ECE 495 Project 5 (October 21, 2015)
Closed-Loop Motor Position Control

Team W8: Bode, Bode, Bode, Bode Plotting Everywhere

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I. Executive Summary

The purpose of project 5 was to design a clock-like display that would allow a user to select a desired color on a clock display and a clock hand would in turn come to rest upon the nearest color of that choice. In order to run this operation a user would make a color selection through a MATLAB menu and once the color has been chosen, the camera sensing system would then differentiate amongst all the colored stickers on the board to find the color of choice. Upon discovering the correct color on the board, the motor would then turn clockwise or counterclockwise in one smooth and complete motion to the desired colored. After stopping on the correct color the clock hand would then return to its starting position (12'o'clock). The objective of this project was to learn motor control and also integrating the motor system with project 4's camera sensing system.

II. Engineering Requirements

Customer Requirements	Engineering Requirements	Tests
Motor must have closed-loop position control	Using MATLAB in conjunction with Simulink to design software with menu-based button commands	Select desired sticker and have hand move to that position
Motor arm must land on centroid of sticker	Shape processing and accurate motor control to ensure accuracy	Run system and select color to see if the desired position if obtained
Motor must move in one smooth motion	Properly tune PID controller gains for fluid motion	Perform HIL testing and run system multiple times to ensure fluid motion
Software must allow user to choose sticker color	Menu that allows for user input	Check for requested user input when software is executed

Figure 1. Customer and Engineering Requirements.

III. Overview of Hardware-in-the-Loop (HIL)

Hardware-In-the Loop or more formally known as HIL utilizes both hardware and software. HIL allows a user to simulate a complex physical subsystem using computer software so that the user does not have to go through the trouble of building, testing and correcting errors in a physical subsystem. With a full simulation, the physical subsystem must be built which takes an adequate amount of time depending on complexity and then you must go through the entire testing process to make sure software is running smoothly, the software is communicating with the hardware correctly, and the hardware is connected correctly. With the full simulation process you run in to the dangers such as there being error before even connecting to the hardware, which may in turn damage your systems hardware costing more money in the long run. By applying HIL you can avoid such physical errors and instead of building the whole physical subsystem before testing, you can simulate the entire system with computer software. By doing so you are able to lower the chances of damaging errors by catching them early in the simulation. For project 5 we were able to use HIL to imitate our real motor. By incorporating Simulink to connect the laptop to the xPC and amplifier to Q4 board we imitated the real motor and sent the output to the laptop as feedback. After doing this we were able to see errors early and debug them to make sure there would be no damage to the real motor once we connected it to the physical subsystem.

IV. Document Simulated Motor Experiments

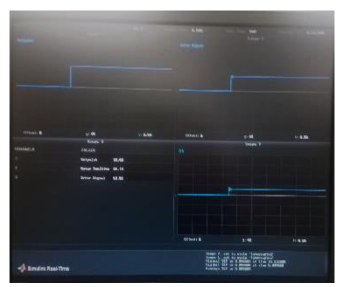
To control the rotation of our motor as it turned to the correct sticker, we utilized a PID controller through Simulink. A PID controller uses three different gains in a feedback loop to ensure that the margin of error in motor rotation to the correct sticker is minimized. The three different gains the controller uses are called proportional, differential, and integral gains.

Proportional gain (K_p) is the most simple, it's a numerical value that ensures the signal being sent to the motor is proportional to the error. The proportional gain is going to be the largest value of the three because its effects on the signal are minimal compared to the next two gains. Proportional gain is mainly used to set up the feedback loop for the next two gains, as it contributes to the main two drawbacks to the signal (peak overshoot and nonzero SSE). A plot of a feedback loop simulation with just proportional gain can be seen in Figure 2 below.

Integral gain (K_i) is a numerical value that is multiplied with $\frac{1}{s}$, where s is the time variable (generally seconds). The integral gain is used in conjunction with the proportional gain to ensure that the steady state error (SSE) approaches zero after an allotted amount of time. The main drawbacks the integral gain contributes to in a feedback loop is it will increase the peak overshoot initially seen in the resulting signal and extend the time it takes for the signal to settle. The integral gain numerical value is going to significantly less than the proportional gain value because of the increased effect it has on the system. A plot of a feedback loop simulation with a proportional gain and integral gain can be seen in Figure 3 below.

