Antenna Azimuth Position Control System Analysis and Controller Implementation

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Executive Summary

The problem presented to our team was to analyze and implement a controller on a off the shelf antenna azimuth position control system. We analyzed the open loop and closed loop characteristics of the system and determined the most stable and implementable controller for the system.

Our suggested solution to the presented problem is to implement a PID controller ahead of the Power Amplifier but after the Preamplifier. This controller would be programmed with the values described in the body of this report. This will allow for better stability and response times of the system described in configuration three.

The implications of not implementing this controller are a non stable response to a step input with configuration three; also the system may saturate components and cause damage to some or all of the elements of the system. This could result in repair costs and replacement of components that can be prevented.

Table of Contents

Figures and Tables

Nomenclature

There are many variables used in the following sections to represent significant inputs, outputs, signals etc. A quick reference is included below to define all used variables.

Schematic Parameters	
Parameter	**Definition**
V	Voltage across Potentiometer [Volts]
N	Turns of potentiometer
K	Preamplifier gain
K_1	Power Amplifier Gain
a	Power Amplifier pole
R_a	Motor Resistance [ohms]
J_a	Motor Inertial constant [kg-m^2]
D_a	Motor Dampening constant [N-m s/rad]
K_b	Back EMF constant [V-s/rad]
K_t	Motor Torque constant [N-m/A]
N_1	Gear teeth
N_2	Gear teeth
N_3	Gear teeth
J_L	Load inertial constant [kg-m^2]
D_L	Load inertial constant [N-m s/rad]
Block Diagram Parameters	
Parameter	**Definition**
K_{pot}	Potentiometer gain
K	Preamplifier gain
K_1	Power Amplifier gain
a	Power Amplifier pole
K_m	Motor and load gain
a_m	Motor and load pole
K_g	Gear ratio

Statement of Problem

Our Design Group was charged with the task developing a new product in a non-defense related area. Based on our team's knowledge and experience in designing control systems our section head has charged our team with three tasks.

- Model, design, and simulate a discrete control system that meets customer specifications for a satellite antenna currently available on the market.
- Suggest an improvement in system performance through the use of a discrete controller and controls engineering analysis.

- Submit this technical report that is readable by peers, details our team's work and provides significant comments about our design and the results of our investigation.

The antenna azimuth control system currently available on the market is described as a servo controlled antenna through the use of gears and feedback potentiometers. The current design lacks any sort of compensator controller that would provide stability control. Our team must analyze the current configuration and determine the stability.

Once the current configuration is analyzed our team must decide on an appropriate compensator to provide ample stability and realistic responses to inputs. Our design must not saturate the components in the current system, yet control the system in a reasonable manner.

In doing this we started out with a few assumptions, and amended the list as we worked. The following assumptions are used in the analysis:

1. The system is well described in the provided project data, that is the values for modeling the motor, gears, load, Preamplifier, Power Amplifier, potentiometers and voltage references are accurate.
2. The transfer functions given for the power amplifier and preamplifier are accurate representations of the system currently in use.
3. The gain of the preamplifier is assumed to be 1 for simplification of analysis and any gain that needed to be implemented will be in the compensator controller.
4. There are no disturbances or interferences in the signals sent between parts of the controller system.

There are four parts to the original given problem statement. These are summarized below.

1. Determine the associated transfer functions of each of the five subsystems of the on market system.
2. Find the system response to a step input with the feedback potentiometer disconnected.
3. Given the current configuration, design a purely proportional controller that achieves the requested response characteristics.
4. Given the current configuration, design any type of controller to achieve the best system response and stability and achieve the given response characteristics.

Analysis

The project was split into four distinct sections and analyzed by section. Matlab was the primary tool used for the analysis and all of the modeling. Below is the analysis of the control system; separated by section.

Section 1

There are 5 subsystems of the overall system, each with its associated transfer function. These are described both in the schematic (Figure 2) and the given block diagram (Figure 1).

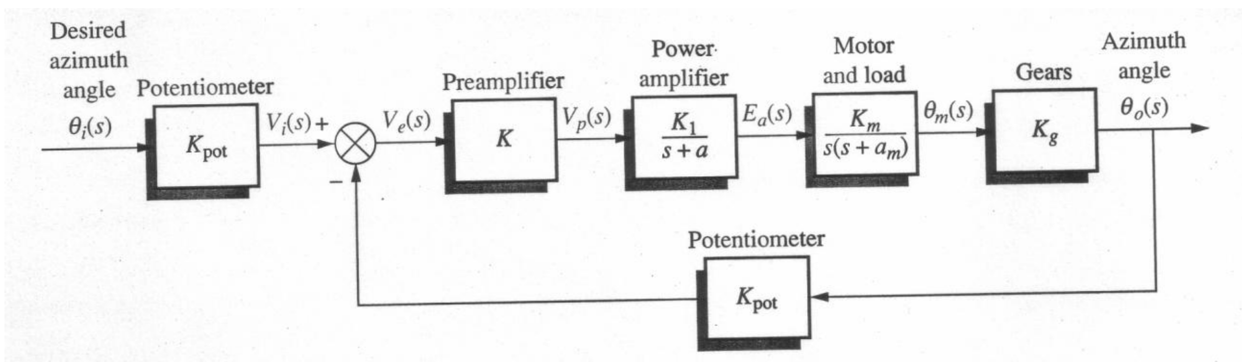


Figure 1 (Provided block diagram)

