Support System for Neutral Atom Magneto-Optical Trap for Quantum Computing Research

Project Readiness Report

Olivia Moos, FeiYang Qin, Walid J Alsharafi, Fabian Li
Faculty Advisor: Matthew Bell

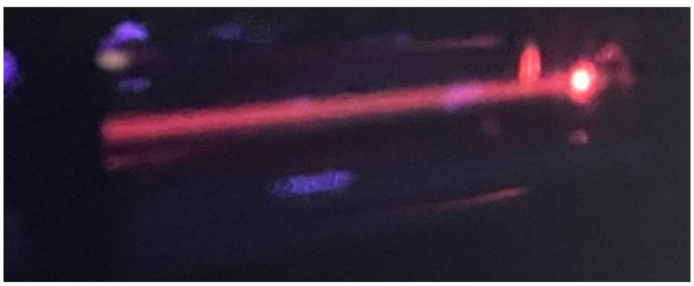

Fig. 1. Rubidium absorbing the laser at a specific wavelength.

Abstract—**Quantum computing leverages the principles of quantum mechanics to revolutionize the field of computing, promising unprecedented computational power. However, current quantum systems face significant challenges, particularly in maintaining stable qubits and achieving scalability. This senior design project focuses on improving the quantum optics subsystem of the Open-Quantum project, an initiative led by Professor Bell at the University of Massachusetts Boston. The primary challenge identified by the student research group is the instability in tuning the system's laser to achieve the precise wavelength of 780.241 nm. Currently, manual adjustments of temperature, piezoelectric, and current control subsystems result in inefficient lab sessions and suboptimal performance. Our project aims to automate the tuning process, enhance stability, and optimize system performance using machine learning and implementing PID loops; the broader goal of making the setup adaptable to other quantum research environments.**

I. INTRODUCTION

Quantum computing, which leverages qubits that can exist in superposition, has the potential to revolutionize various fields by solving complex problems beyond the capabilities of classical computers. However, scaling these systems is hindered by challenges in maintaining stable qubits. A key element in such systems is precise laser control, essential for qubit manipulation. At the University of Massachusetts Boston, the Open-Quantum project, led by Professor Bell, aims to provide students with hands-on experience in quantum engineering through an optics setup integrated with a magneto-optical trap. The project has encountered difficulties in maintaining the precise laser wavelength of 780.241 nm due to manual tuning of subsystems controlling temperature, piezoelectric gradients, and current. These manual adjustments result in inefficiencies and inconsistent performance. This study focuses on automating these processes to improve tuning stability, optimize system efficiency, and expand the system's applicability to other quantum research environments.

II. PROJECT EXECUTIVE SUMMARY

This senior design project seeks to automate the laser tuning process for quantum optics experiments within the Open-Quantum project at UMass Boston, aiming to replace the current manual adjustments with an add-on system that integrates machine learning into a PID control loop. This setup enables real-time adjustments to maintain laser stability and is adaptable to other quantum research applications. Success criteria include achieving automated calibration above 90% accuracy in stability classification, developing a custom PCB for centralized control, implementing a reactive feedback loop, and improving wavelength bandwidth precision from 10^{-4} to 10^{-8}. Key tasks include design and presentation milestones in November, PCB assembly in December, and system validation in March. With a total budget of $1,500, major allocations cover backup costs, custom PCB materials, and machine learning components. This project will streamline lab efficiency for students and researchers and provide a valuable tool for applications needing precise laser tuning. What used to take hours at the beginning of a lab session, can now be condensed into mins.

III. COSTUMER NEEDS

The Open-Quantum project serves as a hands-on initiative for quantum computing research, with students and researchers at the University of Massachusetts Boston as key customers. They need a stable, efficient system for quantum optics experiments to streamline lab sessions and support experimental consistency. Currently, tuning the laser subsystem to the target wavelength of 780.241 nm requires manual adjustments across multiple control elements (temperature, piezoelectric, and current), leading to significant time delays and inefficiencies in the lab. Our project addresses these customer needs by developing an automated tuning solution that leverages machine learning algorithms for real-time stability adjustments. Specifically, this system would benefit researchers and institutions that require precise laser tuning for various applications, providing a reliable and adaptable solution for high-stakes experimental environments. This automated approach aims to reduce preparation time and increase the reliability of quantum system setups. The solution also provides flexibility, allowing for broader applications in other quantum research environments, thus enabling students and researchers to focus on experimental tasks rather than setup challenges.

