Lab # 3

Control of the Servo Positioning Module

Introduction

Project Objectives

In this Lab, your group will implement a PID controller on a real-life control system, the Servo Module, in order to affect an improvement in the system closed loop response. Although all measurements and tuning of the controller in this Lab Project can be easily performed within one session, the second lab session is added to allow room for students to acquaint themselves with a real-life control system and to experiment with it. Your objectives for this project are to:

- Introduce you to operation and control of a real-time control system;
- Experience a successful real-time implementation of the PID controller, where an improvement of the closed loop system response is achieved by finding the “best” settings of the PID Controller so that the defined response specifications are met.

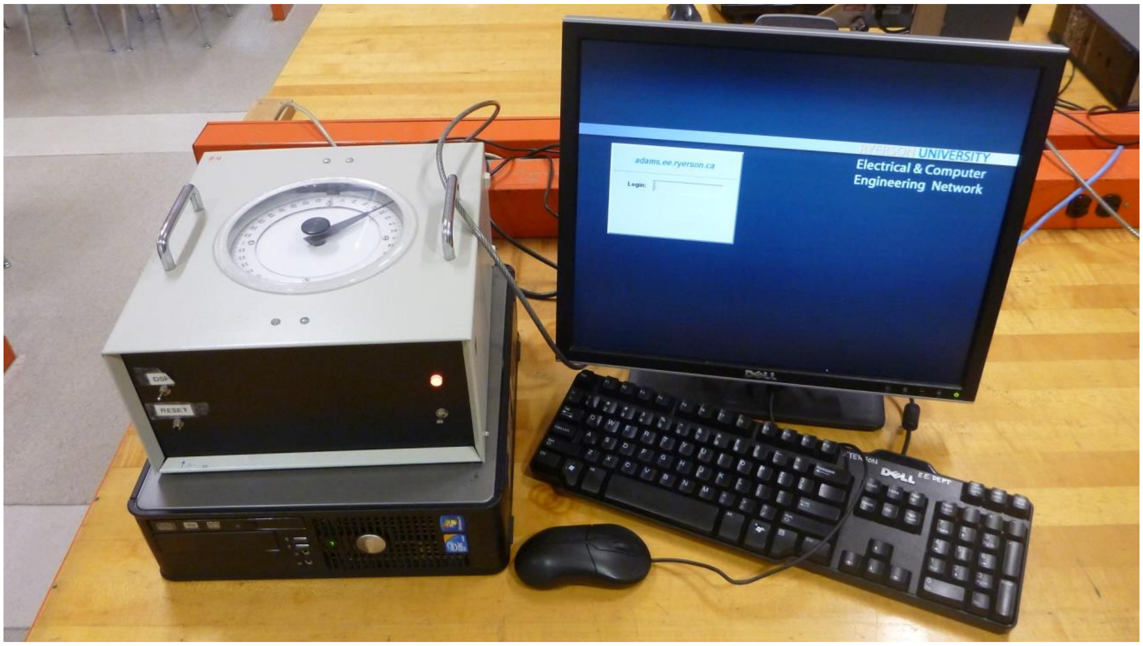

Figure 1: Experimental Setup in the Control Systems Lab

Logistics

This Lab project is a real-life control experiment with a servomotor positioning module. **During the regular semester this Lab is completed over a period of four weeks, in 1.5-hour per week sessions.** You will be working in groups of three, as assigned by your lab Instructor during the first session of this project. You should take note of the number of the Servo Module your group will be working with so that you can continue measurements on the same Module during all sessions. Note that this lab experiment requires access to the servo module, which is only available during regular lab hours. There is no access to the Control Systems Lab ENG413 outside these hours.

Your group will implement a PID Controller on the Servo Module to improve its closed loop system performance, and more specifically, to meet set control objectives. In general, the control objectives are developed based on system analysis and on user requirements. Here, these objectives (transient and error specifications) are explicitly provided for you. The PID Controller settings on the Servo Module will have to be fine-tuned to provide a response as close to meeting the required specs as possible. Please note that your group is expected to obtain the Lab Instructor's sign-off on your working PID Controller Settings.

Lab # 3 reports are due at the beginning of the last lab session – please consult the Course Schedule for the exact date. The written report is a collaborative part and you will receive 80 points (out of 100) for it. The remaining 20 points is an individual component and will depend on how you answer questions in a short interview with the Lab Instructor. You have to be in the lab in person for the interview, or else you will receive a zero for it. The interview will take place during the session when the reports are due. Should you miss the interview with a valid reason (i.e. a medical note handed to the Main Office in the Department), please make sure that your partner hands in the report and then you can make arrangements with the Lead TA for a make-up interview.

