Memorial University of Newfoundland
Faculty of Engineering and Applied Science

ENGI8680 Process Control & Instrumentation
Assignment 4
Design, tune and simulate controllers for selected systems in Matlab/Simulink

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Table of Contents

System 1: Scalable Irrigation System

Assignment 1

Process

System Details, Operation, Objective

Irrigation is the process of giving plants a controlled amount of water. It is an important process for agriculture. The operation is a critical system to maintain and grow large amounts of food. See below for an example system in *Figure 1*.

Figure 1: An example irrigation system [1]

Description

The system I plan to design could be a small scale irrigation system for a greenhouse or garden. By monitoring soil moisture levels we can create a closed loop control system for watering. Figure 2 is the process we are trying to emulate. By added control valves to the watering lines we can undersize our pump by only watering one plant bed, or section at a time. This will also allow different levels of moisture for each plant area based on the needs.

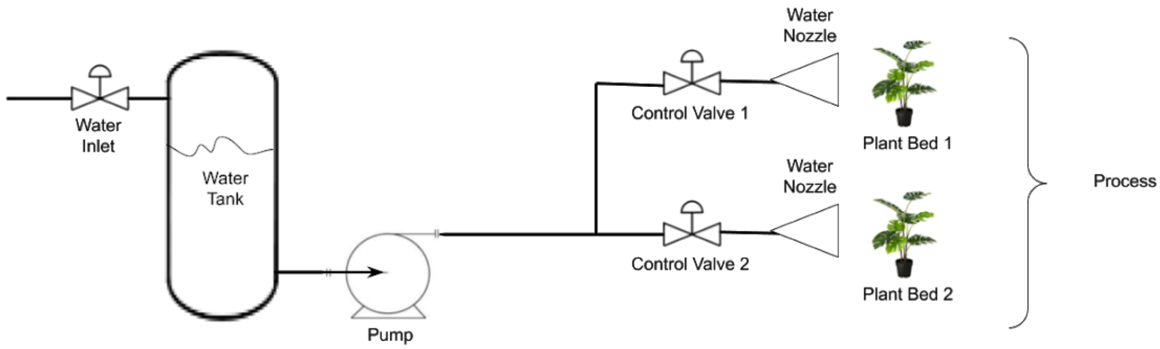


Figure 2: Example greenhouse process

Controlled Variables & System Parameters

Class	Variable	Typical Value	Maximum	Minimum
Input	Water Pumped - V [m^3]	0.1*	1*	0.05*
State Variable	Soil Moisture %	50**	100	0
Output	Moisture			

*Depending on selected pump and modeling after flow or volume water delivered to plants.
*Depending on selected sensor and analog reading

Some of the variables will depend on selection during the next assignment.

Power Supply

Assuming a 12VDC connection is available.

Control objectives

I expect the system step response time to be fast but able to maintain the correct moisture level for a given plant without excessive starting and stopping of the water pump. The main objective will be automatic irrigation while maintaining equipment.

Assignment 2

Instrumentation

Below Figure 3 indicates the required instrumentation, sensors, and actuators required by the system.

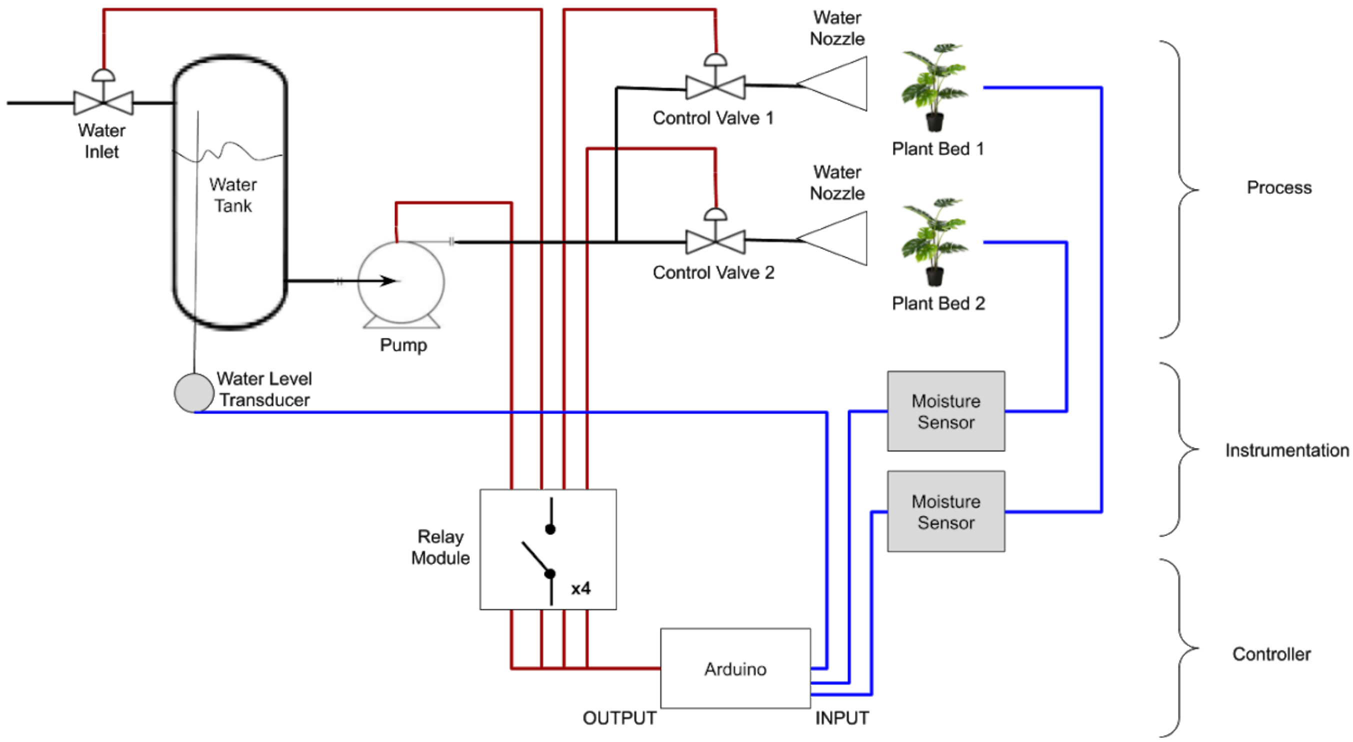


Figure 3: Example greenhouse automatic irrigation system

List of Instrumentation and Actuators

Instrumentation

- Water level transducers
- Moisture Sensor

Actuators

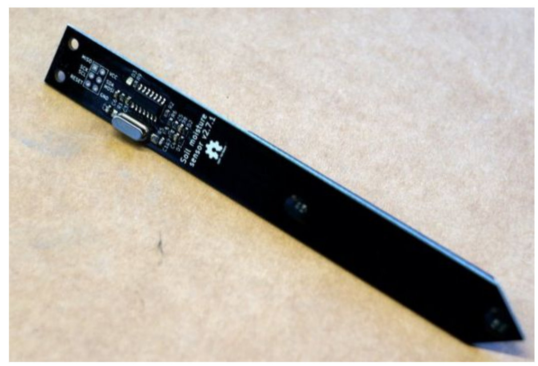
- Water Pump
- Control Valve / Solenoid
- Relay Module

*This design is scalable to multiple plant beds but sensor selection and system simulation can be reused therefore I will continue designed for only one plant bed / row.

Selection Instrumentation and Actuators

Instrumentation

- Water level transducers
    - Ultrasonic Level Measurement method using HC-SR04 Module
    - Datasheet - 5V Supply, compatible with Arduino 5V logic
    - Purchasing - = $2.58 CAD Aliexpress slow ship for lowest cost implementation as per assignment manual.
- Moisture Sensor
    - I2C Soil Moisture Sensor
    - Open Source Moisture sensor, capacitive method selected over resistive to extend life of sensor and combat corrosion.
    - Purchasing - = $13 CAD or for similar module aliexpress slow ship for lowest cost implementation



Actuators

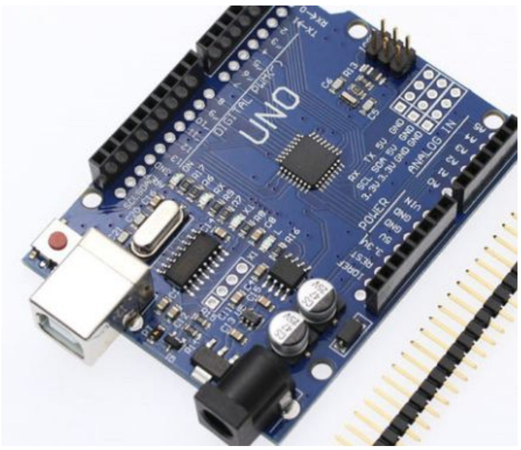
- Water Pump
    - Options are any 12V / 120VAC Water Pump, Water Nozzle spraying pressure is negligible, any pump time besides weak peristaltic pumps are feasible.
    - Operation for 12V / 120VAC will be controlled via relay.
    - Purchasing - = $16.99 CAD
- Control Valve / Solenoid
    - Options are any 12V / 120VAC Solenoid valve that is ~5W, N/C.
    - Operation for 12V / 120VAC will be controlled via relay.
    - Purchasing - = $4.88 CAD
- Relay Module
    - Options are any relay capable of 120VAC and at least 0.5A with x4 relays minimum
    - Purchasing - = $10.86 CAD or aliexpress for lower cost for slow ship alternative.