IV. Design Requirements and Restraints

The design requirements and constraints for this project prioritize customer needs in performance, reliability, and energy efficiency while maintaining a total budget of $1,500. To achieve the desired performance, the system must process an incoming voltage signal in real time and convert it into the wavelength of the laser producing the signal. Based on this wavelength, the system will adjust the laser current through a feedback loop to reach the target wavelength, with PID settings adapting within 30 cycles of a stable sinusoid input. Reliability is essential, requiring the system to maintain over 99% uptime and to detect and shut down in case of errors within 5 stable sinusoid periods to prevent malfunctions. Energy constraints include operating the custom PCB on a 5V power source and connecting the FPGA to a laptop via a standard USB port for power and data. The budget of $1,500 encompasses all necessary materials and components, including the custom PCB, machine learning and PID components, and backup provisions. This careful adherence to budgetary and technical constraints ensures that our design delivers an accurate, efficient laser tuning system, enhancing productivity for students and researchers while remaining adaptable for broader quantum applications.

V. Alternative Designs

A. Linien (Laser locking software utilizing ML)

Automated stabilization of laser wavelength. Linien software, integrated with machine learning algorithms, adjusts laser parameters to achieve and maintain a stable wavelength. It addresses the need for efficient and automated laser locking, reducing manual adjustments.

Linien relies on the Red Pitaya board, which is approximately 400$, and it can only handle 2 Input/Output signals. We want to make more customized version of Linien, where it can handle 3 inputs and 3 outputs.

B. Laser Diode Driver (Manual control)

Precise control of the current supplied to the laser diode. This driver allows for fine-tuned manual control of the laser diode's current, ensuring stability. However, it requires constant adjustments, making it less efficient for setups where automation and consistency are critical.

C. Thermoelectric Cooler

Maintaining stable laser diode temperature. A thermoelectric cooler stabilizes the temperature of the laser diode, preventing thermal drift that can affect laser wavelength. It ensures temperature control without manual intervention, crucial for maintaining laser stability.

D. Kalman Filter (Digital Filtering in FPGA)

Noise reduction and precise signal filtering. Implementing a Kalman filter using an FPGA (Field-Programmable Gate Array) helps filter out noise in the control signals. This enhances the precision of laser stabilization, especially in systems that are sensitive to environmental noise.

VI. Skills and Tools

This project requires a combination of technical skills and tools to meet the design requirements effectively. The team brings expertise in various domains, including machine learning (ML), printed circuit board (PCB) design, circuit analysis, and programming. Below is an overview of each team member's skills and tools, along with a plan for acquiring additional skills to support project milestones. The team includes members with strengths in areas critical to the project, such as ML, circuit design, FPGA, and GUI development. Any additional skills required will be acquired through self-study, online resources, and tool-based training aligned with project milestones.

A. Olivia Moos - Chief Executive Officer

1) Skills: (Proficient in Fusion 360, Python, MATLAB, Arduino, and Digital filters.)
2) Tools: (Fusion 360 for 3D design, MATLAB for signal processing, Arduino for prototyping, and signal analysis tools.)
3) Learning Plan: Plans to enhance FPGA knowledge over the project timeline, specifically by the end of Nov 2024.

B. Fabian Li – Chief Financial Officer

1) Skills: (Proficient in C/C++, MATLAB, LTSpice, and Circuit Analysis.)
2) Tools: (PCB design tools (EasyEDA), MATLAB for algorithm development, LTSpice for circuit simulation, and circuit analysis tools.)
3) Learning Plan: Aims to gain proficiency in ML and the PID loop by end of Nov 2024 to support coding and control system development.

