Queen's University

Department of Electrical and Computer Engineering

Course: ELEC 443

Lab 4: Ball and Beam

Lab Date: Nov 17th, 2023.

Group Members:

Karakus, Jon 20178218
Charlotte Yang 20222284

Table of Contents
5.1Modeling 2
I. Procedure 2
II. Results 2
Table 1.1: Summary of results for the Ball and Beam modeling laboratory........ 3
III. Analysis 3
IV. Conclusions 3
5.2 Control Design and Simulation 4
I.Procedure 4
II. Results 4
Table 2.1 Summary of results for the Ball and Beam Control Designa and Simulation Laboratory. 5
III. Analysis 5
IV. Conclusions 7
5.3 Control Implementation 7
I.Procedure 7
II. Results 7
Table 3.1: Summary of results for the Ball and Beam laboratory........ 8
III. Analysis 8
IV. Conclusions 9

5.1Modeling

I. Procedure

• Briefly describe the main goal of lab portion of modeling the system.

The main goal of the lab portion is to model the Ball and Beam system, specifically focusing on the nonlinear equation of motion. This entails formulating the equation that links the ball's movement to the beam angle, factoring in forces, inertia, and gravity. Furthermore, our aim is to define transfer functions for both the Ball and Beam and Rotary Servo aspects of the system to facilitate in-depth analysis and experimentation.

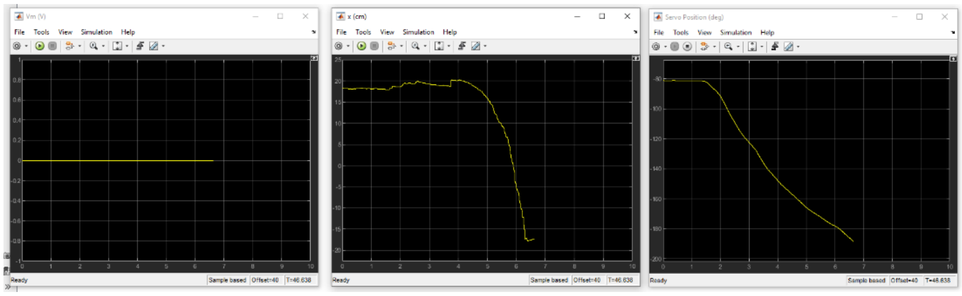
• Briefly describe the hardware interfacing procedure (Section 1.3)

In Section 1.3, within SRV02 QUARC Integration, we create a model incorporating ball position reading based on Figure 1.3 and the Ball and Beam User Manual. We meticulously set up by reading the ball potentiometer on channel #0 and adjusting Ball Sensor Gain to 1. With QUARC running at 0 V on the servo, we validate the 0-5 V signal by moving the ball. Determining the sensor gain for meter measurement (beam length: 16.75 inches), we input it into BB01 Sensor Gain. After confirming ball position measurements and ensuring the servo aligns with model conventions, we fine-tune Simulink if necessary. Gradually increasing Slider Gain while initially disconnecting the Ball and Beam, we document gains with explanations throughout.

II. Results

Do not interpret or analyze the data in this section. Just provide the results.

1. Response plot from step 4 in Section 1.3, Ball position response



2. Validation of modeling conventions in step 5 in Section 1.3

$$K_{bb} = \frac{m_b \times g \times r_{arm} \times (r_b)^2}{\mathcal{L}_{beam} \times \frac{7}{5} \times m_b \times (r_b)2}$$

$= \frac{5}{7} \times \frac{r_{arm \times g}}{\mathcal{L}_{beam}}$

$= \frac{5 \times 9.8 \times 0.0254}{7 \times 0.4255}$

$= 0.4176$

3. Provide applicable data collected in this laboratory (from Table 1.1).

Section / Question	Description	Symbol	Value	Unit
Section 1.2, Question 5	Open-loop model gain	K_{bb}	0.4176	m/rad
Section 1.3, Question 3	Sensor gain	K_{bs}	-0.0257	m/V