Electronics Circuits for Instrumentation

The circuit for this implementation is nothing more than wiring together as per the above block diagram. The selection as an [arduino](#) for the controller will take power from the 12VDC power supply. The water level transducer will work on any digital pin. The moisture sensor will connect via I2C. The relay module will distribute 12V / 120VAC to the solenoid and pump respectively at 5V control level logic.

Appropriate power and shared ground amongst the whole system. It could be enclosed in any junction box such as this one locally available.



Power Supply

As from Assignment 1, Assuming 120VAC connection is available.

- Power Bar - Any power bar from local retailer ~$5
    - Wiring for the pump and any 120VAC item will come from here
- 12V Powersupply
    - Powering the Arduino and the Solenoid through a Relay

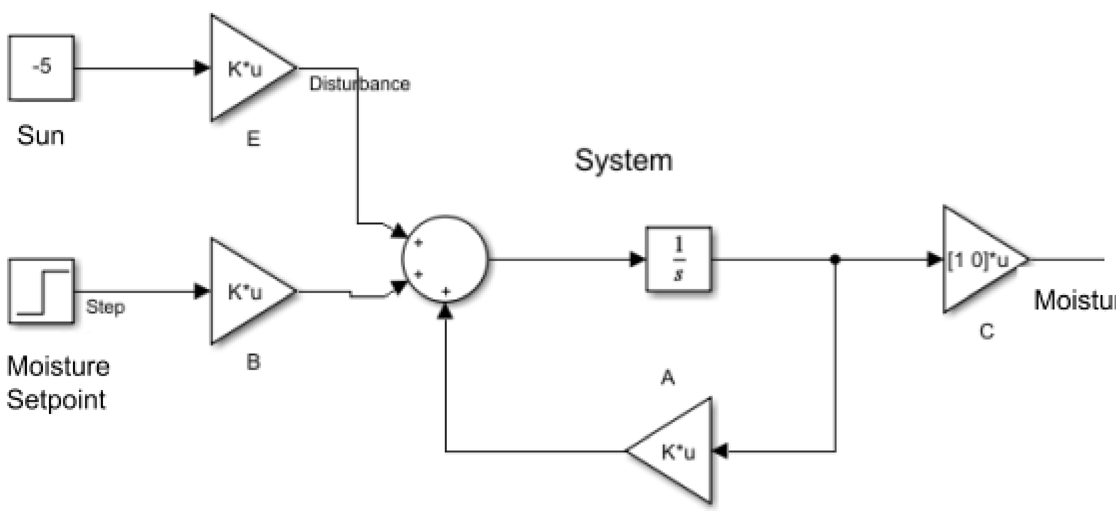
Designed Instrumentation Description

Overall all the parts were selected for lowest cost widely available modules that could be easily substituted for any similar module used by the large arduino community. Selections were made from amazon or aliexpress for the lowest cost. While nearly all selections could be made from either for lowest cost with the only tradeoff being shipping speed for cost.
The moisture sensor was selected from a similar popular model from the linked tindie store, it shows example readings and test code for easy implementation. The wiring for this system is self explanatory as it is just power control through a relay or sensors plugging into an arduino pin.

Assignment 3

A) System Block Diagram

See below Figure for an example system block diagram for this setup. Following the standard state space model with disturbance and labeled blocks. In this example the input to the system would be water pumped or desired soil moisture. From the selected moisture sensors datasheet it can give readings of 0-5V analog or over I2C, this value is scaled between ~0-500. For the purpose of this assignment we can ignore plant watering cycles, and use an example such as carrots optimal soil moisture being 290.
The disturbance of the system would be the change in temperature, we can use the example of the weather heating up or cloud covering being removed as an example to speed up evaporation and plant water usage.
The output of the system is selected to be one of the state variables moisture level. By using moisture reading and disregarding pump water flow it keeps the system simpler, and more cost effective.



B) System Derivation

From using a basic version of water evaporation from this website we can characterize a rough increase in evaporation on a sunny day from the sun.
https://www.engineeringtoolbox.com/evaporation-water-surface-d_690.html
Starting with that equation we can generate a state space model for the moisture control of the greenhouse soil. It is a single order system with one storage element, the soil. See following page.

⇒ Disturbance g_s evaporated water

evaporated water/s
evap coefficient kg/s
Area $[m]^2$
max humidity [kg/kg]
humidity [kg/kg]
time conversion [t]

$$g_s = \theta \cdot A \cdot (x_s - x)/3600$$

$$g_s = 25(1)(0.0146 - 0.0098)/3600 = 3.33 \cdot 10^{-5}\ kg/s$$

$g_s = -3.33 \cdot 10^{-5}$ kg/s water evaporation (comparable to online example rate $3 \cdot 10^{-5}$ ✓)

kg = 1L

⇒ Plant water usage g_P

Rough outline for carrot growth per plant = 15 mL per day

1m² planter ⇒ 100 carrots ⇒ x 15mL per day

$$g_P = 1.5L/day \ /24^3$$

$$g_P = -1.7361 \cdot 10^{-5}\ L/s$$

⇒ Pump flow rate, q [L/s]

selected pump $q = 0.00177\ L/s$

⇒ State space Model

① $\frac{dg_s}{dt} = -3.33 \cdot 10^{-5}\ L/s$ $\quad$ M = moisture (0-500) L/s

② $\frac{dg_P}{dt} = -1.7361 \cdot 10^{-5}\ L/s$

③ $\frac{dq}{dt} = 0.00177\ L/s$

$$\begin{bmatrix} \dot{q} \\ \dot{g}_P \end{bmatrix} = \begin{bmatrix} 0.00177 & 0 \\ 0 & -3.33 \cdot 10^{-5} \end{bmatrix} \begin{bmatrix} q \\ g_P \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} M + \begin{bmatrix} 0 \\ -1.73 \cdot 10^{-5} \end{bmatrix} g_P$$

$$y = \begin{bmatrix} 0 & 0 \end{bmatrix} \begin{bmatrix} q \\ g_P \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} M +$$

C) System I/O

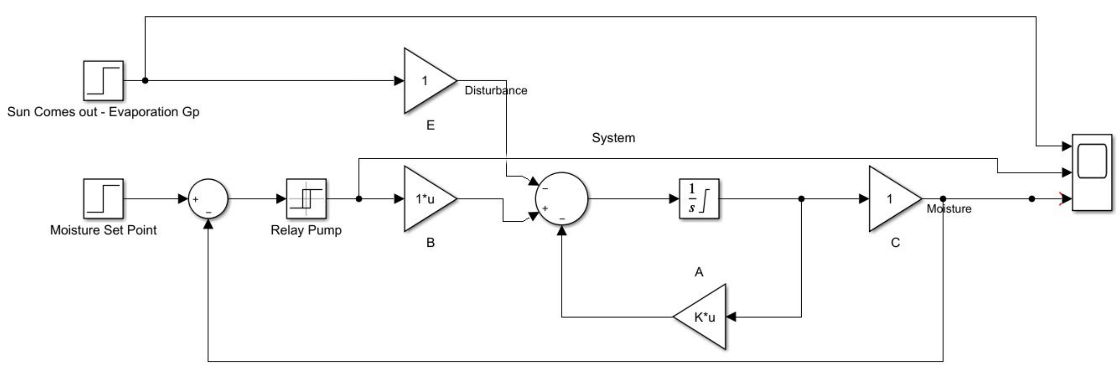
The output is selected as the state variable Tg to make the modeling easier, there is also no D matrix in the solution.

