CHEG401 - Chemical Process Dynamics and Control

Lab 4 - Classical Process Control

Li Pei Soh

Linh Nguyen

Khai Khee Kho

Abdul Fayeed Abdul Kadir

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College of Engineering, Department of Chemical and Biomolecular Engineering

University of Delaware

Newark, Delaware 19711

4.1 Lab 4: Feedback Control

4.1.1 Temperature Control in a Refrigerated Tank

$$y(s) = \frac{-4}{8s+4} u(s)$$

$$h(s) = \frac{1.0}{0.1s+1}$$

$$g_d(s) = \frac{-4}{(2s+1)(0.5s+1)}$$

$$g_v(s) = 0.95$$

1. **SIMULINK Implementation: Represent the control system and all components**
2. **Closed-Loop Stability Analysis**

   Closed-loop transfer function: $CLTF = \frac{g(s)h(s)g_d(s)g_v(s)}{1+g(s)h(s)g_d(s)g_v(s)} = \frac{-3.8Kc(0.1s+1)}{0.8s^2+8.4s+(4-3.8Kc)}$

   Characteristic equation: $0.8s^2 + 8.4s + (4 - 3.8Kc) = 0$

   Routh Test: $4 - 3.8Kc > 0 \rightarrow Kc < 1.0526$

Table 1: Routh Test for Stability

Row 1	0.8	$4 - 3.8Kc$
Row 2	8.4	0
Row 3	$4 - 3.8Kc$	-

3. Controller Design and Implementation

I. Set-Point Tracking

(a) Stable P-only Controller

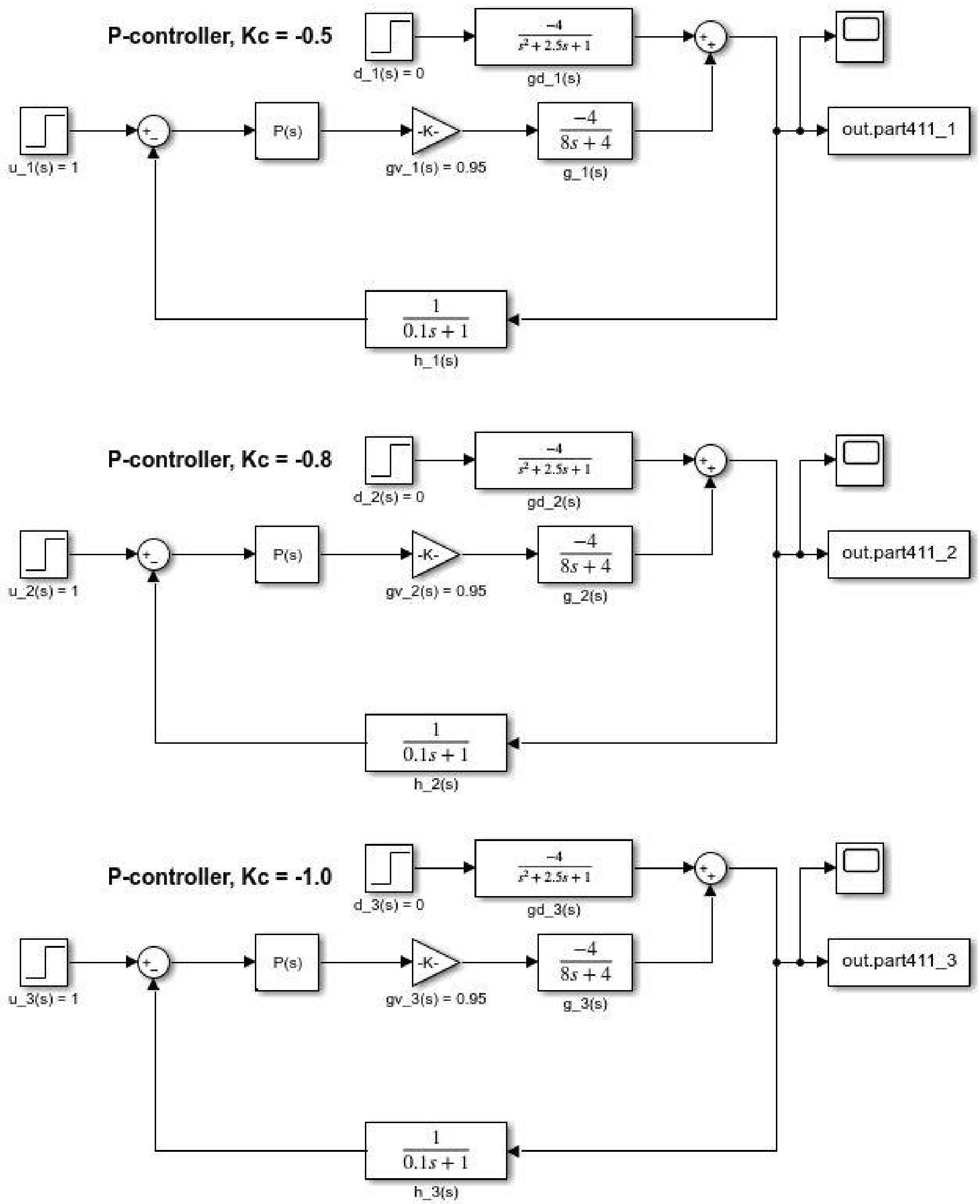


Figure 1. SIMULINK for P Controllers

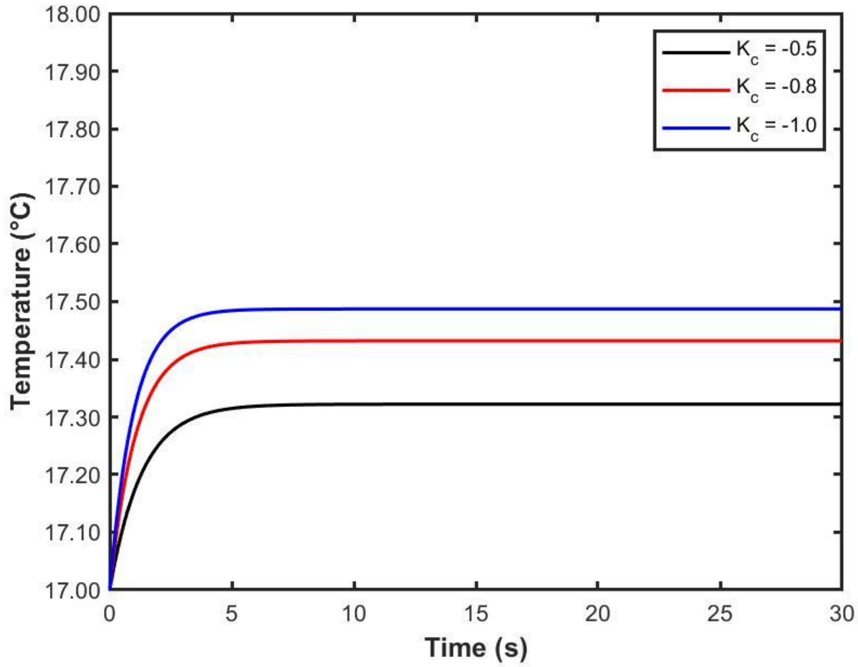


Figure 2. Temperature versus time for P Controllers

Because the material's temperature remains between 15 °C and 20 °C (the two operating limits), therefore, the material will not freeze or explode using the P controller denoted in **Figure 2**.

(b) Unstable P-only Controller

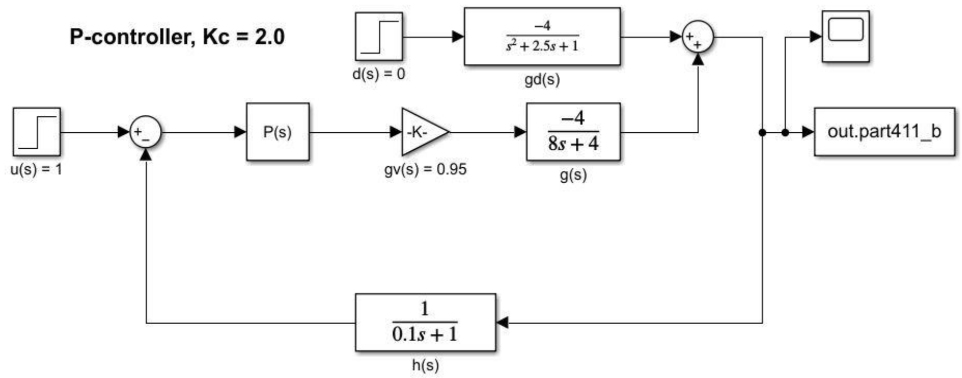


Figure 3. SIMULINK for PI Controllers

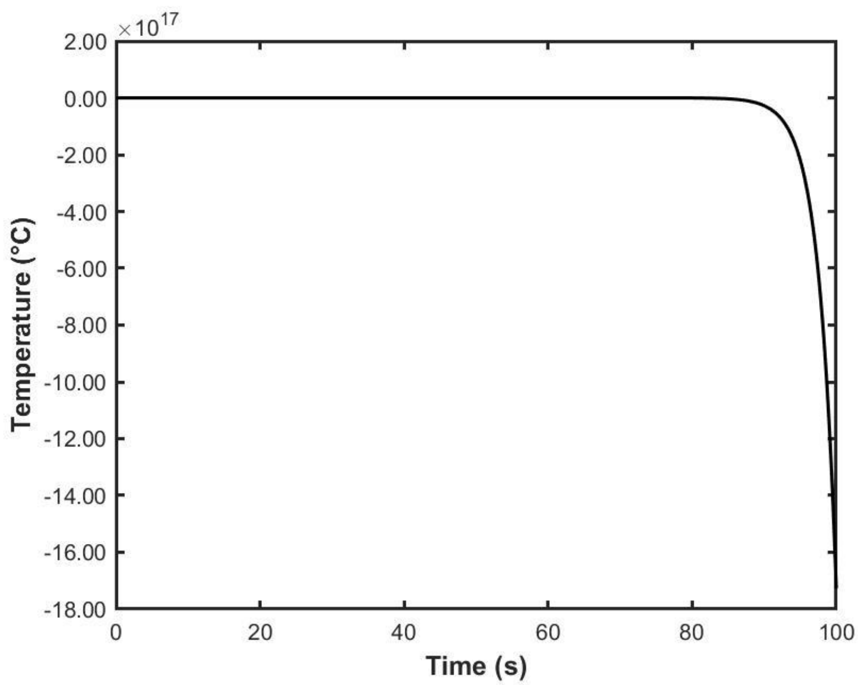


Figure 4. Temperature versus time for PI Controllers

According to **Figure 4**, there is no steady-state temperature when using this unstable P-controller.

