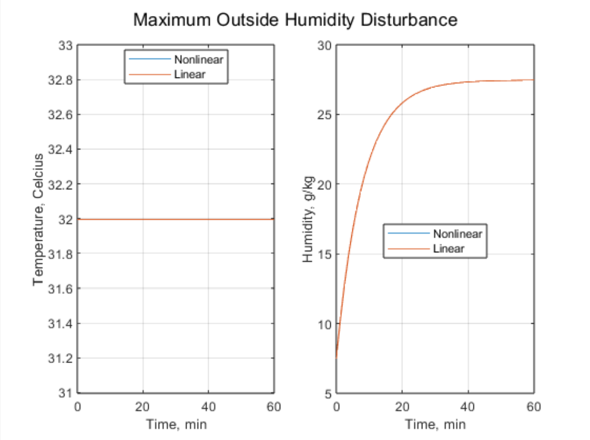
Linear model matches nonlinear system well for most variables over realistic ranges

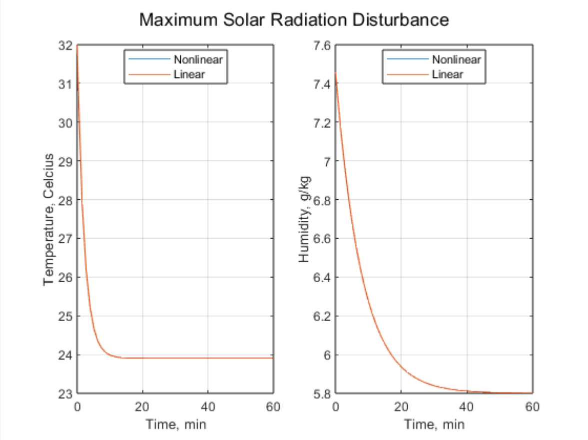
Linear model breaks down under very little change in venting ($\pm 1 m^3/s$)



