ENEL 441 Control Systems 1, Final Exam
Winter 2020

Instructor: John Nielsen

Exam posted on D2L, April 19 @ 9 AM
Deadline for submission of exam into D2L dropbox, April 25 @ 1pm

Instructions

1. Complete your design solution and write these into a Word file. Alternatively, you can write out all of the solutions by hand. Then scan these into a PDF file.

2. Upload the Word or PDF file using the D2L drop box. Submit by April 25 using the D2L drop box by 1 pm. Make sure the file you have uploaded is the version that you intended and that it is complete. Should there be any issue with the D2L submission then you can always email your completed exam file to me directly at nielsenj@ucalgary.ca.

3. The exam consists of a single problem with multiple parts. You will find it similar to the questions of the lab assignments. For all the problem steps clearly explain what you are doing. Part marks cannot be given for incorrect solutions that are not adequately explained. For the marking, there is less emphasis on the final numerical answers and more emphasis on how you solved the problem and the steps taken.

4. A discussion folder regarding the final exam will be opened prior to posting the exam. If you have questions, look through the existing threads as you may find your answer there. If not open a new thread. I will be monitoring the discussion submissions during April 21-25. Furthermore, I will be available via email (nielsenj@ucalgary.ca).

5. Fill in the Student Integrity Form as presented on page 2. Typing in your name is sufficient as you will include the form as part of your exam document to be submitted.

Schulich School of Engineering Academic Integrity Statement

Academic integrity is the foundation of the development and acquisition of knowledge and is based on values of honesty, trust, responsibility, and respect. We expect members of our community to act with integrity.

Research integrity, ethics, and principles of conduct are key to academic integrity. Members of our campus community are required to abide by our institutional code of conduct and promote academic integrity in upholding the University of Calgary's reputation of excellence.

The University of Calgary Principles of Conduct can be found in Section K of the University Calendar.

You are expected to write this exam on your own, without consultation with your peers. The answers on this exam should be reflective of your work and your understanding of the course content.

"Integrity is doing the right thing, even when no one is watching"
-C.S. Lewis

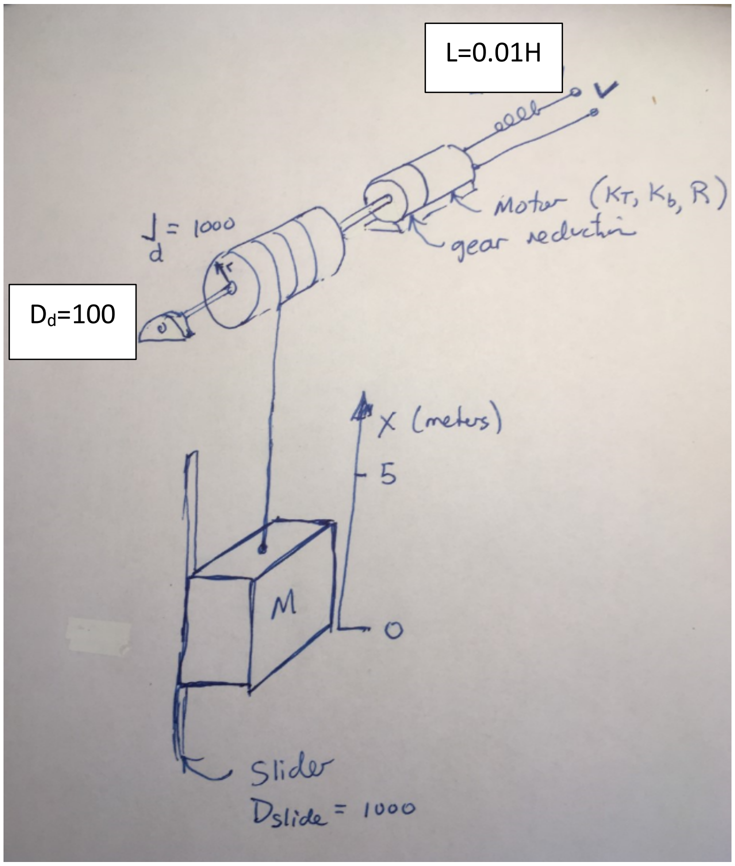
I, _________Farhad Alishov__________, ID# _______30041463______ (First Name Last Name, U of C Student ID Number) do solemnly swear that I have not and will not communicate about this final examination with anyone, especially other students in the course, until after the deadline for submission of exam solutions. The answers on this exam are my own. I did not consult with any other person about the content on this exam prior to submitting my answers. I have conducted myself in an ethical manner that upholds the integrity and dignity of the engineering profession.

I fully understand that disciplinary action may be taken against me if I am discovered to have communicated with anyone about the content or solution of this final examination.

By submitting this final examination, I agree that I have abided by the university's principles of conduct as outlined above.

Exam Problem Statement

It is required to design a control system for an elevator for a high-rise building. A sketch of the elevator system is shown in the figure below:



The elevator car has a mass of M=1000 kg and there can be 0 to 5 people in the elevator each with a mass of 100 kg. Hence the mass of the elevator load can vary between 1000 to 1500 kg. The vertical displacement of the elevator car is x. The slider has a friction coefficient D_{slide} of 1000 newton sec/meter. The cable drum rotational inertia is 1000 kg meter^2. The cable drum bearing has a friction of D_d=100 newton meter sec/rad. The motor coefficients are

$$K_T = 22\ newton\ meter/ampere$$
$$K_b = 25\ volt\ sec/rad$$
$$R = 1\ ohms$$

The motor armature winding inductance is 0.01 Henry.