(c) PI Controller

K_c = -1 was chosen because in **Figure 2**, that value of K_c gives the smallest offset out of all three values of K_c. Values chosen for τ_I are: 1, 2 and 4.

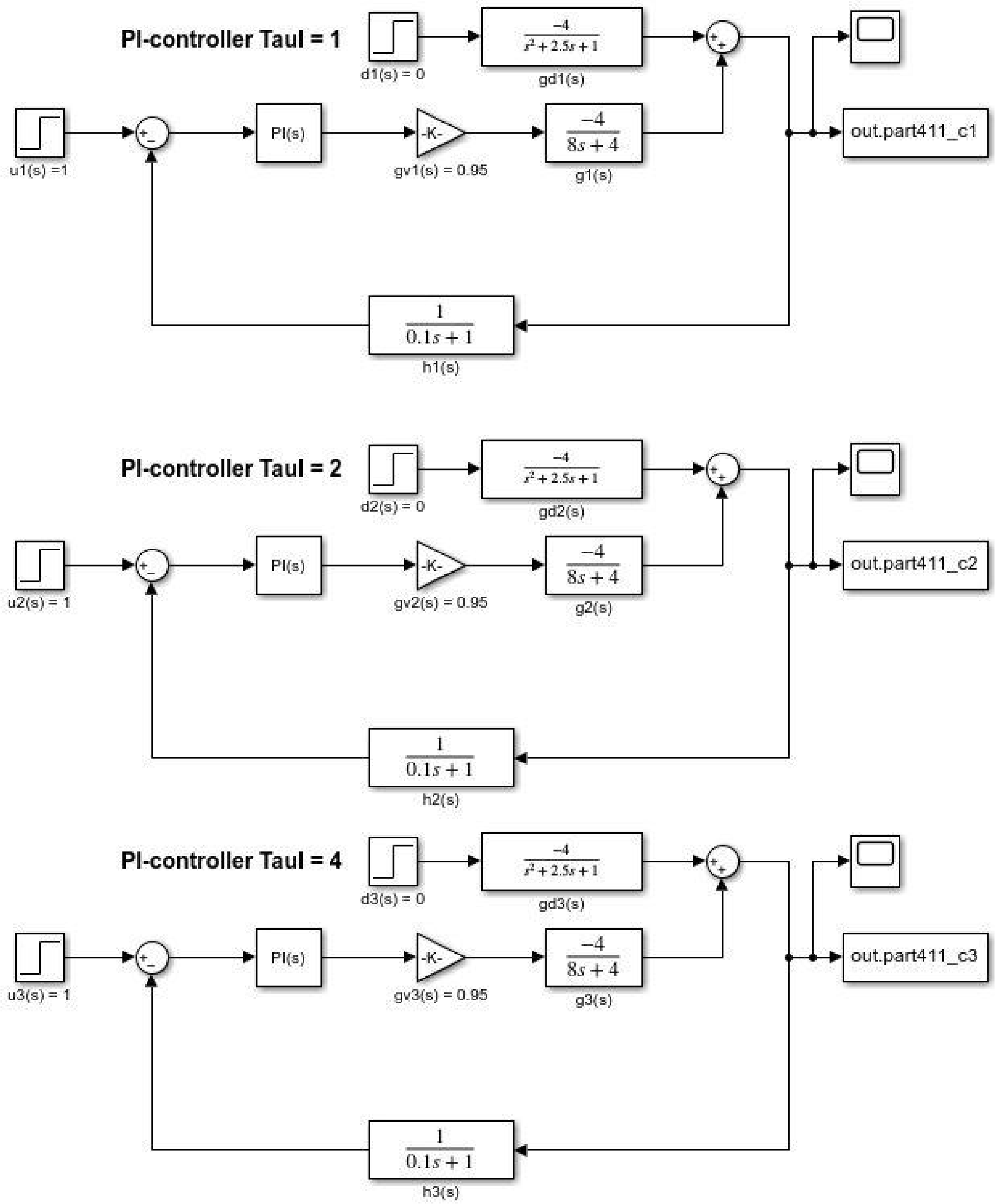


Figure 5. SIMULINK for PI Controllers

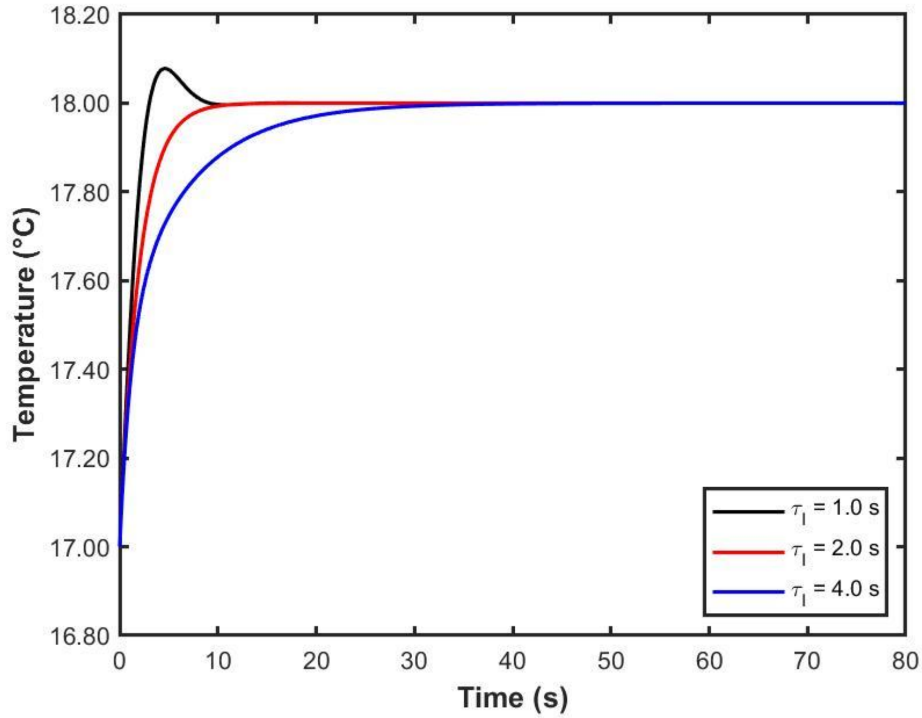


Figure 6. Temperature versus time for PI Controllers

- $\tau_I = 1$ shows overshoot response.
- The higher τ_I , the more sluggish the system responses to the input. This makes sense because τ_I represents integral time.
- The best system out of all three is the one with $\tau_I = 2$ as it doesn't show an overshoot response and also responses to the input faster than the one with $\tau_I = 4$.
- Comparing to P-controller, PI doesn't have any steady-state offset; therefore is better at setpoint tracking

(d) PID Control

K_c = -1 was chosen because in **Figure 2**, that value of K_c gives the smallest offset out of all three values of K_c. τ_I = 2 was chosen as reasons mentioned in part c. Values chosen for τ_D are: 1, 2 and 4.

