MEC 411

LAB #2 : PID Speed Control of a Turntable

Group #11

Matthew Drzymala

Deeba Farhin

Qian Ting Huang

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Abstract

In this lab, a PID turntable speed control system is designed and implemented satisfying specific performance specifications. The controller is implemented using an analog circuit as shown in figure 2. The circuit is wired to result in the three different types of controllers; Proportional (P), Proportional-Integral (PI) and Proportional-Integral-Differential (PID). The analog is disconnected and reconnected to implement the different types of controller. The output waveform is observed using a function generator. When the P controller is implemented, the potentiometer involved is adjusted to get to produce the required output speed. When implementing PI and PID controllers, the potentiometers involved are adjusted to fine tune the output speed wave in order to produce more stable waves. Experimental results obtained are compared to theoretical results obtained using MATLAB. The final values obtained are R_{p2} = 59.019 kΩ, R_i = 0.422 kΩ and R_{d2} = 2.82 kΩ.

Introduction

A PID controller is set up in this experiment to control turntable speed. Experimental results are recorded and compared against theoretical values. The proportional factor gives an output that this the product of the gain and measured error. It corrects instantaneous error. The integral factor store all measured error which can be both positive and negative.It corrects the accumulation of error. The derivative factor corrects the current error as compared to the last recorded value of error. [1]

The turntable is controlled by a DC motor with a tachometer. The tachometer has the parameters listed in table 1.

Table 1: DC Motor and Tachometer.

Performance Parameters	Value	Units	Tolerance
Rated voltage D.C.	@12.0	Volts	-
Rated current	0.944	AMPS	-
Rated continuous torque	14	OZ-IN	-
Peak (momentary) torque	70	OZ-IN	-
Rated speed	800	RPM	± 15%
Rated continuous power out	8.3	Watts	± 15%
No load speed	1000	RPM	MAX
No load current	0.340	AMPS	MAX
Back EMF constant (K_b)	12.0	V/KRPM	± 10%
Torque constant (K_m)	16.2	OZ-IN/A	± 10%
DC armature resistance (R_a)	11.5	OHMS	± 15%
DC armature inductance (L_a)	3.16	mH	± 15%
Armature temperature	155	DEG. C	MAX
Unit weight	12	OZ	MAX
Tachometer voltage gradient	0.52	V/KRPM	

The block diagram for the digital PID turntable speed control system is as shown below:

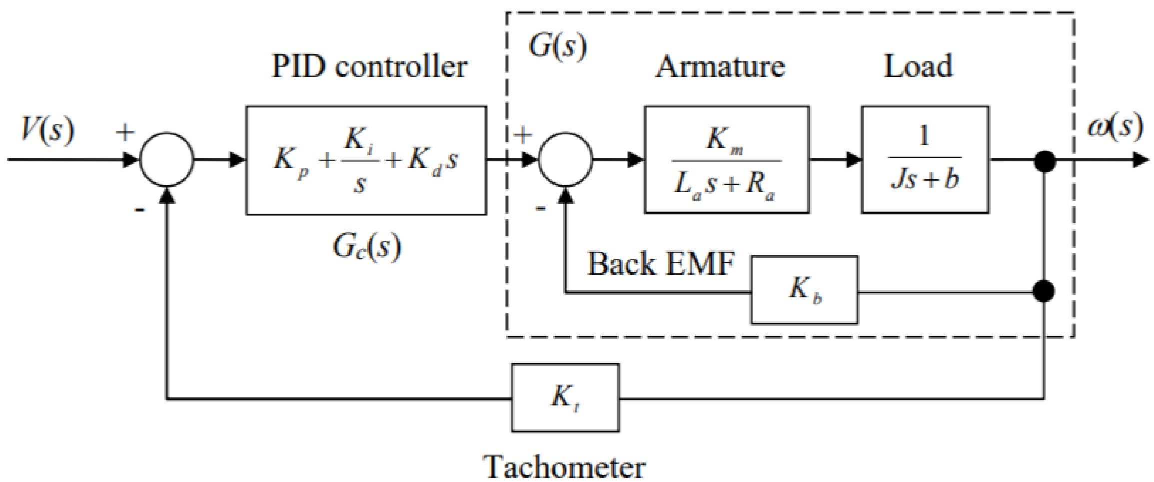


Figure 1: Block Diagram of a PID turntable speed control system [1]