Table 1.1: Summary of results for the Ball and Beam modeling laboratory

III. Analysis

Provide details of your calculations (methods used) for analysis for each of the following:

1. Open-loop model gain in step 3 of Section 1.3.

$$K_{BS} = -16.75 \times \frac{0.0254}{5-(-5)} = -0.0425$$

IV. Conclusions

Interpret your results to arrive at logical conclusions for the following:

1. Whether the hardware follows the modeling conventions in step 5 in Section 1.3.

Yes, the hardware follows the modeling conventions.

$$K_{BB} = \frac{m_b \times g \times r_{arm} \times (r_b)^2}{\mathcal{L}_{beam} \times \frac{7}{5} \times m_b \times (r_b)^2}$$

5.2 Control Design and Simulation

I.Procedure

• Briefly describe the main goal of the control design and simulation.

Control design and simulation aim to craft and validate a controller for a Ball and Beam system. Through simulating the designed controller, incorporating features like a square wave command, saturation block, and defined gains, engineers strive to fulfill performance criteria, uncover potential challenges, and guarantee a successful application in the real-world scenario.

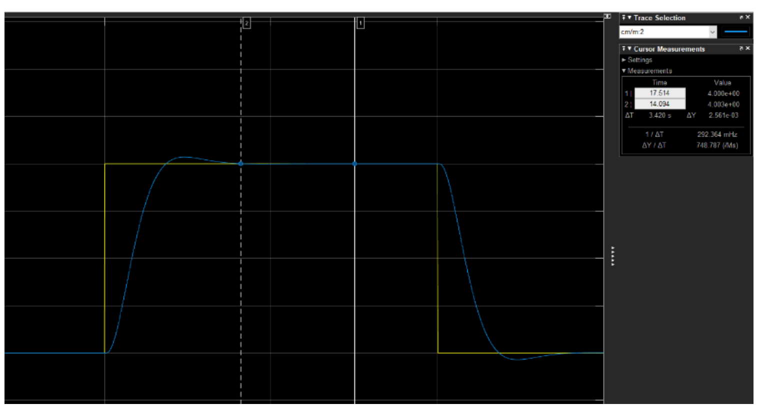
• Briefly describe the control design and simulation procedure (Section 2.3)

In the control design and simulation process (Section 2.3), we begin by simulating the controller for the Ball and Beam system. This involves crafting a Simulink diagram, determining a servo gain, and incorporating a 4 cm square wave command. To restrict the servo angle, a saturation block is introduced. The nonlinear model is implemented within the Ball and Beam Model subsystem. Model gains are input in Matlab, transfer functions are created, and the SISO Control Design tool is utilized. Adjustments to the response are made through the Root Locus Editor to meet specified requirements.

II. Results

Do not interpret or analyze the data in this section. Just provide the results.

1. Response plot from step 6 in Section 2.3, Simulation of PD ball position control



Zoomed In version of ball position plot

2. Provide applicable data collected in this laboratory (from Table 2.1)

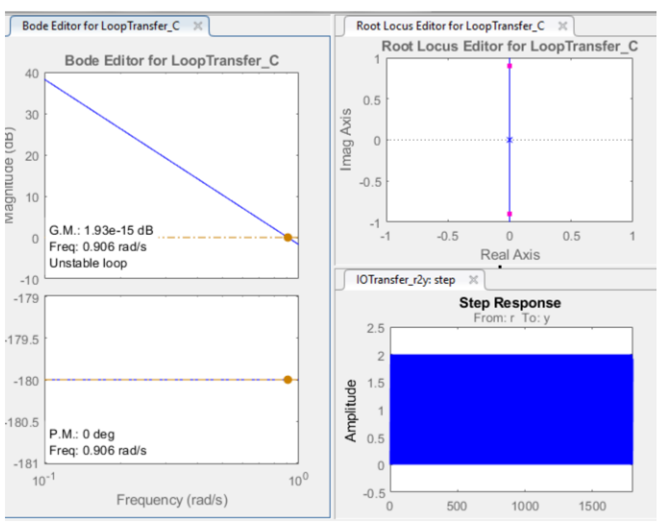
Section / Question	Description	Symbol	Value	Unit
Question 10	**Pre-Lab: PD Control Design**			
	Compensator Gain	K_c	5.655	rad/m
	Compensator Zero	z	1.238	rad/s
Section 2.3, Step 5	**Root Locus Control Design: SISO Tool**			
	Compensator Gain	K_c	5.7019	rad/m
	Compensator Zero	z	+1.215	rad/s
Section 2.3, Step 7	**In-Lab Simulation: PD Control**			
	Percentage overshoot	PO	3.55	%
	Settling time	t_s	2.09	s
	Steady-state error	e_{ss}	0	cm