The motor gear box has a ratio of 10:1 such that the drum rotates one turn for every ten turns of the motor. The drum radius is r=80 cm.

The cable itself is considered to be approximately massless. Also, a strain gauge is provided that can measure the weight of the elevator car with passengers prior to any motion.

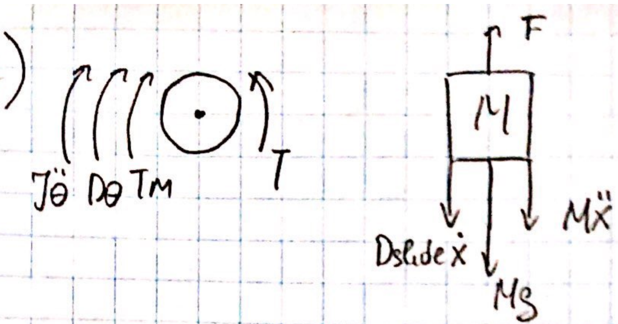
For feedback, the vertical displacement x(t) is sensed and fed back to the control system.

Your objective is to design a control loop for the motor that will give an elevator transit time between the ground and first floor level at 5 meters of about 5 seconds with minimal overshoot and ringing.

Complete, correct and well documented solutions that are supported with simulation and analysis code will be given full marks. You can use any Matlab functions and Simulink simulation blocks. You do not have to use Matlab/Simulink if you would prefer another programming language. The parts A, B, C, D and E carry equal weight in terms of grading.

A) Generate the state space representation for the overall elevator system with voltage v(t) as an input and the elevator car displacement x(t) as the output.

A)



$T = T_M + D\dot{\theta} + J\ddot{\theta}$

$Dw \quad J\dot{w}$

$F = \dot{x} D_{slide} + Mg + M\ddot{x}$

$T_M = \dot{w} D_{slide} + Mg + M\dot{w}$

$T_{dle} = \frac{n_2}{n_1} T = T_M \left(\frac{n_2}{n_1}\right) + J\left(\frac{n_2}{n_1}\right)^2 \dot{w} + D\left(\frac{n_2}{n_1}\right)^2 w$

after we put T_M value...

$T_{dle} = (\dot{x} \tau D_{slide} + \tau Mg\, u(t) + M\tau\ddot{x})\left(\frac{n_2}{n_1}\right)$
$\quad + J\left(\frac{n_2}{n_1}\right)^2 \dot{w} + D\left(\frac{n_2}{n_1}\right)^2 w$

$V = IR + K_b w + Li' \rightarrow \frac{di}{dt} = \dot{I} = \frac{V}{L} - \frac{IR}{L} - \frac{K_b}{L} \cdot \frac{\dot{x}}{\tau}$

$\boxed{\dot{I} = 100V - 100I - 3125\dot{x}}$

$I K_T = (\dot{x} \tau D_{slide} + \tau Mg\, u(t) + M\tau\ddot{x}) \frac{n_2}{n_1}$
$\quad + \frac{J}{\tau}\left(\frac{n_2}{n_1}\right)^2 \ddot{x} + \frac{D_d}{2}\left(\frac{n_2}{n_1}\right)^2$

$22I = 80\dot{x} + \tau g\left(\frac{n_2}{n_1}\right) Mg + M\,0.08\ddot{x} + 12.5\ddot{x} + 1.25\dot{x}$
$\quad = 81.25\dot{x} + (12.5 - 0.08M)\ddot{x} + \tau g\left(\frac{n_2}{n_1}\right) Mg\, u(t)$

$$\ddot{X} = \frac{22I - 81.25\dot{X} - 7g\left(\frac{n_2}{n_1}\right)M_g\, u(t)}{12.5 - 0.08M}$$

this part does not matter to us

$$\begin{bmatrix} \dot{I} \\ \dot{X} \\ \ddot{X} \end{bmatrix} = \underbrace{\begin{bmatrix} -100 & 0 & -3125 \\ 0 & 0 & 1 \\ \frac{22}{12.5-0.08M} & 0 & \frac{-81.25}{12.5-0.08M} \end{bmatrix}}_{A} \begin{bmatrix} I \\ X \\ \dot{X} \end{bmatrix} + \underbrace{\begin{bmatrix} 100 \\ 0 \\ 0 \end{bmatrix}}_{B} V$$

$$y = \underbrace{\begin{bmatrix} 0 & 1 & 0 \end{bmatrix}}_{C} \begin{bmatrix} I \\ X \\ \dot{X} \end{bmatrix} + \underbrace{\begin{bmatrix} 0 \end{bmatrix}}_{D} V$$