Transfer functions is defined as the voltage input over the output, which is the rotational speed of the tachometer. The closed loop transfer function is given by:

$$T(s) = \frac{\omega(s)}{V(s)} = \frac{G_c(s)G(s)}{1 + K_t G_c(s)G(s)} \tag{1}$$

Where

$$G(s) = \frac{K_m}{(L_a s + R_a)(Js + b) + K_b K_m} \approx \frac{K_m}{R_a(Js + b) + K_b K_m} \tag{2}$$

$$G_c(s) = K_p + \frac{K_i}{s} + K_d s \tag{3}$$

The analog circuit is built as shown in figure 2.

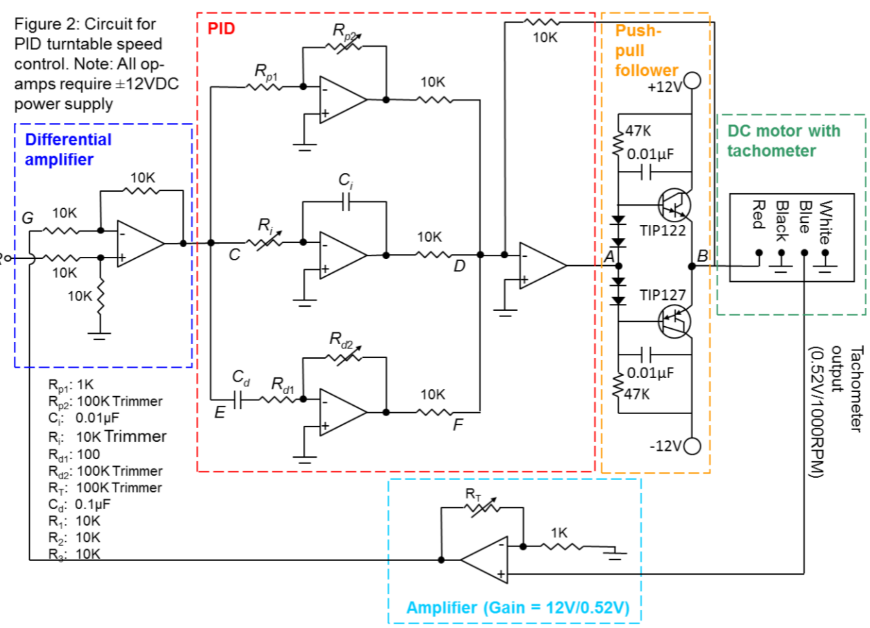


Figure 2: Circuit for PID Turntable Speed Control. [1]

The PID turntable speed control system is comprised of several components; a DC motor, EMF, and tachometer. The DC motor has a rotating armature and there is both a load and back EMF. The tachometer then acts as a sensor for the rest of the system while the EMF is simply a sensor for the DC motor. Now to derive the transfer function for this system begin by analyzing the plant section first. Combining the load and armature gives the following equation.

$$G = \frac{K_m}{L_a s+R_a} \times \frac{1}{Js+b} = \frac{K_m}{(L_a s+R_a)(Js+b)} \tag{4}$$

Now assuming that both La and b are equal to zero the equation can be rewritten which is shown below.

$$G(s) = \frac{\frac{K_m}{(L_a s+R_a)(Js+b)}}{1+\frac{K_m}{(L_a s+R_a)(Js+b)}} = \frac{K_m}{(L_a s+R_a)(Js+b)+K_b K_m} \approx \frac{K_m}{R_a J s+K_b K_m} \tag{5}$$

From the above equation it is determined that the transfer function of the digital PID controller is this equation below.

$$G_c(s) = K_P + \frac{K_i}{s} + K_d s \tag{6}$$

Moving onto the amplifier or gain portion of the circuit. If the input is v_1 and the output is v_o then the following equation is valid. This is the portion of the circuit between the 1k and 100k resistors.

$$i = \frac{v_i}{1K} \tag{7}$$

Knowing that the total current at the node is equal to zero the next equation is derived as follows:

$$\sum i = \frac{v_i}{1K} + \frac{v_o - v_i}{R_1} = 0 \tag{8}$$

In the circuit provided the gain is defined as 12V/0.52V. Using this information v_o can then be found using the following equation.