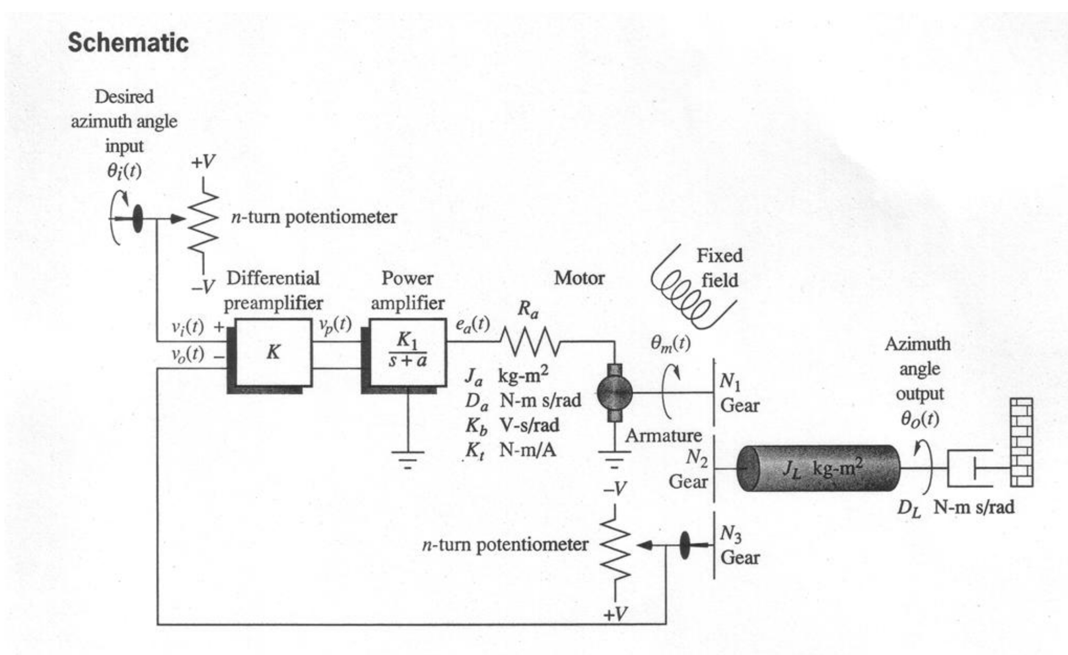


Figure 2 (Provided Schematic)

A table of given values for configuration three is given below, and referred to throughout the report.

Schematic Parameters		
Parameter	**Configuration 1**	**Configuration 3**
V	10	10
N	10	1
K	-	1*
K_1	100	100
a	100	100
R_a	8	5
J_a	0.02	0.05
D_a	0.01	0.01
K_b	0.5	1
K_t	0.5	1
N_1	25	50
N_2	250	250
N_3	250	250
J_L	1	5
D_L	1	3
Block Diagram Parameters		
Parameter	**Configuration 1**	**Configuration 3**
K_{pot}	0.318	3.18
K	-	1*
K_1	100	100
a	100	100
K_m	2.083	0.8
a_m	1.71	1.32
K_g	0.1	0.2

Table 1

Subsystem 1 and 5.

The input and feedback potentiometer each have an associated transfer function, in the form of a gain. The potentiometer changes the input angle, $\emptyset_m(s)$, to a voltage, $V_i(s)$. This ratio is described by the value K_{pot_i}. This value is computed by Equation 1. The value of this gain is determined by the voltage applied to the potentiometer and the number of turns the potentiometer is built for, both of these values are given in Table 1.

$$\frac{V_i(s)}{\emptyset_i(s)} = K_{pot_i} = \frac{V}{n\pi} = \frac{10}{1 * \pi} = 3.18$$

Equation 1

Subsystem 2.

The purpose of the preamplifier is to take the input signal voltage and output a voltage that the power amplifier can use. The Preamplifier is also modeled by a gain that can be specified by the design engineer to achieve a desired output. The Preamplifier is a system in which the input voltage is amplified by some gain K and output as a voltage. The resulting equation therefore is quite simple, as shown in Equation 2.

$$\frac{V_p(s)}{V_e(s)} = K$$

Equation 2

Subsystem 3.

The third subsystem is a Power Amplifier which takes the output voltage from the Preamplifier and converts it to a Voltage that is useable by the motor. This requires the Power Amplifier to output a significant amount of power, something that the Preamplifier is not capable of. The power amplifier type is given in the design schematic and the given block diagram. Also the value of K_1 and a in the transfer function are given in the configuration data.

$$\frac{E_a(s)}{V_p(s)} = \frac{K_1}{s+a}$$

Equation 3

Subsystem 4.

After the Power Amplifier is the motor, attached to the gears and load, which in this case is an antenna. All of these items must be considered when computing the transfer function of the resulting mechanical system. It is assumed that the motor is an armature controlled DC servo motor. This is determined by the note that the motor has a fixed field, which also simplifies the control of the motor.

To derive the transfer function of the subsystem one must find the KVL equation relating the input voltage to the motor to the output position of the armature. Figure 3 shows the general circuit of the motor.

