Laser Alignment

ECE 445: Senior Design

Sean White, Hao Yan, Ruomu Hao
Group 10
TA: Yangge Li
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Abstract

Infrared microscopy is a diagnostic tool used in medical area. However, the beam pointing could be affected by external factors like the drift of modules or vibration by sound. Because this technique requires a high level of sensibility, it is crucial to maintain the stability of the laser beam. The current used method is an open-loop control with a look-up table for the laser pointing, where the performance of the control system isn't very satisfying. A closed-loop feedback control system could be adopted to solve this problem. The position of the laser pointing could be obtained from a quadrant photodiode sensor passed to the processing unit. This sensor can generate a difference signal that can be used as the error signal in a PID controller. The microcontroller will then output a voltage to the servo drivers to correct the beam position.

Contents

1. Introduction

1.1 Objective

A label-free diagnostic tool used in medical area, infrared microscopy is based on the fact that molecular bonds in tissues and cells have a unique spectral signature in IR[1]. However, the beam pointing could be affected by external factors like the drift of modules or vibration by sound. Because this technique requires a high level of sensibility, it is crucial to maintain the stability of the laser beam. Also, since various QCL(Quantum Cascade Lasers)'s would be used in the technique, they need to be aligned co-linearly with respect to each other.

By now the currently used method is a open-loop control with a look-up table for the QCL pointing. However, since this system cannot respond to the errors, the performance of the control system isn't very satisfying. A closed-loop feedback control system could be adopted to solve this problem.

1.2 High Level Requirements

1. The settle time requirements should be 100ms for better time response.
2. For the accuracy, the maximum overshoot Mp should be 20% of the laser diameter (4mm), which is 0.8mm. The steady-state error should be less than 10% of the laser diameter, which is 0.4mm.
3. The design should be compatible with the existing modules in the project. For example, the sensor should be able to detect the laser with specified wavelength and output power, and the result from the feedback control system should be recognized by the Galvanometer and the driver.

2. Design

The final product is comprised of three main components: the laser system, the control system, and the power system. The laser system powers the laser and directs it to hit the Galvanometers, which are mirrors that adjust the x and y trajectory of the laser based upon a voltage input ranging from -10 V to +10 V. The laser then hits the quadrature detector which gives the position of the laser with four voltage values.

These four voltage values are filtered through an RC filter and then fed to the ADC within the microcontroller that will read these voltage values and determine the position of the laser. The control unit is set to expect the laser to be at the center of the quadrature detector, so the microcontroller is running a software Proportional-Derivative Controller that will send out a correction voltage out of the two DACs that will change the x and the y trajectory of the laser in order to center it on the quadrature detector. The output voltage from the DACs is then scaled to a voltage between -10 V and +10 V so it can be used as an input into the Galvanometers to adjust the mirrors.

The voltage regulation system provides -10 V and +10 V to the DAC scaling circuit and -5 V and +5 V to the quadrature circuit that is needed for operation. This is visualized within the block diagram in figure 1.

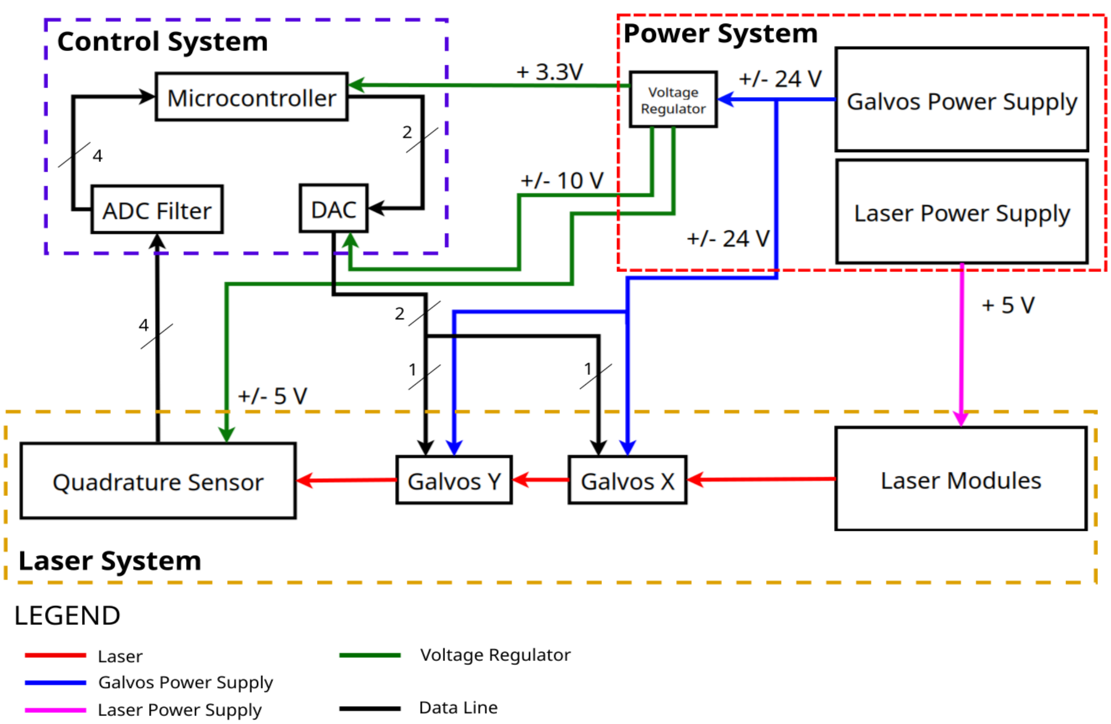


Fig 1. Block Diagram

2.1 Laser System

2.1.1 Laser Modules

The laser that this system was designed for was a green, continuous, visible laser; however, the system will work for any laser in the visible spectrum since the quadrature detector has a good response to light in the visible spectrum. The actual laser system the research team uses is IR, so in the future this quadrature detector will be switched for one that has a good response with 5 - 12 micron wavelengths