$$v_o = 23.08 \times v_i$$

Now moving onto the Push-Pull Follower. This portion along with the gain were constructed in the first lab and used again for this lab. The Push-Pull Followers main job is to amplify the current. 12 volts traveled through the follower and it amplified the transistors within. The diodes are used to bias the transistors towards the given voltage. While this was able to function correctly, there is a downfall to this set up and that is the crossover distortion. This occurs due to the cut-off region of the transistor/diode. The diagram for this portion is shown in the figure below.

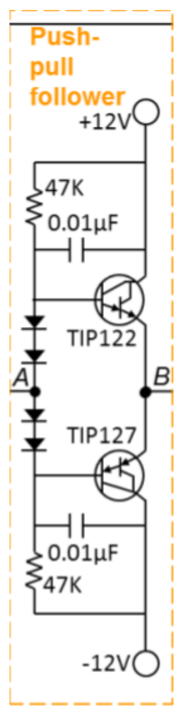


Figure 3: Push-pull follow [1]

Now onto the differential amplifier. All the op-amps we use are assumed to be ideal and thus node a and b are assumed to have the same voltage; Va = Vb. Nodes are denoted in the figure below. The equations afterward are used for determining the current at each point.

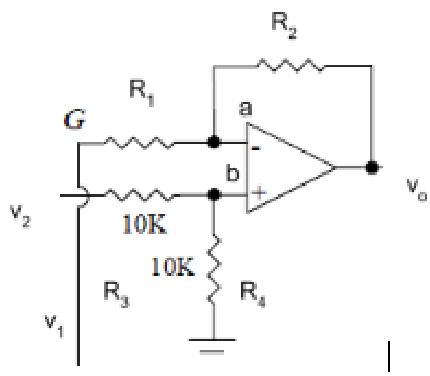


Figure 4: Differential Amplifier [1]

$$I_1 = \frac{V_1 - V_a}{R_1}$$

$$I_2 = \frac{V_2 - V_a}{R_2}$$

$$I_f = \frac{V_a - (-V_o)}{R_3}$$

Now to determine the voltage, V_o, the key is knowing that all the resistor values are equal to each other and thus we get the next equation.

$$V_o = V_2 - V_1$$

Experimental Procedure

Equipment:

- DC Motor
- Tachometer
- Breadboard
- LM324D x2
- TIP 122 (NPN Epitaxial Darlington Transistor)
- TIP 127 (PNP Epitaxial Darlington Transistor)
- Wires
- Screwdriver
- Resistors (1K, 10K, 47K, 100K)
- Capacitors (0.01 µF, 0.1 µF)
- Computer
- Function Generator
- Oscilloscope
- Diodes
- Potentiometers (10K Trimmer, 100k Trimmer)

Procedure:

1. The proposed analog circuit is built according to Figure 2.
2. The function generator is used to supply a square wave of frequency 1 Hz and voltage of 1V to point R.

3. Channel 1 of the oscilloscope is connected to point R and channel 2 is connected to point G. Point G is the feedback voltage and the wave displayed on this channel will indicate the actual speed of the turntable.
4. The circuit is disconnected at C, D, E and F. The circuit is now using a P controller. Resistor R_{p2} is adjusted so that the output speed comes close to the input speed. The potentiometer is then removed and its resistance is measured. All the necessary parameters and waveforms are recorded.
5. The circuit is reconnected at point C and D. The circuit is now a PI controller. R_{p2} and R_i are now adjusted to control the output speed and to adjust the stability of the wave. The potentiometers are removed to measure the resistances. All the necessary parameters and waveforms are recorded.
6. The circuit is reconnected at E and F to produce a PID controller. The three trimmers; R_i, R_{p2} and R_{d2}, are adjusted to produce the required wave. The potentiometers are measured. All necessary parameters and waveforms are recorded.

<u>Results</u>

The goal of this lab is to design a PID controller for the turntable speed control system by selecting potentiometer values for the analog circuit so that the system will meet the following specifications: Percentage overshoot is to be less than 10%. Settling time to within 2% of the final value is to be less than 500ms. Rise time is to be less than 200ms.