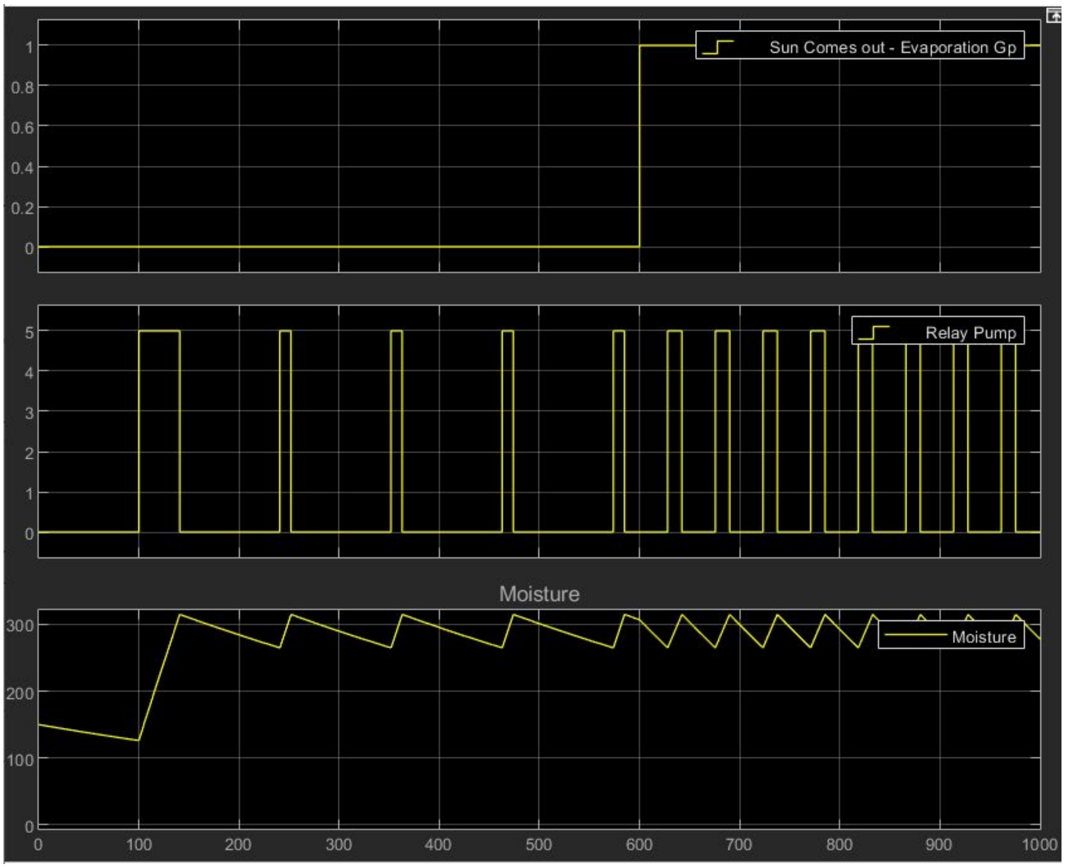
Class	Variable	Typical Value	Maximum	Minimum
Input	Moisture Set	290	500	0
Disturbance	Sun Evap gp	-3.33x10^-5	-3.33x10^-5	0
State Variable	Plant Water Usage gp	-1.73x10^-5	-1.73x10^-5	0
State Variable	Water Pumped	0.00177	0.00177	0
Output	Moisture	290	330	260

D) Simulation

This graph was taken from the initial block diagram basic simulation. It shows Moisture dropping to water usage until the pump starts.

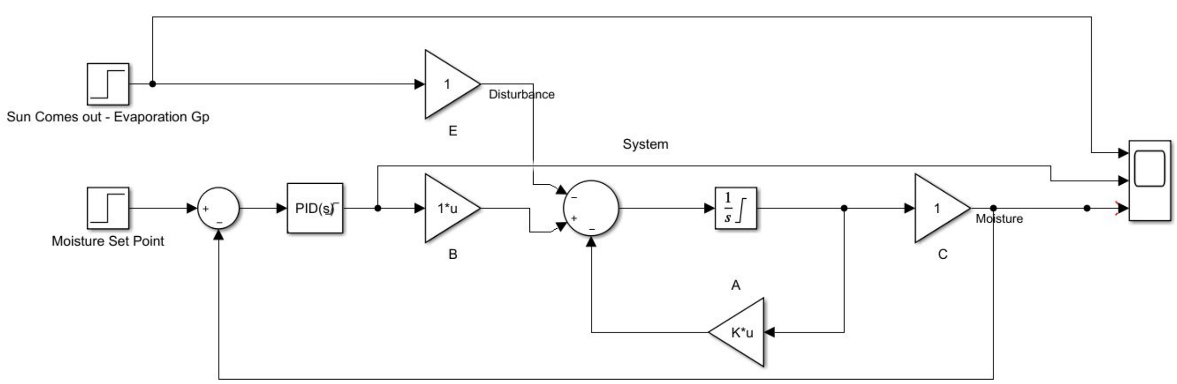
Then I added some basic ON/OFF control for the simulation with a relay for the pump. It can be seen that once the sun comes out and the evaporation increases the pump turns on more often to maintain the set moisture level.



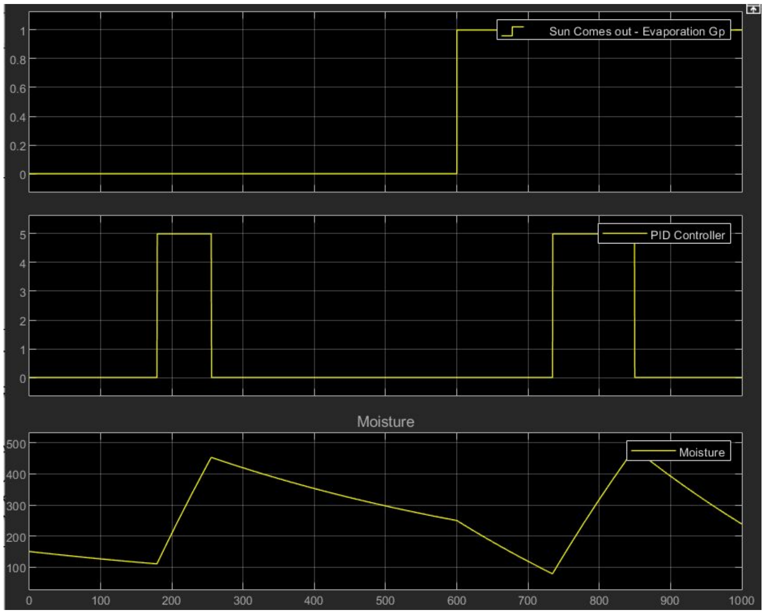


C) Simulation - PID Controller

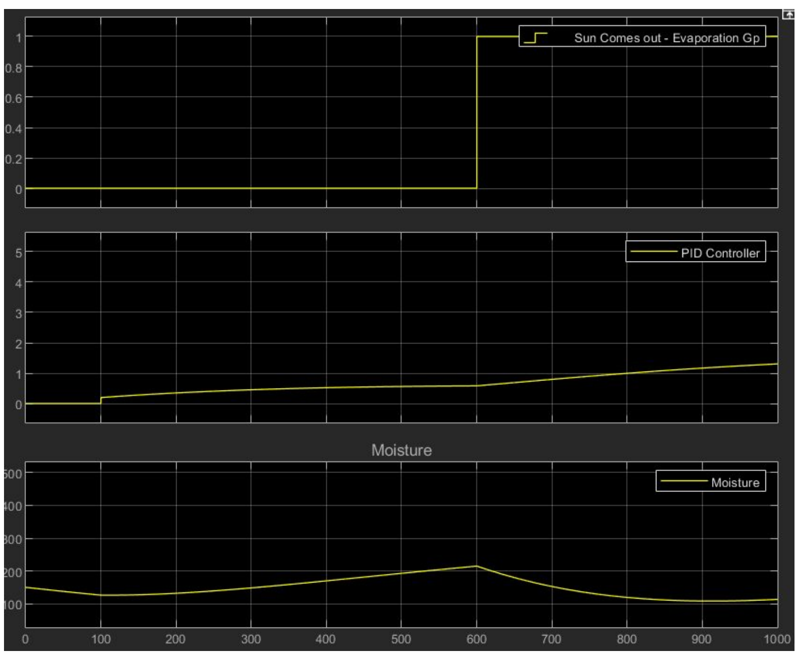
Below is the attached simulink model. By upgrading to a PID controller we can use a pump with SCR or flow control. This will allow the PID controller to respond to changing sun without starting and stopping the heater a lot. The PID was tuned using the simulink Tuner for optimal response.