C. Walid J Alsharafi - Chief Operating Officer

1) Skills: (Proficient in C/C++, MATLAB, LTSpice, Soldering, and Circuit Analysis.)

2) Tools: (Soldering kit, LTSpice for circuit simulations, MATLAB for data analysis, and PCB design software.)

3) Learning Plan: Plans to learn FPGA, PID loop integration, and lock-in amplifier (LIA) use, completing this training by end of Nov 2024.

D. FeiYang Qin - Chief Technology Officer

1) Skills: (Proficient in Python/C, Assembly, MATLAB, Circuit Analysis, and Signal and Systems.)

2) Tools: (Vivavdo/ Ukeil Vision for FPGA development, Signal Processing Toolbox, and Raspberry Pi.)

3) Learning Plan: Aims to enhance skills in soldering and ML, specifically focusing on LIA by end of Nov 2024.

E. Additional Skills and Timeline

1) Machine Learning (ML): Key for automation; team members will reach proficiency by February 2025.

2) FPGA and PID Loop: Crucial for system control; planned training completion by December 2024.

3) Lock-in Amplifier (LIA): For signal processing in tuning; training completed by December 2024.

VII. Proposed Design Description

We propose an add-on system to enhance the current optical setup by automating laser tuning. Our solution integrates machine learning within a PID loop to dynamically control the laser's current, locking it to the precise wavelength of 780.241 nm. This system works alongside existing hardware, ensuring compatibility with various optical setups.

Uniqueness:

A. Automated Tuning

Utilizing machine learning for real-time adjustments, eliminating manual tuning and reducing setup time

B. Portable

Compact design ideal for institutional and corporate lab research

C. Market Application

Applicable in quantum research, telecommunications, medical imaging, and any field requiring precise laser control. The aim for this project gives way for a versatility that allows easy integration into diverse setups, broadening its market potential

VIII. System Diagram

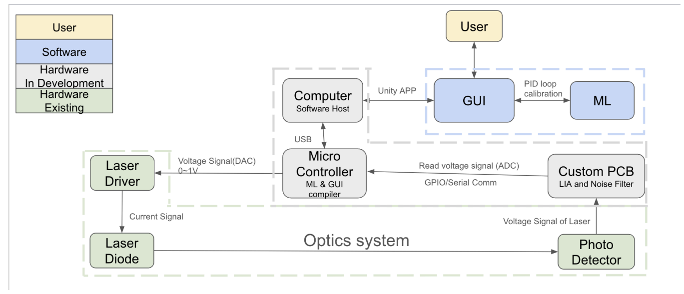

Fig. 2. Subsystems are clearly defined by boundary and color. The green components are existing hardware that our implementations will need to interact with as a part of the support system we plan to develop.

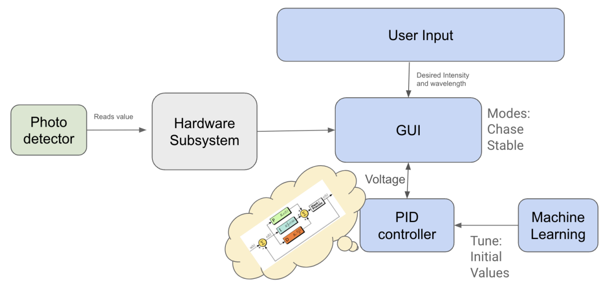

Figure 2.1 Machine learning Subsystem, showing how Machine learning interacts with the PID controller and how the user can affect it.

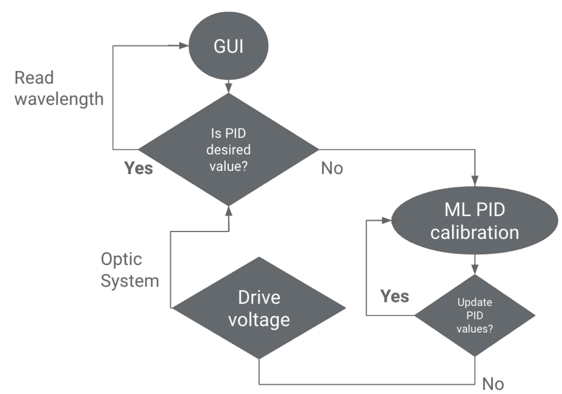

Figure 2.2 PID controller inner working flow chart.