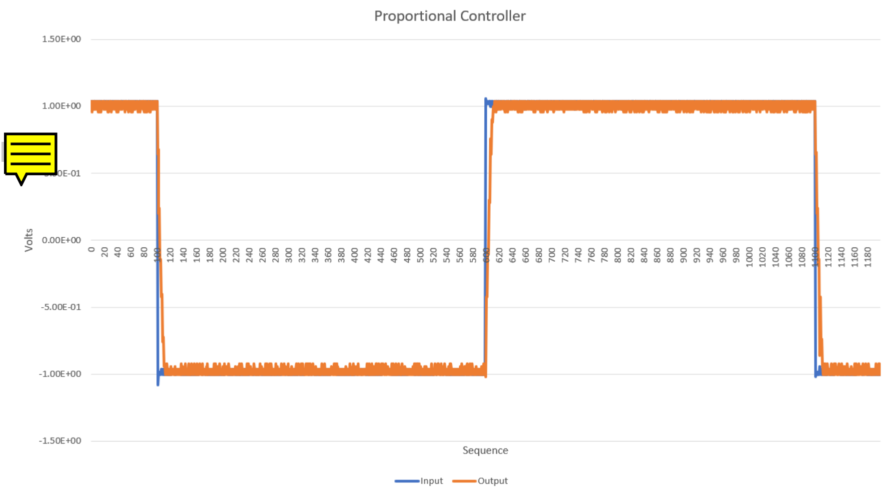


Figure 5: Rotational Speed of Turntable from P Controller

This is a feedback control with a Proportional Control. Only the proportional gain is connected because points C, D, E, and F were disconnected from the circuit system shown in figure 2. Amplitude change mostly only occurs when it is a proportional control. The potentiometer was adjusted until the output was as close to the input as possible while keeping the system stable. The value obtained for R_{p2} was 59.019 kΩ.