Differential gain (K_d) is a numerical value that is multiplied with s, where s is the time variable (generally seconds). The differential gain is used in conjunction with the other two gains to minimize the initial overshoot of the signal, thus allowing the signal to settle faster. The primary drawback the differential gain introduces is instability from a zero at the origin which greatly affects the system as can be seen in Figure 4, however the pole the integral gain places at the origin cancels this from the system when they are used together. The differential gain value is generally a value between the other two gains so as to ensure the system reaches its desired value in a timely manner within the system's constraints. A plot of the feedback loop simulation with all the gains can be seen in Figure 5 below.





Figures 2, 3 and 4. Proportional, Integral, and Differential Gain Simulation Responses (from left to right).

Figure 5. Implemented PID System Gain Simulation Response.

V. Document Tohoku Motor Experiments

We simulated the circuit in Simulink and achieved a functional PID controller that fit our parameters with values $K_p = 0.5$, $K_i = 0.026$, and $K_d = 0.011$. These values allowed for an error no greater than five degrees away from our desired value and a settling time within about three seconds. The motor functioned properly as long as it was initially set to the desired starting point before executing the program in MATLAB, otherwise it would assume it's at the starting position when it's off and thus be constantly be off by the same angle value.

The proportional gain was used to affect the signal to the motor to ensure that the motor would approach the desired value. The K_p could not be used to achieve the exact value of the angle but helped the motor near the value so that the integral gain could minimize the steady state error more. The effects of the proportional gain on the motor from the MATLAB code can be seen in Figure 6 below.

The integral gain was used to minimize the steady state error seen by the feedback control signal fed into the motor so that the error would be reduced after a period of time. The main downfall of the integral gain is that it will increase the peak overshoot initially observed in the signal to the motor. The effects of the integral gain in conjunction with the proportional gain on the motor from the MATLAB code can be seen in Figure 7 below.

The differential gain was used to reduce the initial peak overshoot the signal possesses. The differential gain value must be curtailed in the circuit so that it doesn't reach the correct angle too quickly and rush the motor. The effects of the differential gain in conjunction with the other two gains will make an ideal PID controller for our motor based on the values we found through the Simulink simulations, which can be seen in Figure 9 below. However by itself, the differential gain doesn't function properly on its own due to the zero at the origin which can be seen in Figure 8.

Figures 6, 7, and 8. Proportional, Integral, and Derivate Gain Motor Responses (from left to right).

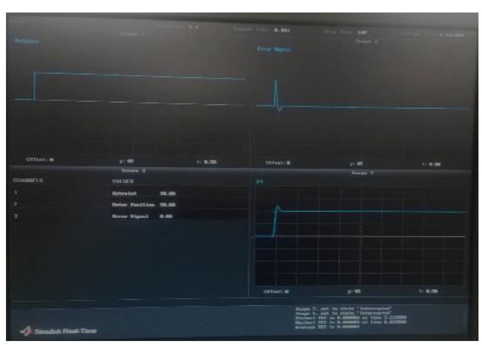


Figure 9. Implement System Gain Motor Response.

VI. Document and Evaluate Game Design:

The hardware portion of our game design consisted of the given Tohoku motor, pieces or cardboard, pieces of wood, amplifier, and two lamps. Our first step for constructing the game board was to cut a hole out of the center of the game board, and placing it over the motor, so that the moving part of the motor will rest inside the created hole. With this set up, however, we had issues with the paper not being level. The edges of the paper would fall and rest on the table, which was not an ideal situation for the camera to gather images properly. In order to fix this problem, we cut out a 12” x 9” piece of cardboard to place underneath the piece of paper. This way, the flimsy paper has something more firm to rest on and will remain parallel to the table and camera at all times.

Once the game board was level, we built a stand for our camera to rest upon over it utilizing a basic wooden arch with three pieces of plywood. We observed that the camera imaging did capture all the area it needed to, but that there was some excess around the outside of the board that would be best if it was removed from the image. In order to fix this problem we decided to move the game board closer to the camera. This would allow the stickers to show up larger on the images that were being captured, and would also eliminate unnecessary objects in the images.