2.1.2 Galvanometers

These were provided by the research team and are used to change the trajectory of the laser in both the x and y direction. They have two mirrors that can have their angles adjusted through an analog input voltage between -10 V and 10 V. Mechanically, the galvos needed to be mounted to the bench within the lab, so an enclosement needed to be designed to ensure that the mirrors would be as stable as possible. Figure 2 shows a 3-D model of the acrylic enclosement. This design had mounting holes for both mounting it to the table and mounting the galvos to the base of the enclosement.

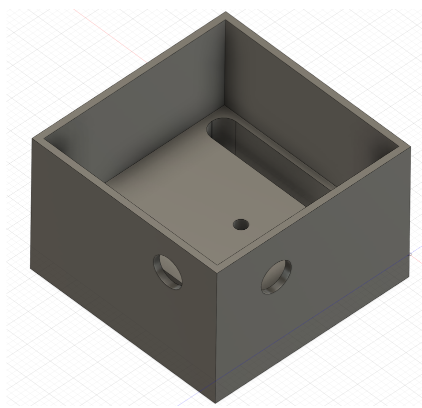


Fig 2. Galvanometer Enclosement

2.1.3 Quadrature Sensor

The sensor, from the product datasheet, has the physical layout shown in Figure 3, where the four currents flow from PIN 3,4,6,1 respectively and into PIN5 together. The circuit schematic is as illustrated in Figure 4 below :

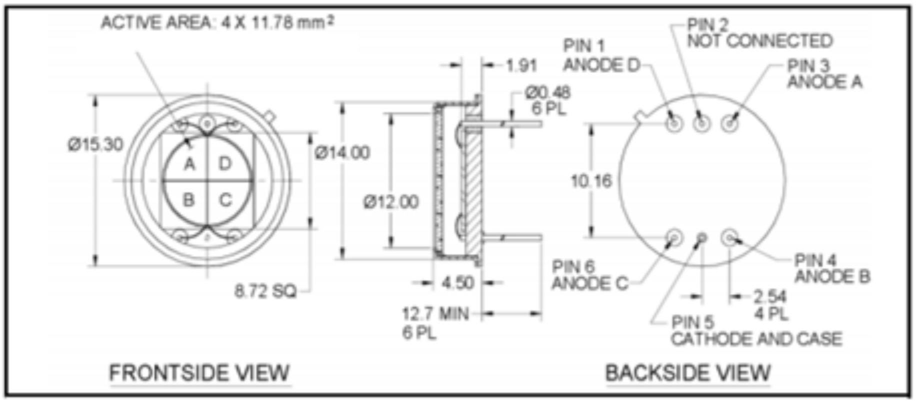


Fig 3. quadrature sensor physical layout[2]

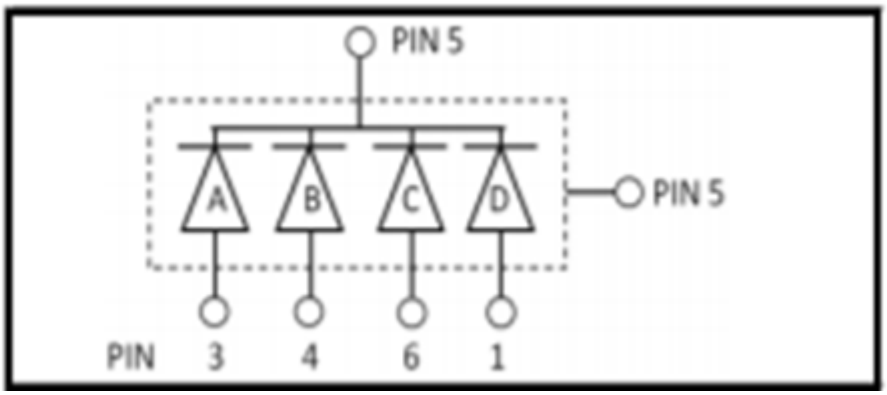
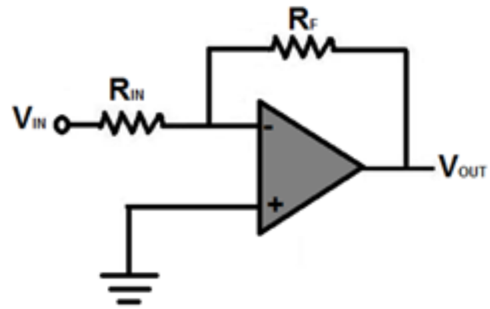


Fig 4. quadrature sensor circuit schematic

Since the laser source is placed on the bench horizontally, a vertical PCB was designed for the sensor being mounted on the side of a second PCB that is horizontally placed. This assembly is realized by adopting one female connector and a 90-degree angled connector.