For the software subsystem, the ML learning will be used to analysis and affect the outputting voltage signal, while the GUI is created to allow access for users.

In the hardware subsystem, a custom PCB is created to improve upon the signal to noise ratio, a Micro Controller is the connection point between the custom PCB and the computer as a media to bridge the connection between the custom PCB, the laser driver and the computer. Lastly the computer is used to host the software subsystem.

IX. Project-Specific Success Criteria (PSSCs)

We have five project-specific success criteria that will guide us throughout the course of the project. These five main goals are listed below:

A. Machine learning for automated tuning

To meet the customer, need if automating the laser tuning process, we will implement a machine learning algorithm in the calibration process of the system.

B. Custom PCB for Control and Function Implementation

Operation of the system will be simplified for users by centralizing the control and monitoring of the system.

C. Reactive feedback loop

Using a PID controller, a feedback loop will evaluate the system in real-time, sending data to the machine learning algorithm for adjustment of parameters as needed and managing any system malfunctions via our central control unit.

D. User friendly interface and system compatibility

Designing an intuitive user-friendly interface that works in parallel to the current system as well as similar systems will ensure ease of use for future students and researchers.

E. Signal to Noise Ratio

As a part of the optics system, the laser goes through a neutral density filter which reduces the signal strength significantly. To find the wavelength information from the reduced signal, filters will be implemented to improve the signal to noise ratio.

X. Project-Specific Success Criteria (PSSCs) Break Throughs

A. For Machine learning for Automated tuning, we have collected enough data to start a simple binary classification algorithm that is able to identify the different modes of wavelength the laser can be in, shown in Figure 3.

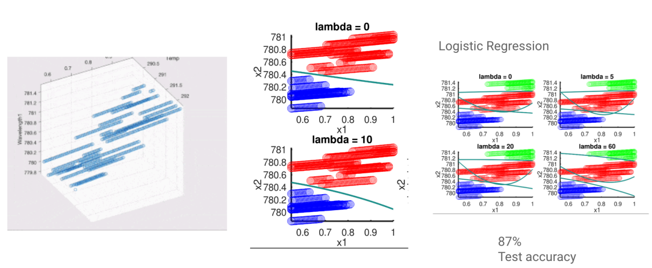

Figure 3 Machine Learning Data and classification

B. For the custom PCB, we have simulated an setup and also tested it on a breadboard, the circuit operates, but we don't know its efficiency and strength of noise reduction, so more experiments will be needed, shown in Figure 3.1. We have started PCB design however this is later than we planned in the Gantt chart, this can be shown in the critical task where we are slightly late.

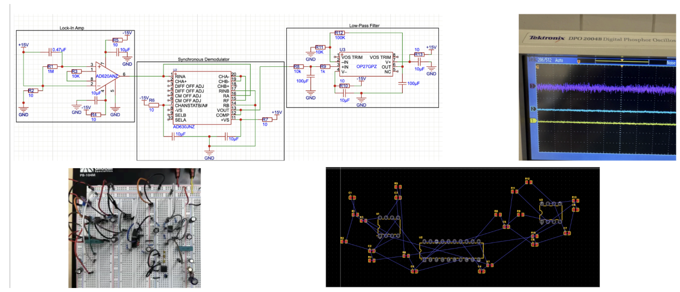

Figure 3.1 Machine Learning, circuit diagram, breadboard and beginning of PCB design.

C. For the reactive feedback loop that is the PID controller, we have implemented the code into the GUI and it currently functions well. We will be running some stress test on the performance of the PID loop.