> You will need to a get a sign-off on the Grading Sheet from your Lab Instructor, indicating that you successfully demonstrated your compensated system response. If your report does not have it, 30 points will be deducted from your lab report total of 80 points.

Pre-Lab: Getting Familiarized with the System Description

> This part of the project is to be completed individually before coming to the Controls Lab.

Having completed Lab # 2, and from the Course Notes, by now you should be familiar with the PID Controller theory and tuning. However, you need to acquaint yourself with all Lab # 3 Appendices **before** you start. Appendix A contains the description of our real-time control system, the Servo Positioning Module in ENG413. Appendix B contains instructions on how to use the computer interface to operate the Servo Module. Appendix C discusses the Integrator

Anti-Windup. Appendix D contains, for your guidance, samples of graphs of servo data collected by previous cohorts of ELE639 students.

PART 1: Uncompensated Servo Module Response

First, we will perform measurements on the Servo in an uncompensated configuration - do so, set the controller Proportional Gain to 1. This is equivalent to running the closed loop system without a controller.

All data collected on the servo should be saved to a file, created with an **xxx.dat** extension (ASCII format). Such files can be loaded into MATLAB workspace by typing: **load xxx.dat** at the MATLAB command line.

Note that since MATLAB default for the "load" command is binary **.mat** files, it is important that you specify the **.dat** extension in the command line so that MATLAB understands you are loading an ASCII data file. Saving data in a file will allow you to later plot the data using MATLAB. Check to make sure that you can load the data properly, and that you have saved input, output, and time variables. Practice a little bit to make sure you can get this working - otherwise you will waste a lot of time re-running tests.

When you are ready, collect the following measurements in the **Nominal Range -** this is the range where non-linear effects of the Servo Module operation are the least visible. Servo Module response in the Nominal Range (-50^0 to $+50^0$) should not saturate controller output and should be the closest to an ideal LTI representation of the system.

1. Set the controller to Proportional Mode, and set the Proportional Gain to 1.
2. Make sure you are taking measurements within the **Nominal Range** for your servo:
   a. Start with a $\pm 50^0$ square wave input, i.e. with an amplitude of 100^0. Using bi-directional input will allow you to observe if the response of your servo is symmetrical, or it differs depending on the polarity. In the report you should describe what may be the reason for such differences.
   b. If you find that the amplitude is too large and you begin to see saturation, you should reduce the amplitude of the input. However, dropping the input amplitude too much will cause the system response to be affected by the “Dead-zone” effect. You may have to decide to go with uni-directional signal, i.e. the square wave going only from 0 to $+50^0$, as a compromise between getting caught in saturation (high amplitude input) and “dead-zone” (low amplitude input).
3. Once the amplitude of your input is set, adjust the period and the duration of the square wave to display make sure you can display three to four positive slopes and three negative slopes.

Why do we want to display several cycles? Because of the highly nonlinear static friction, the first response of the servo from the stand-still will always be very different from the consecutive cycles. Once the servo settles into movement, and viscous (linear) friction takes over, the subsequent cycles of the response should be repetitive. If you capture and plot 3-4 cycles of the settled response, you will be able to see this.

4. Store square wave results in an ASCII file, to be compared later with the response of the servo under a PID controller.

5. Next, use the unit ramp input (1 radian/per second, or approx. 57^o per second) - use a saw-tooth waveform - and record the system response. Store ramp results in an ASCII file, to be compared later with the response of the servo under a PID controller.

PART 2: Compensated Servo Module Response

Intended System Performance

The objective of control design is to maintain the system stability at all times (implicit objective) and to improve the system tracking performance both in transient state and in steady state (explicit objectives). You should try to meet as many requirements listed below as you can.

System operating requirements (user requirements) are quantified as a set of Performance Requirements, using standard measures of the response quality. Ideally, your compensated Servo Module system operating in a **Nominal Range**, should meet the following set of Performance Specifications:

1. Less than 10% Percent Overshoot (PO) in the system closed loop step response;
2. Settling Time ($T_{settle(\pm 2\%)}$ - use $\pm 2\%$ criterion) less than 0.3 seconds in the system closed loop step response;
3. Rise Time ($T_{rise(10-90\%)}$ - use $10-90\%$ criterion) less than 0.15 seconds - in the system closed loop step response;
4. Zero Steady State Error ($e_{ss(step)\%}$) in the system closed loop step response;
5. Steady State Error ($e_{ss(ramp)}$) of the closed loop unit ramp (1 radian/per second, or approx. 57^o per second) response to within 0.03 radians (approx. 2 degrees) within a time shorter than 0.3 seconds.