After transferring the sensor currents into the horizontal amplifying PCB, this current information is converted into voltage signals for future process by the microcontroller. This conversion is achieved by op-amps and resistors. Because the currents are low in value, inverting amplifier has a better response to the change of laser presence than the non-inverting amplifier, so I put two inverting amplifiers for each quadrant signal to get a positive final value. The equation for the gain of an inverting amplifier is as shown in Fig 5:



$$\text{Gain} = \frac{R_F}{R_{IN}}$$

Fig 5. inverting amplifier I/O equation

Based on this and the sensor layout, the amplifying circuit was built. The input resistance, R_{in}, was picked to be 10k Ω, and R_f is 20k Ω in the circuit. The second amplifier for each current has R_{in} as 5k Ω and R_f as 20k Ω, so the overall gain is positive. The board design is shown in Figure 6.

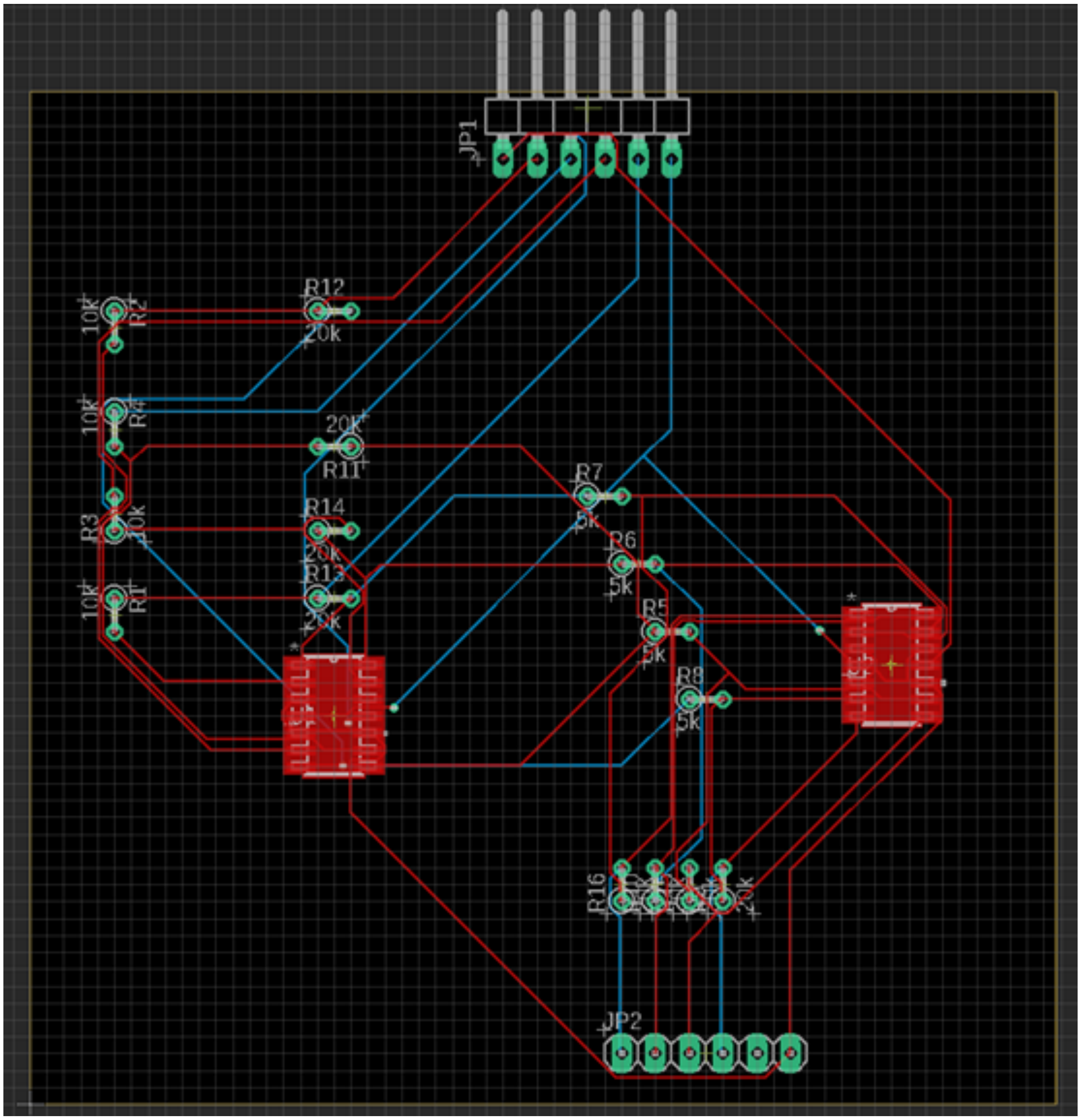


Fig 6. amplifying circuit PCB design

2.2 Control System

The control system currently uses a Proportional-Derivative software controller housed within the microcontroller to align the laser to the center. This type of control was chosen due to the variety of disturbances that can cause the laser to drift off of its original position--this control would be able to correct for this based on the constants given to the Proportional and Derivative portions of the equation.