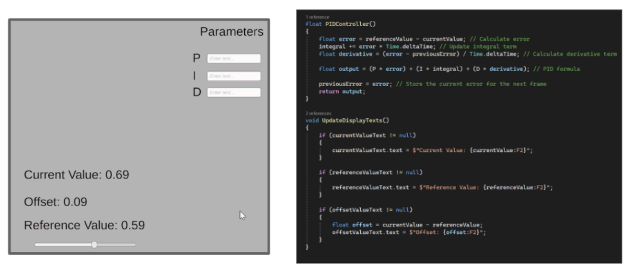

Figure 3.2 PID loop in GUI, and relevant code

D. For the GUI, as stated in C. we have incorporated the PID controller into it, and we have also planned out the design of the GUI shown in Figure 3.3. We are looking to further utilize the empty spaces and implement the buttons, alerts, input fields and the graphing area.

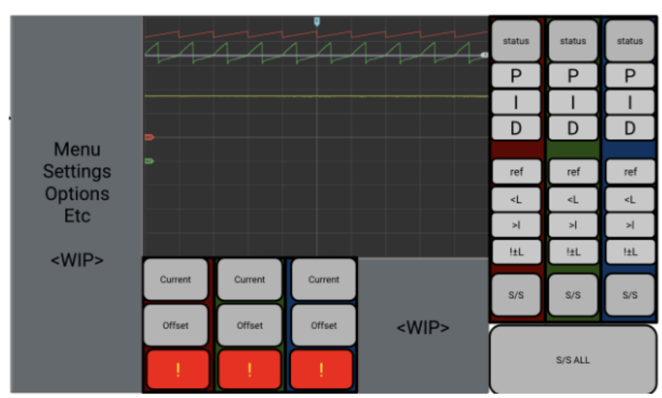

Figure 3.3 GUI Design.

E. Lastly, for the Signal to Noise Ratio, we were able to use the breadboard created in B. to reduce the noise of a signal from purple to blue, we are looking to quantify this reduction and also make sure this is not a reading error and we understanding how the circuit behaves.

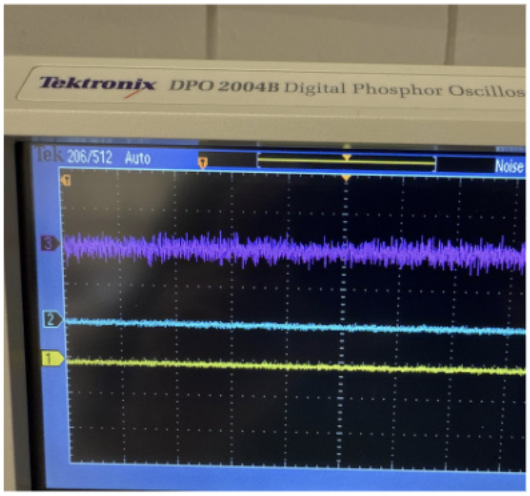

Figure 3.4 Signals readout from the breadboard In and Out

XI. Validation Tests, Ethical, and Safety Considerations

Ensuring the successful implementation of the Project-Specific Success Criteria, validation tests are put in place to verify our achievements, ethical considerations are also used to examine the legitimacy of the data collected; and the safety considerations are implemented to protect the team as the engineers, and the consumers who will inevitably be using our product.

A. Validation Testing

1) Using the Cost function, associated with machine learning algorithms, the improvement of the algorithms can be seen and calculated. Depending on the nature of the algorithm, an ROC graph can also be created to look at the categorization ability of the algorithm. The results are quantitatively measured and analyzed.

   Currently, we were able to get a 87% accuracy in the classification algorithm which shows the algorithm is seeing patterns but can't define it well, we will be tuning the parameters to improve this accuracy.

2) Functionality test, and stress test will be introduced to test the weakness of the custom PCB.

   As the PCB has not been built yet, we will be conducting experiments on the breadboard, to see potential faults and choke points that requires redundancy design.

3) The PID reactive speed will be tested through the input speed and output speed as a measurement in ms. To ensure real time feedback, the software needs to do calculations within fractions of a second to ensure the best stabilization. This will be quantitatively measured.