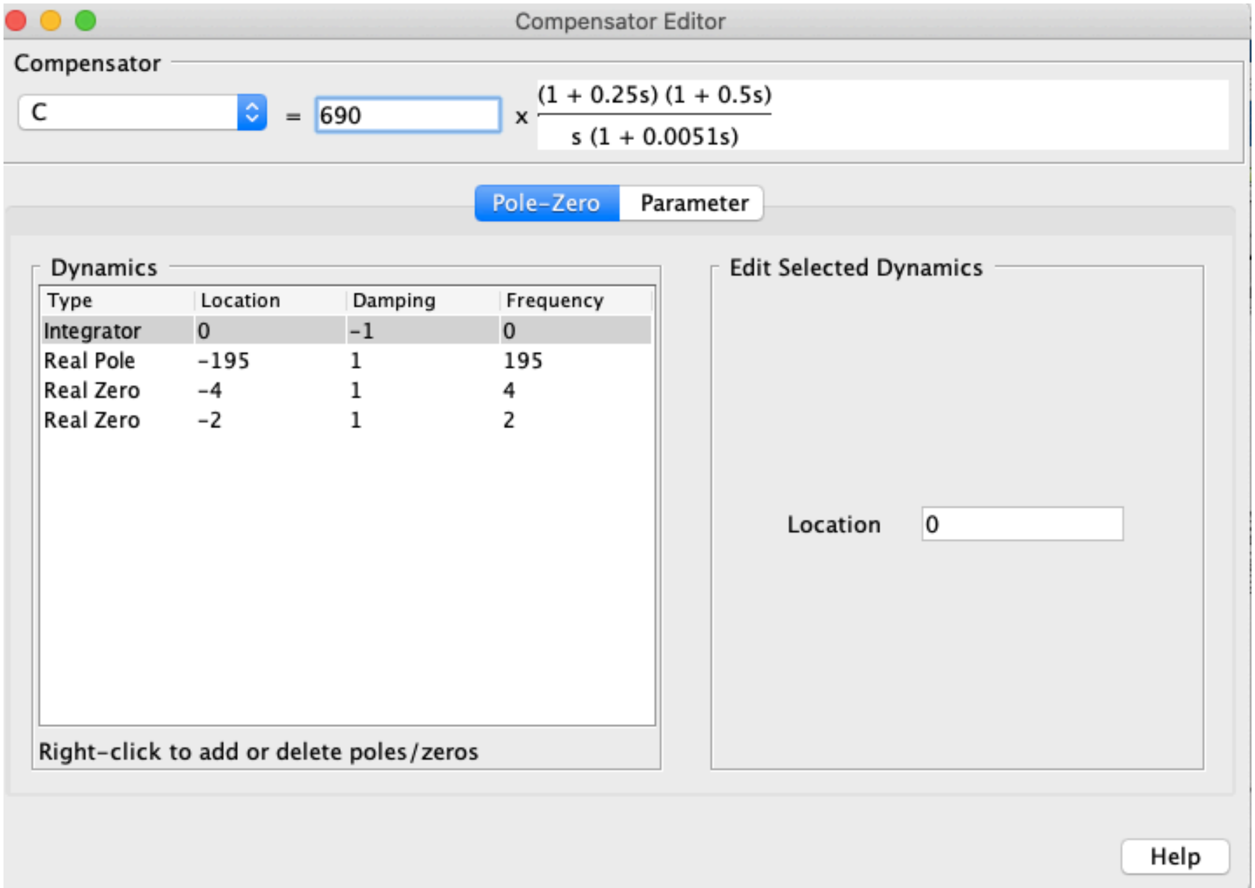
Input $V(t)$
Output $X(t)$

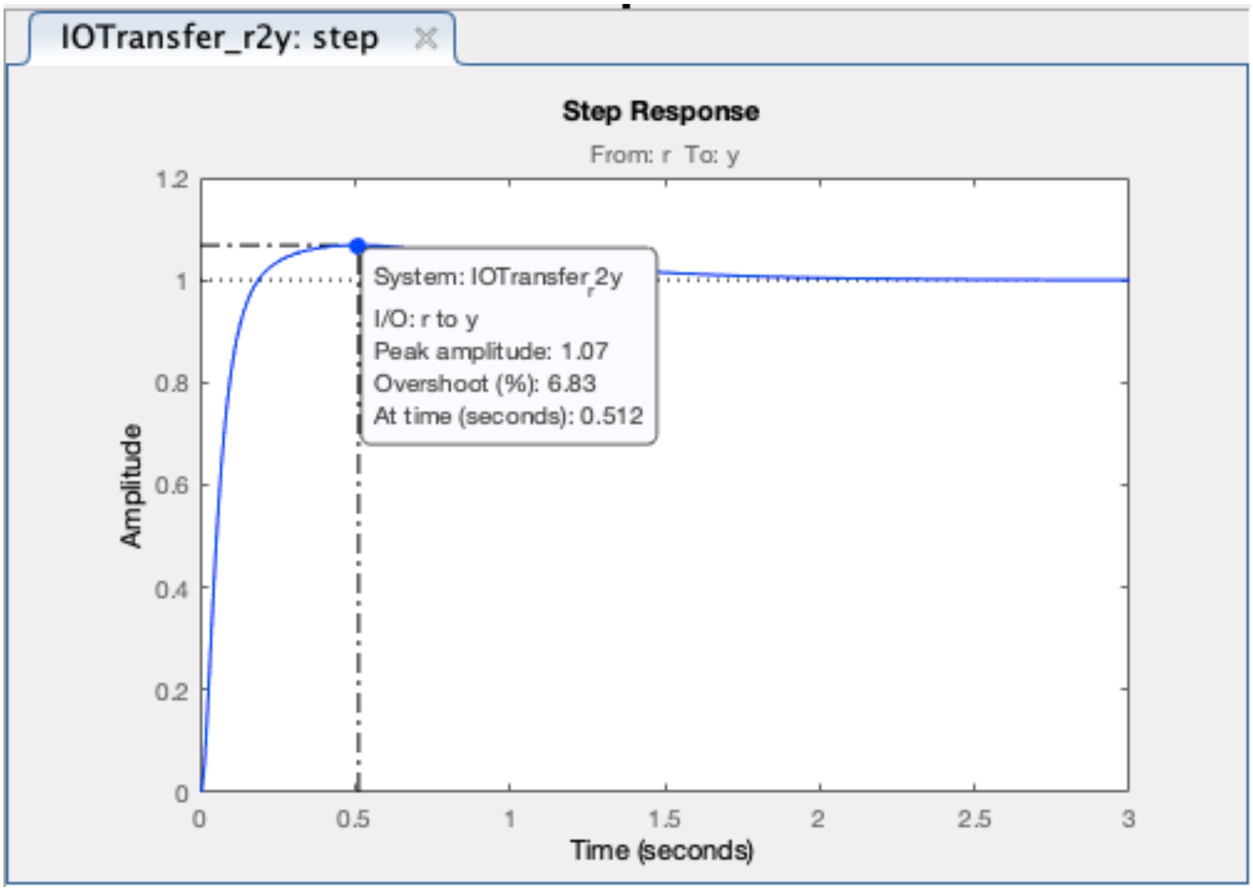
B) Design a digital compensator based on a type II loop that updates at a rate of 10 kHz. The reference input is the desired vertical displacement. The output sensor gives the actual elevator car height. The reason for the type II control loop, is that the elevator manufacture would like to use a ramp function for the reference input, denoted as $x_{ref}(t)$. This gives a softer start and stop to the elevator. It also allows for a more direct control of the elevator speed.

```
%% B
syms s
mass = 1500;
A = [-100 0 -3125; 0 0 1; 22/(12.5+0.08*mass) 0 -81.25/(12.5+0.08*mass)];
B = [100; 0; 0];
C = [0 1 0];
D = [0];

StateSpace = (C*inv(s*eye(3)-A)*B);
FivePeople = pole(tf([1760], [106 10665 61500 0]));
sisotool(tf([1760], [106 10665 61500 0]));

Compensator = tf([16819 100914 134552], [1 195 0]);
C2D_10KHz = c2d(Compensator, 1/10000);
C2D_10Hz  = c2d(Compensator, 1/10);
```