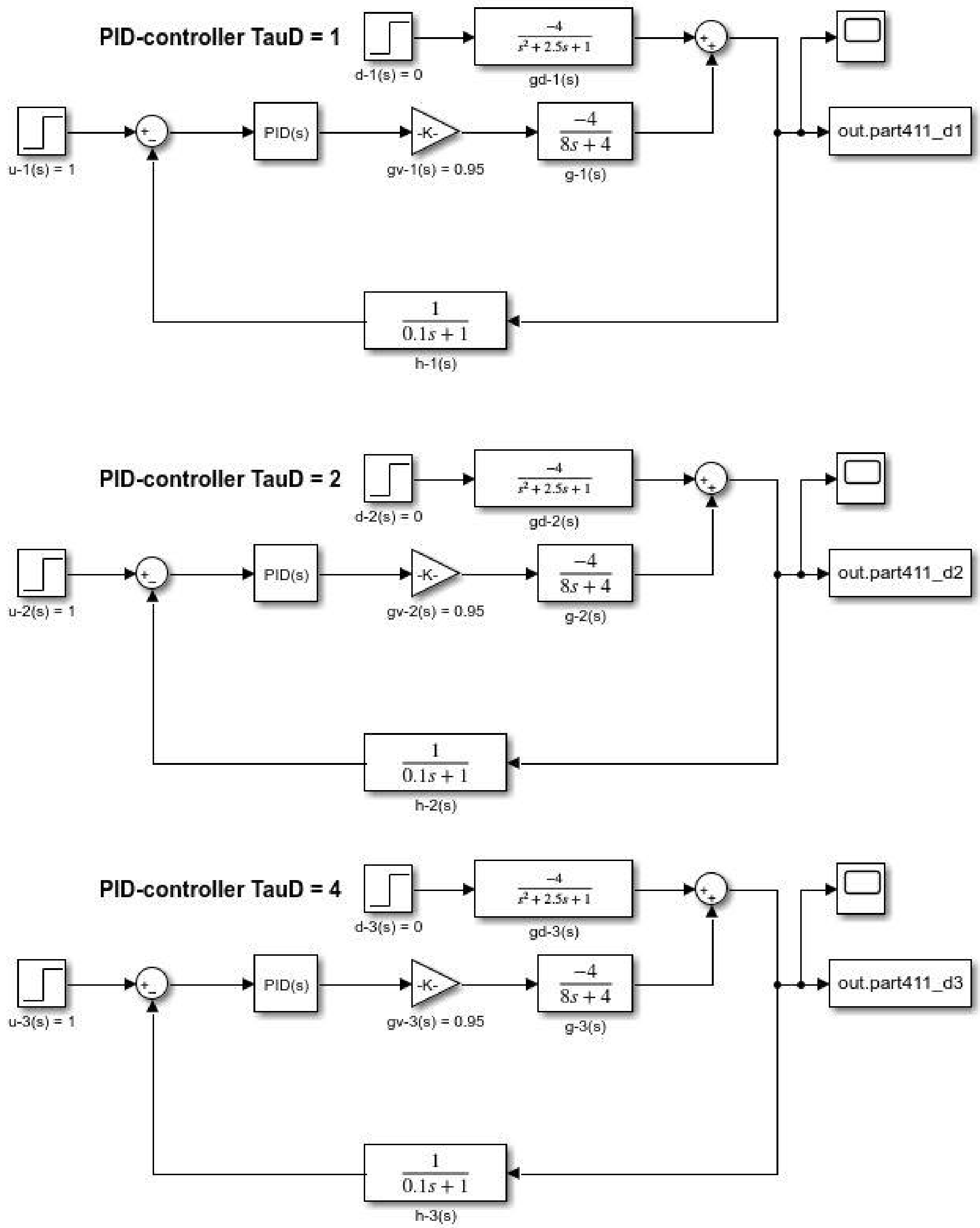


Figure 7. SIMULINK for PID Controllers

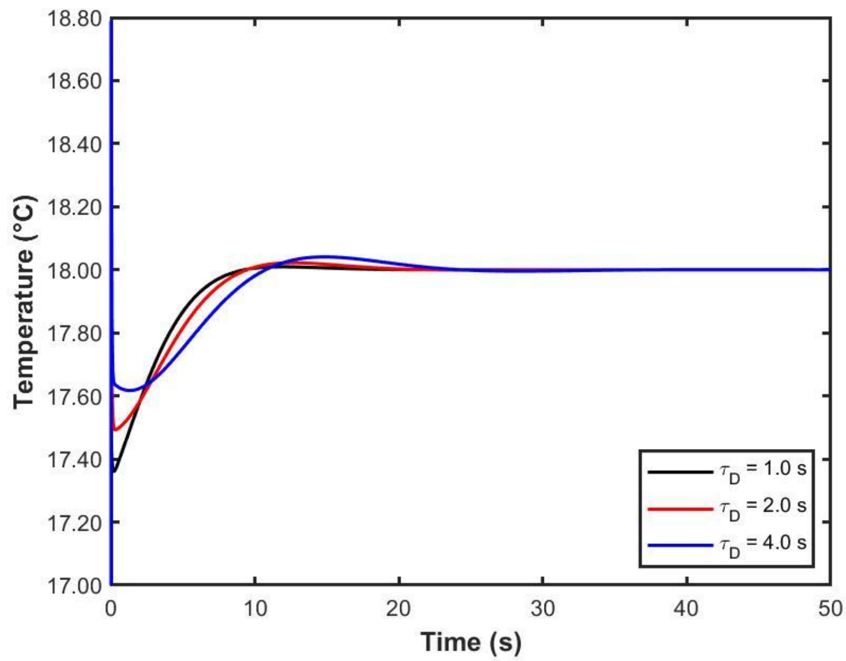


Figure 8. Temperature versus time for PID Controllers

- $\tau_D = 2$ and $\tau_D = 4$ shows overshoot response.
- The best system out of all three is the one with $\tau_D = 1$ as it doesn't show an overshoot response
- Compared to P-controller, PID doesn't have any steady-state offset; therefore is better at setpoint tracking.
- Compared to the PI controller, PID is not as suitable for this system. According to **Figure 8**, there is a sharp increase in temperature in every graph and this makes it harder to keep the temperature in control. As if we choose a different τ_D different , there could be a sharp increase exceeding 20 °C, which may result in explosion of the material.
- **Therefore, PI is the most suitable for this system and the best servo controller is PI controller with K = -1 and $\tau_I = 2$.**

4. Controller Design and Implementation II. Disturbance Rejection

(a) How effectively does it reject this disturbance?

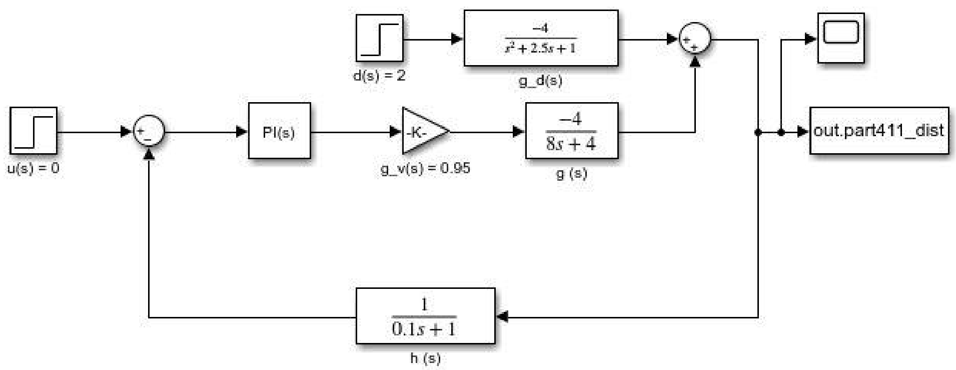


Figure 9. SIMULINK for best controller (PI, K = -1 and τ_I = 2) with disturbance tracking.

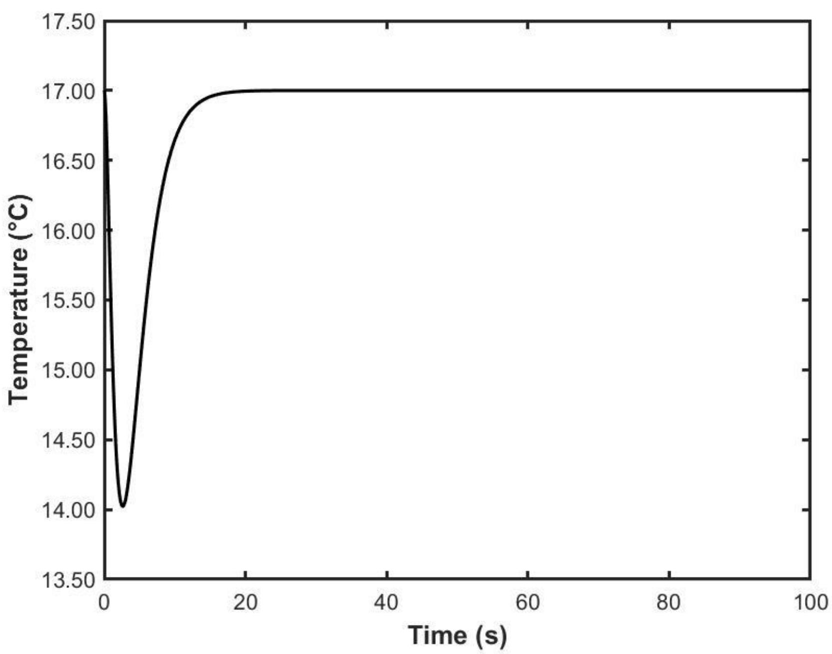


Figure 10. Temperature versus time for best controller (PI, K = -1 and τ_I = 2) with disturbance tracking.

As the temperature has a sharp decrease to 14 °C according to **Figure 10**, the material would freeze as the freezing point is 15 °C.