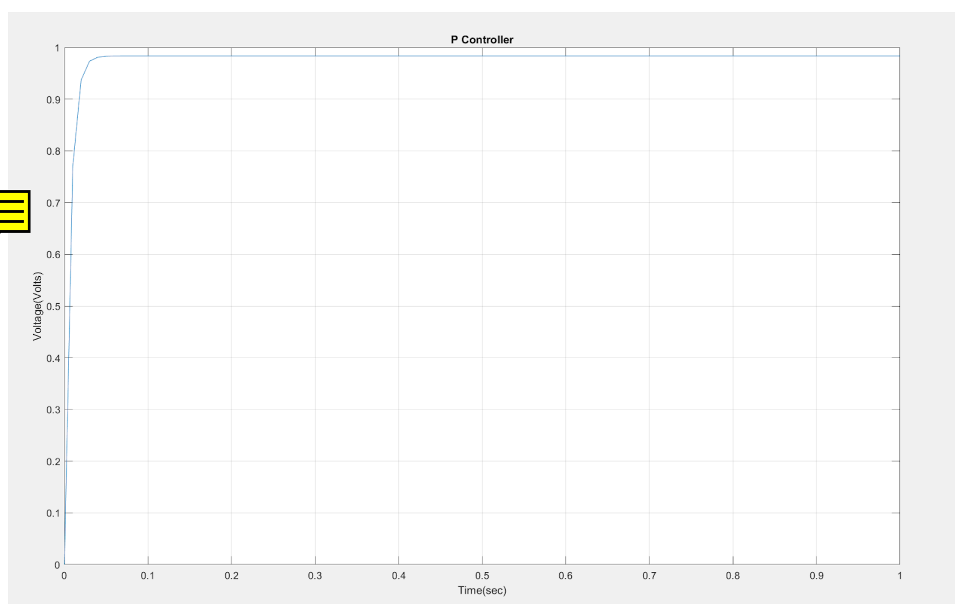


Figure 6: Simulated Response of P Controller

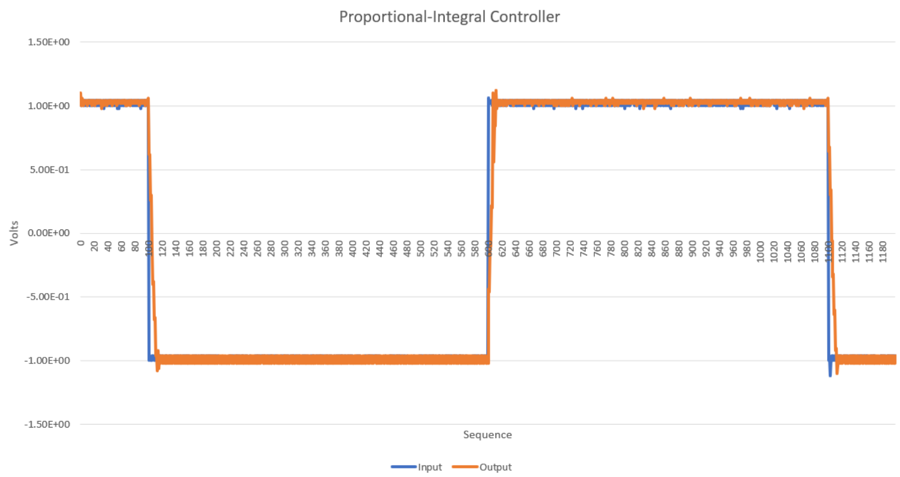


Figure 7: Rotational Speed of Turntable from PI Controller

The circuit system shown in figure 2 is reconnected at point C and D and becomes a PI (Proportional-Integral) controller. R_{p2} was kept constant while R_i was adjusted until the output was as close to the input as possible while keeping the system stable. The noise level for a PI controller is much lower than when the system was a P controller. The value obtained for R_i was 0.422 kΩ.