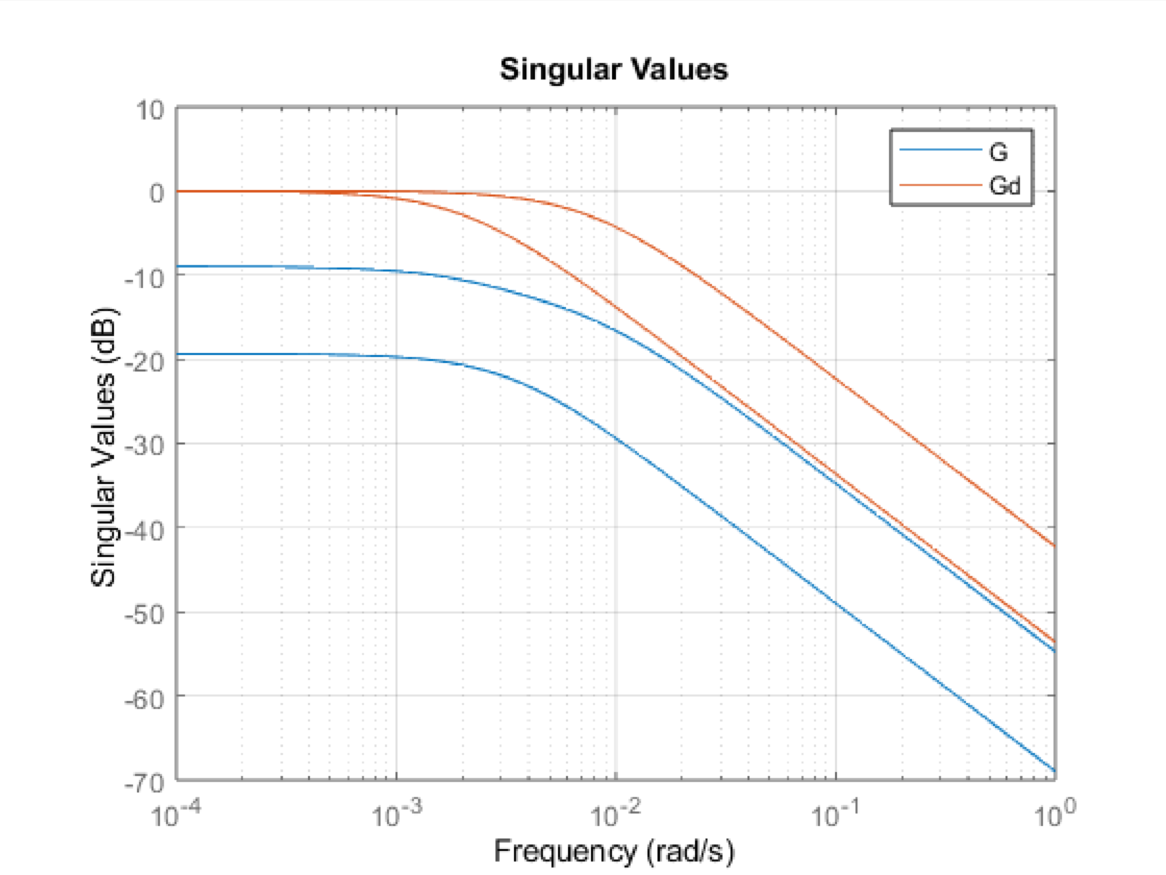


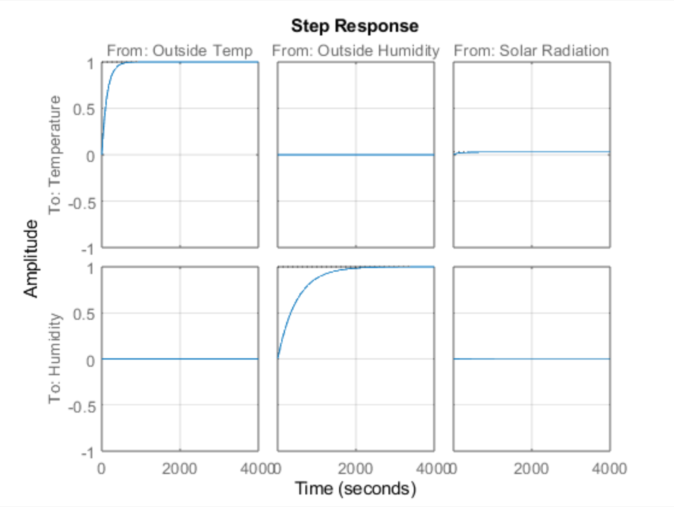


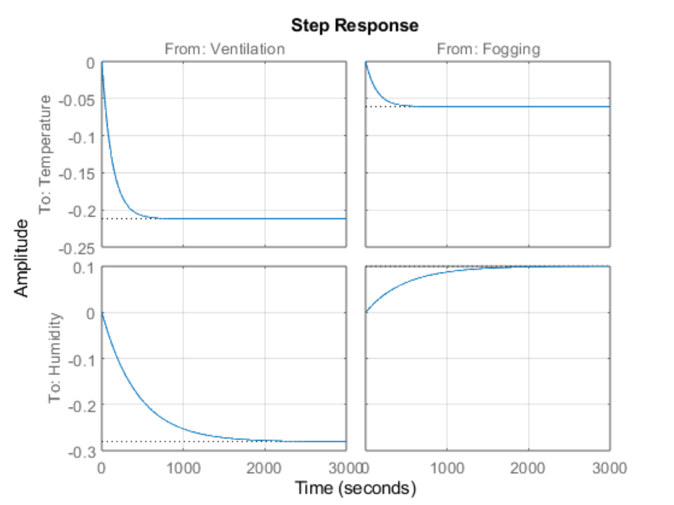




SYSTEM INSIGHTS: DISTURBANCE RESPONSES







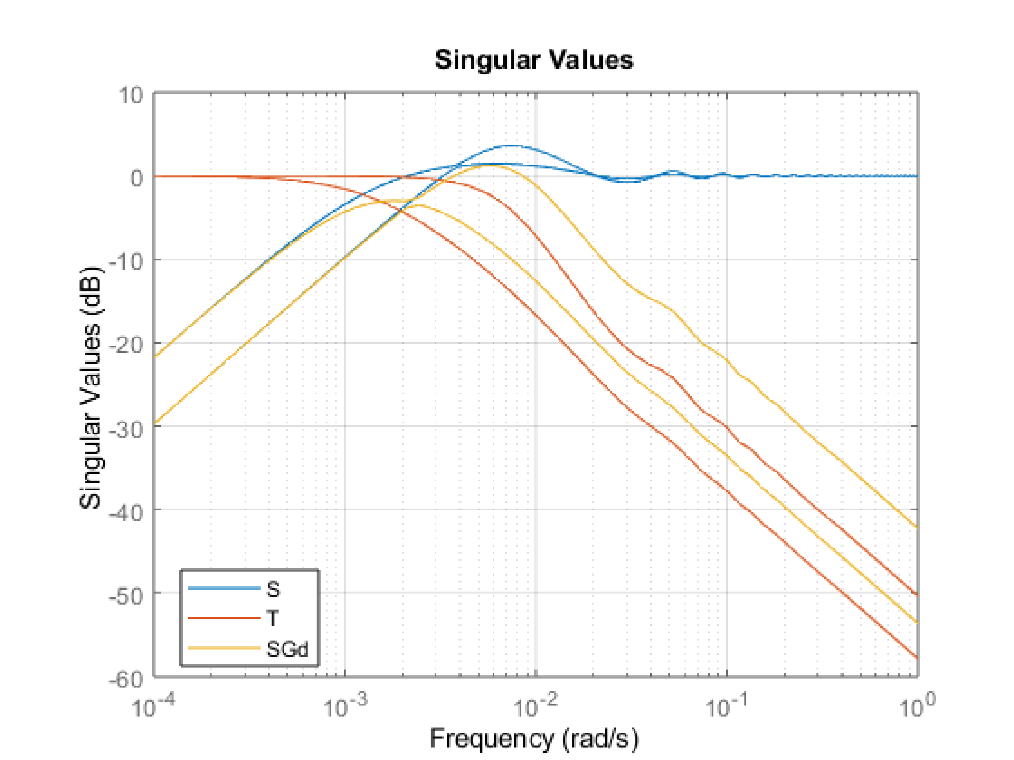
SYSTEM INSIGHTS: S,T, AND SG$_D$