Table 2.1 Summary of results for the Ball and Beam Control Designa and Simulation Laboratory.

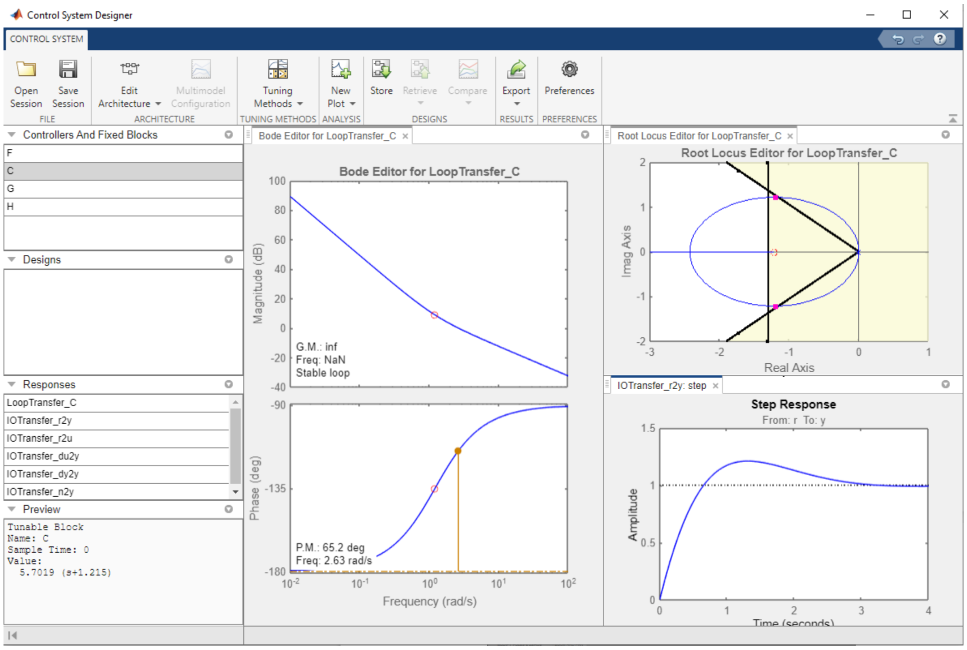
III. Analysis

Provide details of your calculations(methods used) for analysis for each of the following:

1. Open-loop root locus in step 2 of Section 2.3.



2. Resulting compensator from root locus design in step 5 of Section 2.3, PD control designed using SISO tool.



The K_c value was set with the goal of attempt to get as close to the value of 5.655 found in the prelab while also trying to get the z value as close to 1.238 rad/sec as found on the prelab. Playing around the the location of the poles we were able to achieve a K_c value of 5.7019 and a z value of 1.215 rad/sec. These results were very close to the target values calculated during the prelab.

3. Steady state error, the settling time and percent overshoot in step 7 in Section 2.3, Simulation of PD ball position control.