(b) The parameters chosen for the PI controller is: $\mathbf{K_c = -6, \tau_I = 1s}$

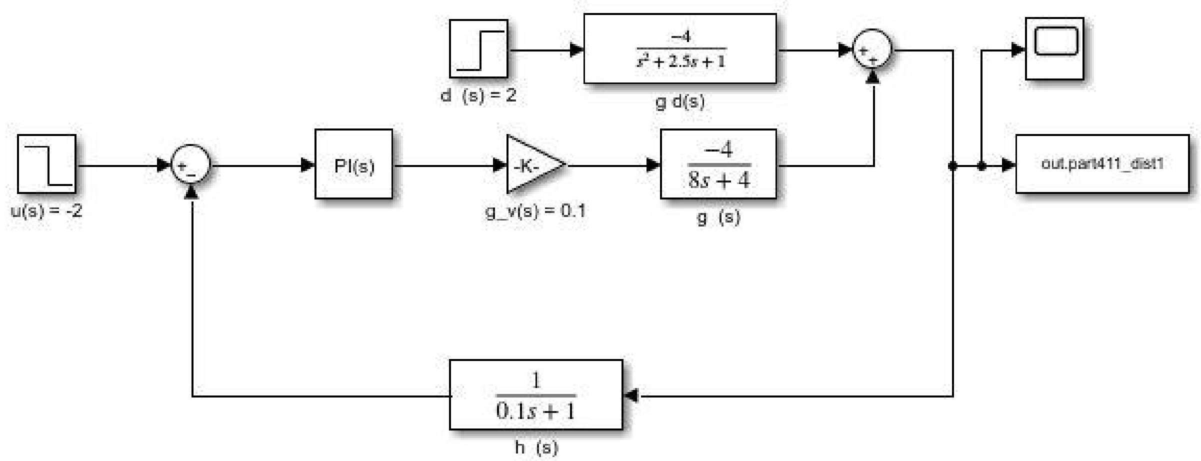


Figure 11. SIMULINK for PI controller with adjusted parameters and disturbance tracking

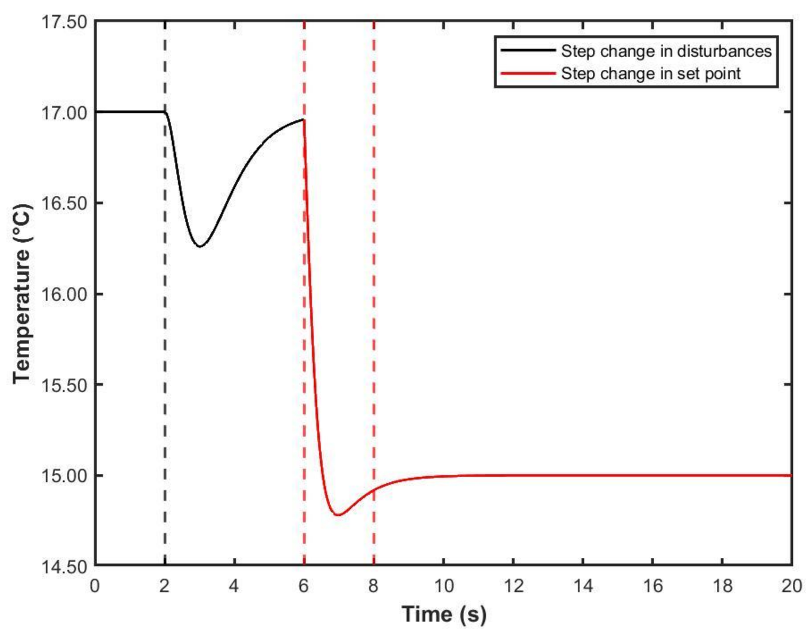


Figure 12. Temperature versus time for PI controller with adjusted parameters and disturbance tracking

Criteria:

1. **A step change of +2°C in the disturbance, implemented at t = 2s, results in a maximum deviation from the set-point that is smaller than 1°C**

   As seen in **Figure 12**, the maximum deviation is roughly -0.75 °C at around t = 2.8s after the **+2°C** step change in the disturbance.

2. **A step change of −2◦C in the set-point, implemented at t = 6s, results in a response that is within 0.5°C of the new set-point 2 seconds after the step change.**

   As seen in **Figure 12**, the new set-point is 15 °C. After the step-change of -2 °C in the set point, the temperature drops to roughly 14.8 °C at t = 7s, which is within 0.5°C of the new set-point 2 seconds after the step change.

4.1.2 Transition Control of a Polymerization Reactor

$$\frac{d\xi_1}{dt} = 10(6 - \xi_1) - 2.4568\xi_1\sqrt{\xi_2}$$

$$\frac{d\xi_2}{dt} = 80\mu - 10.1022\xi_2,\ \mu\ is\ volumetric\ flow\ rate\ of\ initiator$$

$$\frac{d\xi_3}{dt} = 0.0024121\xi_1\sqrt{\xi_2} + 0.112191\xi_2 - 10\xi_3$$

$$\frac{d\xi_4}{dt} = 245.978\xi_1\sqrt{\xi_2} - 10\xi_4$$

$$\zeta = \frac{\xi_4}{\xi_3},\ number\ average\ molecular\ weight\ (NAMW)$$

$$\eta(t) = \zeta(t - \alpha) + \epsilon,\ \alpha = 0.1\ hr$$

$$[\xi^*_1, \xi^*_2, \xi^*_3, \xi^*_4] = [5.506774,\ 0.132906,\ 0.0019752,\ 49.38182]$$

$$\mu^* = 0.016783\ m^3/hr,\ \eta^* = 25000.5,\ \eta^*_{new} = 37500,\ 35000 < \eta^* < 40000$$

1. **Process Identification**

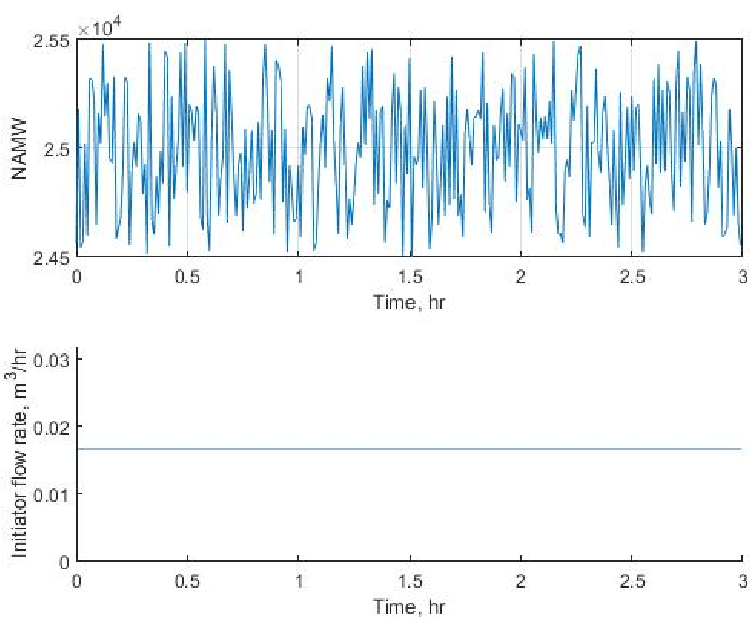


Figure 13. MATLAB plot generated using code in CANVAS, μ^* =0.016783.

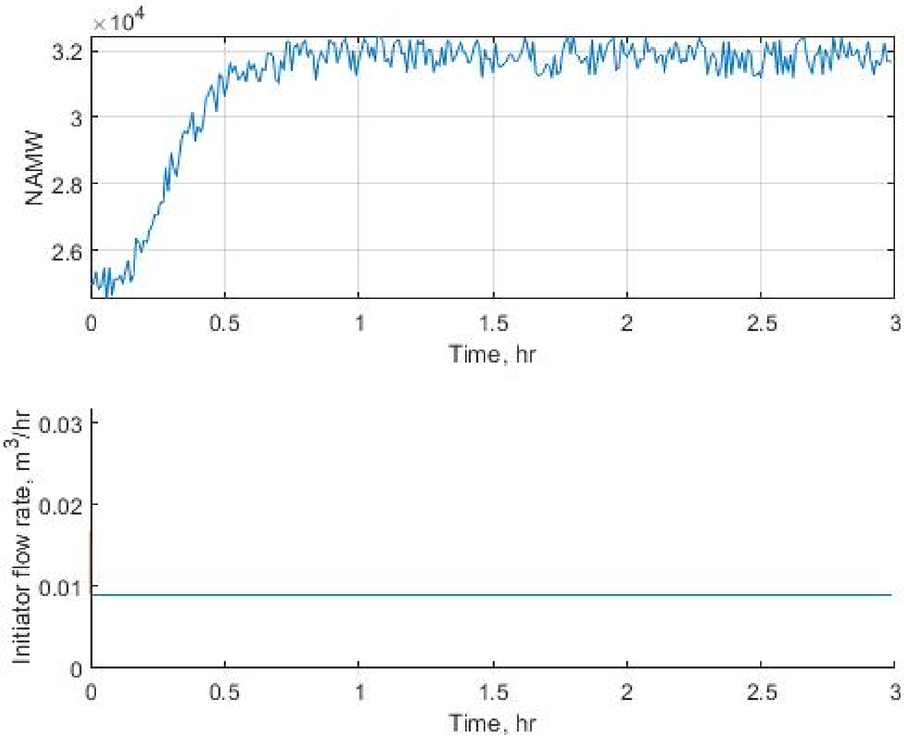


Figure 14. MATLAB plot generated using code in CANVAS, μ^{*} =0.009.