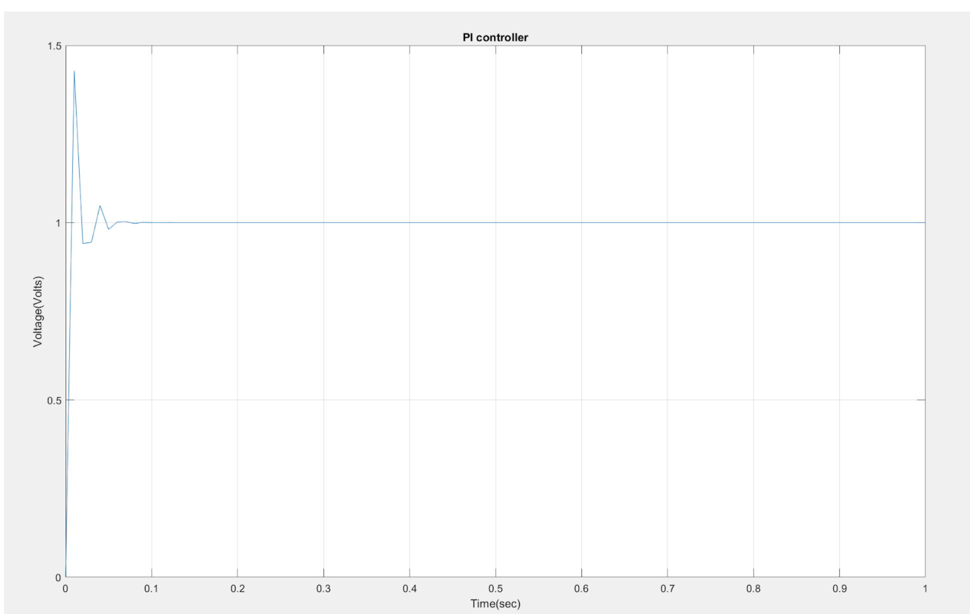


Figure 8: Simulated Response of PI Controller

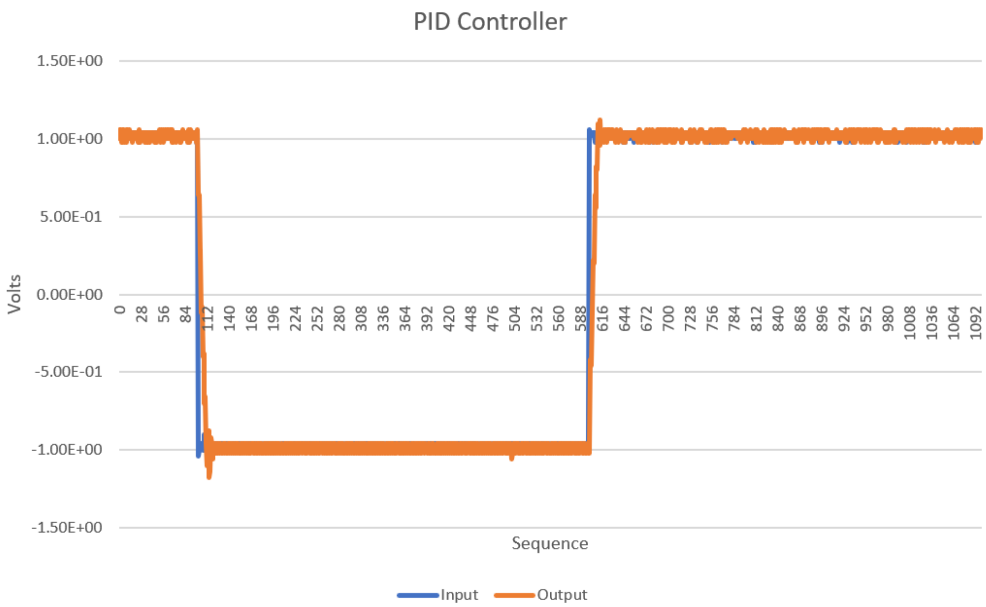


Figure 9: Rotational Speed of Turntable from PID Controller

The circuit system in figure 2 is reconnected at points E and F and now the circuit becomes a PID (Proportional-Integral-Derivative) controller. R_{p2} and R_i was kept constant while R_{d2} was adjusted until the output was as close to the input as possible while keeping the system stable. While a P controller is mainly used for amplitude adjustment, a PI and PID controller is mostly used for noise adjustment. The potentiometer was turned until the noise level was as low as possible. The final value obtained for R_{d2} was 2.82 kΩ.

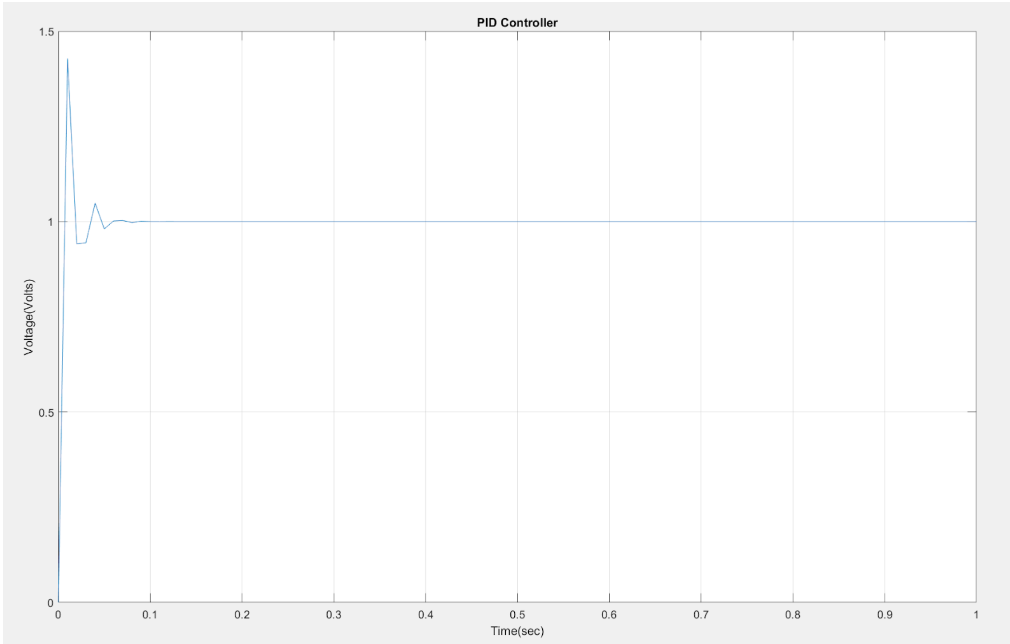


Figure 10: Simulated Response of PID Controller

The table below shows the values of the output response produced by MATLAB for each controller. The results are based on the values of $R_{p2,}$ $R_{i,}$ R_{d2} stated above. The code used to stimulate each response is shown in the Appendix.