Steady state error was calculated by measuring the difference between the desired output and actual output waveforms once the output had reached a steady state. Through analysis this was found to be 0.00 cm.
Settling time was found through analysis; and obtained when the system reached steady state within a $\pm$ 2 % value. The time it took fot the system to reach settling time was about 2.094s.
Percent overshoot was calculated using the following equation:

$$PO = \frac{y_{Max} - y_0}{R_0} \times 100\%$$

The value found for y_{Max} was 8.284 and the value for y_0 was set to equal 8. This resulted in a percent overshoot equal to 3.55%.

4. Reasons why the control specifications are not met in step 8 in Section 2.3
Reasons why the control specifications could fail to be met during implementation would include improper mechanical calibration of the physical system as well as the tunning and fine adjustment of the servo offset angle.

IV. Conclusions

Interpret your results to arrive at logical conclusions for the following:

1. Whether the controller meets the specifications in step 7 in Section 2.3, Simulation of PD ball position control

All control specifications are met with a high degree of effectiveness. They are all substantially below the threshold for the specification range, in theory based on the simulation we would expect that the implemtation phase with the PD controller would preform very well.

5.3 Control Implementation

I.Procedure

• Briefly describe the main goal of this experiment.

The purpose of this experiment is to actually implement the simulated ball and beam experiment with added PD controller. The aim is to satisfy the control specificaions of steady state error less than 0.5 cm, a settling time under 3 sections and a percent overshoot under 5.0%. If necessary system will be tunned to best fit the specifications.

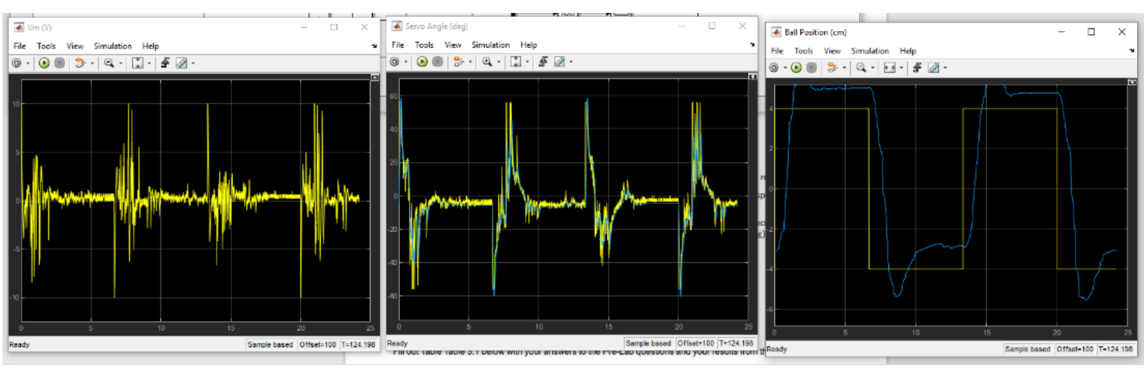
• Briefly describe the experimental procedure (Section 3.2)

Implementation was done by setting the amplitude gain to 0 cm, and running the controller with PD gains that were found in section 2. These gains were; K_c = 5.7019 rad/m and z = 1.215. The system was ran with the implemented PD controller, to improve results with respect to the specification, the system was tuned by adjusting the Theta Cmd Offset.