   The PID loop has only been built

4) User friendly interface will be tested via consumer feedback, and compatibility of operating systems.
5) The signal to noise ratio of the input should be improved through filtering subsystems. This will be quantitatively measured.

B. Ethical & Safety Considerations:

1) IEC 60825-1

This outlines laser safety, protection of user and the system.

2) IEC 61010-1

This Focuses on PCB design, consider faulty system causing shock hazard, or leaking to the metal in the environment.

3) IEEE 1149.1

This is the standard for testing integrated circuits, looking at the functionality of the board and checking for shorts and open circuits; it is also useful for debugging.

4) ISO 27001

Minimizes Operator error through simple GUI design, and implements emergency stops and other precautions.

XII. Risk Management and Alternative Goals

The 5 PSSCs are no small feat, to achieve these goals, risk assessment is required, and a plan for management is created as follows:

A. Machine Learning Calibration:

1) Risk: Inaccurate predictions could cause system failure.
2) Mitigation: Implement a fallback manual calibration process.

B. Custom PCB:

1) Risk: PCB failure due to environmental factors.
2) Mitigation: Add hardware redundancy and conduct thorough environmental testing.

C. Feedback Loop:

1) Risk: Slow feedback response could destabilize the system.
2) Mitigation: Implement real-time diagnostics and fallback to safe mode if response exceeds tolerance.

D. User Interface Compatibility:

1) Risk: Incompatibility with future devices.
2) Mitigation: Adopt an open-source platform for easier future integrations.

E. Signal to Noise Ratio:

1) Risk: The photo detector can't produce a significant signal for the filter to identify.
2) Mitigation: Gradually improve the Filter and identify how alternative products achieve their results.

XIII. MS Project Gannt Chart and Budget

The Gantt chart with key milestones and budget allocation for the duration of our project shown below was created using the Microsoft Project.

Formal Design	**99%**	**Mon 10/14/24**	**Mon 10/28/24**		
Formal Design Report	100%	Mon 10/14/24	Mon 10/21/24	7 days	4 Hours
Formal Design Presentation	100%	Fri 10/18/24	Thu 10/24/24	6 days	4 Hours
Research	**100%**	**Mon 10/21/24**	**Sun 12/1/24**		
Market Research	100%	Mon 10/21/24	Sun 12/1/24	41 days	24 Hours
ML Design Research	100%	Mon 10/21/24	Fri 11/1/24	11 days	8 Hours
GUI Design Research	100%	Mon 10/21/24	Fri 11/1/24	11 days	8 Hours
PID Design Research	100%	Mon 10/21/24	Fri 11/1/24	11 days	8 Hours
LIA Design Research	100%	Mon 10/21/24	Fri 11/1/24	11 days	8 Hours
PCB Design Research	100%	Mon 10/21/24	Fri 11/1/24	11 days	8 Hours
Design Validation Research	100%	Mon 11/4/24	Fri 11/8/24	4 days	4 Hours
Concrete Budgetting	100%	Mon 11/4/24	Fri 11/8/24	4 days	4 Hours
Soldering Practice Material	100%	Mon 11/4/24	Fri 11/8/24	4 days	4 Hours
Study Session 1	**100%**	**Fri 11/8/24**	**Fri 11/22/24**		
ML	100%	Mon 11/4/24	Mon 11/18/24	14 days	8 Hours
Soldering	100%	Mon 11/11/24	Fri 11/22/24	11 days	8 Hours
PCB Design	100%	Mon 11/4/24	Mon 11/18/24	14 days	8 Hours
GUI Design	100%	Mon 11/4/24	Mon 11/18/24	14 days	8 Hours
lock in amplifier Design	100%	Mon 11/4/24	Mon 11/18/24	14 days	8 Hours
PID loop Design	100%	Mon 11/4/24	Mon 11/18/24	14 days	8 Hours
Project Readiness	**100%**	**Mon 11/25/24**	**Mon 12/9/24**		
Project Readiness Report	100%	Mon 11/25/24	Mon 12/2/24	7 days	4 Hours
Project Readiness Presentation	100%	Wed 11/27/24	Mon 12/9/24	12 days	7 Hours
Ordering	**0%**	**Sun 12/1/24**	**Mon 1/6/25**		
Custom PCB Order	0%	Sun 12/1/24	Thu 12/12/24	11 days	7 Hours
Ordering Components	0%	Sun 12/1/24	Mon 1/6/25	36 days	20 Hours
Construction	**0%**	**Mon 1/27/25**	**Fri 3/7/25**		
Physical Assembly	0%	Mon 1/27/25	Fri 2/21/25	25 days	16 Hours
ML Code	0%	Mon 1/27/25	Fri 2/21/25	25 days	16 Hours
GUI Code	0%	Mon 1/27/25	Fri 2/21/25	25 days	16 Hours
Casing Design	0%	Mon 1/27/25	Fri 3/7/25	39 days	24 Hours
Design Validation	**0%**	**Mon 3/3/25**	**Mon 3/17/25**		
PSSC Validation/Ethical/Safety Tests	0%	Mon 2/24/25	Mon 3/3/25	7 days	4 Hours