We then moved the board up and down while checking a live feed from the camera in order to find the right spot to place the board. This “sweet spot” would produce an image that would contain all edges of the board, but no excess. During this process we found that raising the board 1.75” would be perfect. We then built four wooden blocks, each 1.75” high, that we used to mount the cardboard so that the game board would remain at the correct height (as can be seen in Figure 11). Later in testing we observed that shifting the board upwards did not capture the board fully now, instead of removing the blocks we added more blocks and cardboard (about 2.25”) on top of the camera stand to fix this problem (as can be seen in Figure 10).

Figure 10. Camera Stand with Wooden Blocks.

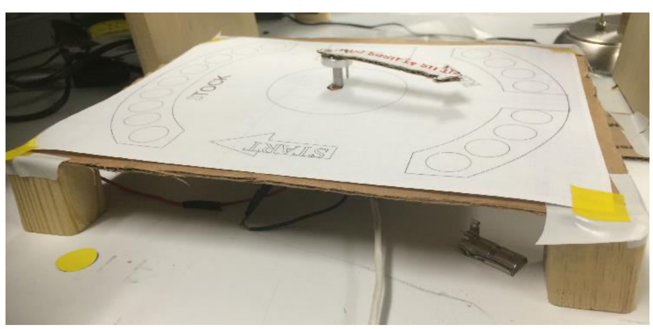


Figure 11. Game Board with Wooden Blocks.

Once our camera was centered over the game board and could capture the full board, we connected the motor to the amplifier and began to test the system. We found that the board would shift as the motor spun, particularly at faster RPM. This problem was fixed by attaching the stand and the game board itself together (via more cardboard/tape, as seen in the top right of Figure 11), since the force of the motor rotating could not shift the full weight of the system. In this stage we attached a pointer to the motor as well to see if the added mass would be able to shift the board as well, which was not the case.

Finally two lamps were added to the system (one clipped on the camera stand to provide an overview light and one behind the stand for a side illumination, as can be seen in Figure 12). These helped remove any ambient light affecting the image processing of the game board and more importantly the stickers. We learned a lot in constructing this system, primarily through trial and error. What we've gathered will ultimately help us when designing the system for our final project.

Figure 12. Final Design.

VII. Safety Analysis

Description of Component or Subsystem	Failure Mode (Hazard)	Symptom	Effect	Probability of Failure	Severity of Effect	Risk Index
Wooden Project Mount	Catches Fire	Exposure to flame	Open flames; may spread to other project components	D	II	II-D
	Falls Over	Uneven legs on mount	May hit person (hand, etc.); may fall on other project components and break them	B	III	III-B
HP Pro Web Camera	USB plug broken / bent	Won't plug into host CPU	Exposure to wires with low voltage; connection failure	C	III	III-C
	Cord frayed / weakened	Loose wire visible; impaired signal	Exposure to wires, possible fire; connection instability	D	III	III-D
ASUS ROG G750JS Host PC	Overheats	CPU feels hot to touch	Burns on skin; internal CPU failure	D	III	III-D
	Fuse blown	No light on fuse; incorrect results from system	Results incorrect; internal system failure	A	III	III-A
Dell Target PC	Overheats	CPU feels hot to touch	Burns on skin; internal CPU failure	D	III	III-D
	Fuse blown	No light on fuse; incorrect results from system	Results incorrect; internal system failure	A	III	III-A
Tohoku DC Motor	Input higher than rating	Unexpected noises; feels hot to touch; motor spinning at unexpected speeds	Burns on skin; internal failure of motor; fire possible	C	II	II-C
	Cord frayed/ weakened	Loose wire visible; impaired connection	Exposure to wires; possible fire; connection instability	D	III	III-D
Techron Linear Amplifier	Plug broken / bent	Weakened or no power to amplifier	Exposure to part of bent component (possibly energized if plugged in)	C	III	III-C
	Cord frayed/ weakened	Loose wires visible; impaired connection	Possible system failure; fire possible	D	II	II-D
	Input higher than rating	Hot to touch; unexpected output values	Internal system failure; fire possible	C	II	II-C
Quanser Q4 Board	Component bent/ broken	Unstable connection; no connection	Inaccurate results; system failure	C	III	III-C
	Input over rating	Board hot to touch; no results; skewed results	Inaccurate results; system failure; fire possible	C	II	II-C
	Connection cord frayed/ weakened	Loose wires visible; inaccurate results	System failure; fire possible	C	III	III-C
Project Wiring	Cord frayed/ weakened	Visible loose wires; inaccurate results	System failure; incorrect values sent to components	C	III	III-C
	Plug broken/ bent	Incorrect results	System failure; incorrect results; exposure to active component	C	III	III-C

Figure 13. DFMEA Table.