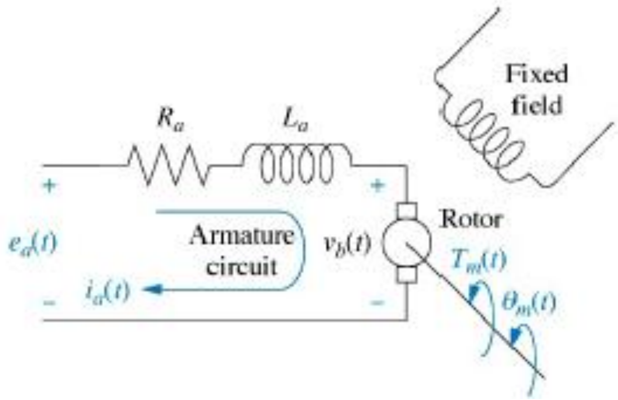


Figure 3 (Courtesy Memorial University, Canada)

The resulting KVL equation is shown in Equation 4. We are only concerned with the input voltage, and we have no information regarding the input current, thus it would be useful to replace the current term I_a with its equivalent Torque term, shown in Equation 5.

$$R_i I_a(s) + L_a s\, I_a(s) + V_b(s) = e_a(s)$$

Equation 4

$$T_m(s) = K_t I_a(s) \therefore I_a(s) = \frac{T_m(s)}{K_t}$$

Equation 5

This results in an equation with no current term, but instead a motor torque. This torque term can be replaced by a term relating torque to motor speed, position, inertia and dampening. One can replace the back EMF term V_b with a term that relates back EMF to the derivative of speed, which is position, a term we will need to create the transfer function. These are both show in Equation 6 and Equation 7.

$$V_b(s) = K_b s \emptyset_m(s)$$

Equation 6

$$T_m(s) = (Js^2 + D_m s)\emptyset_m(s)$$

Equation 7

Thus replacing the corresponding variables with their equivalents into Equation 4, and simplifying creates Equation 8.

$$\frac{(Js^2 + D_m S)(R_a + L_a s)\emptyset_m(s)}{K_t} + K_b s \emptyset_m(s) = E_a(s)$$

Equation 8

This is making use of the assumption that this is a fixed field motor, which makes K_b and K_t equal. Both of these values are given; for configuration three they are 1. Then pulling $\emptyset_m(s)$ to the outside yields Equation 9.

$$\left[\frac{(Js^2 + D_m S)(R_a + L_a s) + K_b K_t s}{K_t}\right] \emptyset_m(s) = E_a(s)$$

Equation 9

Assuming that R_a>>L_a one can further simplify to Equation 10.

$$\frac{\emptyset_m(s)}{E_a(s)} = \frac{\frac{K_t}{JR_a}}{s(s + \frac{D_m R_a + K_b K_t}{JR_a})}$$

Equation 10

The dampening and inertial components of the system are connected to the motor through a set of gears. This changes their effective values as seen by the motor and must be compensated for in the mathematics. This can be done using Equation 12 and Equation 13. Here you can see that the dampening and inertial components of the antenna are adjusted by the gear ratios, as seen in Equation 11.

$$K_g = \frac{N_1}{N_2} = 0.2$$

Equation 11

$$J = J_a + J_L(K_g)^2 = 0.25$$

Equation 12

$$D_m = D_a + D_L(K_g)^2 = 0.13$$

Equation 13

Equation 10 is in the same form as the given transfer function for the motor and load, thus we can relate the variables K_m, and a_m. This, along with their computed values, can be seen in Equation 14 and Equation 15.

$$K_m = \frac{K_t}{JR_a} = \frac{1}{.25 * 5} = 0.8$$

Equation 14

$$a_m = \frac{D_m R_a + K_b K_a}{JR_a} = \frac{.13 * 5 + 1 * 1}{.25 * 5} = 1.32$$

Equation 15

Section 2

For part 2 we were instructed to assume an open loop system in which there is no feedback. This is illustrated in Figure 4.

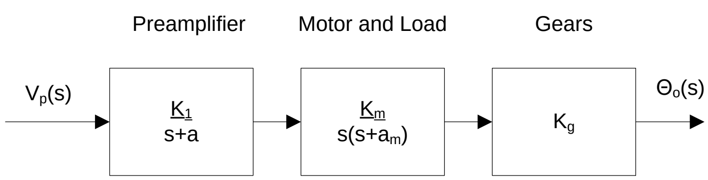


Figure 4

We then applied an input in the form of a step to the Power Amplifier and plotted the output angle of the system. This result can be seen in Figure 5.