Implementing the Proportional Controller on the Servo Module

1. Make sure you are operating within the Nominal Range for your Servo Module – see above for the uncompensated system. Make sure that you use the same frequency of the waveform as in Part 1 so that you will be able to overlay the compensated system responses (under P Control) with the uncompensated responses collected in Part 1.

2. Choose the P controller configuration in the *servo* program menu, and gradually increase and decrease the gain value. Observe the effect of Proportional Gain on the system response, and on specifications:

    a. Which specifications improve and which deteriorate as the Gain increases/decreases? Make sure you check the system response both for the square wave input and the saw-tooth input (ramp).

    b. At what point is the impact of nonlinearities visible? HINT: you should see the effect of saturation for high gain values, and the effect of “dead-zone” for low gain values.

    c. Is it possible to meet the specifications with Proportional Controller only? HINT: it is not expected that you would do so.

3. Choose the “best” response under Proportional Control, i.e. one that is closest to meeting the specifications, save it for Post-Lab discussion and plotting. Make sure to collect both step (square wave) and ramp (saw-tooth wave) results in a data file and take note of the controller gain.

Notes on PID Controller Design

Recall the similar task from Lab # 2. Here, as in Lab # 2, your task is to come up with a **significant improvement** of your system closed loop response by implementing the PID Controller. Your objective is to meet (or exceed) the Performance Specifications for the Servo. You will demonstrate the quality of your design by showing your system compensated response vs. the uncompensated response. Please note that, unlike in Lab # 2, you are dealing here with real-time control of a system that is non-linear. Thus, even though you are going to make the best effort to operate within the Nominal Range, where we hope the effect of such non-linearities is minimal, there will be some differences, as compared with a linear system behaviour. You should discuss such differences in your report.

The quality of your PID controller will be again judged by two factors:

- How dramatic the improvement is, compared with the uncompensated system;
- How in-depth your approach is, i.e. how are you able to connect it with the theory learned in the course.

The least-insightful approach to finding the “best” PID Controller setting that improve the system response is to follow a “Trial-and-Error” approach, experimenting directly on the Servo Module, and it will be marked accordingly.

You may also choose to follow a more organized empirical tuning method, i.e. Ziegler-Nichols “Ultimate Gain” method, again, working directly with the servo. Note that Ziegler-Nichols “Process reaction” method is not applicable here – you should discuss why that is in your report.

If you decide to simply "tune" your PID Controller (either by trial-and-error or by Ziegler-Nichols approach), you can "add value" to your "design" by first performing the simulations in SIMULINK, using the **linear** model for the servo, as derived from the nominal values – see Appendix A. You would tune the PID Controller on the simulated model, then implement the controller parameter values on the actual servo, and fine-tune it. If you choose this approach, you should comment on differences between the expected system behaviour (SIMULINK model) and the actual system behaviour (real-time implementation), and on what the sources of these differences are.

Finally, you may choose to inform your design by making references to theory, for example using the concept of a "Dominant Poles" Closed Loop Model, showing the Root Locus analysis of your compensated system, and performing calculations of the Proportional Gain, based on the Root Locus theory. To do so, you should use a linear model derived for the servo based on the nominal values of its parameters, and perform SIMULINK simulations to support your analysis and design. You should also comment on any differences between the expected system behaviour (model) and the actual system behaviour (real-time implementation). This analytical approach would be most valuable, as it would demonstrate how well you can apply theory learned in the course to your design.

NOTE 1: If you opt for SIMULINK simulations to support your design, whether you are just "tuning" your PID Controller, or you are investigating Root Locus/dominant poles model, you should use the **parallel** PID Controller structure, since such is implemented on the actual servo.

NOTE 2: To simplify the matters, you can use a linear SIMULINK model of the closed loop system. Of course, it is also possible to make the simulations more realistic by using the **non-linear** servo model (i.e. by adding the saturation and dead-zone blocks), but this is **optional**.

Implementing the PID Controller on the Servo Module

1. Make sure you are operating within the Nominal Range for your Servo Module – see above. Make sure that you use the same frequency of the waveform as in Part 1 so that you will be able to overlay the compensated system responses (under P and PID Control) with the uncompensated responses collected in Part 1.