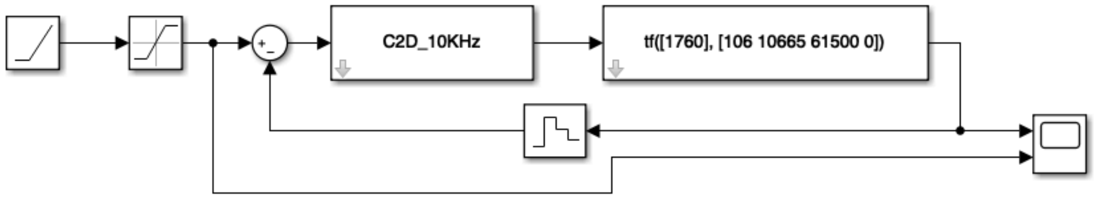

Compensator Editor
Compensator
C = 690 × (1 + 0.25s) (1 + 0.5s) / s (1 + 0.0051s)
Pole-Zero
Parameter
Dynamics
Type
Location
Damping
Frequency
Integrator 0 -1 0
Real Pole -195 1 195
Real Zero -4 1 4
Real Zero -2 1 2
Right-click to add or delete poles/zeros
Edit Selected Dynamics
Location 0
Help

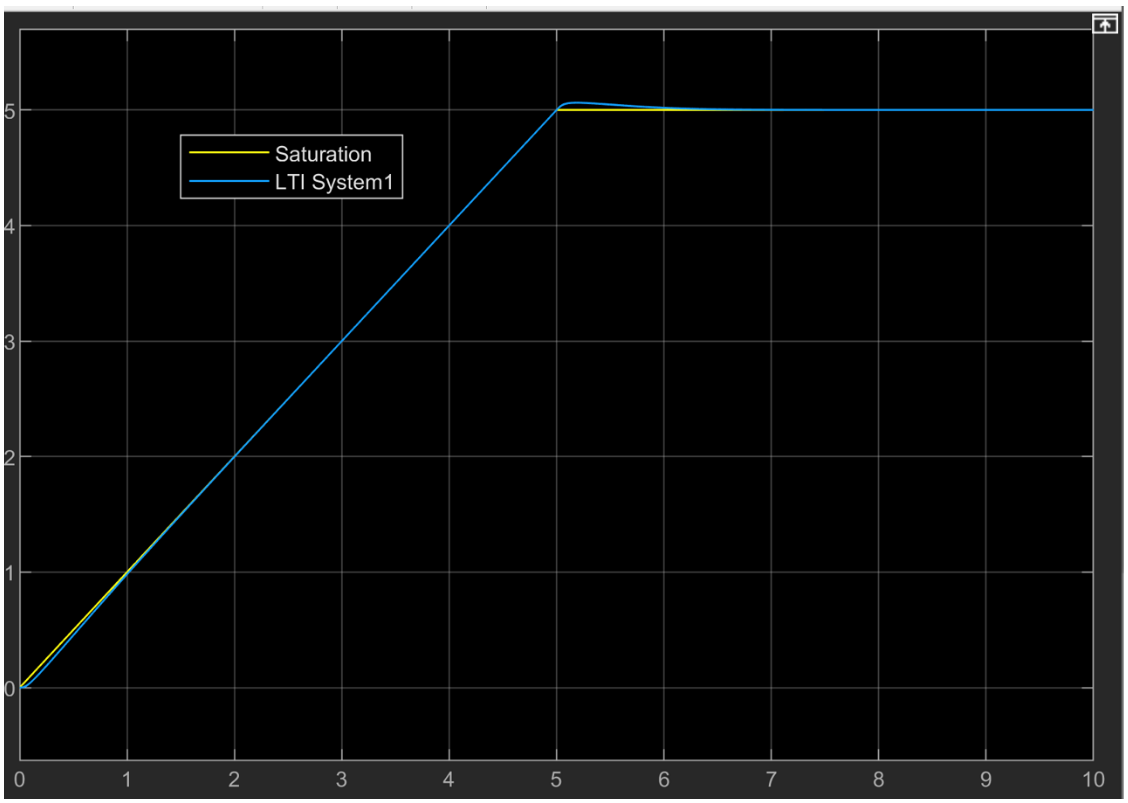


$$\text{Compens.} = 16819\left[\frac{(4+s)(2+s)}{s(195+s)}\right]$$

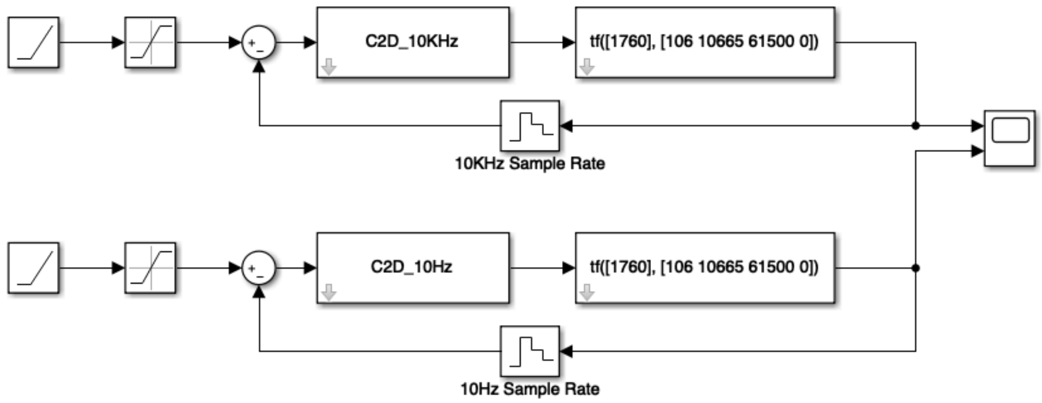
$$= 16819\left[\frac{8+6s+s^2}{s^2+195s}\right]$$

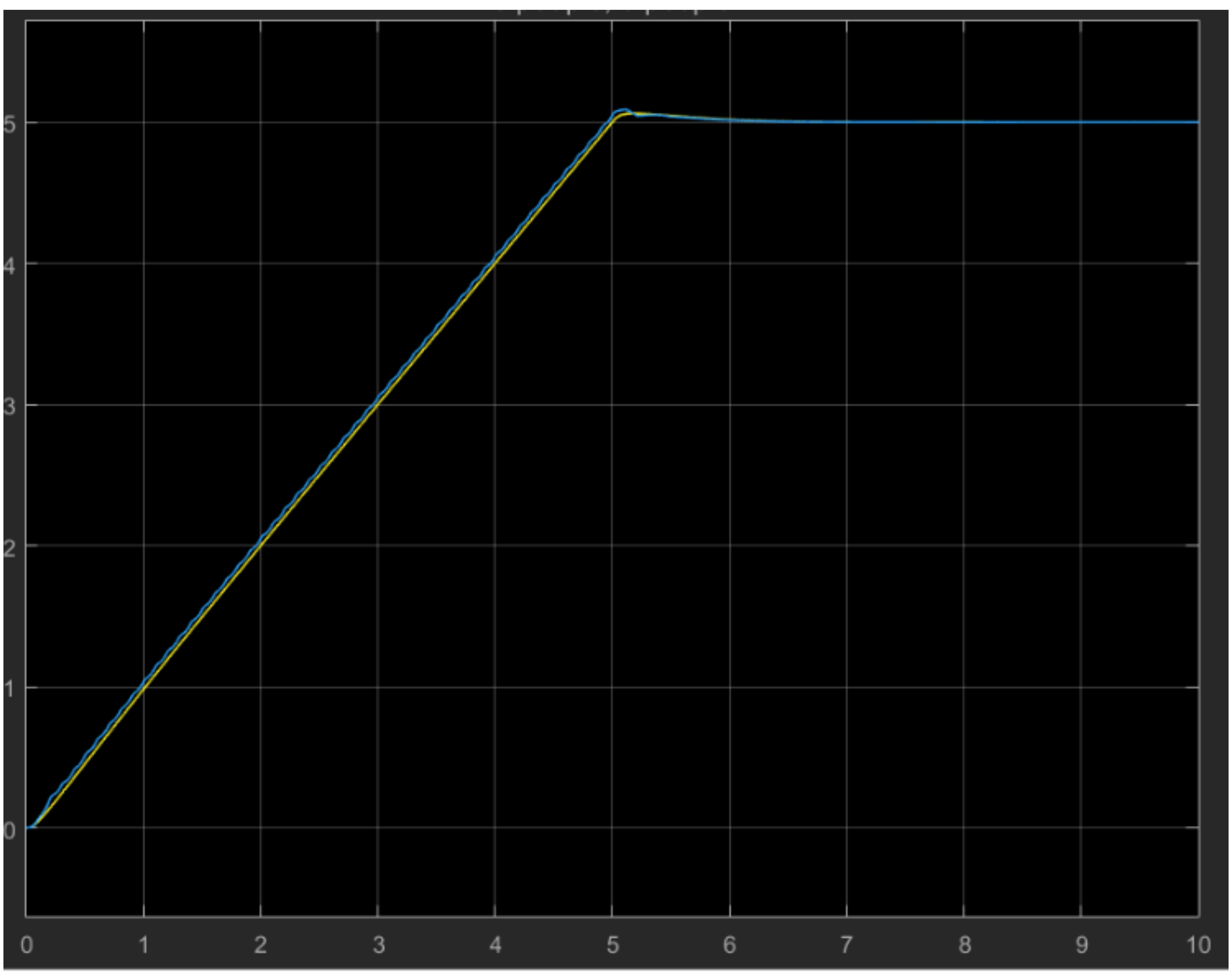
$$\frac{16819s^2 + 100914s + 134552}{s^2+195s}$$