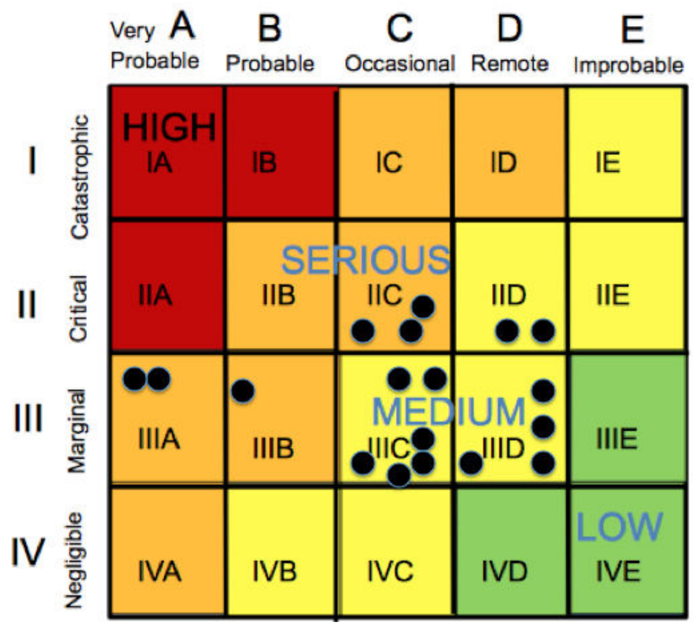


Figure 14. Risk Assessment Matrix.

Hazard Probability Levels			
Description	**Level**	**Individual Item**	**Fleet or Inventory**
Frequent	A	Likely to occur	Continuously experienced
Probable	B	Will occur several times in the life of item	Will occur frequently
Occasional	C	Likely to occur sometime in the life of item	Will occur several times
Remote	D	Unlikely, but possible to occur in life of item	Unlikely but reasonably possible to occur
Improbable	E	So unlikely that it can be assumed occurrence may not be experienced	Unlikely but possible to occur

Figure 15. Probability of Failure Table.

Hazard Severity Categories	
Category	**Definition**
Catastrophic (I)	Death or permanent injury. Loss of major system or equipment. Major property damage. Severe environment damage
Critical (II)	Extensive damage to equipment or systems. Severe injuries. Significant damage to property or the environment.
Marginal (III)	Minor damage to equipment or systems, property, or the environment. Injury or illness.
Negligible (IV)	Little or no adverse impact. First aid or minor medical treatment. Slight equipment or system damage but fully functional and serviceable. Little or no property or environment damage.

Figure 16. Risk Index Table.

Safety analysis revealed that there was low risk using our design and that our design was safe to use. Figure 13 shows the DFMEA table constructed for our project, which shows all of the risks associated with the final design. Figure 14 shows the risk assessment matrix for the project. Figures 15 and 16 show the constraints used to design Figures 13 and 14. Risks in the project were minimized by:

- Shielding all cables connected to the robot.
- Covering any exposed wiring with electrical tape.
- Soldering the data lines from the Tohoku motor to an encoder input jack.
- Isolating the power leads from the Tohoku motor to the back of the Techron Amplifier and securing them away from the design itself.
- Utilizing soft materials such as Styrofoam for all parts that jutted out of the design.
- Securing the clock hand to the Tohoku motor with screws.
- Utilizing wood tape to round off all sharp corners on the design.
- Clamping one of the lamps to the design to ensure it would not fall.
- Velcro-ing all external attachments (such as the camera) to the design.

VIII. Summary

In this project we made a system centering on a clock hand attached to the Tohoku DC motor. The system implemented properly tuned closed-loop position control on the motor, which meant that every time the user input a command to move the clock hand on the motor to a color of sticker, the clock hand moved in one fluid motion clockwise or counterclockwise to the centroid of the sticker. The system's software was designed with a user friendly menu containing options for image processing and moving the motor arm to red, blue, yellow, and green stickers. Error checking was also implemented in this system, so if the user tried to enter something invalid (for example, trying to move to a sticker before image processing), the MATLAB output window would inform the user of the error and means to correct it. Every time a command to point to a specific color sticker was input, the clock hand would point to the first nearest color sticker starting from the 12 o'clock position where the system always initialized to.