Estimated parameters obtained from Figure 14:

$$y(\infty) = (3.2 - 2.5) \times 10^{4} = 0.7 \times 10^{4},\ A = 0.016783 - 0.009 = 0.007783$$

$$y(\infty) = \frac{K}{A},\ K = \frac{0.7\times10^{4}}{0.00783} = 8.99 * 10^{5}$$

$$\alpha = 0.11,\ \tau = \frac{y(\infty)}{\sigma},\ \sigma = \frac{3.2\times10^{4}-2.5\times10^{4}}{0.5-0.11} = 1.79 \times 10^{4},\ \tau = \frac{0.7\times10^{4}}{1.79\times10^{4}} = 0.39$$

$$y(s) = \frac{Ke^{-\alpha s}}{\tau s+1}u(s) = \frac{8.99\times10^{5}e^{-0.11s}}{0.39s+1}u(s)$$

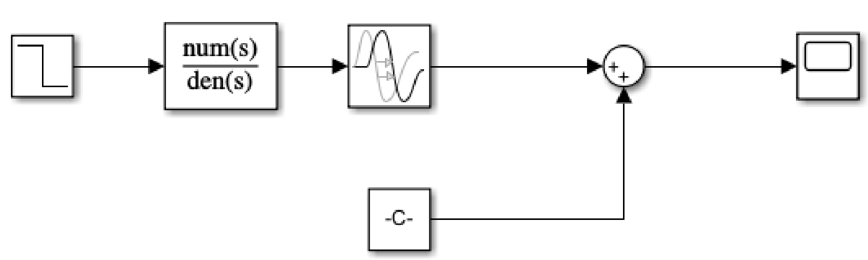


Figure 15. SIMULINK setup using estimated parameters above.

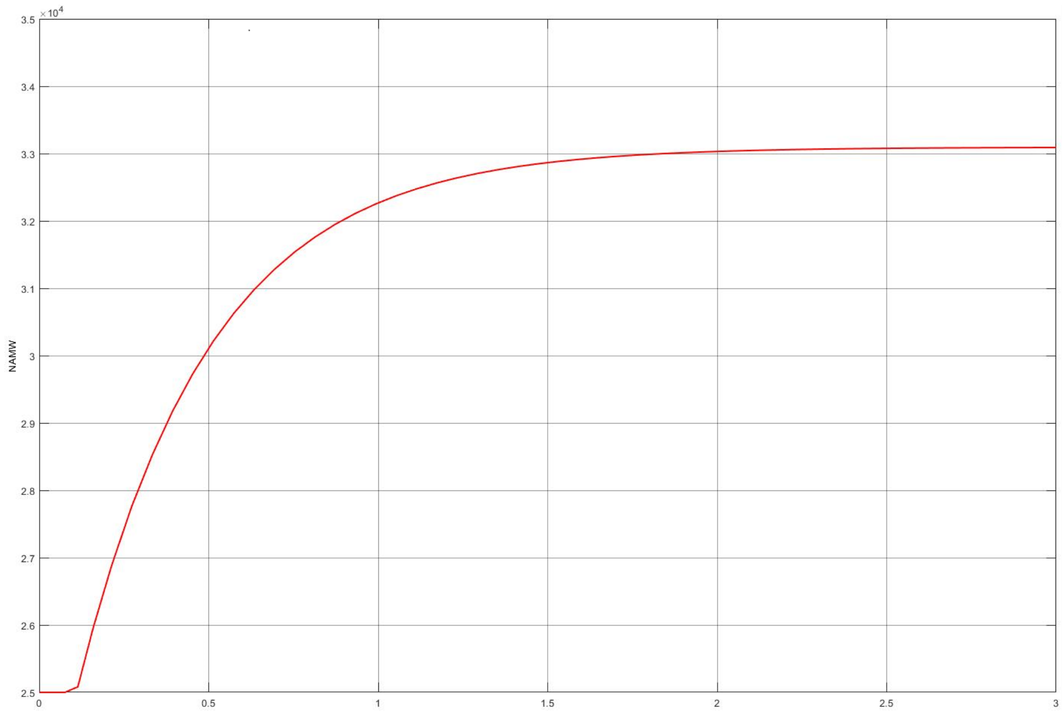


Figure 16. MATLAB plot using parameters above.

How well the model fits the step response data?

Based on Figure 16, K is around $3.3*10^4$ which is very close to the estimated K ($3.2*10^4$). The $\boldsymbol{\alpha}$ and $\boldsymbol{\tau}$ value are also close to the estimated value. The model fits the step response data well since both of them have similar trends.

2. Controller Design

Briefly justify your choice and show the resulting controller parameter explicitly.

The controller type and tuning rule chosen is PID and IMC approximate model PID tuning rules. PID has no offset and results in a smaller oscillatory response. Ziegler-Nichols and Cohen-Coon are somewhat overly aggressive. ITAE, Direct Synthesis and IMC tunings are quite good. No disturbance and τ_r . Therefore IMC tunings are chosen.

From Table 15.2 in textbook, IMC approximate model PID tuning rules:

$\lambda > 0.2\tau,\ \lambda > 0.078,\ lets\,\lambda = 1$

$K_c = \frac{2\tau+\alpha}{2K(\lambda+\alpha)} = \frac{2(0.39)+0.11}{2(8.99*10^5)(1.11)} = 4.46 * 10^{-6}$

$\tau_I = \tau + \frac{\alpha}{2} = 0.39 + \frac{0.11}{2} = 0.445$

$\tau_D = \frac{\tau\alpha}{2\tau+\alpha} = \frac{0.39*0.11}{2*0.39+0.11} = 0.0482$

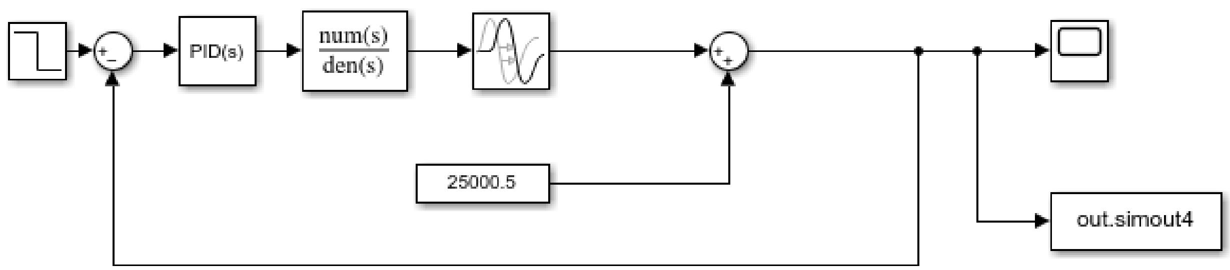


Figure. SIMULINK for Controller Design

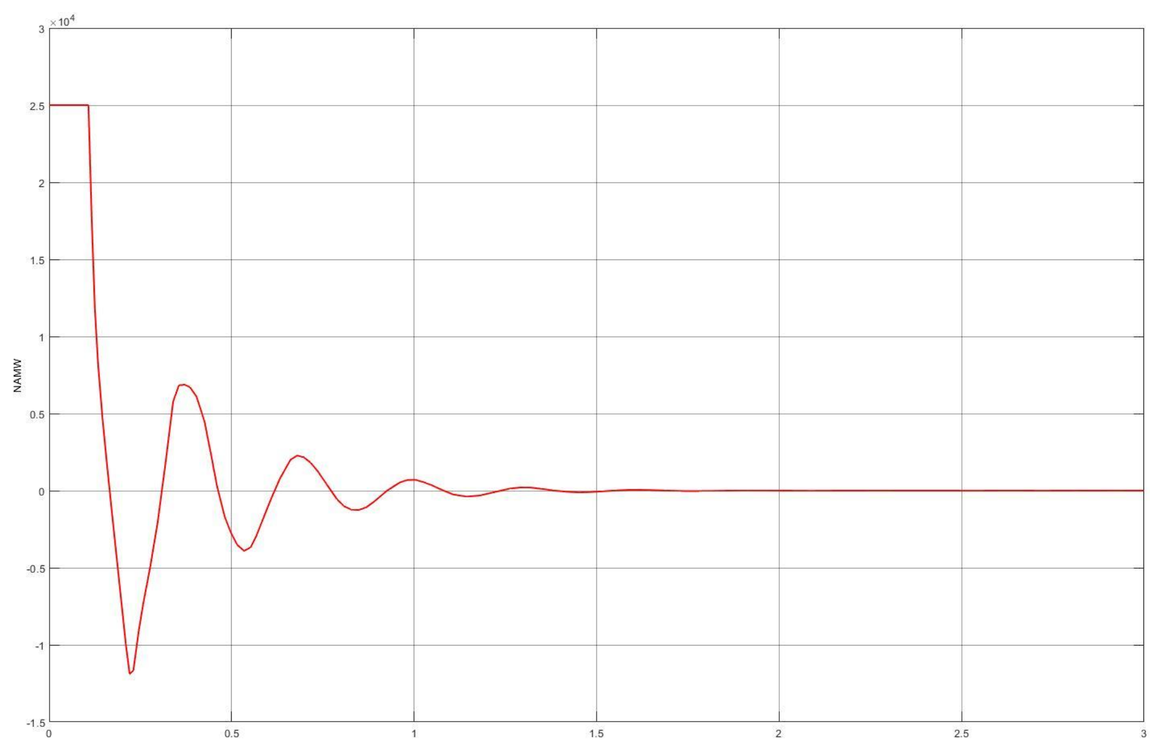
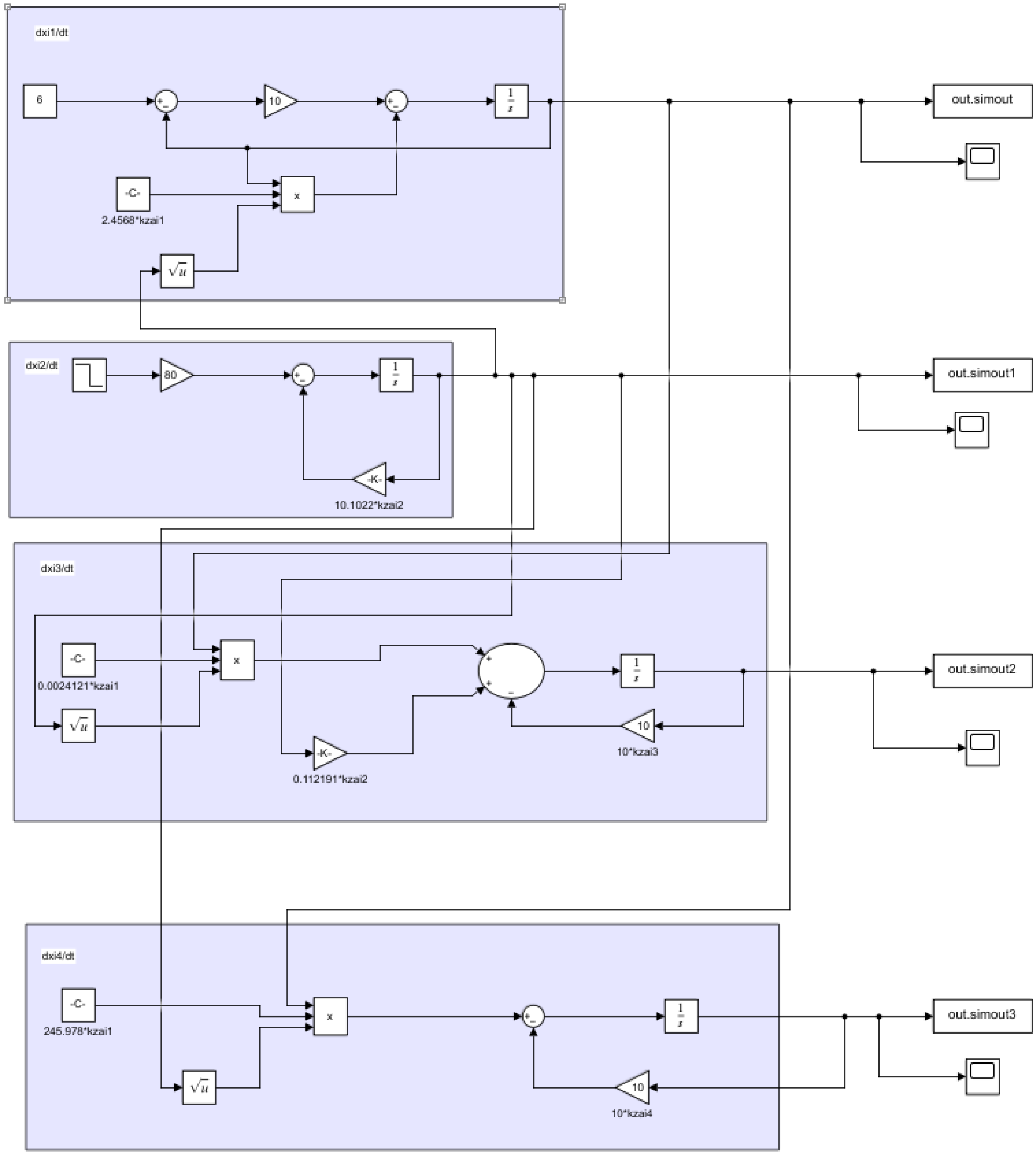