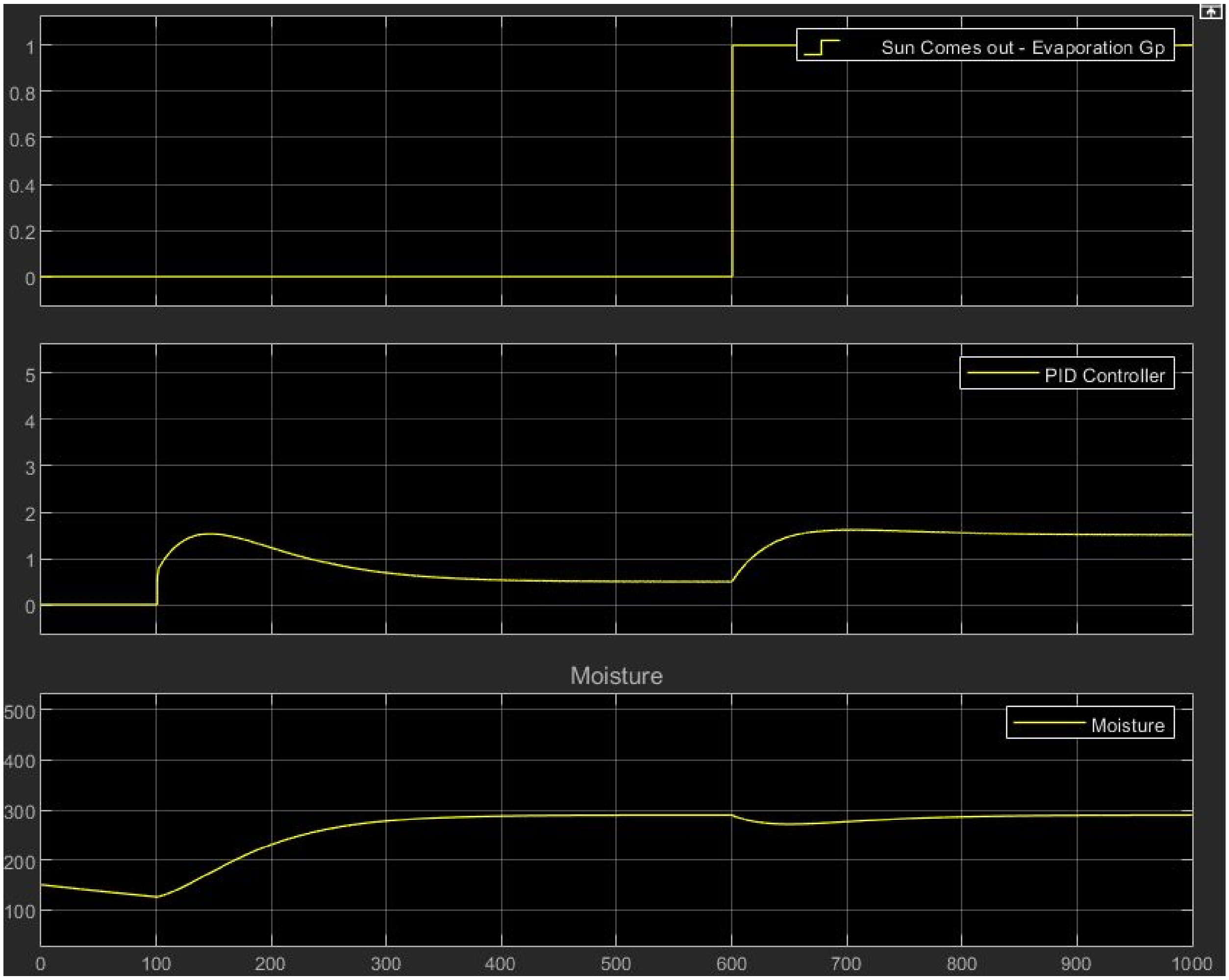
Before Tuning.



After tuning the PID controller we still have a very slow response time.



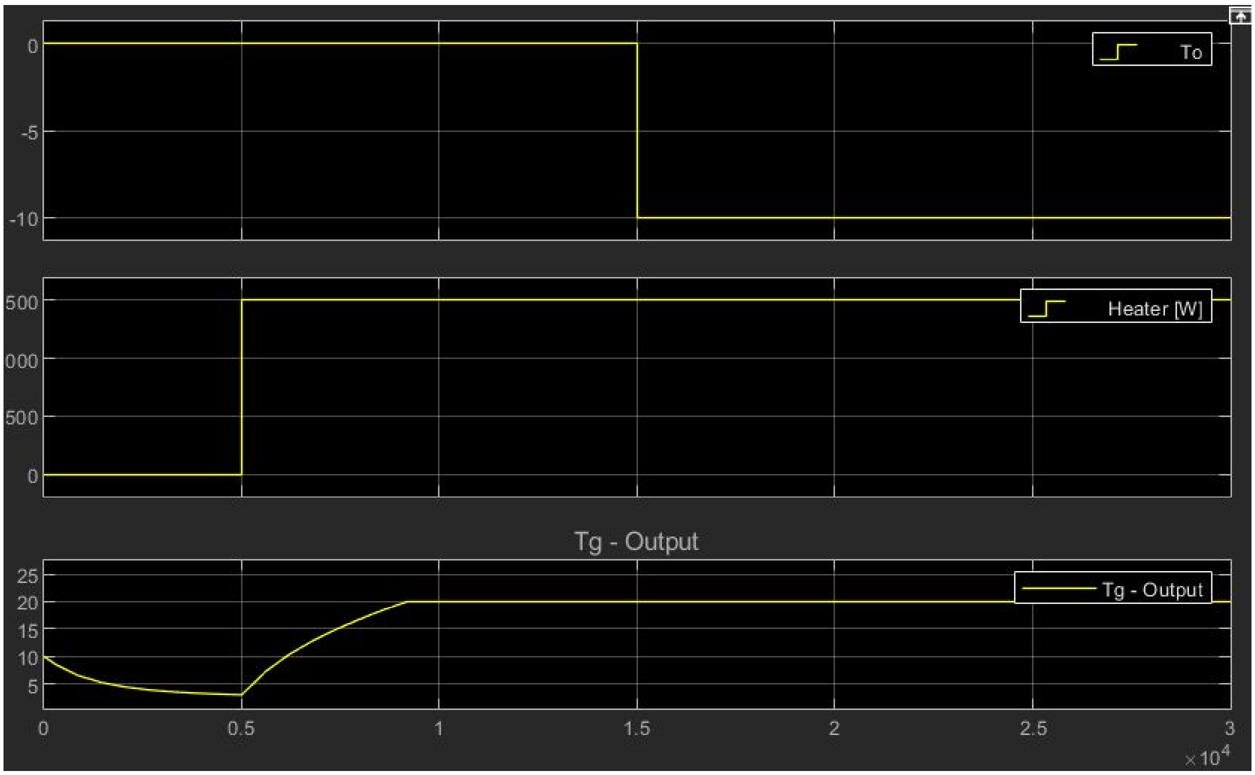
Final desired model shape with a fast response time within the limits of our pump power.