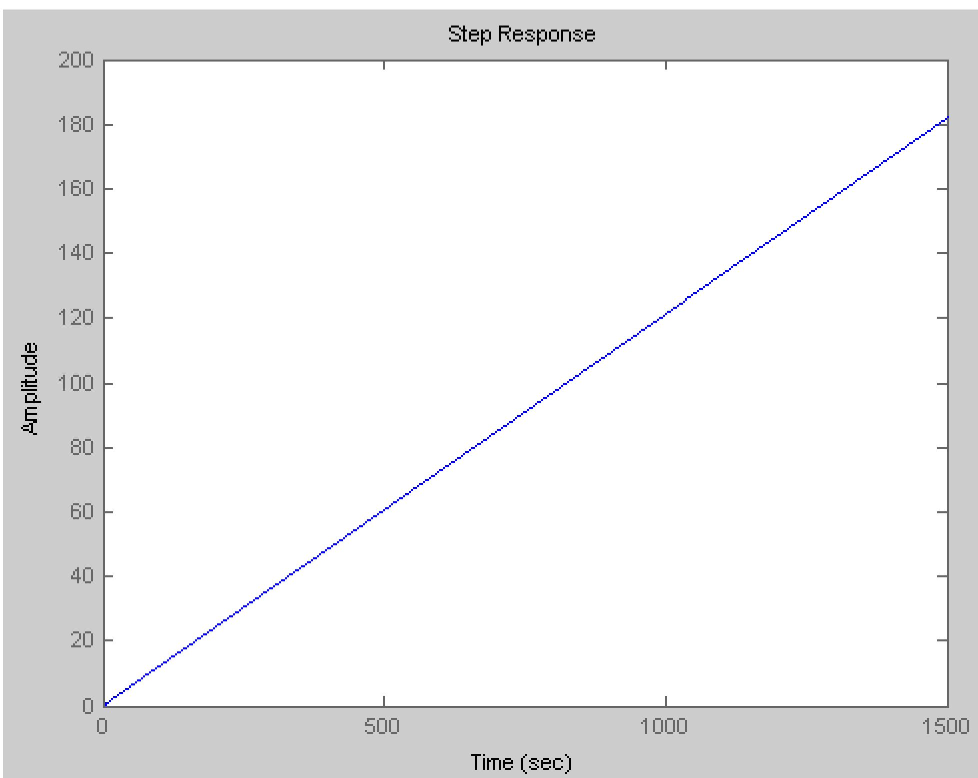


Figure 5 Step Response of the Open Loop System

One can see that the step response of the open loop system is unstable and results in a ramp output that will quickly saturate the components of the system. This response shows that the dampening ratio is 1 and the natural frequency is 0.

Section 3

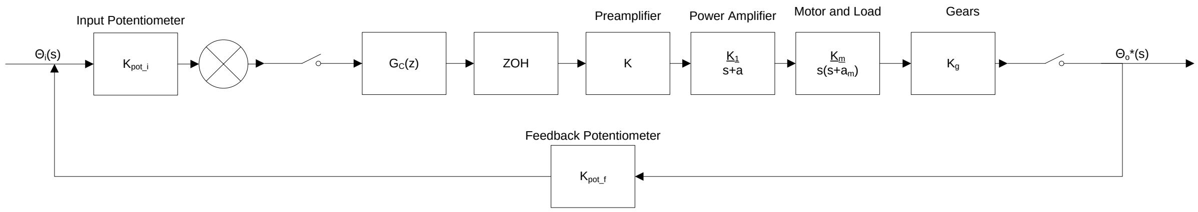


Figure 6 Block Diagram

1) Derivations of transfer function for the closed-loop system:

$$\theta_0(s) = K_g * \frac{K_m}{s(s+a_m)} * \frac{K_1}{(s+a)} * K * C^*(s) * V_e{}^*(s)$$

Equation 16

$$V_e(s) = V_i(s) - \theta_0{}^*(s) * K_{pot}$$

Equation 17

$$V_i(s) = \theta_i(s) * K_{pot}$$

Equation 18

$$V_e{}^*(s) = \theta_i{}^*(s) * K_{pot} - \theta_0{}^*(s) * K_{pot}$$

Equation 19

Substitute Equation 19 into (1):

$$\theta_0(s) = K_g * \frac{K_m}{s(s+a_m)} * \frac{K_1}{(s+a)} * K * C^*(s) * (\theta_i{}^*(s) * K_{pot} - \theta_0{}^*(s) * K_{pot})$$

Equation 20

From Equation 20: we can get:

$$\frac{\theta_0{}^*(s)}{\theta_i{}^*(s)} = \frac{(Gp\_s)^* * C^*(s)}{1 + (Gp\_s)^* * C^*(s)}$$