$$\bar{\sigma}(T) \approx 1 \text{ for } \omega < 0.001\ \frac{rad}{s}$$

- Good tracking at steady state
- Good noise rejection

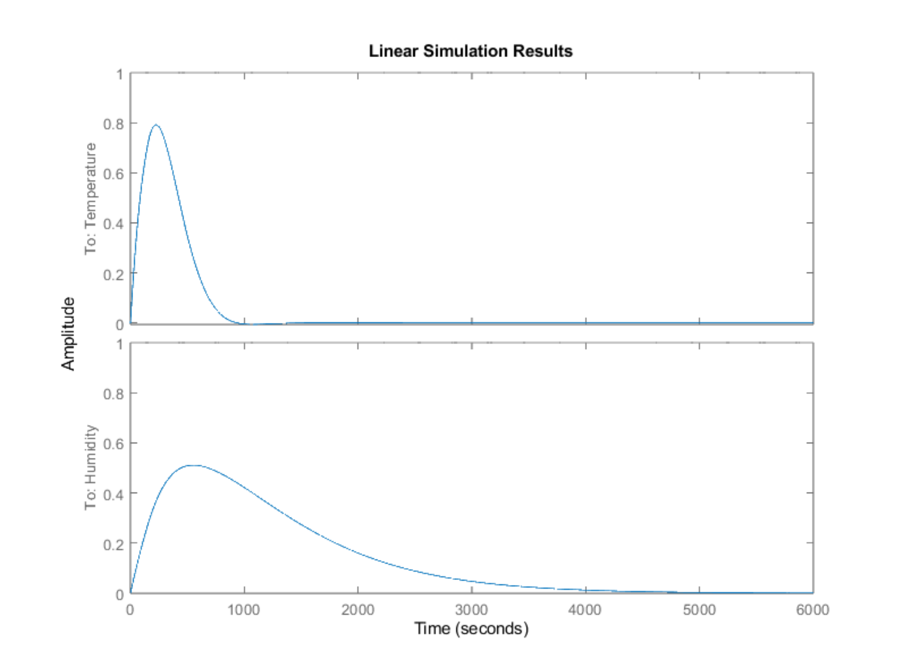
$$\bar{\sigma}(SG_d) > 3\text{dB}, 0.002<\omega<0.012$$