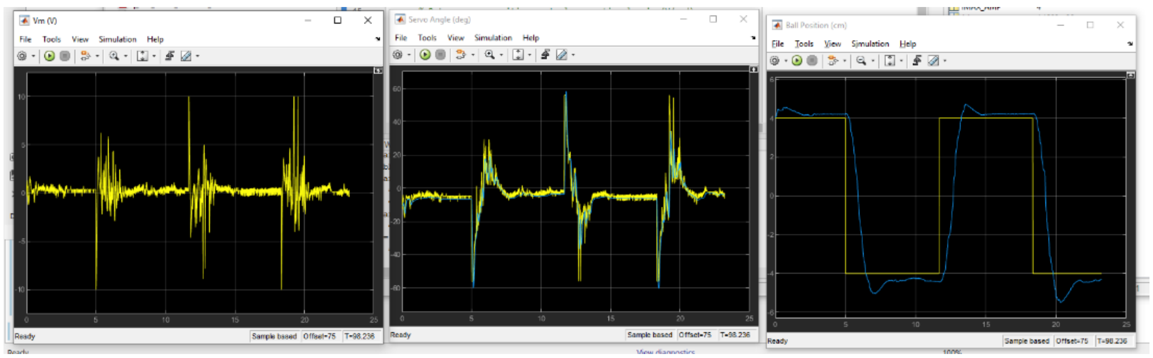
II. Results

Do not interpret or analyze the data in this section. Just provide the results.

1. Response plot from step 4 in Section 3.2, for Implementation of PD ball position control.



2. Response plot from step 6 in Section 3.2, for Implementation of tuned PD ball position control.



3. Provide applicable data collected in this laboratory (from Table 3.1).

Section / Question	**Description**	**Symbol**	**Value**	**Unit**
Section 3.2, step 5	**In-Lab Implementation: PD Control**			
	Compensator Gain	K_c	5.655	rad/m
	Compensator Zero	z	1.238	rad/s
	Servo proportional gain	k_p	12	V/rad
	Servo offset angle	θ_{off}	4	deg
	Percentage overshoot	PO	8.625	%
	Settling time	t_s	3.23	s
	Steady-state error	e_{ss}	0.196	cm

Table 3.1: Summary of results for the Ball and Beam laboratory.

III. Analysis

1.Step section 3.2

Steady state error was calculated by measuring the difference between the desired output and actual output waveforms once the output had reached a steady state. Through analysis this was found to be 0.96 cm.

Settling time was found through analysis; and obtained when the system reached steady state within a $\pm$ 2 % value. The time it took fot the system to reach settling time was about 3.92s.

Percent overshoot was calculated using the following equation:

$$PO = \frac{y_{Max} - y_0}{R_0} \times 100\%$$

The value found for y_{Max} was 9.76 and the value for y_0 was set to equal 8. This resulted in a percent overshoot equal to 22.00%.

2. Control tuning method in step 6 in Section 3.2

The machine had been calibrated and before preforming a recalibration for tuning purposes we adjusted the Theta Cmd Offset to try and meet the design specifications. Through a series of trial and error we determined that the best result was obtained at a servo offset angle of 4 degrees.

3. Steady state error, the settling time and percent overshoot in step 7 in Section 3.2, Implementation of tuned PD ball position control

Steady state error was calculated by measuring the difference between the desired output and actual output waveforms once the output waveform has reached a steady state. This was found to be 0.196 cm.
Settling time was found through analysis for when the system reaches steady state within a $\pm$ 2% value. The time it took for the system to reach settling time was about 3.2s.

The percent overshoot of the system was calculated using the following equation:

$$PO = \frac{y_{Max} - y_0}{R_0} \times 100\%$$

The value found for y_{Max} was 8.69 and the value for y_0 was set to equal 8. This resulted in a percent over shoot equal to 8.625%.

IV. Conclusions

Interpret your results to arrive at logical conclusions for the following:
1. Whether the controller meets the specifications in step 5 in Section 3.2, Implementation of PD ball position controller.

As apparent in the results results from section 3.2 the addition of the servo offset tuning lead to incredible improvements in attempts to reach the system specifications. The steady state error reduced 79.6% closer to the system specification. The settling time reduced by 19.2% getting closer to the system specifications and the percent overshoot decreased by 13.375%.
In terms of meeting the specifications, the system met the steady state error speficiation very effectly falling much below the threshold. The settling time was very close to the system specifications falling about 0.2 seconds longer than the desired time. The percent overshoot was also very close to the system specification being 3.625% over the system specification. Overall our designed system with the implemented PD controller met the specifications requirements to a moderate degree of effectiveness. One parameter was very much on target and the other two were very close to the desired range. The tuning of the system with the PD controller lead to significantly better results?