The coordinates of the laser were fed into an equation that would estimate the total voltage change in order to move the laser back to the (0,0) coordinate based upon the mirror angle calculations based on Figure 7. Equations (1) and (2) show the X and Y estimated output voltage change.

$$X\ voltage\ change\ =\ (arctan(2 * x_{current}/distZ) * 180/pi)^\circ\ *\ 0.5\,V/^\circ \quad (1)$$
$$Y\ voltage\ change\ =\ (arctan(y_{current}/distZ) * 180/pi)^\circ\ *\ 0.5\,V/^\circ \quad (2)$$

With distZ being the total distance away from the quadrant detector and X-current and Y-current being the current laser coordinate. The addition of the 0.5 V/°was due to the galvos changing angle by 1° per 0.5V applied to the galvos controller

The following equation (3) was used to calculate the output control:

$$control\ output\ =\ P(CurrentError\ -\ ExpectedValue)\ +\ D(CurrentError - LastError) \quad (3)$$

Where *P* is the proportional control constant and *D* is the derivative control constant

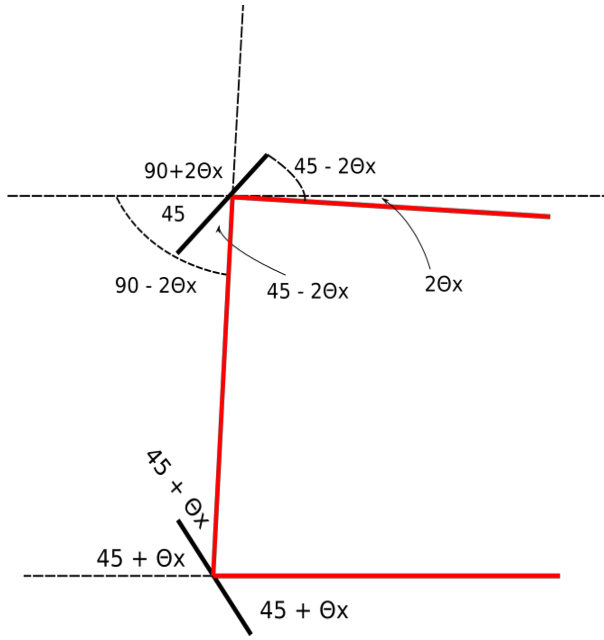


Fig. 7 Mirror Angle Calculations for Galvos Mirrors

2.2.1 Microcontroller

The TMS320F28379D[3] microcontroller was used for this project due to its 200 Mhz processor as well as its included four 16/12-bit ADC and three 12-bit DAC units. Due to the microcontroller's complexity, it was decided that the LAUNCHXL-F28379D development board would be used in order to focus on the rest of the control system. This was powered through both 3.3 V on board pins and well as usb for debugging.

2.2.2 ADC Filter

This was an addition that was not in the original design. Due to high-frequency noise coming from the galvanometer power supply, there needed to be a hardware RC filter before the ADC input to get accurate readings. The current designed filter shown in Figure 8 is not optimized to the noise that the system receives, so improvements can still be made to this portion

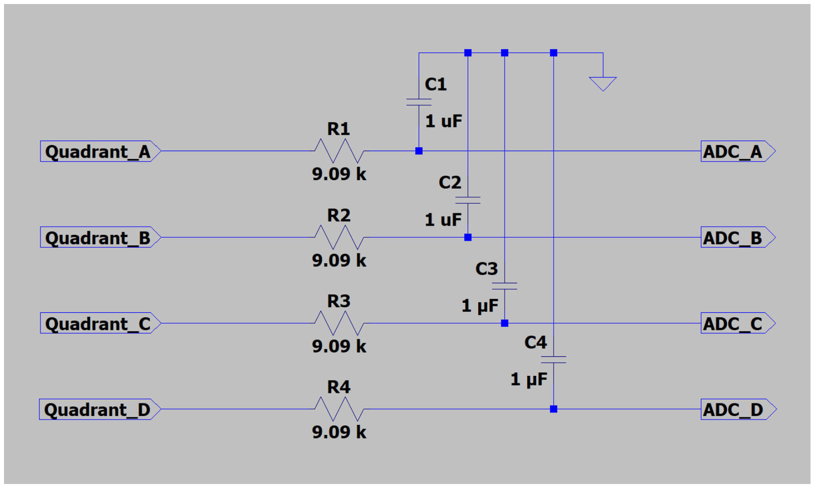


Fig 8. ADC Filter Schematic

2.2.3 DAC Scaling

The Galvanometers mentioned previously require an analog voltage between - 10 and 10 V to set the position of the mirrors. The DAC on the microcontroller only outputs a voltage between 0 and 3 V so the circuit pictured in Figure 9 solves this problem by scaling this voltage between the -10 and 10V values. A linear TLC OP Amp was decided as the main component of this circuit due to its low noise during operation as well as its rail-to-rail voltage scaling.