Table 1 was created in MS Project, Using PowerPoint, a more visualized timeline is created as Fig.3

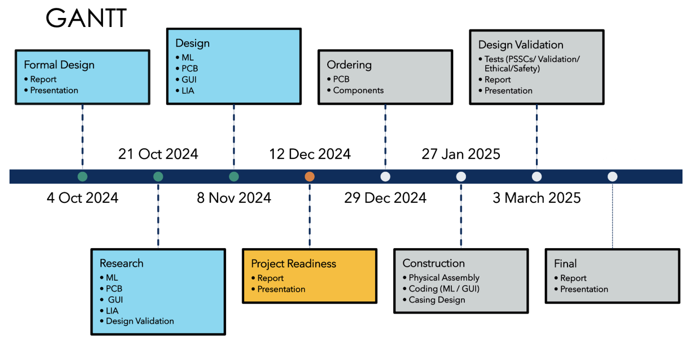

Fig. 5. Shows the GANTT chart timeline which is the simplified version of Table *1*

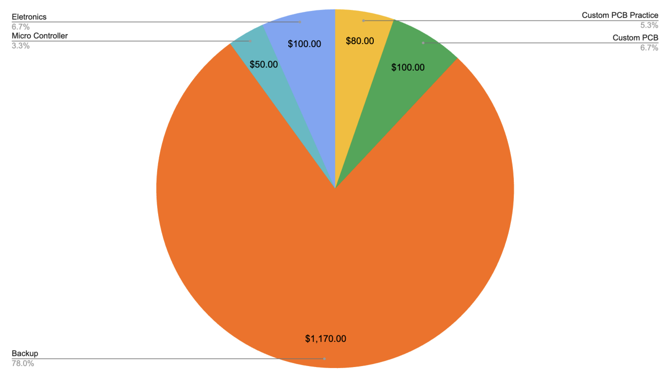

Fig. 6. Cost Analysis pie chart shows the Cost percentages, 1170$(78%) of the total budget is kept as backup in case of any changes or emergencies.

Name	Scheduled Start	Scheduled Finish	% Complete	Resource Names	Work Hours
Formal Design Report	Mon 10/14/24	Mon 10/21/24	100%	Fabian Li,FeiYang Qin,Olivia Moos,Walid J Alsharafi	4 Hours
Formal Design Presentation	Fri 10/18/24	Thu 10/24/24	100%	Fabian Li,FeiYang Qin,Olivia Moos,Walid J Alsharafi	4 Hours
Project Readiness Report	Mon 11/25/24	Mon 12/2/24	100%	Fabian Li,FeiYang Qin,Olivia Moos,Walid J Alsharafi	4 Hours
Project Readiness Presentation	Wed 11/27/24	Mon 12/9/24	100%	Fabian Li,FeiYang Qin,Olivia Moos,Walid J Alsharafi	7 Hours
Custom PCB Order	Mon 12/30/24	Fri 1/10/25	0%	Fabian Li,Custom PCB[1]	7 Hours
Ordering Components	Mon 12/30/24	Tue 2/4/25	0%	Fabian Li,Eletronics Material[1],FPGA[1]	20 Hours
Physical Assembly	Mon 1/27/25	Mon 2/24/25	0%	Fabian Li,Olivia Moos,Walid J Alsharafi	16 Hours

Fig. 7. Critical Task outlines tasks that cannot be pushed back; these are of utmost importance and will be monitored and completed as scheduled.