2. Choose the PID controller configuration in the *servo* program menu, and enter the controller parameter values.

3. Do a quick check of the step response specs and ramp response specs - are the required specs met? If the answer is NO, try fine-tuning the Controller parameters.

4. Next explore using a PID+A (PID plus Anti-windup) Control. What is its effect - is it easier to meet the required specs?

5. Choose the “best” response under PID (or PID-A, if that is what you decided on) Control, i.e. one that is closest to meeting the specifications, save it for Post-Lab discussion and plotting. Make sure to collect both step (square wave) and ramp (saw-tooth wave) results in a data file and take note of the controller parameters. Note that the Controller settings have to be the same for both inputs (step and ramp).
6. Once you are confident that you obtained the "best possible" result, demonstrate it to your Lab Instructor who will verify it and sign in an appropriate box on your Grading Sheet.

Part 3: PID Controller Operation outside the Nominal range

In this part you will focus closer on the effect of non-linear phenomena (saturation and dead-zone) on the Servo Module response. Note that for the sake of brevity, we will only explore the pulse inputs and will only compare the uncompensated system with the system under PID Control, i.e. no discussion of Proportional only Control.

Saturation

If we increase the amplitude of the input signal, gradually the system gets out of its nominal operating range and the nonlinear effects of saturation can be observed. To see the effect of controller saturation very clearly, take measurements for a square wave input with an amplitude of $\pm 300^0$. This large amplitude signal should completely saturate the D/A device at the controller output. IMPORTANT: Do not adjust the Controller settings! We do not expect to meet the specifications once the system works outside the nominal range – in this Part, we are only observing the effect of the saturation on the system response under control, once the Controller parameters have been set.

1. Start with the uncompensated system by setting the controller back to Proportional Mode and the Proportional Gain to 1. Take measurements for a $\pm 300^0$ square wave input, i.e. with an amplitude of 600^0. If you find that the amplitude is too large, try the square wave going only from 0 to $+300^0$. Again, adjust the period and the duration of the square wave to display make sure you can display three to four positive slopes and three negative slopes. Store square wave (i.e. step) results in an ASCII file, to be used as a benchmark for the response of the servo under a PID controller.

2. Choose the PID controller configuration in the *servo* program menu, and enter the same Controller parameter values as your final settings for the nominal range, at first without the Anti-windup. Take measurements for a $\pm 300^0$ square wave input. Make sure that you use the same frequency of the waveform as in item 1 so that you will be able to overlay the compensated system responses with the uncompensated responses from item 1 above. Store results in an ASCII file.

3. Next, use a PID+A (PID plus Anti-windup) Control – adjust the Anti-windup Time Constant for the “best” response. Take measurements for a $\pm 300^0$ square wave input. Make sure that

you use the same frequency of the waveform as in items 1 and 2 so that you will be able to overlay the system responses and show the effect (if any) of the Anti-windup scheme. Store results in an ASCII file.

Gear Backlash and Static Friction (Stiction)

If we decrease the amplitude of the input signal, gradually the system gets out of its nominal operating range and the nonlinear effect of Deadzone (stiction and gearlash) can be observed. To see the effect very clearly, take measurements for a square wave input with an amplitude of $\pm 20^0$. The amplitude signal should now be small enough for the controller output to "get stuck" in the dead-zone and illustrate the effect of this non-linearity on the system response. . IMPORTANT: Do not adjust the Controller settings! We do not expect to meet the specifications once the system works outside the nominal range – in this Part, we are only observing the effect of the "dead-zone" on the system response under control, once the Controller parameters have been set.

1. Start with the uncompensated system by setting the controller back to Proportional Mode and the Proportional Gain to 1.

2. Take measurements for a $\pm 20^0$ square wave input, i.e. with an amplitude of 40^0. If you find that the amplitude is too large, try the square wave going only from 0 to $+20^0$. Again, adjust the period and the duration of the square wave to display make sure you can display three to four positive slopes and three negative slopes. Store results in an ASCII file, to be used as a benchmark for the response of the servo under a PID controller.

3. Choose the PID controller configuration in the *servo* program menu, and enter the same Controller parameter values as your final settings for the nominal range, at first without the Anti-windup. Take measurements for a $\pm 20^0$ square wave input. Make sure that you use the same frequency of the waveform as in item 1 so that you will be able to overlay the compensated system responses with the uncompensated responses from item 1 above. Store results in an ASCII file.