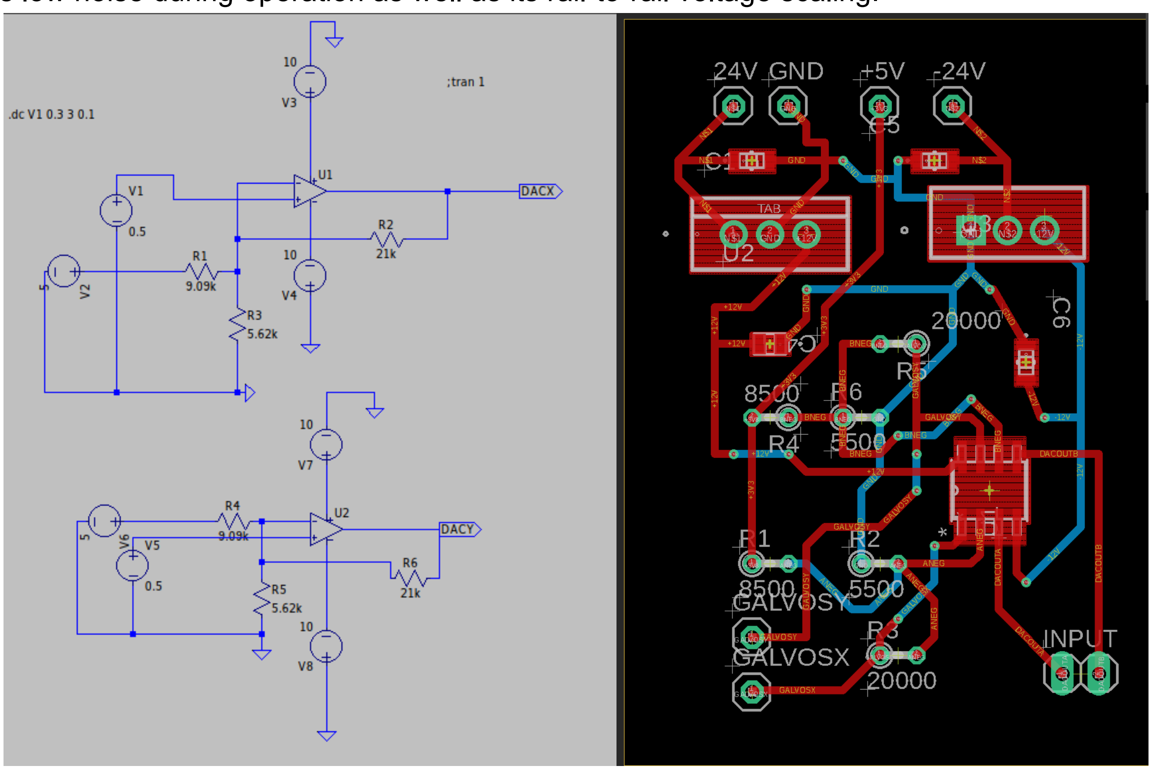


Fig 9. DAC Schematic and PCB Board

2.3 Power System

2.3.1 Galvos Power Supply

The galvos power supply is a 24 V, 4.5 A Power supply that is used to power the galvanometers. This will also be used as the input into the voltage regulator. The +10 and -10V will come from the Galvos Controller which has an output of that.

2.3.2 Voltage Regulator

We have used two sets of voltage regulators, one is to regulate the 24 V galvo supply to -12 V DAC OP Amp, the other is to transfer the 12 V from the Lab kit to 5 V to supply the sensor board. We chose above linear regulators for this project is mainly because we do not need any switching at all.

2.4 Software Flowchart

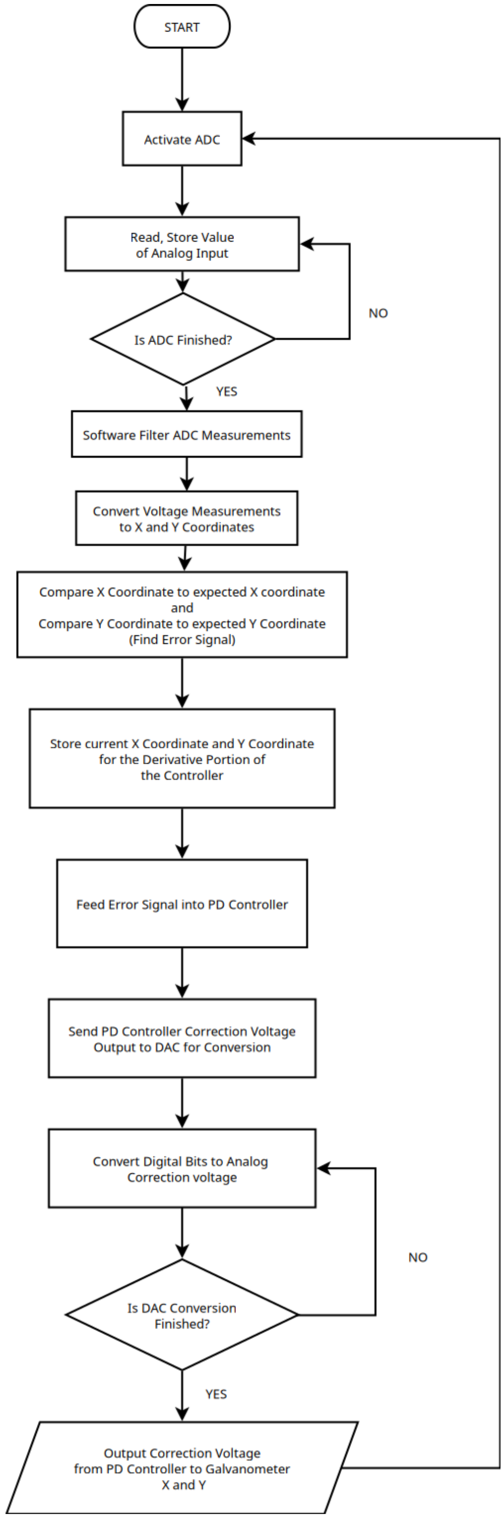


Fig 10. Software Flowchart

3. Design Verification

3.1 Sensor Circuit

3.1.1 Amplifying Circuit

After the amplifying circuit was built, a simple test was performed to observe the amplifying factor of one quadrant. The amplification was achieved and the result is included later in Table 1, where the signals were obtained after amplification.