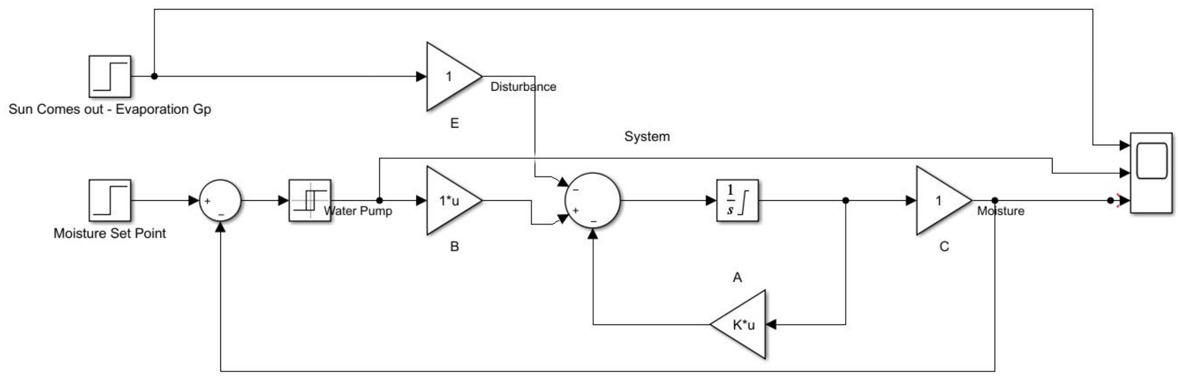
Assignment 4

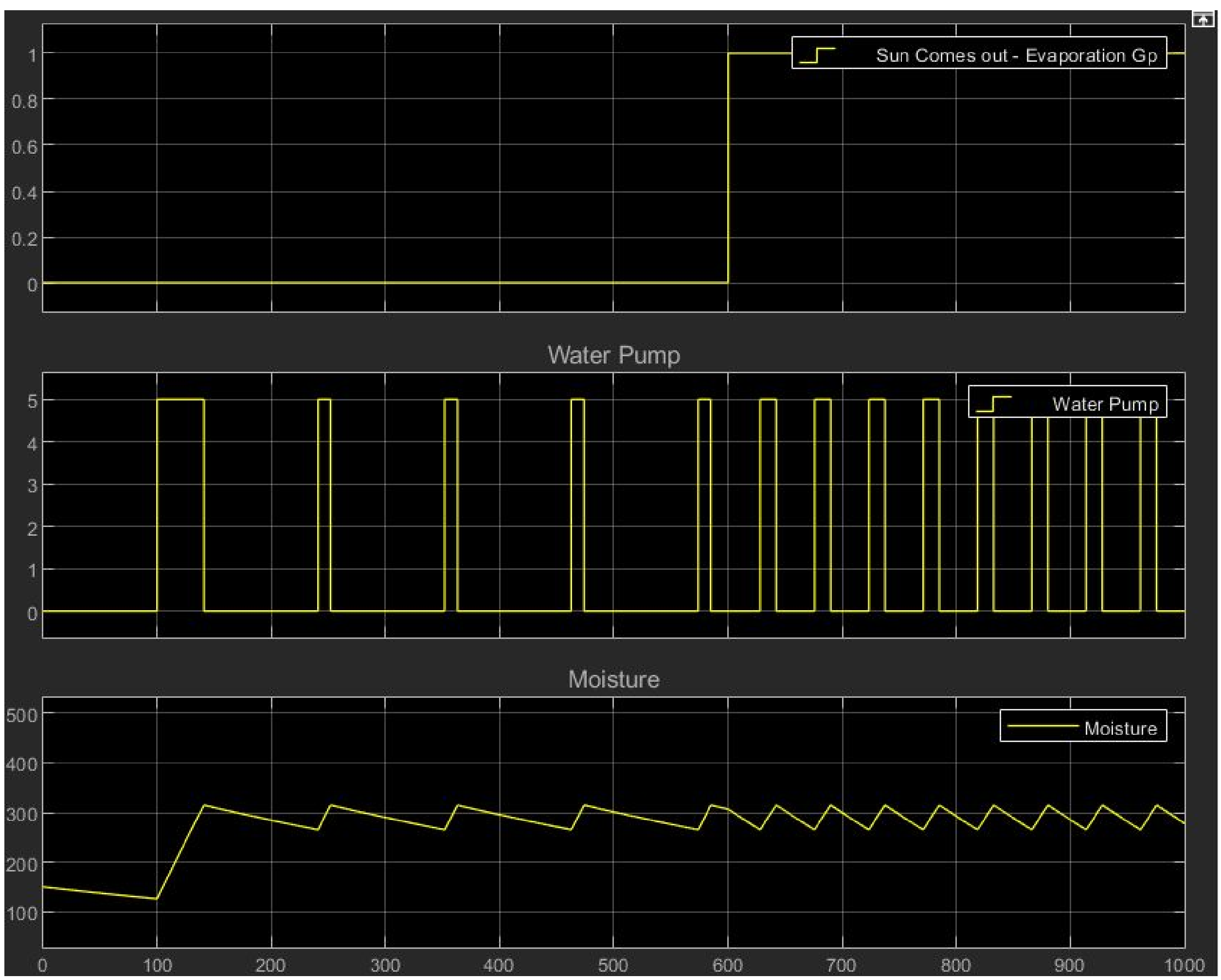
A) ON/OFF Controller

This graph was taken from the initial block diagram basic simulation. It shows Moisture dropping to water usage until the pump starts.

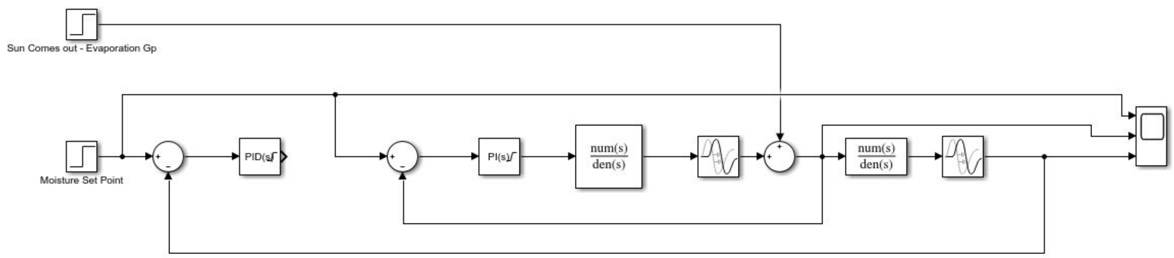


Then I added some basic ON/OFF control for the simulation with a relay for the pump. It can be seen that once the sun comes out and the evaporation increases the pump turns on more often to maintain the set moisture level.


Sun Comes out - Evaporation Gp
1
Disturbance
E
System
Moisture Set Point
Water Pump
1*u
B
1
C
Moisture
A
K*u


Sun Comes out - Evaporation Gp
Water Pump
Water Pump
Moisture
Moisture

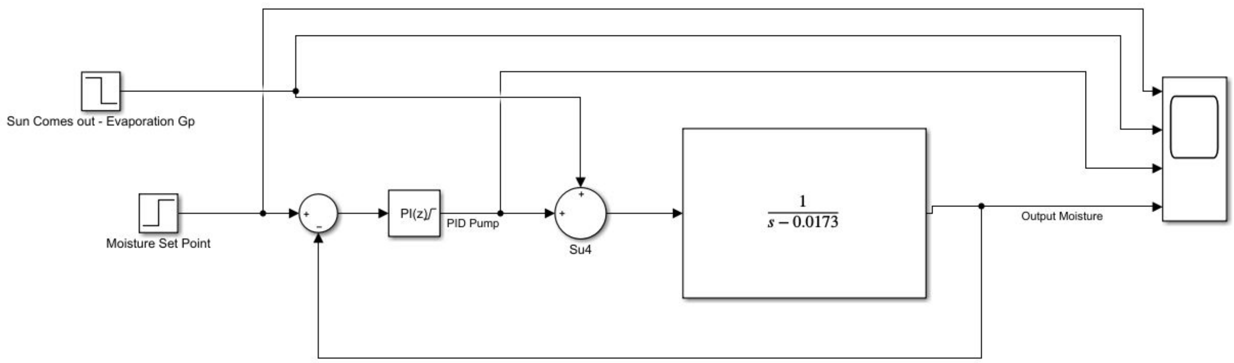
B) Continuous Cascade Controller



I first tried splitting my plant to have the inner loop control the outside sun evaporation disturbance while the main outer loop controlled the heater. I set up the diagram as per the lecture notes to first tune the inner loop PI with the outside main PID disconnected. I think I did not split my plant correctly as the simulation would not work with a cascade controller.

C) Discrete PI/PID Controller

Below is the attached simulink model. By upgrading to a PID controller we can use a pump with SCR or power control. This will allow the PID controller to respond to changing sun evaporation without starting and stopping the pump a lot. The discrete PID was tuned using the simulink Tuner for optimal response. I created the transfer function with Matlab. This one never worked.



System 2: Greenhouse Heating

Assignment 1

Process

System Details, Operation, Objective

Growing crops and plants in windy, cold places like Newfoundland is near impossible in the winter. By adding a temperature control process we can grow food in the cold season, see *Figure 5 below for a heated greenhouse*.

Figure 5: An heated greenhouse. [2]

Description

The system I plan to design could be a small scale heating system for a small greenhouse structure. By monitoring temperature inside the greenhouse we can create a closed loop control system for heating. Figure 6 is the process we are trying to emulate.

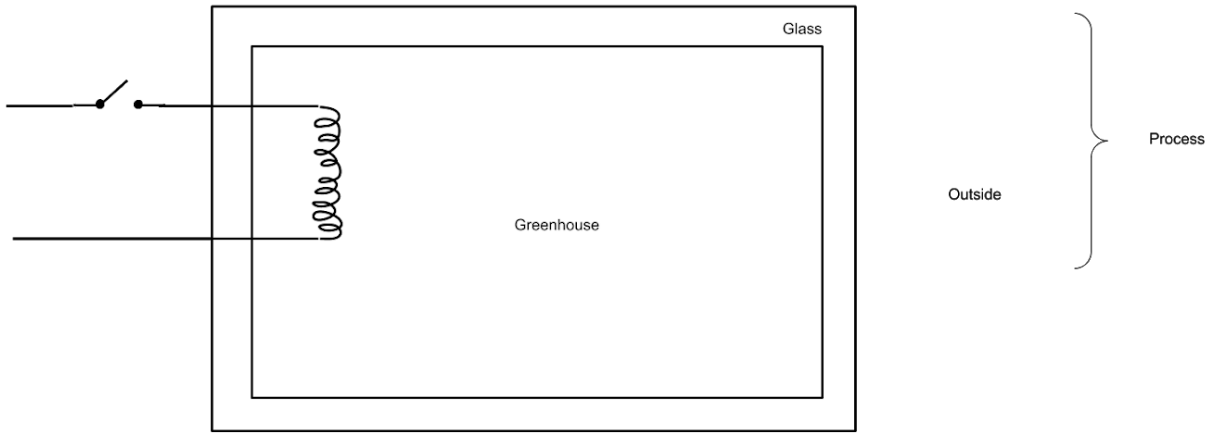


Figure 6: Example greenhouse temperature control process

Controlled Variables & System Parameters

Class	Variable	Typical Value	Maximum	Minimum
Input	Heater - q [W]	1000*	5000	1000
Input	Outside Temp - To [C]	5	15	-10
State Variable	Temp Greenhouse air - Tg [C]	10	15	5
State Variable	Temp Glass Wall - Tgw [C]	6	15	-10
Output	Temp Greenhouse air - Tg [C]	10	15	5

***Depending on selected model, and what plants I decide to grow after more research

Assuming the greenhouse will have glass pane construction with typical C and R values from lecture notes. For the simulation portion of the assignments I could gather temperature data over time for Newfoundland.

Power Supply

Assuming a 120VAC connection is available.

Control objectives

I expect the system step response time to be slow but able to maintain the inside temperature without excessive starting and stopping of the space heater.

Assignment 2

Instrumentation

Below Figure 7 indicates the required instrumentation, sensors, and actuators required by the system.