C2D_10KHz
tf([1760], [106 10665 61500 0])


Saturation
LTI System1
0
1
2
3
4
5
0
1
2
3
4
5
6
7
8
9
10

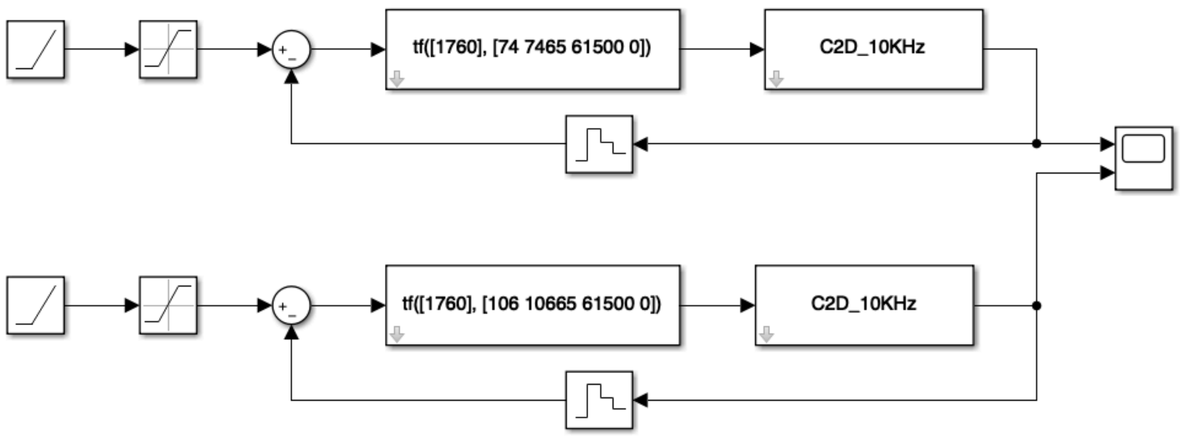
C) Suppose that the displacement feedback from the elevator is only at a rate of 10 observations of x(t) per second. What is the consequence of this reduced feedback rate?





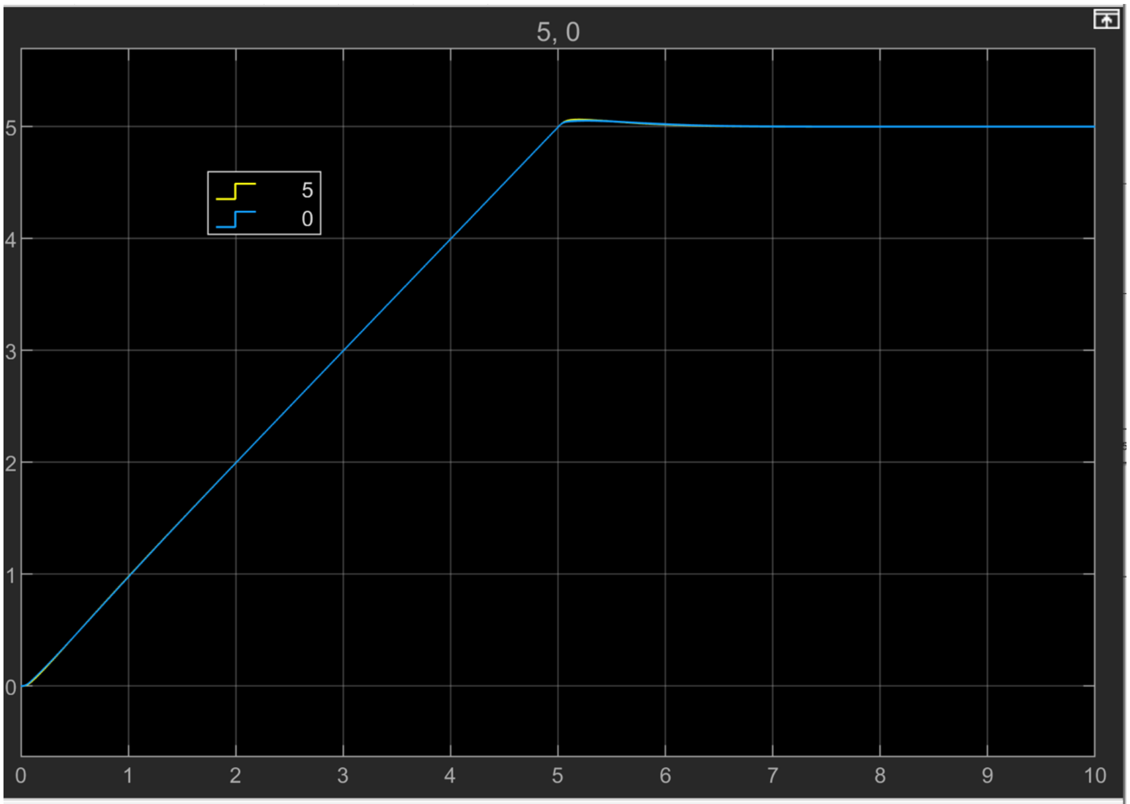
They both settle at about the same time are the same. 10 Hz sample had a bigger overshoot and a larger oscillation, since with the higher sample rate, we get the lower error.