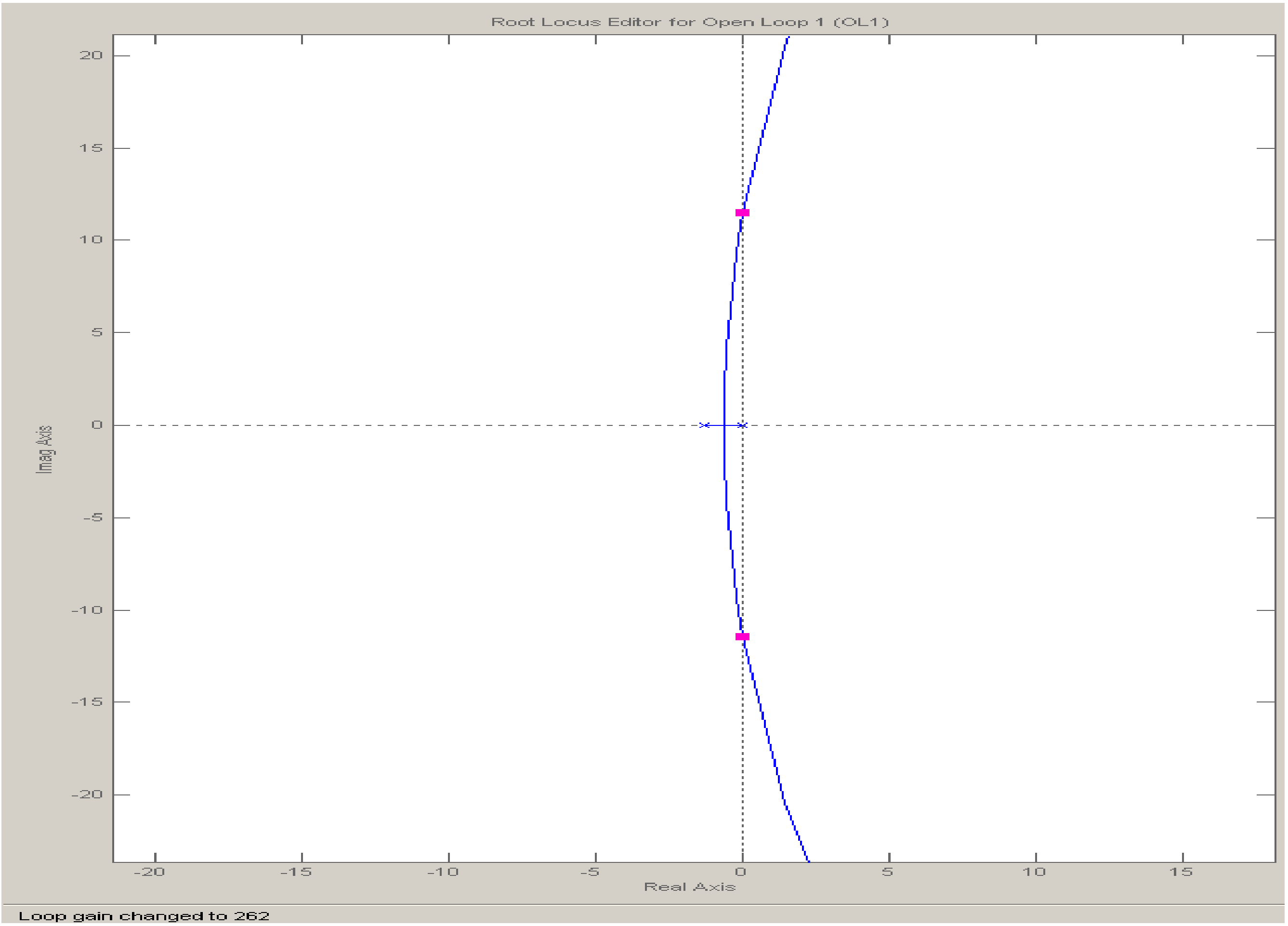
Where $(Gp\_s)^* = K_g * \frac{K_m}{s(s+a_m)} * \frac{K_1}{(s+a)} * K * K_{pot}$

$$G_{p_s}(s) = \frac{50.88}{s(s+1.32)(s+100)}$$

$$C(z) = K$$

Then we can get the discrete transfer function: $\frac{\theta_0(z)}{\theta_i(z)} = \frac{G_{ZAS}(z)*C(z)}{1+G_{ZAS}(z)*C(z)}$

Using MATLAB sisotool we found the stable range of the gain, K, is from 0.000279 to 262.



The range of proportional controller, k*50.88=loop gain, is from 0 to 5.149. We make the k of preamplifier to be 1 and use proportional controller, k= 5.149.

When the C (z) =1 the system response to a unit step input: see Figure 7

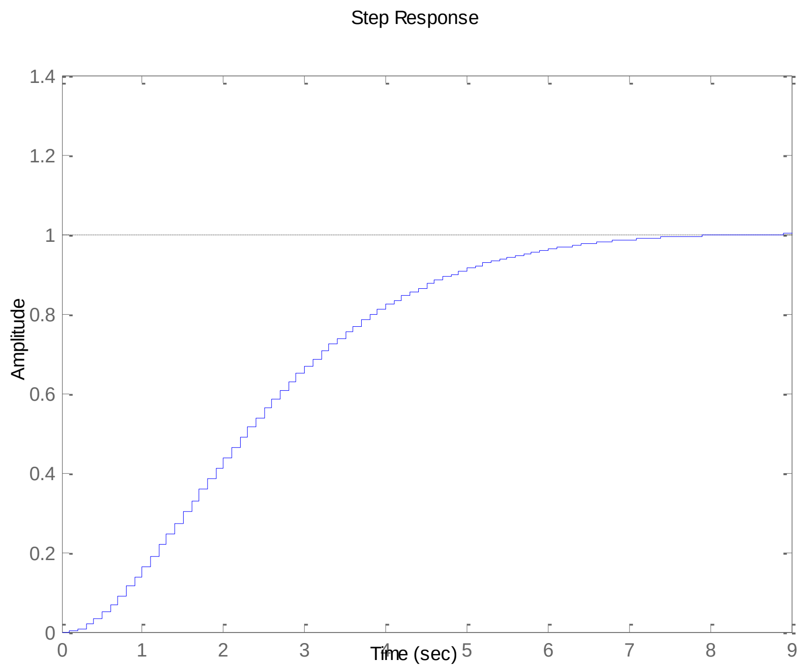


Figure 7

Then we change the C (z) =5.149. The system response to a unit step input: see Figure 8