Table 2: System Output Performances

	P Controller	PI Controller	PID Controller
Rising Time (sec)	0.015619	0.005600	0.005600
SettlingTime (sec)	0.037364	0.054203	0.054215
SettlingMin (volts)	0.936900	0.941300	0.941600
SettlingMax (volts)	0.983300	1.428600	1.428300
Overshoot (%)	0.000000	42.857500	42.828200
Undershoot (%)	0.000000	0.000000	0.000000
Peak (volts)	0.983300	1.428600	1.428300
PeakTime (sec)	0.250000	0.020000	0.020000

Error Analysis

One of the reasons for the large discrepancy in the percentage overshoot values could be because many of the components used in the speed control system have high tolerance values. Therefore, there is more room for errors to occur. Another reason could be because the value for R_i is very low. When the resistor value is very low, meter loading will cause measurement errors to occur. Lastly, the potentiometers used are prone to mechanical and electrical degradation affecting the performance and accuracy so they are not suitable for continuous use. [3]

Below is a table of the tolerances of all the parameters used in the control system:

Table 3: Tolerances of performance parameters

Performance Parameters	**Tolerance**
Rated speed	±15%
Rated continuous power out	±15%
Back EMF constant (K_b)	±10%
Torque constant (K_m)	±10%
DC armature resistance (R_a)	±15%
DC armature inductance (L_a)	±15%
All resistors	±5%

Discussion

From the results section it can be seen that most of the design requirements were met. The settling time is to be less than 500ms and within 2% of the final value. For all three of the controllers this standard was met. The rise time is to be less than 200ms. This requirement was also met with all three controllers. The percentage overshoot is to be less than 10%. This requirement was not met with all controllers. For both the PI and PID our overshoot was determined to be 42% which is much higher than the desired outcome.

This is most likely due to improper adjustment of the derivative gain which in the circuit is part of the derivative amplifier. The derivative gain works to reduce overshoot and provide damping to the system. However, if this is adjusted too much the system response will be suppressed. Our system was well within the desired values for both the settling time and rise time so it is believed that by adjusting the derivative amplifier correctly the rise and settling time would increase and reduce the overshoot [2].

The derivative gain is not used in the P controller and this is why there is no overshoot able to be calculated at this portion of the lab. Then once it is introduced in the PI controller the overshoot jumps. A value for the adjustable resistor within the derivative gain was chosen to be too high which led to the large overshoot. This is not adjusted in the PID system which is why the overshoot remains at a very similar value.

Conclusion

- The results of three controllers satisfied most of the requirements set for the control system.
- The large overshoot was caused by an incorrect adjustment of the resistor within the derivative gain.
- Adjustment of the derivative gain should lead to an increase in rise and settling time. The goal would be to increase them within desired values while bringing down the overshoot to something more acceptable.

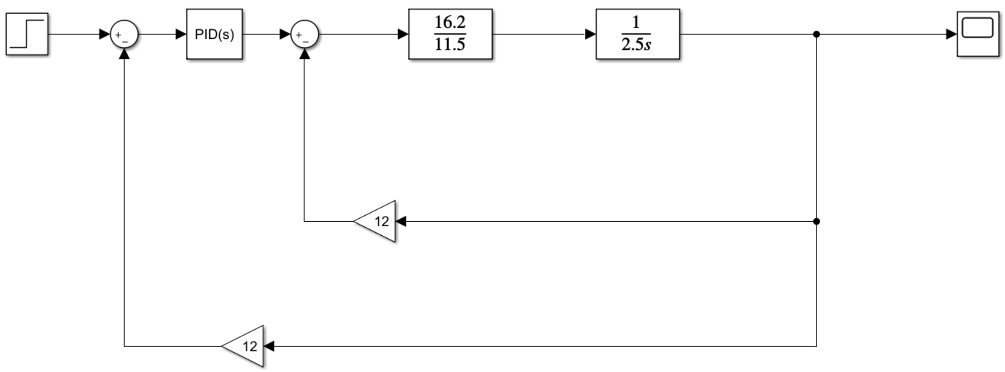
References

[1] Machtay, Noah. “PID Speed Control of a Turntable.” *MEC 411 Lab 2.* Stony Brook University, Fall 2019. Print. October 26, 2019

[2] Collins, Danielle. “Overshoot and Undershoot in Servo Control Systems.” *Motion Control Tips*, www.motioncontroltips.com/how-to-address-overshoot-in-servo-control/. October 26, 2019

[3] “Potentiometers, Preset Potentiometers and Rheostats.” *Basic Electronics Tutorials*, 23 Sept. 2019, www.electronics-tutorials.ws/resistor/potentiometer.html.