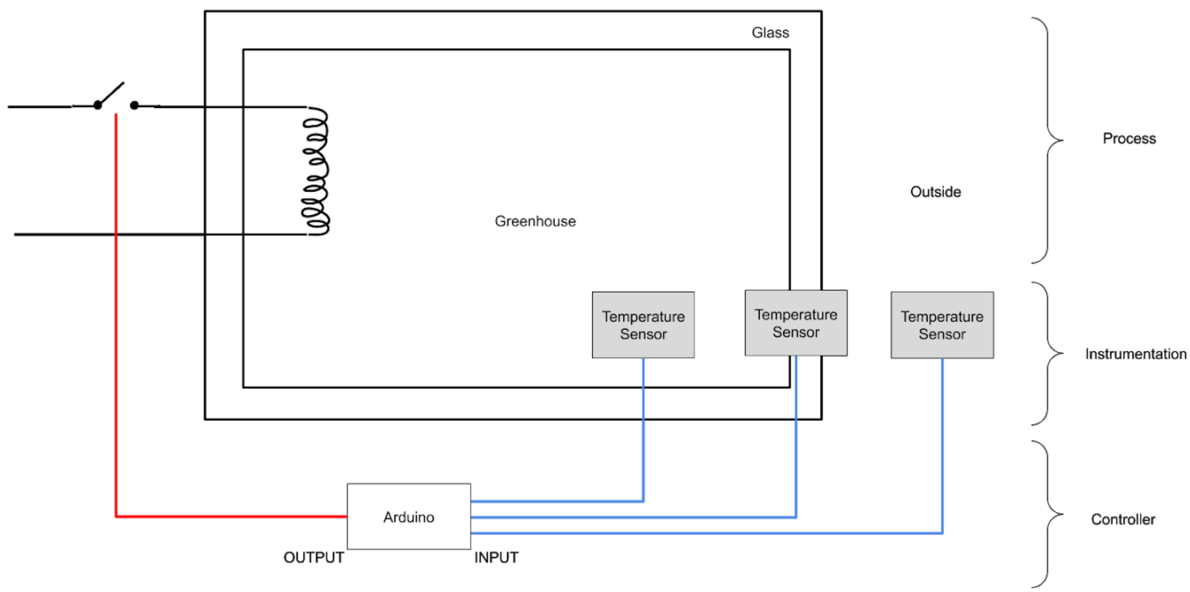


Figure 7: Example greenhouse heating system

List of Instrumentation and Actuators

Instrumentation

- Temperature Sensor

Actuators

- Relay Module for Heater

Selection Instrumentation and Actuators

Instrumentation

- DS18B20 Temperature Sensor
    - Ultrasonic Level Measurement method using HC-SR04 Module
    - Datasheet - 5V Supply, compatible with Arduino 5V logic
    - Purchasing - = $3.26 CAD Aliexpress slow ship for lowest cost implementation as per assignment manual.

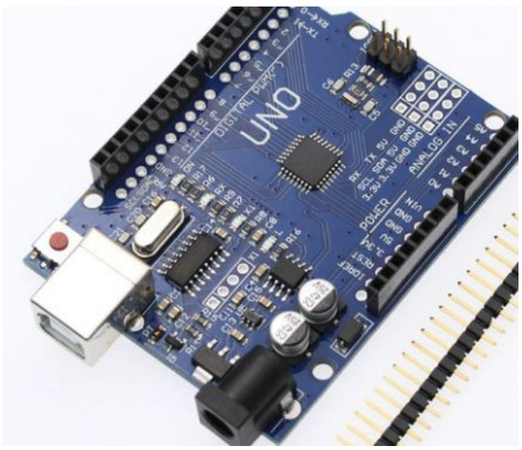
Actuators

- Relay Module
    - Options are any relay capable of 120VAC and at least 10A with x1 relay minimum
    - Purchasing - = $10.86 CAD or aliexpress for lower cost for slow ship alternative.

Electronics Circuits for Instrumentation

The circuit for this implementation is nothing more than wiring together as per the above block diagram. The selection as an [arduino](#) for the controller will take power from the 12VDC power supply. The temperature sensor will accept 5V power and work with any I/O pin over 1wire communication. The relay module will distribute 120VAC to any space heater.

Appropriate power and shared ground amongst the whole system. It could be enclosed in any junction box such as this [one](#) locally available.



Power Supply

As from Assignment 1, Assuming 120VAC connection is available.

- [Power Bar](#) - Any power bar from local retailer ~$5
    - Wiring for the pump and any 120VAC item will come from here
- [12V Powersupply](#)
    - Powering the Arduino and the Solenoid through a Relay

Designed Instrumentation Description

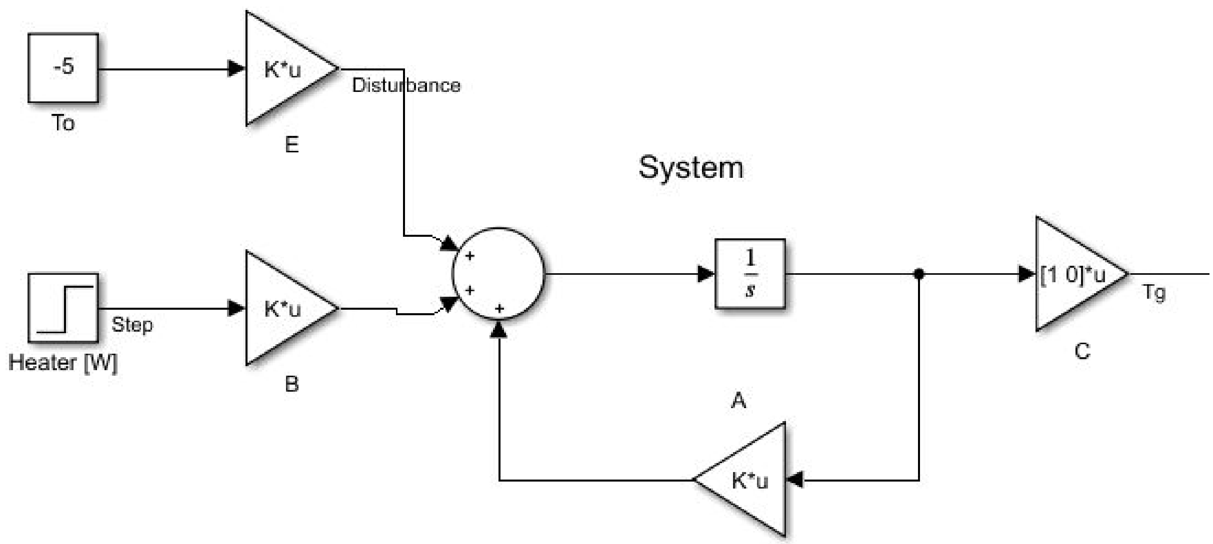
Overall all the parts were selected for lowest cost widely available modules that could be easily substituted for any similar module used by the large arduino community. Selections were made from amazon or aliexpress for the lowest cost. While nearly all selections could be made from either for lowest cost with the only tradeoff being shipping speed for cost.
These DS18B20 digital sensors have a long operation life when enclosed in their stainless steel weatherproof option. There are open source libraries available for the digital 1wire communications. The operation and instrumentation for this model is simple, read temperature

from the three selected options and then perform the PID control on the arduino to actuate the relay will minimize relay activation to maximize the lifetime of the part.

Assignment 3

A) System Block Diagram

See below Figure for an example system block diagram for this setup. Following the standard state space model with disturbance with labeled blocks. In this example the Outside temperature is set to a constant -5, with the heater power q being the input.



B) System Derivation

Starting with the thermal capacitance equation we can generate a state space model for the temperature control of the greenhouse. It is a second order system with two storage elements, the air temperature inside the greenhouse Tg and the temperature of the walls Tw. The R and C values was taken from the lecture notes for air and glass.

T_g = Greenhouse Temp

T_o = Outside Temp

T_w = Wall temp

R = Thermal Resitance

C = specific heat

q = input heat

⇒ We know $R = \frac{\Delta T}{Q} \longrightarrow q = \frac{T_2 - T_1}{R}$

$\therefore q_{gw} = \frac{T_g - T_w}{R_r}$ & $q_{wo} = \frac{T_w - T_o}{R_w}$

⇒ Using thermal capacitance equation

$$\sum q_1 - q_2 = mc\frac{dT_g}{dt}$$

1) Greenhouse

$$q - \frac{T_g - T_w}{R_g} = C_1 \frac{dT_g}{dt}$$

2) Wall

$$\frac{T_g - T_w}{R_g} - \frac{T_w - T_o}{R_w} = C_2 \frac{dT_w}{dt}$$

① $$\frac{dT_g}{dt} = \frac{T_w}{R_g C_1} - \frac{T_g}{R_g C_1} + \frac{q}{C_1}$$

② $$\frac{dT_w}{dt} = \frac{T_g}{R_g C_2} + \frac{T_o}{R_w C_2} - T_w\left(\frac{1}{R_g C_2} + \frac{1}{C_2 R_w}\right)$$

⇒ State Space

$$\begin{bmatrix} \dot{T}_g \\ \dot{T}_w \end{bmatrix} = \begin{bmatrix} \frac{-1}{C_1 R_g} & \frac{1}{R_g C_1} \\ \frac{1}{R_g C_2} & -\left(\frac{1}{R_g C_2} + \frac{1}{C_2 R_w}\right) \end{bmatrix} \begin{bmatrix} T_g \\ T_w \end{bmatrix} + \begin{bmatrix} \frac{1}{C_1} \\ 0 \end{bmatrix} q + \begin{bmatrix} 0 \\ \frac{1}{R_w C_2} \end{bmatrix} T_o$$