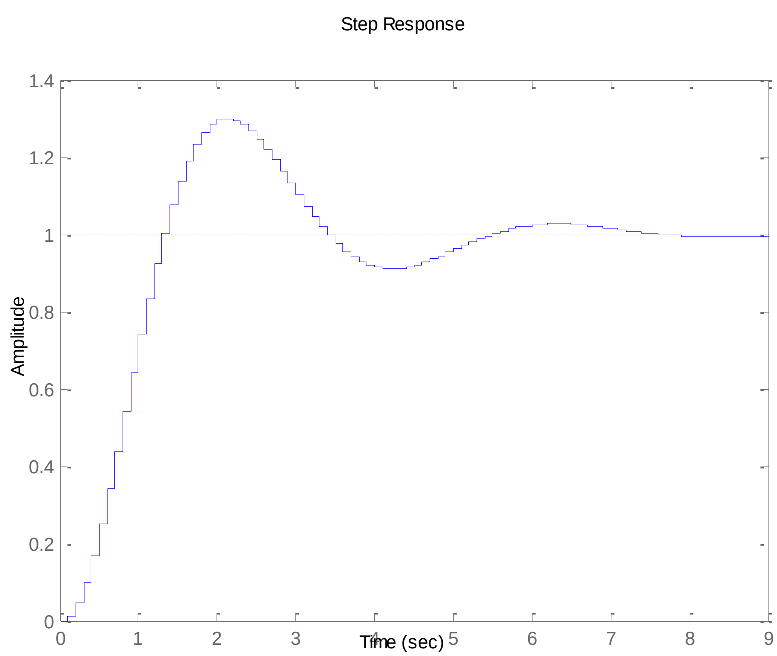


Figure 8

2) The stable range of the loop gain is from 0.000279 to 262.

3) From the Figure 8

Controller K	**1**	**3**	**5.149**
Peak time	9 sec	3 sec	2.2 sec
Percent overshoot	0%	17%	30%
Rise time	3.2 sec	1.4 sec	0.995 sec
Settling time	6.5 sec	6 sec	5 sec

Table 2

4) The value of K that yields a 10% overshoot to a unit step input is 2.33.

5) The steady-state error to the unit step input is: $e_{ss} = \frac{1}{1+K_p}$

Where $K_p = L(z)$ and z=1

The steady-state error to the ramp input is:$e_{ss} = \frac{1}{K_v}$

Where $K_v = \frac{(z-1)L(z)}{T}$ and z=1

L (z) =$\frac{0.0020042(z+1.339)(z+0.01679)K}{(z-1)(x-0.8763)(z-4.54e-005)}$

6) From part (5) we can find the steady-state error to the unit step input is 0 rather than 5%.

So the 5% steady-state error is to the ramp input, and due to this error we can get the k=2.33.

Section 4

The procedure of specify a discrete compensator:

1) To meet the conditions of part 4, we can use sisotool of MATLAB to cancel the pole at z=0.876 and add a pole at z=0.84375, then change the gain k to push the poles to the desired location.