This project built skills in two areas: tuning DC motors and integrating DC motor control into MATLAB code. Tuning DC motors is the process of matching K_p, K_i, and K_d in a PID controller to appropriate values to achieve fluid and stable motor response. Hardware-in-the-loop (HIL) testing is very useful in this process. Integrating DC motor control into MATLAB code involves using the xpc MATLAB command and its various members, such as start, stop, getparam, and setparam. The skills practiced in this project are required to use a DC motor. They will be integral in the final whack-a-mole project, where the DC motor will move a mechanical arm across a rail to "whack moles".

IX. References

[1] A. Kapadia. ECE 4950 - Integrated System Design [Online]. Available: http://people.clemson.edu/~akapadi/ece4950_references.html. Cited: 10/21/2015.

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Score	Points		ABET Outcome
	5	General Report Format - Professional Looking Document/Preparation (whole document) a) Fonts, margins (11pt, times new roman, single spaced. 1" margins on all sides). Follows the page limitations below. b) Spelling and grammar are correct. c) Layout of pictures – all figures need captions and must be referenced in text. d) References. Use IEEE reference format. *e) Report components are included in team website.*	g
	5	**Page 1: Title, Group Name, Group Members, and Date** **Executive Summary** (1 well written paragraph) Provide an overview of this project. Briefly what did you do and what did you learned.	g
	5	**Page 2: Engineering Requirements** (<1 page) Considering only the Clock system, make a three column table that lists Customer Requirements in the first column, the resulting Engineering Requirements in the second column, and the third column describes the Tests that will be done on the prototype to verify that your design meets each requirement. Note: One customer requirement may branch to multiple engineering requirements.	g
		The following should be a narrative report that describes your design decisions and final design, e.g., don't just have a flowchart without text that explains it.	
	20	**Page 3: Overview of hardware-in-the-loop (HIL)** (<1/2 page) • Describe HIL. What is the difference between a full simulation and a hardware-in-the-loop simulation? • What is the power of HIL? **Page 4: Document Simulated Motor Experiments** (<1 page) Describe what you have done and learned: • **Plots** that show the effects of changing the gains (reference signal, actual position). What happens when you change the proportional gain, derivative gain, integral gain? • Describe in words how the gains affect the system. **Page 5: Document Tohoku Motor Experiments** (<1 page) Describe what you have done and learned: • **Plots** that show the effects of changing the gains (reference signal, actual position) • Describe in words how the gains affect the system. • Describe the relationship between the simulated motor experiments and the real motor experiments. **Page 6-7: Document and Evaluate Clock Design** (<2 pages) Describe the main features of your prototype. • Not a detailed design, but provide enough detail so that someone could build a copy of the prototype. • Show, **including plots**, the closed-loop response of your clock arm to 0.5, 1, and 2 sec increments.	k
	15	**Page 8-9: Safety Analysis** (<2 pages) This project must be safe for use by the customer. Perform and document a DFMEA for your project. Document your analysis using the DFMEA Table and Risk Assessment Matrix shown in the class notes. Show that you have implemented the results of the analysis to make your design safe; that is, describe what have you changed as a result of the safety analysis? Can you conclude the system is safe?	c
		Page 10: Summary (<1/2 pages) What was done in this exercise and how might the tools examined contribute to the final project.	
	50	**Laboratory Demonstration of Prototype**. Make a short video (it doesn't have to be pretty, just understandable) and upload directly to your website (not a YouTube link). Show: 1. GUI on the host and that pushing buttons controls the robot. 2. Performance for 1 second intervals a. Show clock hand moving, show target display for a few seconds, talk about setting gains. b. Push "stop" and then "reset". Show what happens, e.g. does it take shortest path to zero? c. Push "reset" as it is running, show what happens. 3. Performance for 2 second intervals. Show clock hand moving, show target display for a few seconds. 4. Show performance for 1/2 second intervals. Show clock hand moving, show target display for a few seconds. 5. Show the overall system including electrical connections to the motor and wiring of the encoder connector. Is it well built? Neat wiring?	c