$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} T_g \\ T_w \end{bmatrix} + \begin{bmatrix} 0 \end{bmatrix} q$$

output = Greenhouse Temp

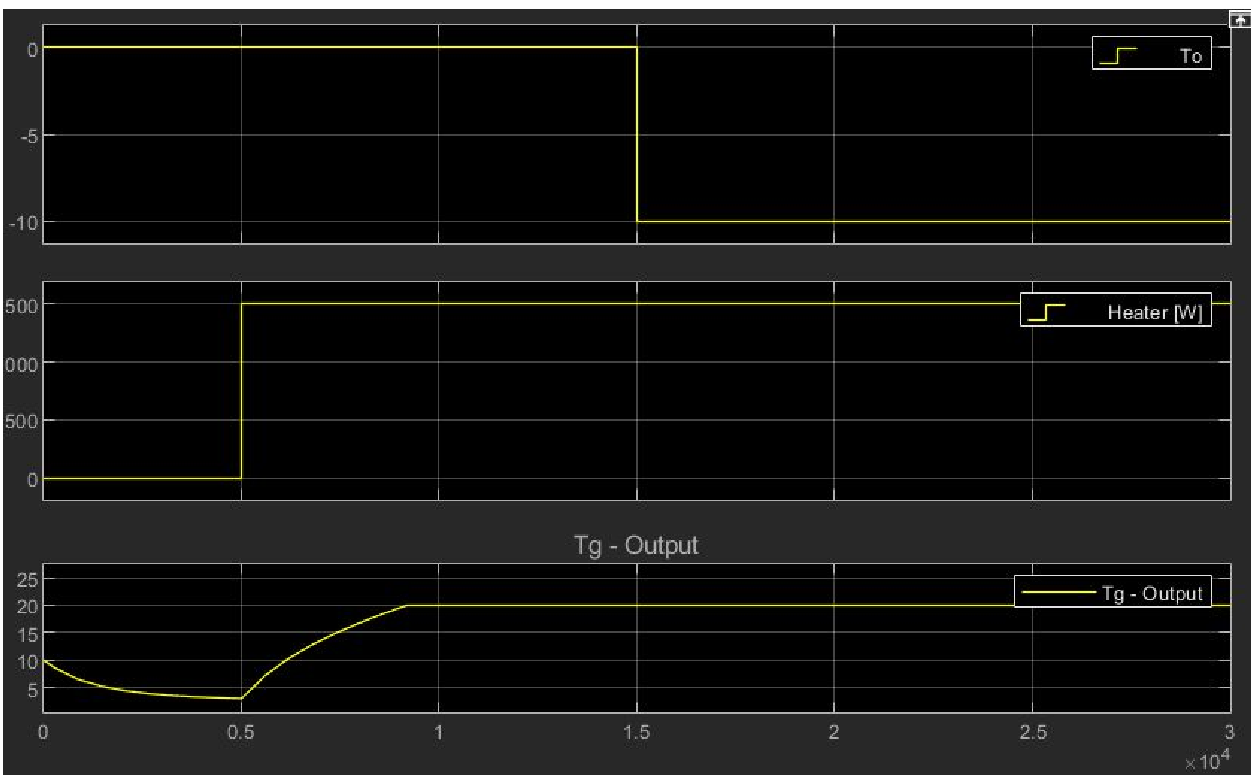
C) System I/O

The output is selected as the state variable Tg to make the modeling easier, there is also no D matrix in the solution.

Class	Variable	Typical Value	Maximum	Minimum
Input	Temp Set - T [C]	12	20	0
Disturbance	Outside Temp - To [C]	0	10	-10
State Variable	Temp Greenhouse air - Tg [C]	12	20	0
State Variable	Temp Glass Wall - Tgw [C]	6	15	-10
Output	Temp Greenhouse air - Tg [C]	12	20	`0

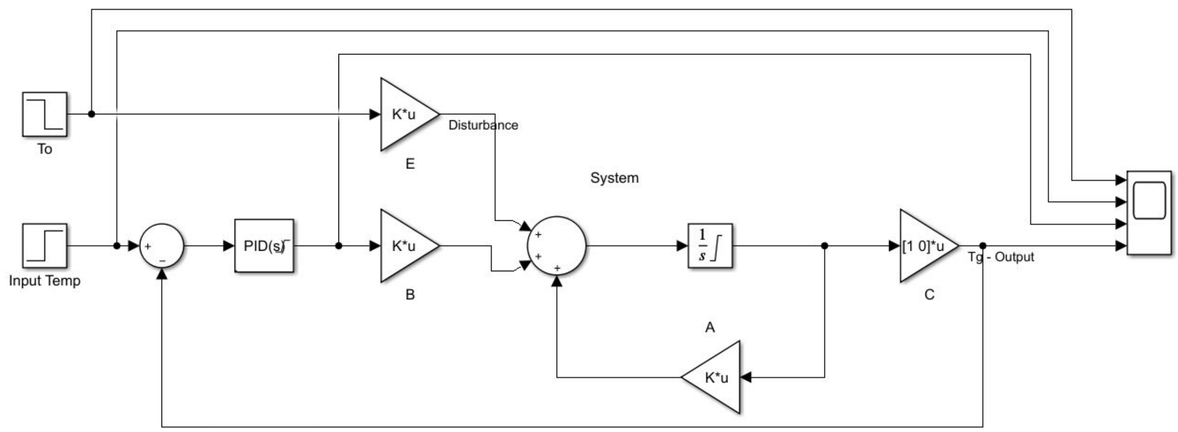
D) Simulation

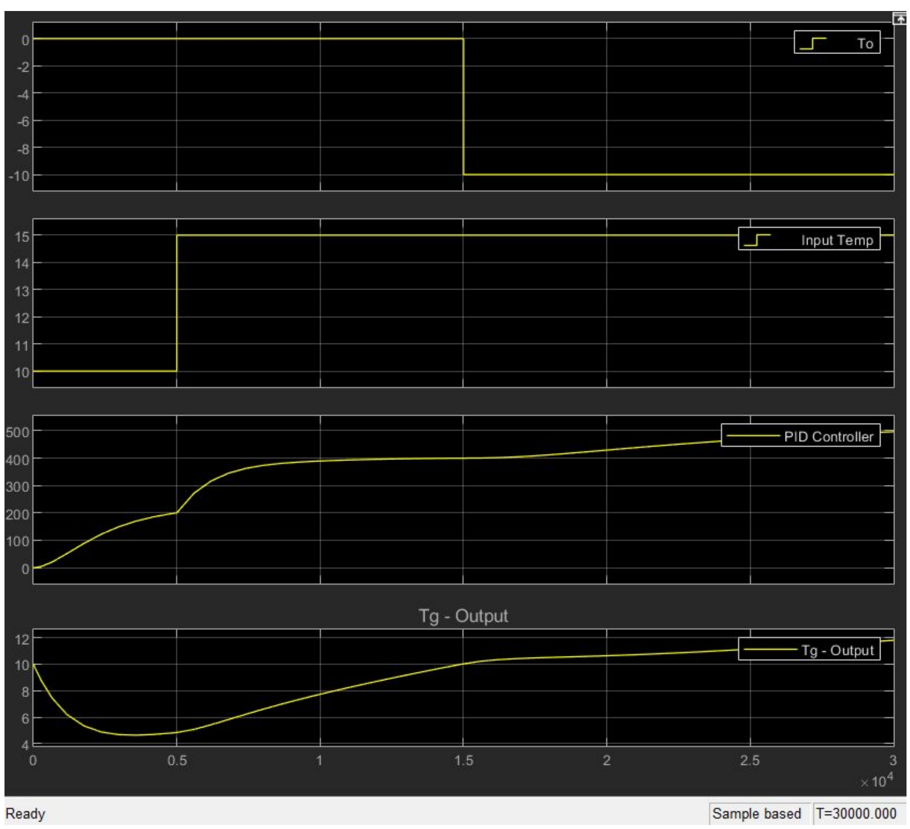
This graph was taken from the initial block diagram basic simulation. It shows Tg dropping due to heat loss until the Heater clicks in.



C) Simulation - PID Controller

Below is the attached simulink model. By upgrading to a PID controller we can use a heater with SCR or power control. This will allow the PID controller to respond to changing temperatures without starting and stopping the heater a lot. The input was changed from heat to the desired temperature set point. The PID was tuned using the simulink Tuner for optimal response.