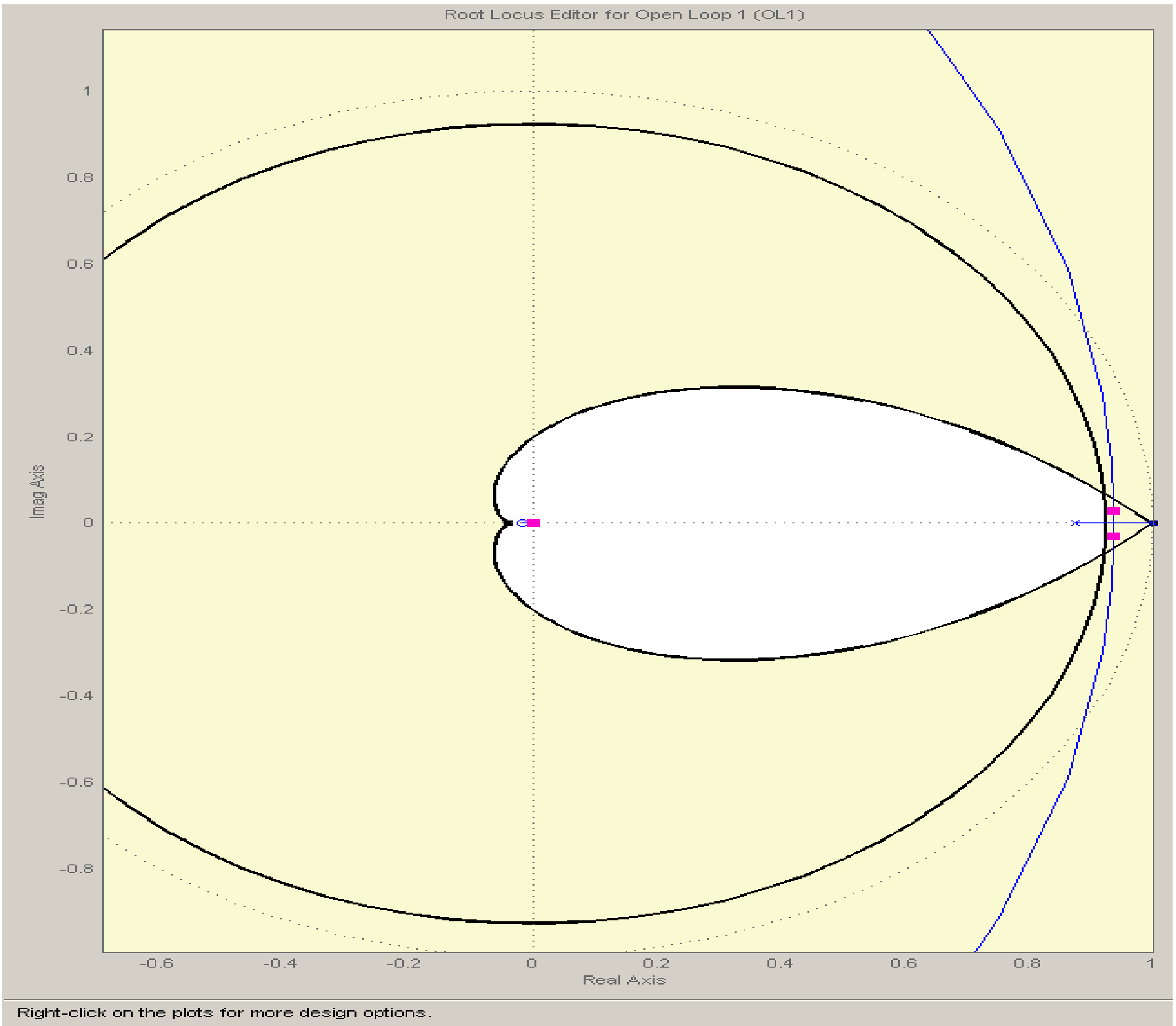


Figure 9

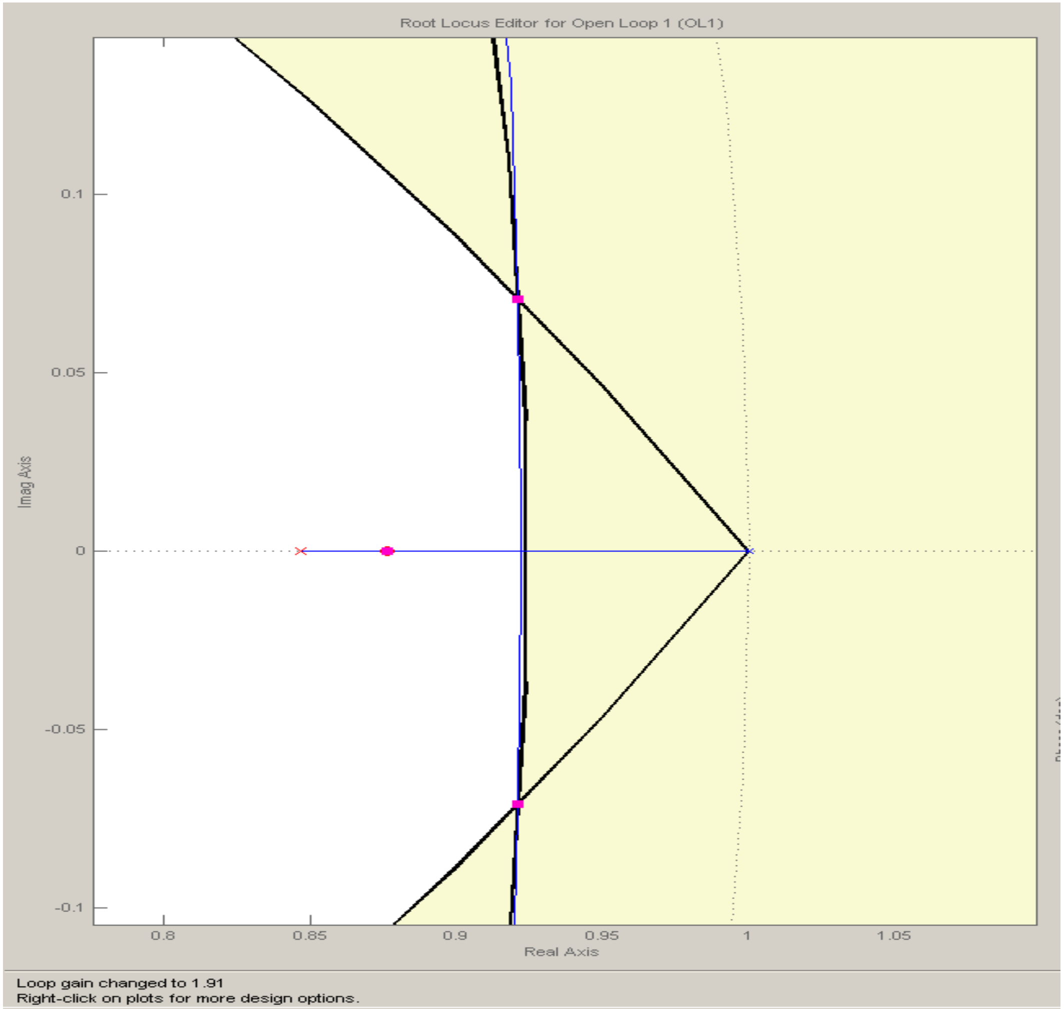


Figure 10

From the sisotool we can get the discrete compensator C (z):