Figure. PID controller with IMC estimated parameters

3. Controller Implementation



No idea what to do T.T

4. Results Presentation

4.1.3 Feedback Stabilization in Human Balance Keeping

1. **SIMULINK Implementation**

$$g(s) = \frac{3}{4s^2-1},\ y(s) = \frac{3}{4s^2-1}u(s) + d(s)$$

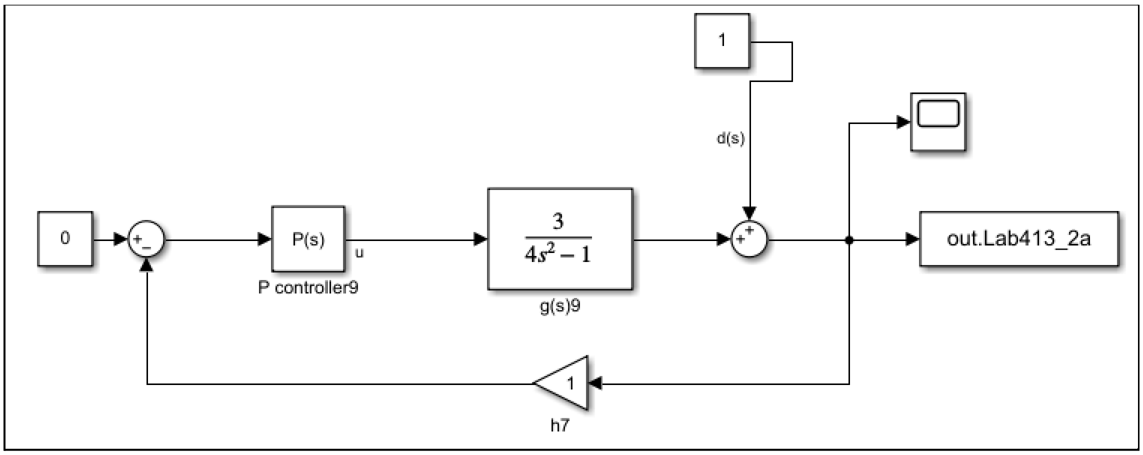


Figure 17. Simulink set-up for a closed-loop system in response to constant input disturbance.

2. **Feedback Stabilization I**

(a)

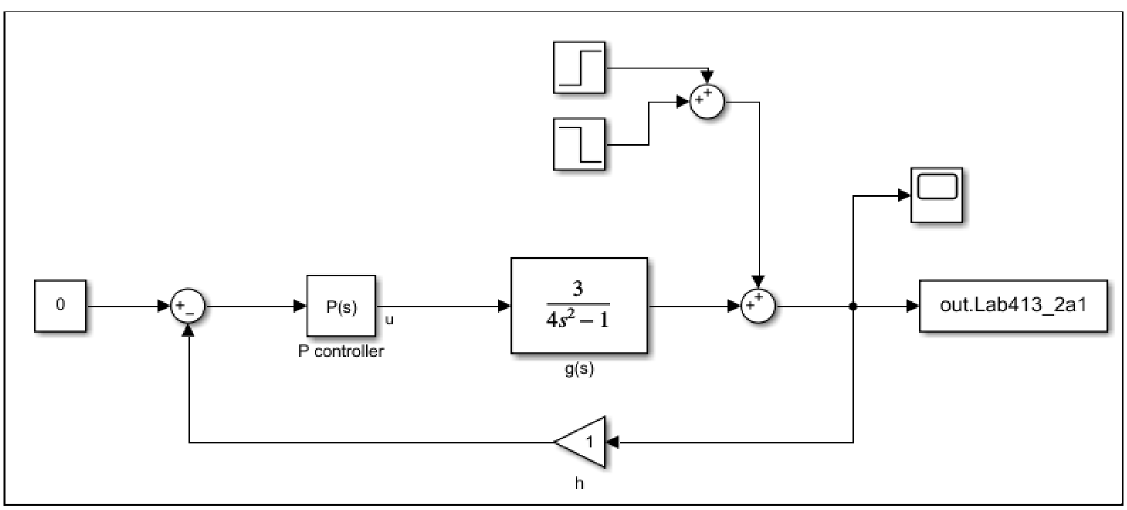


Figure 18. Simulink set-up for a closed-loop system in response to rectangular pulse input disturbance.

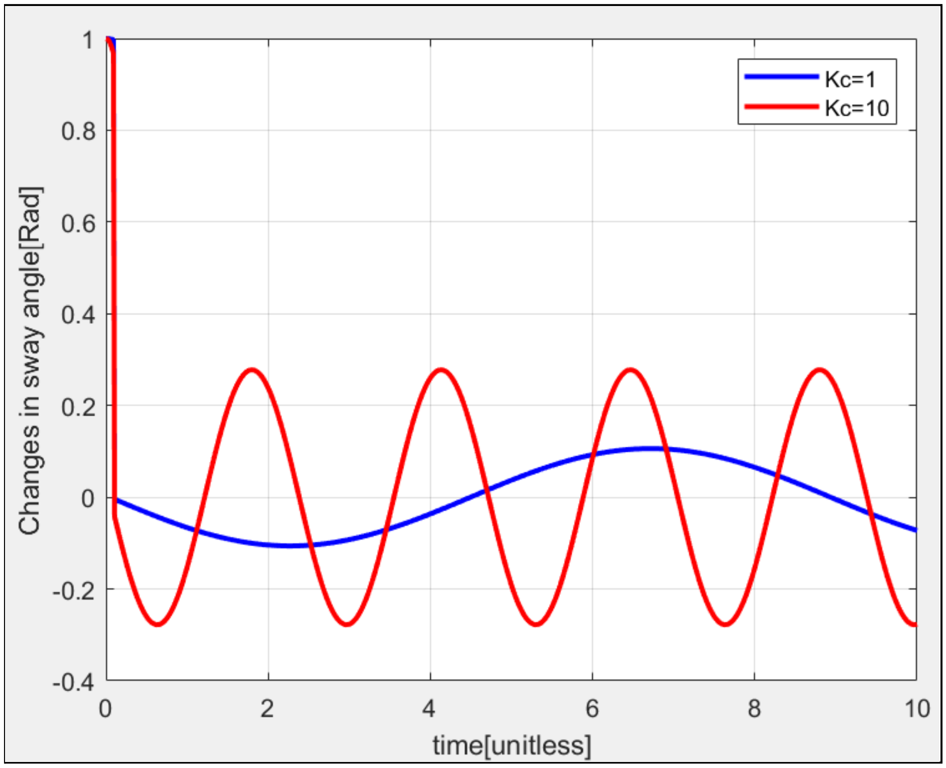


Figure 19. Response of the system under P control, with h(s)=1, d(t) as a pulse input of magnitude 1, lasting for 0.1 time units, and different Kc values.