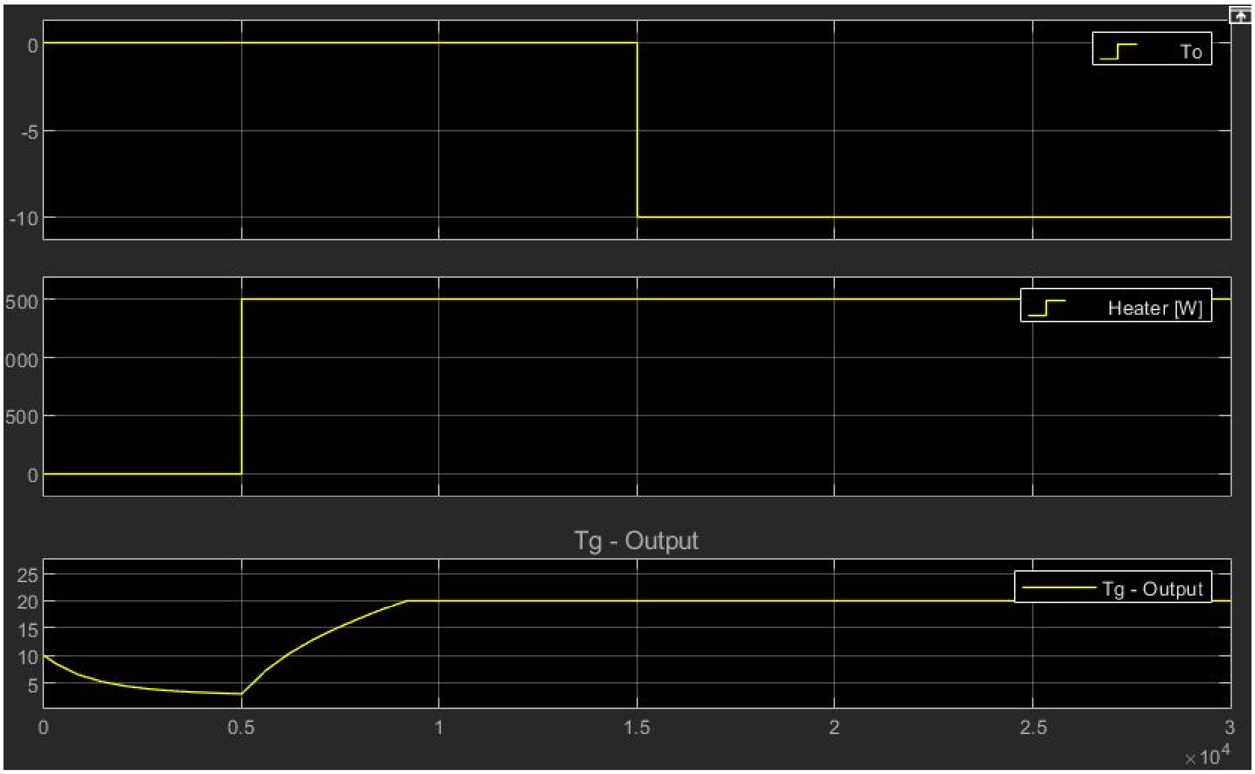




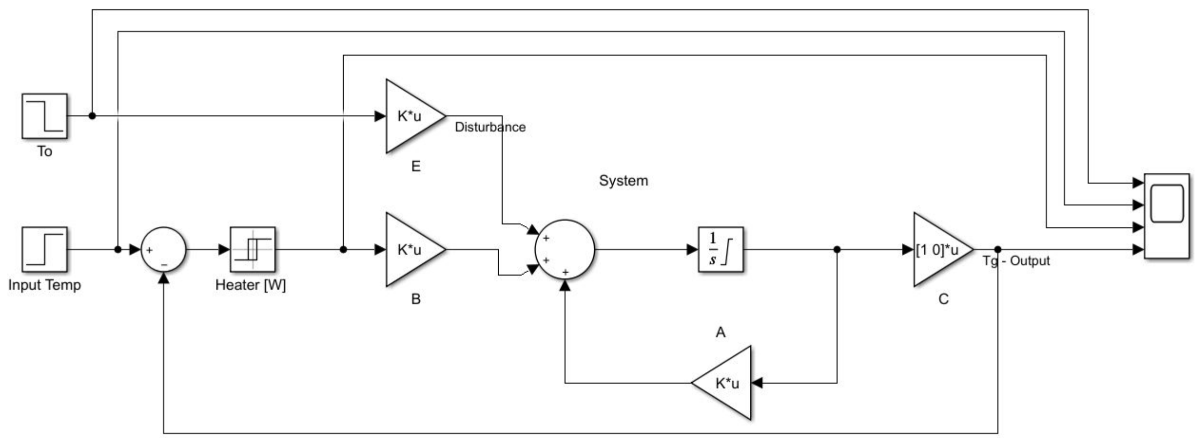
Assignment 4

A) ON/OFF Controller

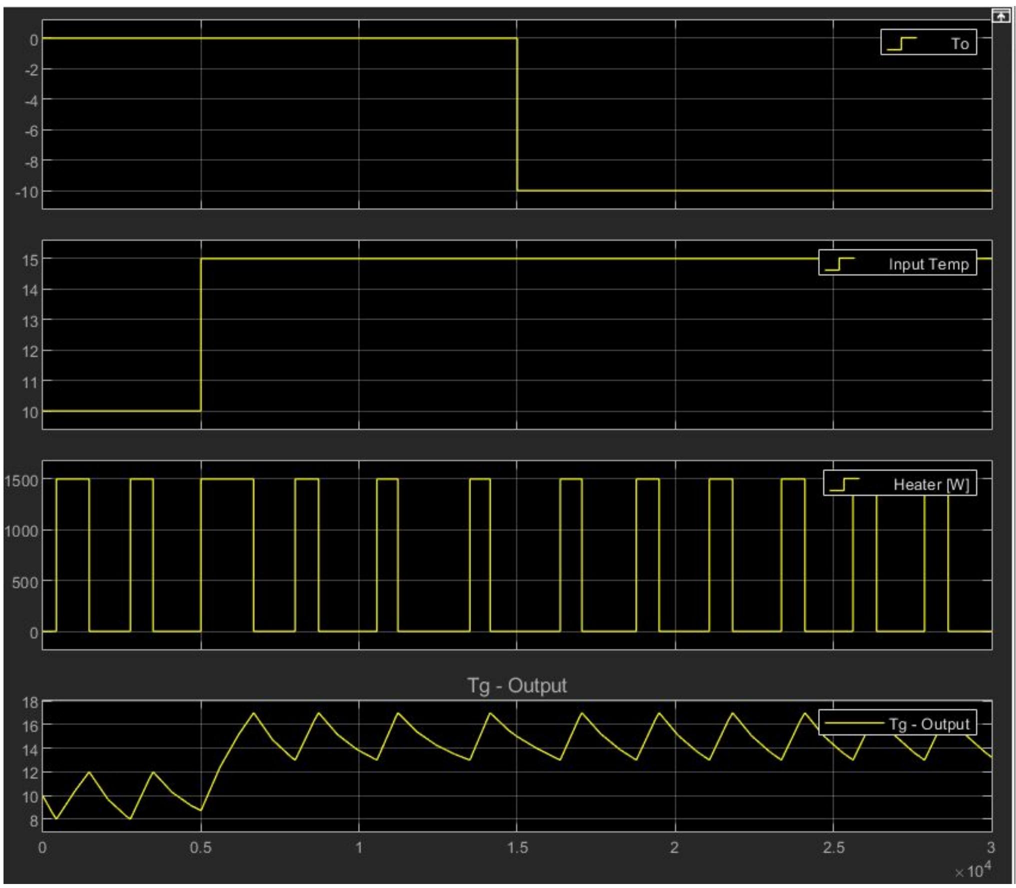
This graph was taken from the initial block diagram basic simulation. It shows Tg dropping due to heat loss until the Heater clicks in.



Then I added some basic ON/OFF control for the simulation as seen on the following page. The outside temperature was also modeled as a step response to show the heater activated more often when the outside temperature was lower.

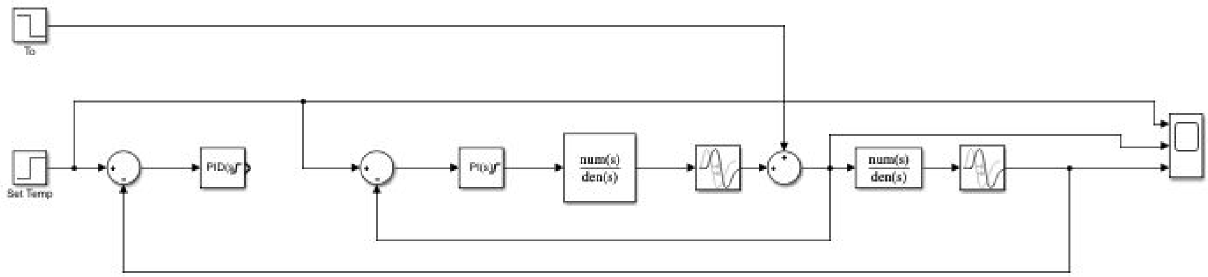


To
Input Temp
Heater [W]
K*u
Disturbance
E
System
K*u
B
1/s
[1 0]*u
Tg - Output
C
A
K*u



To
Input Temp
Heater [W]
Tg - Output

B) Continuous Cascade Controller



I first tried splitting my plant to have the inner loop control the outside temperature disturbance while the main outer loop controlled the heater. I set up the diagram as per the lecture notes to first tune the inner loop PI with the outside main PID disconnected. I think I did not split my plant correctly as the simulation would not work with a cascade controller.

C) Discrete PI/PID Controller

Below is the attached simulink model. By upgrading to a PID controller we can use a heater with SCR or power control. This will allow the PID controller to respond to changing temperatures without starting and stopping the heater a lot. The input was changed from heat to the desired temperature set point. The PID was tuned using the simulink Tuner for optimal response. The PID was set to discrete time sampling instead of continuous.