Appendix



Appendix 1: MATLAB PID block diagram

P controller

```
km = 16.2*0.02835*9.81*0.0254;
Ra = 11.5;
J = 2.5*0.02835*9.81*0.0254^2;
b = 0;
kb = 12/(1000*2*3.14/60);
kt = 12/(1000*2*3.14/60);
Rp1 = 1000;
Rd1 = 100;
Ci = 0;
Cd = 0;
Rp2 = 59019;
Ri = 0;
Rd2 = 0;
kp = Rp2/Rp1;
ki = 0;
kd = 0;
t = 0:0.01:1;
num = [kd*km kp*km ki*km];
den = [Ra*J+kt*km*kd Ra*b+kb*km+kt*km*kp kt*km*ki];
sys = tf(num,den);
y = kt*step(sys,t);
P_Contoller = stepinfo(y)
figure(1);
plot(t,y);
title('P Controller');
xlabel('Time(sec)');
ylabel('Voltage(Volts)');
grid on
```

Appendix 2: MATLAB Simulation Code for P Controller

PI controller

```
km = 16.2*0.02835*9.81*0.0254;
Ra = 11.5;
J = 2.5*0.02835*9.81*0.0254^2;
b = 0;
kb = 12/(1000*2*3.14/60);
kt = 12/(1000*2*3.14/60);
Rp1 = 1000;
Rd1 = 100;
Ci = 0.01*10e-6;
Cd = 0;
Rp2 = 59019;
Ri = 422;
Rd2 = 0;
kp = Rp2/Rp1;
ki = 1/(Ri*Ci);
kd = 0;
t = 0:0.01:1;
num = [kd*km kp*km ki*km];
den = [Ra*J+kt*km*kd Ra*b+kb*km+kt*km*kp kt*km*ki];
sys = tf(num,den);
y = kt*step(sys,t);
PI_Contoller = stepinfo(y)
figure(2);
plot(t,y);
title('PI controller');
xlabel('Time(sec)');
ylabel('Voltage(Volts)');
grid on
```

Appendix 3: MATLAB Stimulation Code for PI Controller

PID Controller

```
km = 16.2*0.02835*9.81*0.0254;
Ra = 11.5;
J = 2.5*0.02835*9.81*0.0254^2;
b = 0;
kb = 12/(1000*2*3.14/60);
kt = 12/(1000*2*3.14/60);
Rp1 = 1000;
Rd1 = 100;
Ci = 0.01*10e-6;
Cd = 0.01*10e-6;
Rp2 = 59019;
Ri = 422;
Rd2 = 2820;
kp = Rp2/Rp1;
ki = 1/(Ri*Ci);
kd = Rd2*Cd;
t = 0:0.01:1;
num = [kd*km kp*km ki*km];
den = [Ra*J+kt*km*kd Ra*b+kb*km+kt*km*kp kt*km*ki];
sys = tf(num,den);
y = kt*step(sys,t);
PID_Contoller = stepinfo(y)
figure(3)
plot(t,y);
title('PID Controller');
xlabel('Time(sec)');
ylabel('Voltage(Volts)');
grid on
```

Appendix 4: MATLAB Stimulation Code for PID Controller

Comment Summary

Page 4

1. cite.

Page 6

2. Show how to retrieve the output waveform.

Page 8

3. Show the relationship between potentiometer values and PID gains.
4. Please provide the derivation of transfer function for amplifiers in PID controller.

Page 11

5. Use legend to signify the colors in the plot.
6. You need to show result using a square wave.

Page 16

7. Please compare and explain the
   differences between the two control systems.

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8. Recommendations should be provided.