D) Consider using the strain gauge for measurement of the elevator car weight prior to motion. Is it of significance? Does it change the elevator car control dynamics significantly if there is 0 or 5 people in the elevator? Support your answer with calculations of changes in the poles of the elevator car plant when people are added.




```
%% D
syms s
mass = 1000;
A = [-100 0 -3125; 0 0 1; 22/(12.5+0.08*mass) 0 -81.25/(12.5+0.08*mass)]
B = [100; 0; 0];
C = [0 1 0];
D = [0];

StateSpace = (C*inv(s*eye(3)-A)*B)
ZeroPeople = pole(tf([1760], [74 7665 61500 0]))
%sisotool(tf([1760], [74 7665 61500 0]));
```


5, 0
5
0
0
1
2
3
4
5
0
1
2
3
4
5
6
7
8
9
10

FivePeople =

0

-94.4718

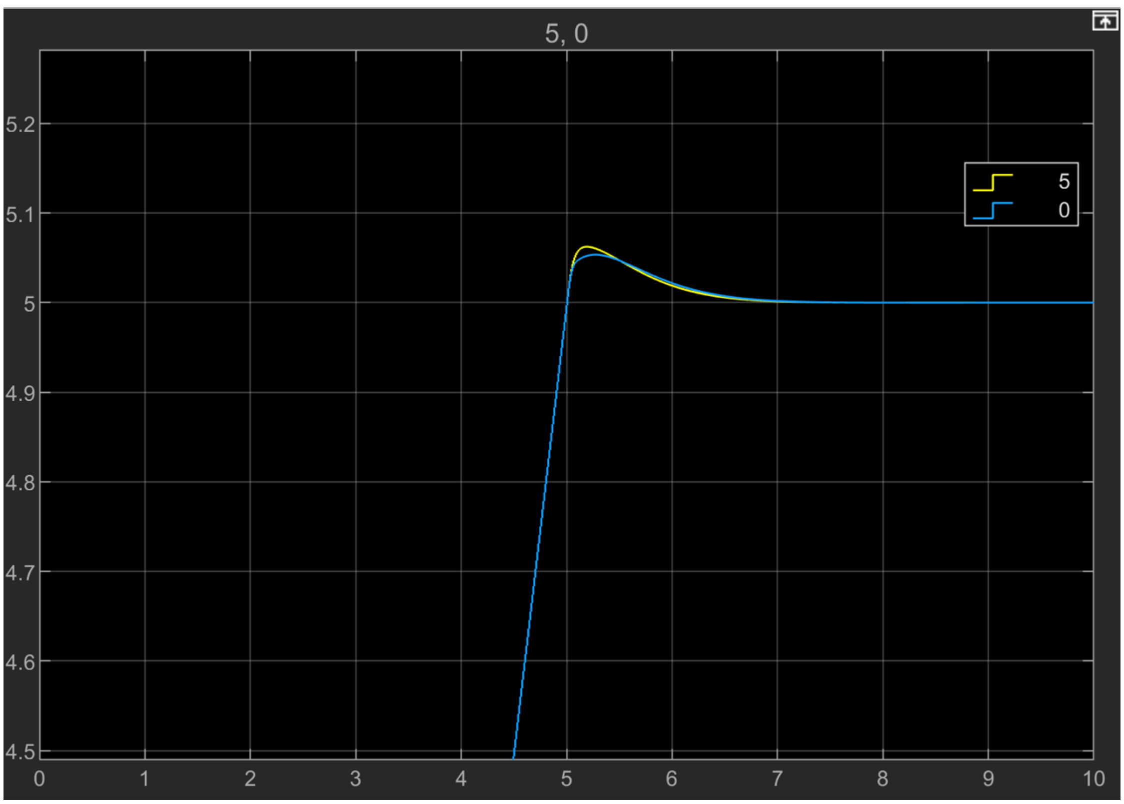
-6.1414

ZeroPeople =

0

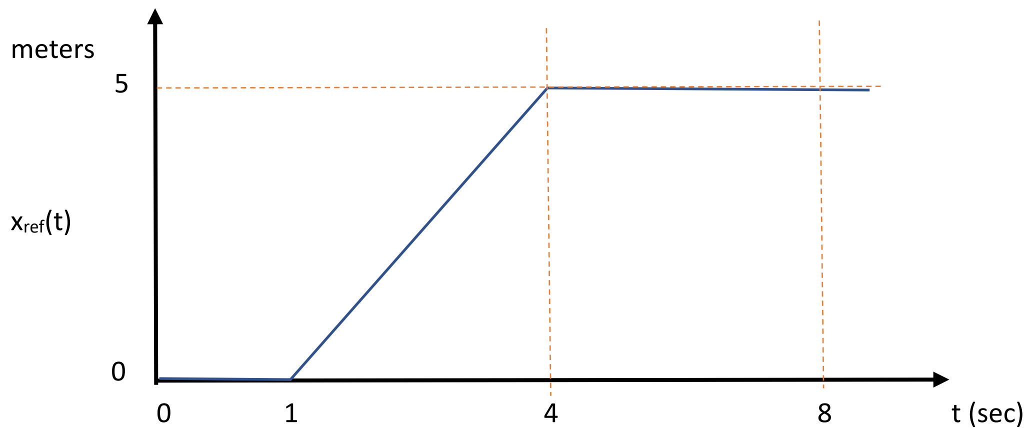
-94.8159

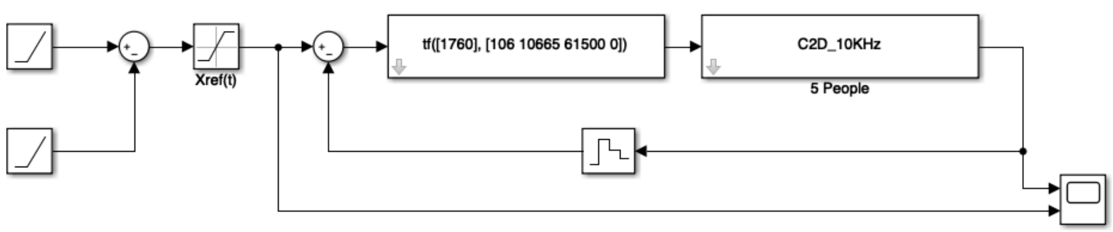
-8.7652

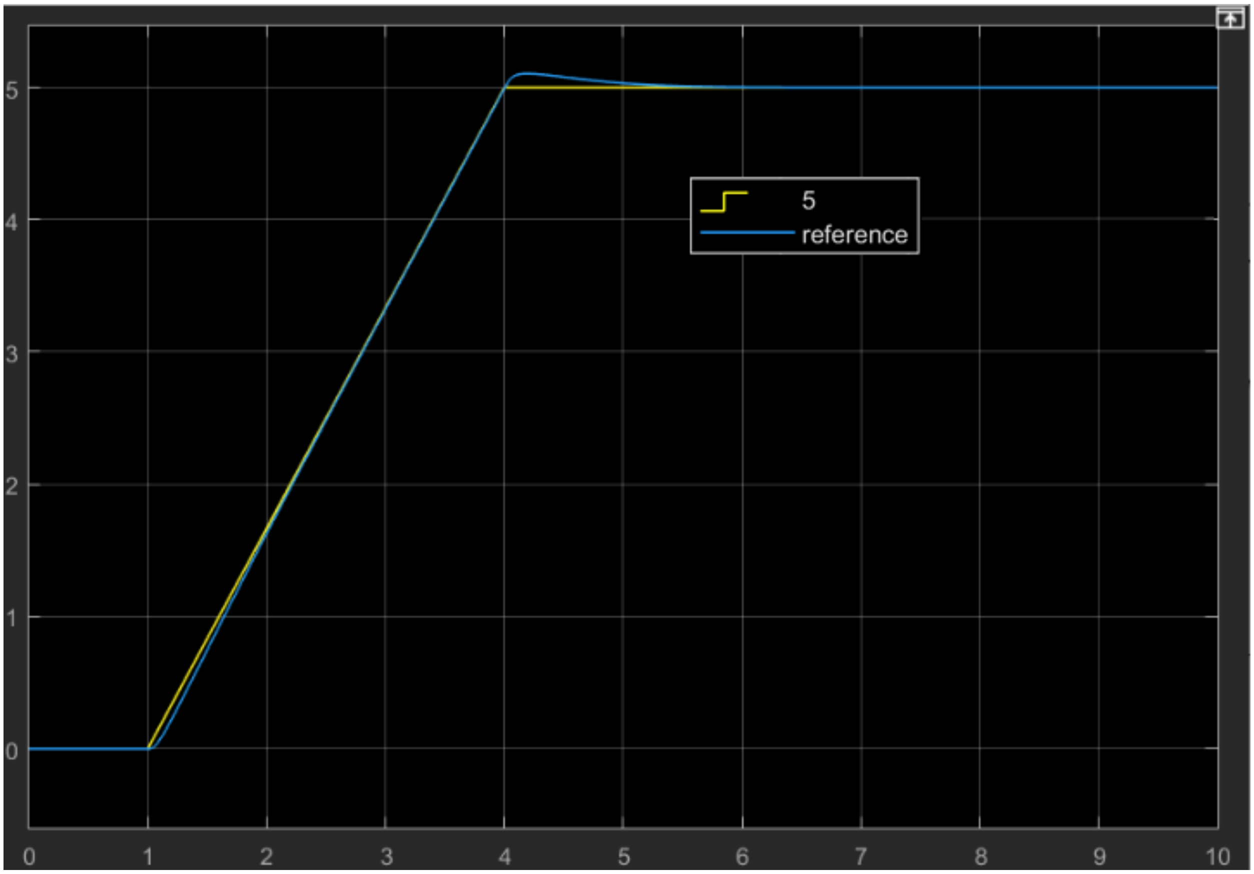


There is not much difference between 5 or 0 people in terms of control dynamics. Even the poles are very similar to each other. The same compensator will be appropriate in both cases. We do, however, see the change in the mass, which subsequently implies the change in transfer function. The car without people seems to settle its output a bit faster.

E) Provide a simulation of the elevator system response for the reference input of $x_{ref}()$ as plotted on the following page. You can use Simulink for this simulation or write a simulation based on a Matlab script file. Include enough output of Matlab and Simulink so that your solution can be verified. That is, include the matlab script and image of the Simulink model, graphs, scope outputs etc. You do not have to include the Simulink files. (You can also use any other programming language for this problem.)






5
reference
0
1
2
3
4
5
6
7
8
9
10