(b) Figure shows that the system response is unstable as oscillatory behavior persists, which means the system is unstable. The closed loop characteristic equation for this P control system is $1+g*g_c=0$, which gives $4s^2 - 1 + 3K_c = 0$; for any values of K_c, at least one of the roots obtained from this equation will be positive, thus it cannot be stabilized.

3. Feedback Stabilization II

(a)

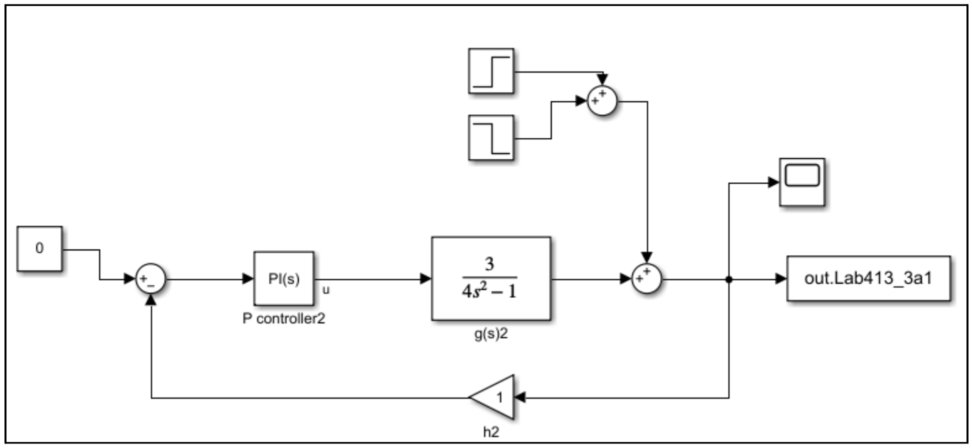


Figure 20. Simulink set-up for a closed-loop system under PI controller in response to pulse input disturbance, with Kc=10.

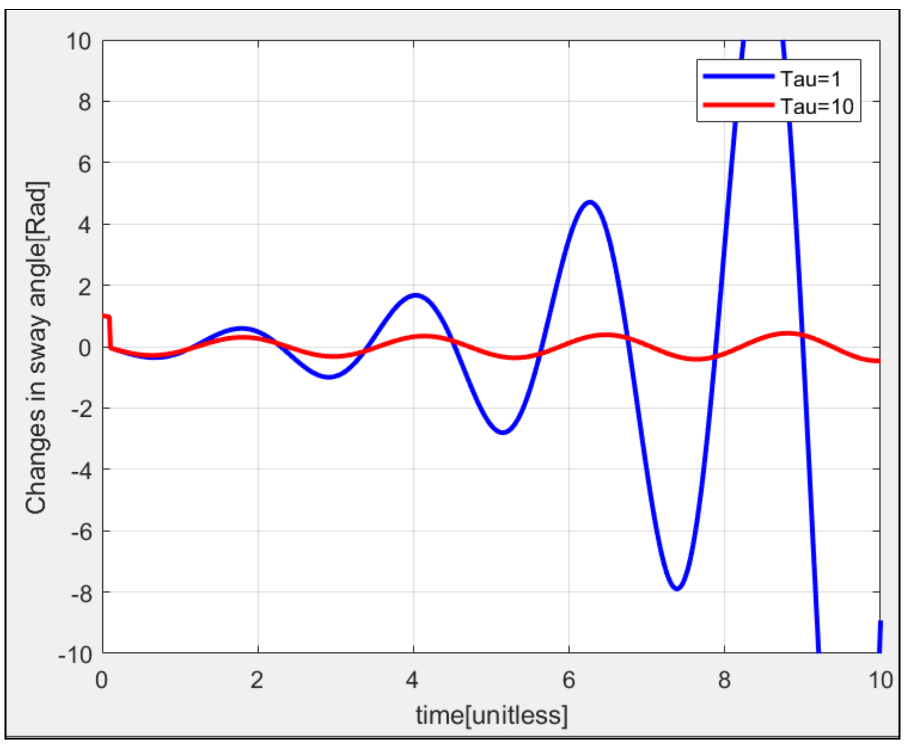


Figure 21. Response of the system under PI control, with h(s)=1, d(t) as a pulse input of magnitude 1, lasting for 0.1 time units, K_c=10, with τ_I=1 or 10.

(b) Figure shows that the system response is unstable as oscillatory behavior persists. The closed loop characteristic equation for this PI control system is $1+g^*g_c=0$, which is $4\tau_I s^3+(3K_c\tau_I-\tau_I)s+3K_c=0$; for any values of K_c and τ_I, at least one of the roots obtained from this equation will be positive, thus it cannot be stabilized. Thus, there is no values of K_c or τ_I that will stabilize the open loop unstable system in Eq. 4.9.

4. Feedback Stabilization III

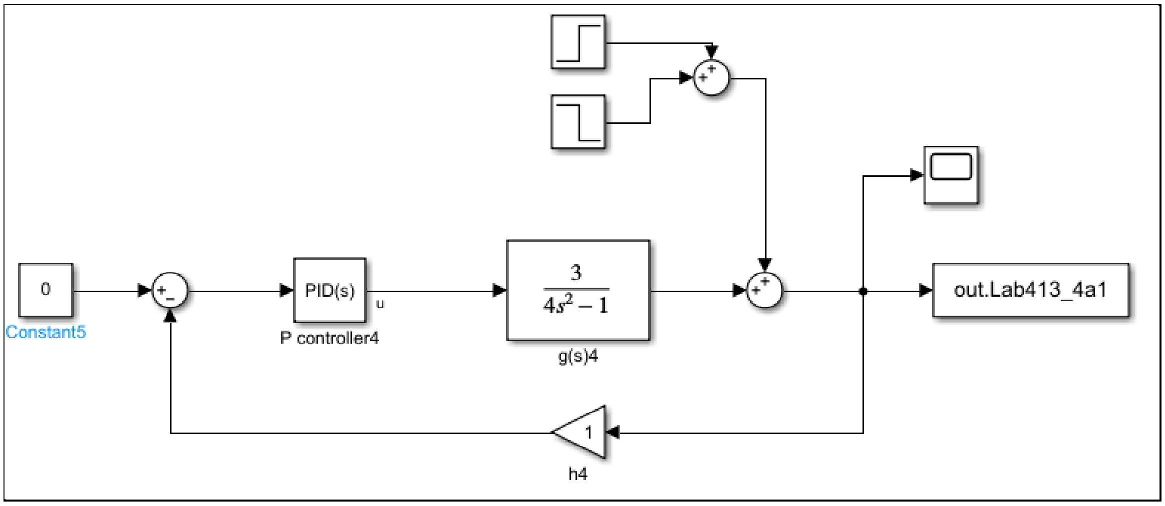


Figure 22. Simulink set up for the system under PID control, with h(s)=1, d(t) as a pulse input of magnitude 1, lasting for 0.1 time units, K_c=10, with τ_I=1, and changing τ_D.

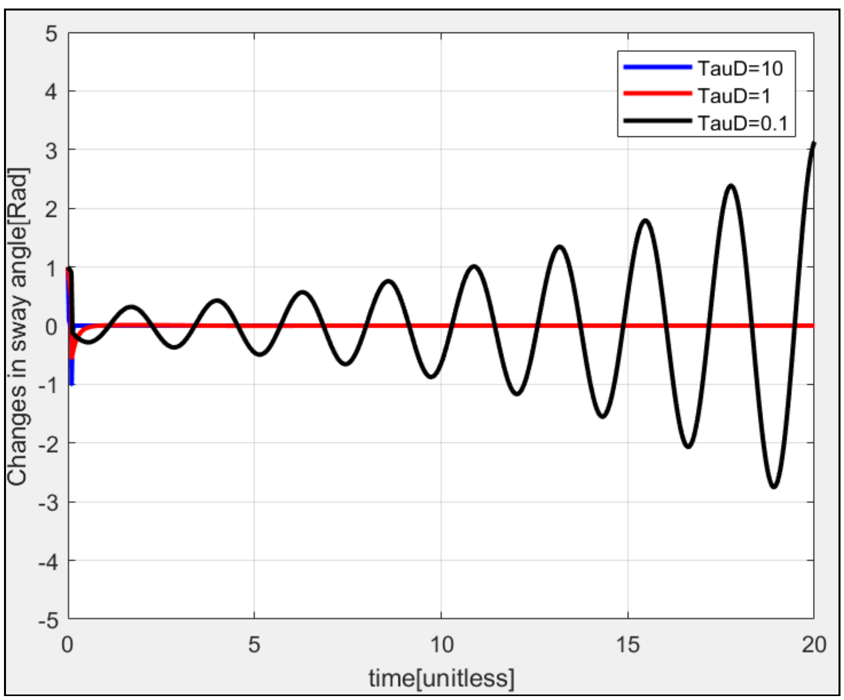


Figure 23. Response of the system under PID control, with h(s)=1, d(t) as a pulse input of magnitude 1, lasting for 0.1 time units, K_c=10, with τ_I=1, and changing τ_D.The blue

line and red line are overlapping after ~1 time unit because they converge to 0 in steady state.