3.1.2 Sensor Circuit Responsivity

Then the amplifying circuit with the quadrant sensor signals was tested. The result is in Table 1:

Table 1: responsivity for the amplifying circuit

Quadrant	Vmin /mV	Vmax /V
A	0.338	1.17
B	0.327	1.01
C	0.344	1.15
D	0.358	1.28

The minimum voltage output occurs when the laser shines on the quadrant diagonal to the one measured. The maximum voltage output occurs when the laser shines on the quadrant measured. Because the laser direction is not fixed on the breadboard test, and because the laser tested has its power output varying by time, the result is not perfectly stable. But from the table we can see that the sensor is very sensitive to reflect the position change of the laser. To get the X and Y coordinate of the laser, we add two quadrants and subtract the other two quadrants from the result to get either the X or Y position.

The test to get X and Y position is conducted with one of my group members, and the result is listed in Table 2. We could observe that the sensor works well reflecting the laser's position change.

Table 2: calculated X and Y position of the laser in the breadboard test

Coordinate	Equation	Min /V	Max /V
X	B+C-A-D	0.3	2.8
Y	A+B-C-D	0.3	2.9

For the requirements and verification in the Design Document proposed, the listed requirements and verifications are satisfied by the test result. The output of the sensor varies clearly with the green laser input, whose wavelength falls into 500-565 nm, which is the range proposed. Since we are working on the continuous laser, the timing requirement is not applicable in our case. Generally, the design succeeds in meeting the requirements.

3.2 DAC Scaling Circuit

The DAC scaling circuit needed to be between -10 V and +10 V to make full use of the galvos controller. Measuring the output of the DAC scaling circuit resulted in a linear response shown in Figure 11, which is beneficial for accurately adjusting the laser position no matter what the current position of the laser is. The actual output voltage was slightly less than -10 to 10 V; however, if the galvos receive a voltage outside of those bounds it could damage the system. It is better to have the voltage slightly lower to ensure the galvos are not damaged in the process of adjusting the laser position.

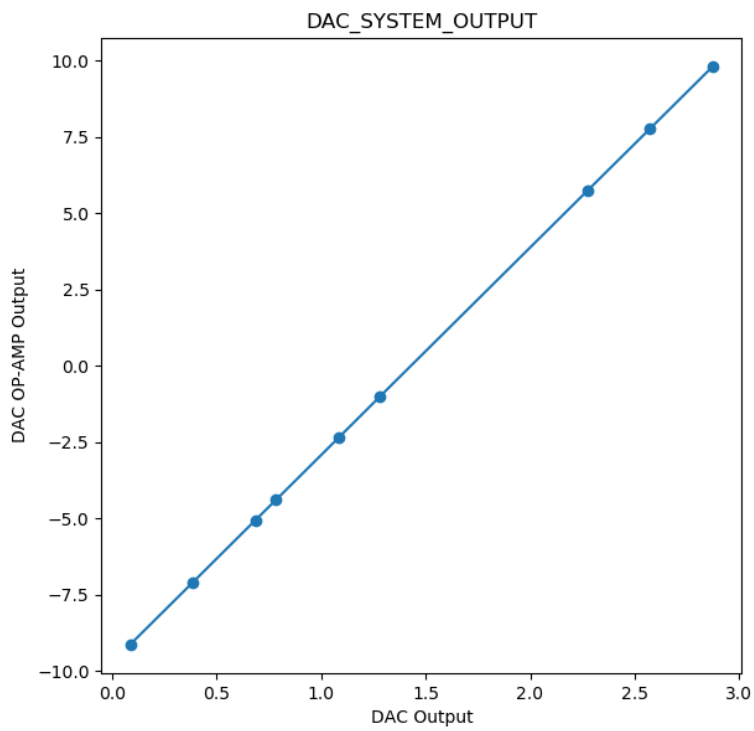


Fig 11. DAC Scaling Circuit Output

3.3 Control System

3.3.1 Control System Adjusts Laser Position to Center

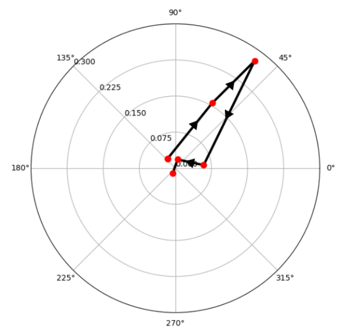


Fig 12. Control System Trajectory following change in laser position

The first three points in Figure 12 show when the quadrant detector was moved to the left and down. This resulted in the laser's position shifting to the upper-right side of the detector. As a result, the final three points are when the control system recognizes this and adjusts the mirrors to move the laser to the center of the detector.