Post-Lab Calculations and Discussions

Following are the points that should be discussed in the lab write-up, with references to saved plots to support observations and conclusions. While the list is exhaustive, it is left to the students to decide how to best structure and group the points to make a coherent narrative.

Part 1: Uncompensated Servo Module System

1. Present the response of your uncompensated servo system in a nominal range:
   a. When you started with the pulse input of $\pm 50^0$, did your system show any nonlinearities?
   b. If so, can you identify whether it was a) saturation, b) dead-zone effect? How did you adjust the system parameters to ensure the system response is as close to being linear as possible? Discuss.
2. Calculate the time response specifications described in Part 2, as measured for the uncompensated system. Does the uncompensated system meet any of these specs? HINT: Since you are going to calculate the same specs for the compensated system, present both in one Table for an easy comparison.
3. Consider the uncompensated system step and ramp responses - what is the System Type? Do the step and ramp response conform with those expected for this System Type? If not, explain why?

Part 2: Compensated Servo Module System – P vs. PID (or PID+A) Control

1. Discuss observed differences between Proportional only and PID Control.
2. Discuss how you arrived at the PID Controller settings - did you use the "trial & error" or any of the Ziegler-Nichols methods?
3. Did you experiment with the Anti-windup Controller setting? Did it make a difference in your compensated system response?
4. What were the final settings of your Controller that gave you the "best possible" response for the nominal range of pulse inputs?
5. Present the "best possible" response of your compensated servo system in the nominal range. How did you adjust the controller parameters to ensure the compensated system response is as close to being linear as possible? Compare the uncompensated specs with the “best” Proportional Control and with the “best” PID Control settings.

a. To do so, first port the step data to MATLAB, choose a segment of your square waveform that will correspond to a step response - one of the positive slopes (choose third one, where the system settles into repetitions) and plot the three responses to the chosen segment of the pulse wave.

b. Evaluate the specs of your system step response: compare the three responses (it may be a good idea to tabulate these results). Did your controller meet the required specs for the step response?

c. Next, port the ramp data to MATLAB and evaluate the specs of your system ramp response: compare the three responses (it may be a good idea to tabulate these results). Did you meet the required specs for the ramp response?

d. If answer to any of the specs is no, discuss why you think you were unable to meet the specs.

6. Discuss the improvements in the system response under P, then PID (or PID+A) Control, as compared to the uncompensated system. Consider both the steady state tracking (i.e. discuss the steady state errors) and the transient performance.

Part 3: Compensated Servo Module System outside the Nominal Range

1. Compare the response of your uncompensated and compensated servo system outside the nominal range with the pulse input of $\pm 300^0$ - did your system show the effect of saturation? Was it more visible for one of the responses? If so, which one? Discuss the performance specs both for the uncompensated and the compensated system - did they change as compared to the nominal range performance and if so, how. Discuss the effect of the PID Controller with saturation present, as compared to the nominal range. Did you experiment with the Anti-windup Controller setting? Did it make a difference in your compensated system response? Did you try to change the PID Controller settings? To what effect?

2. Compare the response of your uncompensated and compensated servo system outside the nominal range with the pulse input of $\pm 20^0$ - did your system show the effect of the dead-zone? Was it more visible for one of the responses? If so, which one? Discuss the performance specs both for the uncompensated and the compensated system - did they change as compared to the nominal range performance and if so, how. What can you say about the steady state error of the uncompensated system? Was it more pronounced than in the nominal range? Was it consistent with the system type? If not, discuss why. Discuss the effect of the PID Controller with dead-zone present, as compared to the nominal range. Did you experiment with the Anti-windup Controller setting? Did it make a difference in your compensated system response? Did you try to change the PID Controller settings? To what effect?

3. Calculate the step response specifications for both inputs ($\pm 300^0$ and $\pm 20^0$) and use them to discuss the system response under PID (or PID+A) Control outside of the nominal range, as compared to the nominal range performance.

Instructions for the Write-up

Following are some general guidelines on the write-up - please refer to the website for more information. As well, the Professor will be showing in class examples of good and poor reports, explaining what the issues were that affected the report mark.