The presence of an integrator with a PID controller will stabilize the system. As shown in Figure ?, the response achieves steady state after the disturbance when τ_D=10 and 1. When τ_D decreases, we can see that the oscillatory behavior in response becomes more intense. This is because when τ_D decreases to a small value, the impact of $\tau_D s$ in PID controller transfer function: $K_c(1+\frac{1}{\tau_I s}+\tau_D s)$ also decreases. When the τ_D is very small, $\tau_D s$ becomes negligible in PID controller function, and the PID controller transfer function becomes just the same as PI controller transfer function, the system becomes unstable.

5. Effect of Sensor Delay

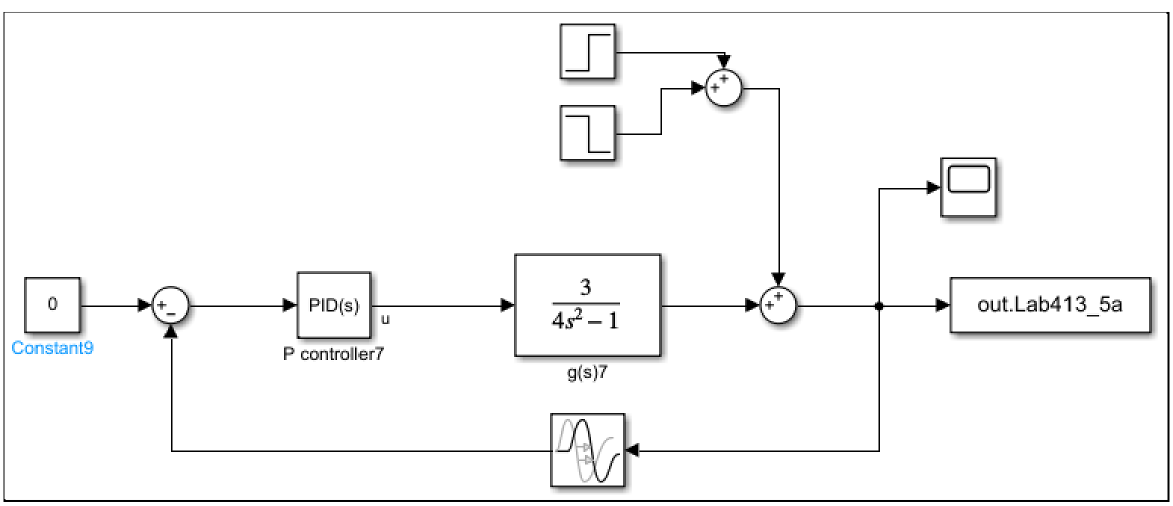
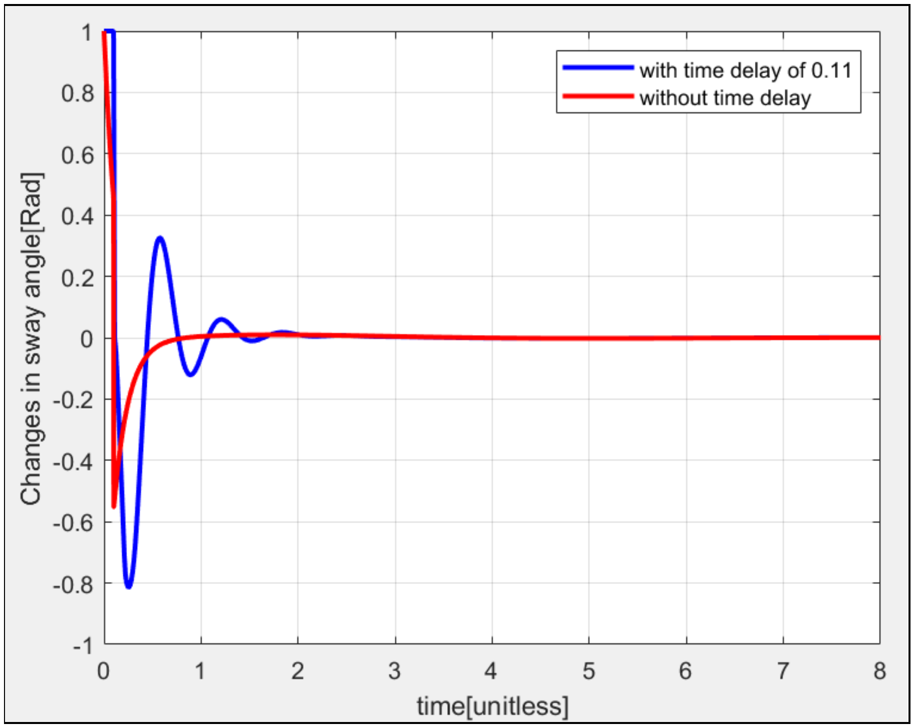


Figure 24. Simulink set up for the system under PID control, with d(t) as a pulse input of magnitude 1, lasting for 0.1 time units, K_c=10, with τ_I=1, τ_D=1.0, and a time delay.



(a)

Figure 25. Response of the system under PID control, with d(t) as a pulse input of magnitude 1, lasting for 0.1 time units, K_c=10, with τ_I=1, τ_D=1.0. The blue line is with time delay, with h(t)=$e^{-0.11s}$. The red line is without time delay, so h(t)=1.

By comparing the 2 responses, although both systems reach steady state at about the same time(~4 time unit), the system with time delay gives a more sensitive response toward the pulse input of disturbance, as it bounces(upward and downward) more than the system without time delay. Besides that, the system with time delay is able to show relatively more oscillations before reaching the steady state.

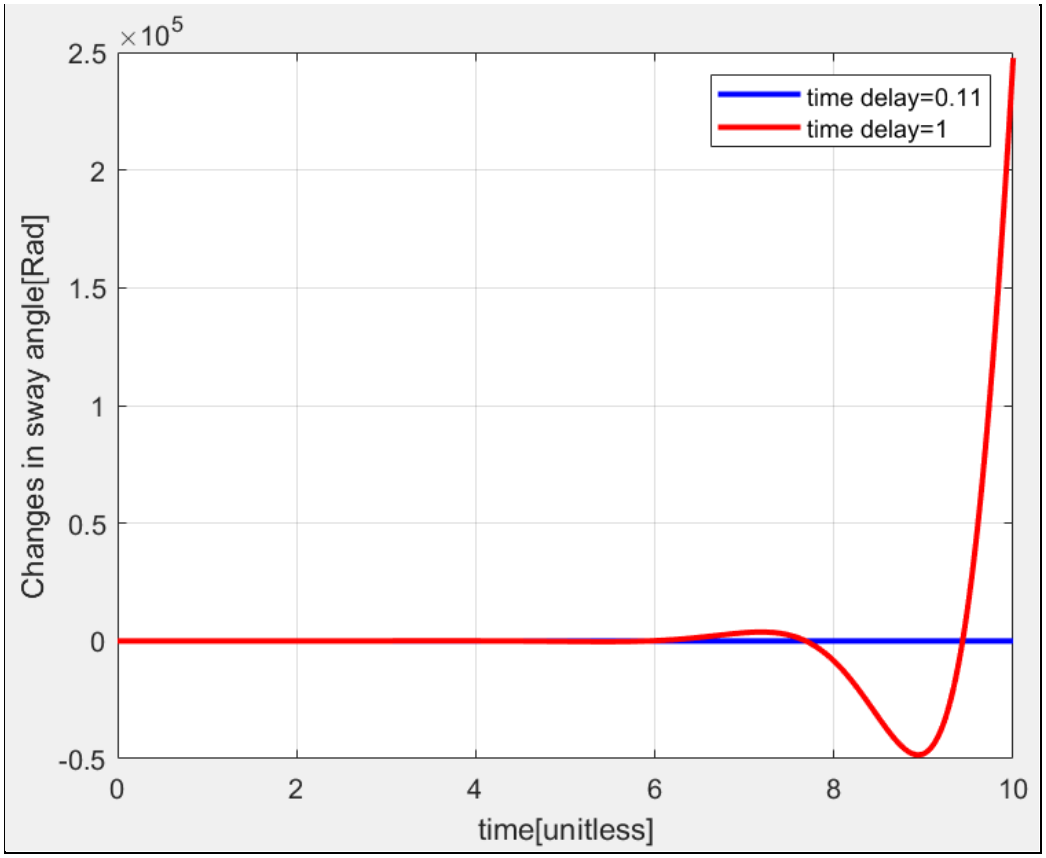
(b) 

Figure 26. Response of the system under PID control, with d(t) as a pulse input of magnitude 1, lasting for 0.1 time units, K_c=10, with τ_I=1, τ_D=1.0, with different time delays.

With increased time delay(1 time unit), the change in sway angle increases a lot, and does not converge in steady state, the system becomes unstable.

6. Implication for the Elderly

Our results can help to predict the human balance among the elderly. Our result shows that the increase of time delay will increase the change in sway angle and can lead to the system to be unstable, and does not converge to a steady state; the response will grow exponentially when time delay is large, the person loses his/her balance. Besides that, our result shows that the decrease in the ‘effective’ derivative time will cause the system to show an increasing oscillatory pattern in longer time, thus causing the system to be unstable. Our results and the mathematical model developed can be used to give effective predictions for balance keeping in the elderly.