3.3.2 Steady State Error

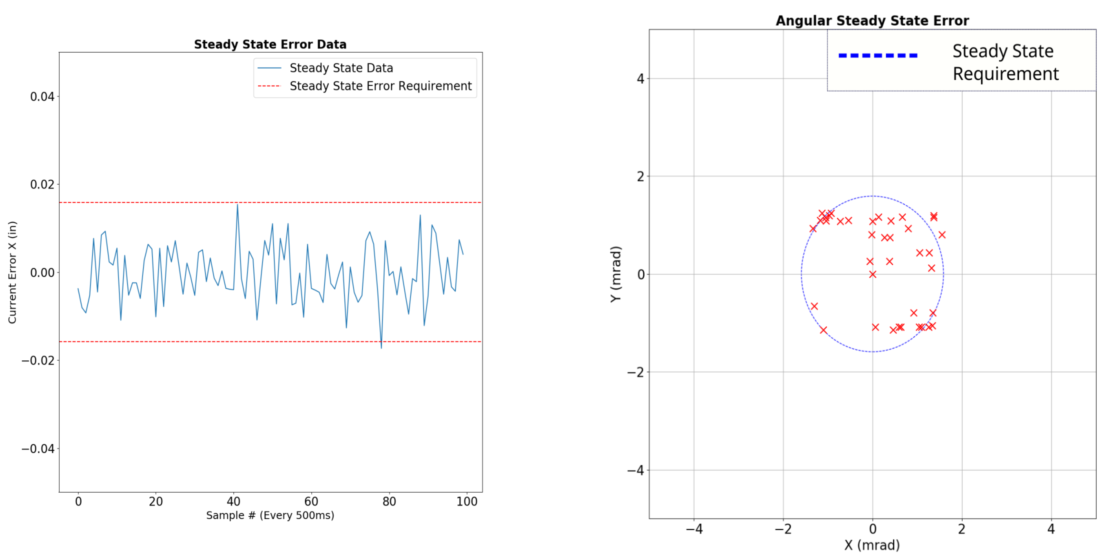


Fig 13. Stationary Laser pointed at center of quadrant detector data

The steady state error requirement at times is not satisfied due to the noise from the ADC data collection. This data was taken at a 10 inch distance away from the quadrant detector, so if the detector was closer, the requirement would be satisfied. If the ADC filters were optimized for the noise entering the system, the steady state error requirement would be met.

3.3.3 Rise time and Overshoot

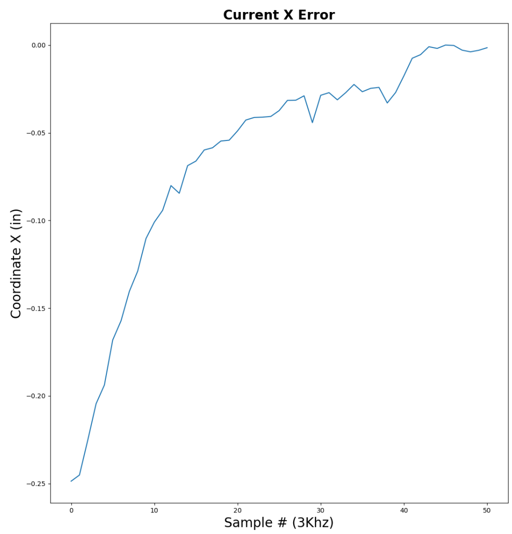


Fig 14.. Current Error Rise Time Graph

The rise time of figure 7 was computed using the knowledge that the sample rate of each iteration of our loop was 3 Khz. Using this data alone, it was expected that the control system would have an approximate 20 ms rise time. However, the DAC and the galvos do not react at that speed, so the actual rise time was 500 ms. Increasing the gains would improve this to the 100 ms goal, but the noise issue with the ADC would have to be fixed first, so the system could be stable at those higher control gains.

The overshoot requirement of being under 20% was met due to the system actually being underdamped. This is not ideal however, since this means the system is not taking full advantage of the required specs. Ideally, the system would be as close to 20% as possible in order to decrease the rise time.

4. Cost

4.1 Parts

Table 3. Part Costs Table

Part Name	Description	Manufacturer	Quantity	Unit Cost($)	Total Cost($)
OPA2180-Q1	OP Amp for DAC	Texas Instruments	1	1.24	1.24
TLC2264ID	Op Amp for Quadrant	Texas Instruments	2	1.01	2.02
QP50-6-TO8	Quadrant Detector	First Sensor	1	118.64	118.64
Molex #02-08-2004	Molex Connector	Molex	25	0.04	0.95
Molex #15-24-4048	Molex Housing	Molex	4	0.35	1.40
LAUNCHXL-F28379D	Microcontroller Test Board	Texas Instruments	1	33.79	33.79
LM7805CT	5 V Voltage Regulator	Texas Instruments	1	2.00	2.00
LM7812CT	12 V Voltage Regulator	Texas Instruments	1	$1.53	1.53
L79L05ABZ-AP	-5 V Voltage Regulator	STMicroelectronics	1	0.45	0.45
L78L05ACZ	5 V Voltage Regulator	STMicroelectronics	1	0.38	0.38
LM7912CT	-12 V Voltage Regulator	Texas Instruments	1	1.53	1.96
LM317	Voltage Regulator	ON semiconductor	2	1.58	3.16
3266W-1-203	Trimmer Resistor	Bourns	6	5.85	35.10
Total					202.62

4.2 Labor

For the labor costs we will consider the average entry level Electrical Engineer salary at $33/hr with each of us working 12 hours per week for the 12 weeks of the design and development phase of the project:

$$\$33 * 3\,people * 12\,hours * 12\,weeks = \$14256$$

GRAND TOTAL: $14,458.62

5. Conclusion and Future Work

Overall, our proposed high-level requirements are met, except for the rise time specification and steady state error. This is because the mirrors on the Galvo take time to rotate to a new position, even with the new voltage input. With the percentage as seen in the actual lab, the rise time would satisfy the proposed spec. The system is compatible with the existing lab equipment, and can improve the drifting of the laser position. For all sub-module requirements, only the steady-state noise does not fully fall into the tolerance range. This could be further modified by improving the hardware filters or perform software-wise filtering.