1. The written report is to be word-processed, including any formulae that you may need. The first page is a standard cover page (posted on the website) which has to be signed by all three members of the group. The report will not be accepted without the signatures.
2. The second page is a grading sheet - please write the names of group members in appropriate boxes, and the assigned data set number. You have to obtain a signature from your lab Instructor verifying that you demonstrated your working PID Controller. If your report does not have the Instructor's signature, 30 points will be deducted from your lab report total.
3. The third page is an Executive Summary - your “bottom line” results and observations have to be stated in this one-page Executive Summary, and then expanded on in the main body of the report. It is best to write the Executive Summary last, when you have a clear overview of the entire report.
4. A maximum of fifteen (15) single-sided pages of content (i.e. not counting the cover, grading sheet and executive summary pages) are allowed. To make your report easy to follow, use separate headers for each part of the project. Use page numbering! Use at least point 11 font size throughout the report.
5. Figures have to be properly labeled and referred to in the body of the report. Plots have to be created in MATLAB, with all traces properly labeled, large enough to be easily legible, and included in the main body of the report. Since you have limited space, don't waste it on single-trace plots - learn how to show multiple trace plots in a single figure - these work best anyway, if you want to illustrate a discussion of differences in responses, say between compensated and uncompensated responses.
6. Quality of writing, spelling, clarity and overall presentation is very important in an engineering report and the Canadian Engineering Accreditation Board (CEAB) requires that we pay attention to developing good writing skills. Accordingly, a significant part of your mark will depend on how you write your observations and conclusions, not just on whether your numerical results are correct.

CHECK LIST

Before you hand in the report, please go through this check list to make sure you have not missed something important. Note that this check list is just for you and your partner and you do not submit it in your report.

Form: layout, figures, etc.

- [ ] On your Grading Sheet, do you have the signature of your Lab Instructor confirming that you demonstrated your PID Controller implementation? If not, your lab report mark will be discounted by 30 points.
- [ ] Did you write and include the Executive Summary?
- [ ] Did all partners sign the Cover page? The report will not be accepted without these signatures.
- [ ] Are the content pages of your lab report numbered? If not, you will lose points.
- [ ] Did you count content pages? Every page exceeding the specified number will cause a deduction.
- [ ] Did you write the servo number in the appropriate space on the Grading Sheet? If it is missing, you will lose points.
- [ ] Are all your numerical results and equations properly type-set? Any hand-written equations, as well as for equations copied from MATLAB will cause deductions.
- [ ] Since graphs take up space, are all the Figures you included in the report essential and contributing to your discussions? Specifically, do you discuss all Figures? If not, you will lose points for any Figures that are not discussed in the report.
- [ ] Do your Figures have proper time scales? Do you have too much of your response in the steady state, or the opposite, your response does not reach the steady state? If so, you will lose points.
- [ ] Are all traces in your Figures easily identifiable? In particular, if you are printing in Black & White, have you used different markers for different traces? Do all your Figures have legends to identify each trace? If not, you will lose points.
- [ ] Are all your Figures properly labeled? Are they included in the body of your report, not at the end? Also remember that any reference to a Figure must be made before the Figure appears in the text, not after.
- [ ] General impression: is your report easy to read and visually pleasing? Are the results easily located? Do you have separate headings for each of the parts? Consider using Tables to present your results. Break up large blocks of text into separate paragraphs,

make sure that there is enough "white space" in your report to make it easy to read. If you are not sure, ask a friend to have a look at your report and get his/her feedback.

Content: discussions, observations, spelling, grammar.

- ☐ Did you discuss if and how the PID Control improved the system performance (both steady state and transient) when the system operated in the nominal range?
- ☐ Did you obtain and then compare the required specs for the compensated vs. uncompensated system in the nominal range?
- ☐ Did you observe and if so, discuss, any nonlinear effects in your system response (uncompensated, compensated) when the system operated in the nominal range?
- ☐ Did you discuss how you arrived at the final "best" PID Controller settings? Did you use the Anti-windup? If so, discuss its effect.
- ☐ Did you obtain and then compare the required specs for the compensated vs. uncompensated system for both case outside the nominal range?
- ☐ Did you discuss the system performance outside the nominal range? Did you discuss the effect of nonlinearities?
- ☐ Did you discuss the PID Controller effectiveness outside the nominal range as compared to the nominal range?
- ☐ Did you check your report for spelling, punctuation, grammar errors and logical flow of your narrative? There will be deductions for poor basic writing skills.

Academic Integrity

- ☐ Are all figures, text and equations included in this report created by you and your partners and 100% original? Remember that your signature on the Cover Page signifies that it is, and that you are fully aware of the consequences should it be otherwise.

- ☐ Are any of the components of your report copied from the Course Notes, Lecture Slides or Lab Instructions? If so, this is your last chance to remove them, because you do not have permission to copy any of the course materials, whether or not you make a reference to the source.