XIV. Suggestions Received

Questions asked by Professor Zografopoulos looked into the purpose of FPGA and how the machine learning works.

FPGA is an alternative to the custom built lock in amplifier, we want to compare their efficiency and

Acknowledgment

The team thanks Matthew Bell, Chair and Associate Professor of Engineering; Tomas Materdey, Senior Lecturer of Engineering; Walter Buchwald, Associate Professor of Engineering; Professor Chen, Professor Dahl, Professor Hamad, Professor Patel, Professor Rahaim, Professor Sun, Professor Rodrigues, Professor Zhang, Professor Zografopoulos, Director of Technical Ops Andrew Davis, and Administrative Assistant Natachia Kotomori for teaching and providing support to the team, valued scientific knowledge and assistances that allows the team to stand here today.

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FeiYang Qin

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Walid J Alsharafi

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Fabian Li

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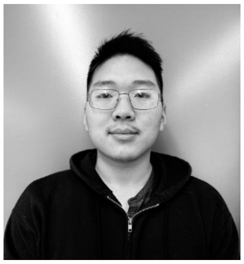
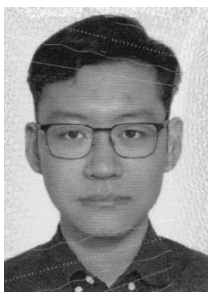
Matthew Bell (CM/TM)



Fabian Li born on October 5, 2000, in Boston, Massachusetts, is currently pursuing a B.S. in Electrical Engineering at the University of Massachusetts Boston, with an expected graduation in May 2025. Alongside his studies, he serves as a Corporal in the United States Marine Corps Reserves, demonstrating leadership and discipline. Since his sophomore year, he has led various projects, enhancing his skills in teamwork and project management. His current work focuses on developing a microcontroller unit with AI capabilities for autonomous laser calibration. Post-graduation, Fabian plans to leverage his expertise in electrical engineering and AI to drive innovation in autonomous systems.



FeiYang Qin was born in ChongQing China in 2003. He received the IB high school diploma from Yokohama International School. He is currently attending the University of Massachusetts – Boston in search of a Bachelor of Science degree in the field of Computer Engineering. Expected graduation in May 2025. Along with his ongoing pursuit of the degree, he is also working alongside a group of undergraduates to explore the Magnetic Optical Trap's application in Qubit simulation.

Walid Alsharafi was born in Amman, Jordan, on April 10, 2003. He is currently pursuing a B.S. degree in Electrical Engineering at the University of Massachusetts Boston, with an expected graduation in May 2025. His academic achievements include membership in the National Society of Leadership and Success and recognition on the Dean's List at Mass Bay Community College. He has also gained practical experience as a Software Engineering Intern at TraceLink and as a Maintenance Technician at Toyota, where he developed skills in agile software development and electro-mechanical assembly. His interests include drone technology, home automation, and robotics, and is passionate about exploring innovative engineering solutions.

Olivia Moos was born in Hyannis, Massachusetts USA in 2002. She is currently pursuing a BS degree in Computer Engineering with a physics minor at University of Massachusetts – Boston graduating in 2025. Olivia has experience working on campus at the MakerSpace since 2022, helping grow the 3D printing studio and student project center to be a hub for student learning, innovation, and practical experience. She has teaching experience through designing and instructing workshops both at the UMB MakerSpace and as a hired contractor for an digital education grant program. As an undergraduate student, Olivia has served as a peer mentor for underclassmen, as well as founded the robotics and engineering club. She is now pursuing research in quantum electronics under the Quantum Electronics Lab, helping to start the lab's undergraduate research group.