For the future work, the integration of our designed system could be improved by combining PCBs used into one whole board and adding peripherals so it could meet the physical requirements in the lab bench. Also, when working with the pulsed laser in the future, we need to replace the sensor with a new one that could detect pulsed laser, and synchronize the system so each sub-module could process the pulsed laser data. Moreover, further work would be applied to study the source of noise and we would work on noise suppression to improve the performance of the control effort.

This project belongs to a research group which is working a developing FTIR and QCL instrumentation for infrared spectroscopic imaging[4]. As a relatively important part of their entire model, IEEE Code of Ethics #10[5] is applied here, to help and assist their laser pointing stability from an active feedback controller.

Laser safety is a main part in our laboratory, according to IEEE Code of Ethics #9[5], additional training is required to ensure our eligibility working in this specific laboratory. When working in the lab, it is suggest not wearing expose large amount of skin, when the laser is turned on, safety goggles with corresponding spectrum are required at all time. We also need to be aware that there is no possible reflective medium along the path of any model in the lab, in case of unexpected reflected laser point to any lab personal.

If we successfully accomplish our task, reaches the ultimate goal of this project, IEEE Code of Ethic #5[5] fits here. As we improve the performance of the model, the closed loop feedback system will adjust the beam and make it stable. we hope this project can have a support on the diagnostic tool as mentioned above, and eventually put on a clinical application if possible.

Reference

[1] Yamuna Phal, (27 August, 2019), “Proposed solution schematic”, [online] Available at: https://courses.engr.illinois.edu/ece445/lectures/FA_2019_Lectures/Pitches/Pitch_ECE-445.pdf [Accessed 12, Sep, 2019,]

[2] D. Marett, “Conspiracy of Light,” welcome.html, 2012. [Online]. Available: http://www.conspiracyoflight.com/Quadrant/Quadrant.html. [Accessed: 02-Oct-2019].

[3] Texas Instruments, “TMS320F2837xD Dual-Core Delfino™ Microcontrollers,” TMS320F2837xD Datasheet, Aug. 2014 [Revised Nov. 2018].

[4] Pearson, P. (2019). [online] Available at: https://chemimage.illinois.edu/Yamuna-Phal.html [Accessed 17 Sep. 2019].

[5] Ieee.org. (2019). IEEE Code of Ethics. [online] Available at: https://www.ieee.org/about/corporate/governance/p7-8.html [Accessed 11 Dec. 2019].

Appendix A: R&V Tables

Laser System:

Requirement	Verification
For Visible Lasers, must detect 500-565 nm.	A. Shine Laser on Detector B. Check voltage of leads with multimeter C. Compare Voltage measurement to actual coordinate D. If it matches with +/- 5% then the laser is detected
Successfully obtain signals for each quadrant	A. Take the reading of each quadrant without laser shining. B. Shine the laser on each quadrant of the detector and observe the change

Control System - ADC:

Requirement	Verification
ADC within the microcontroller can read the 2.5V signal for the 12-bit ADC mode	A. Send a 2.5V constant voltage from a power supply to the ADC input B. Store the value within the microcontroller that was read from the ADC C. Verify the ADC reads within +/- 5% of the output of the power supply D. Alternatively, measure voltage into the ADC pins and compare ADC readings during any test
DAC within the microcontroller can output a consistent 2.5V constant	A. Set the DAC to output 2.5V within the microcontroller (corresponding to 12-bit representation of 2730) B. Using a multimeter measure the output of the DAC. C. Verify that voltage is 2.5V +/- 5% and stabilizes around that value within +/- 1%

Control System - DAC:

Requirement	Verification
Can output -10 - +10 V and remain steady within +/- 5% of value	A. Send a 3V constant voltage through the DAC system B. Measure the output of the DAC System C. Check to see if the output is within 5% of 10V D. Send a 0.3V constant voltage through the DAC system E. Measure the output of the DAC System F. Check to see if the output is within 5% of -10V G. If C and F are true, then this passes
Can drive the galvanometers through its output	A. Set a specific DAC output through the microcontroller B. Measure the angle of the mirror to see if the corresponding voltage outputs the correct angle

Control System - microcontroller:

Requirement	Verification
Control effort meet the specs	A. Obtain laser position data from an arbitrary disturbance B. Plot and analyse the position change due to control effort C. Check if it meets the specs proposed:
The read measurement remains stable overtime such that the voltage for a particular position will not vary	A. Obtain laser position data from an arbitrary disturbance B. Plot and analyse the error change due to control effort C. Check if the steady-state error is within +/- 1% of each other then pass

Power System:

Requirement	Verification
The voltage regulator supplies 12V and 5V +/- 5% to the microcontroller from a 24V source	A. Power the voltage regulators using the power source B. Measure the output voltage of the voltage regulators using a multimeter C. Verify that the output voltage is within 12V and 5V
Maintain a temperature below 125° C with each of the regulators	A. Power the voltage regulators using the power supply B. Using a temperature probe, measure the temperature of the regulators C. Verify that the regulators maintain a temperature below 125° C