- Bad disturbance rejection in this range

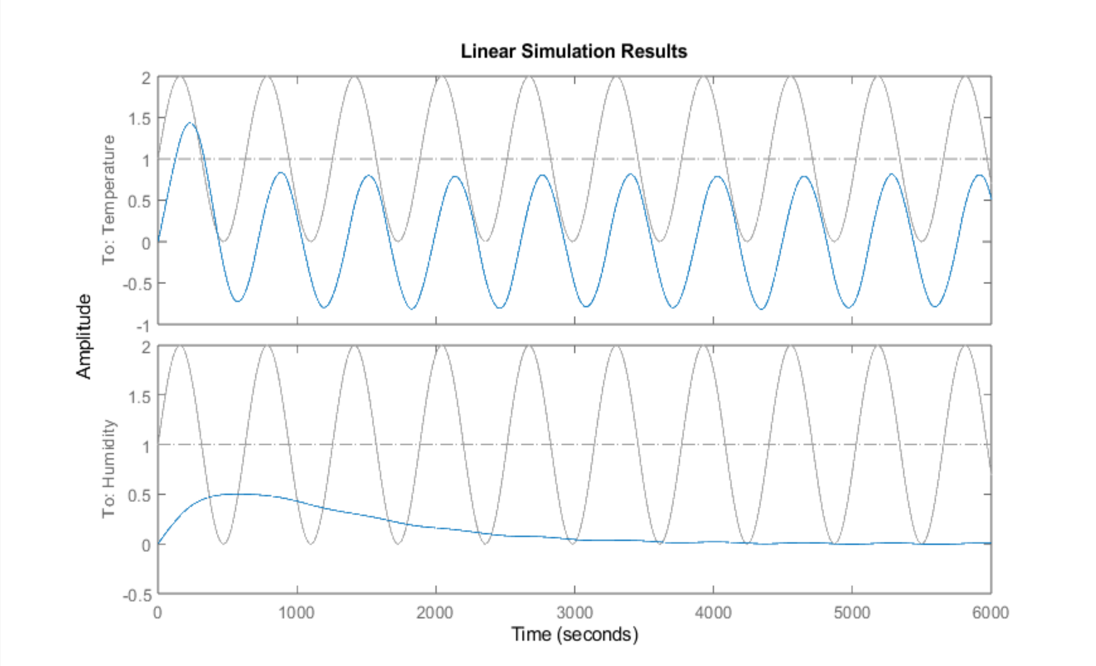


DISTURBANCE REJECTION

Outside Temperature Step Response (ω=0)



Outside Temperature Response(ω=0.01)



REFERENCES

[1] G. Cevallos, J. Pinzon, and O. Camacho, “A microclimate greenhouse multivariable control: A guide to use hardware in the Loop Simulation,” *2022 IEEE International Conference on Automation/XXV Congress of the Chilean Association of Automatic Control (ICA-ACCA)*, 2022.

[2] *Energy Producing Greenhouse: Organic Photovoltaics Integrated Greenhouse.* 2023.

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