C (w) = $\frac{1.9113(1+0.81w)}{(1+0.64w)}$ where w= (z-1)/T and T=0.1

Transfer it to the discrete form:

$$C(z) = \frac{2.419(z - 0.876)}{(z - 0.84375)}$$

Equation 21

The system response to the unit step input:

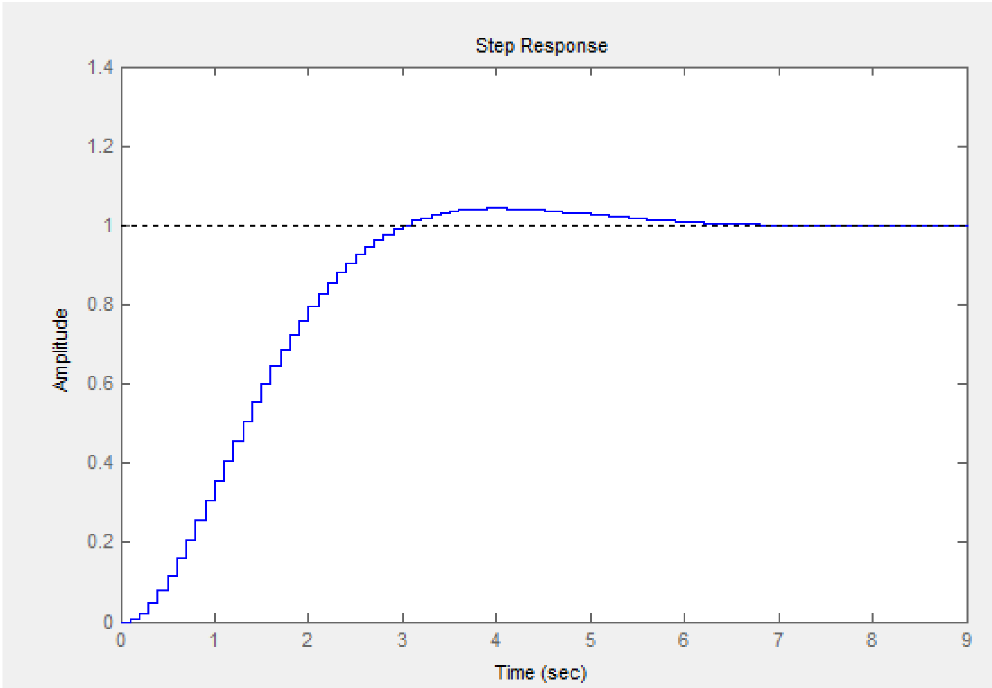


Figure 11

If we change the sampling time to 5 sec to disturb our system, the step response will be unstable:

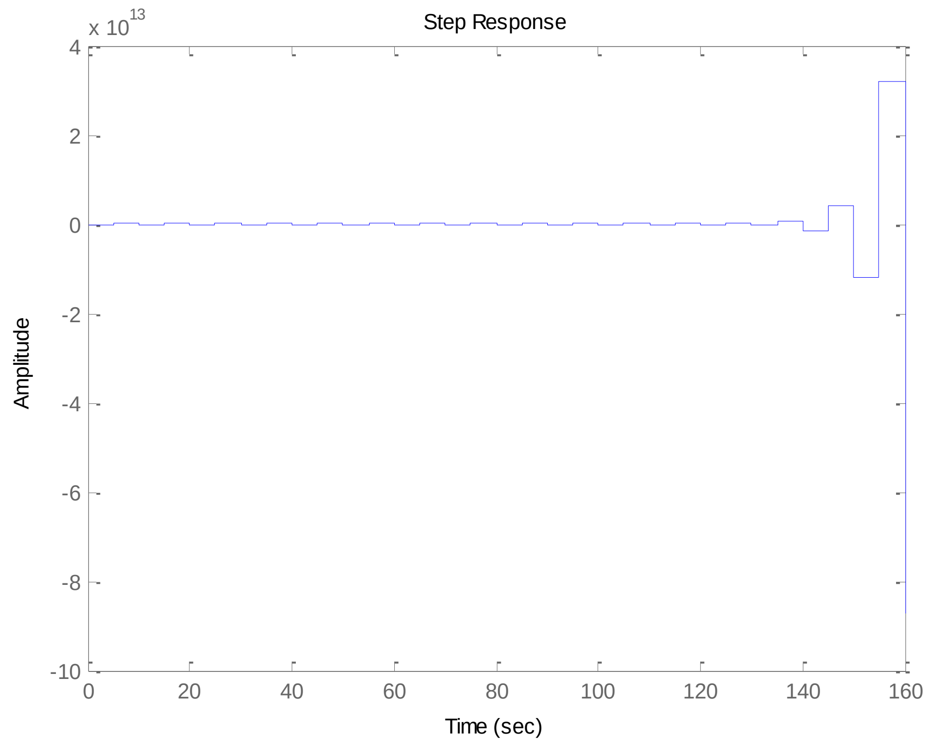

Step Response
x 10^13
4
2
0
-2
-4
-6
-8
-10
Amplitude
0
20
40
60
80
100
120
140
160
Time (sec)

Figure 12

Discussion

After all of the analysis was completed the system was well understood and possible solutions have been presented above. The system is initially unstable when hit with a step input. This is not the case after implementation of a discrete PID controller.

Our recommendation is to implement a discrete PID controller of the form in Equation 21. This will provide ample stability and response characteristics.