Department of Electrical and Computer Engineering
ECE 4820 Senior Design II
Project Final Report

WESTERN MICHIGAN UNIVERSITY

Automated Reflection High-Energy Electron Diffraction Image Capture and Analysis System

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ABSTRACT

Molecular beam epitaxy is a process used for creating thin films of single-crystal materials for manufacturing semiconductors and nanotechnology structures. During the molecular beam epitaxy process, reflection high-energy electron diffraction capture analysis is utilized to acquire information about the surface of the substrate, including roughness, structural properties, and growth rate. Before completion of this project, this sensitive and potentially dangerous process is being controlled manually in a local research facility. Although this has been performed by trained professionals, there is always the presence of human error which leads to inaccurate results and potential safety hazards. For this project, an automated system was designed and constructed to perform each part of this task and provide the user with accurate results. A microcontroller was programmed to control 1) a servo motor custom mounted on the shutter knob, 2) a stepper motor to actuate the sample rotation knob, 3) triggering the capture camera, 4) trajectory of the electron beam gun upon the sample, and 5) sending of the images to the lab computer. This computer used a machine learning program that verified the quality of the image and displayed the resulting classification on a user interface. Additionally, safety measures including manual and digital stop features, warning lights embedded in the control station, and security codes implemented within the user interface have been set in place to mitigate hazards and prevent accidents. This automated system has improved the overall efficiency and safety of performing this task as well as improved the precision and accuracy of results.

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PROJECT TITLE: AUTOMATED CONTROL SYSTEM FOR RHEED CAPTURE ANALYSIS

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Contact person and email address &/or telephone Robert A. Makin (robert.makin@wmich.edu)

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Design team has requested the sponsor to verify in writing to the course coordinator that all promised deliverables have been received. YES __X__ NO____ (please check)

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* Those teams with a sponsor must have the sponsor provide the **course coordinator** with written evidence that they have provided the sponsor with a copy of the final project report as well as other items that the team has promised to the sponsor. The evidence could be a short note via email, fax, or US mail from the sponsor indicating receipt of a copy of the report and all promised deliverables. From Dr. John Gesink, and Dr. Damon Miller. Version 4 September 2013. © 2024 Dr. Dinesh Maddipatla

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WMU Senior Design Lab for space to work on our project.

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SUMMARY

Due to the rapid growth and expansion of technology, previous methods for performing a given task can be replaced with a control system that provides faster results and more benefits. Taking this into consideration, manually operating a reflection high-energy electron diffraction (RHEED) process during molecular beam epitaxy is a very tedious and potentially dangerous process if the conditions within the vacuum chamber aren't monitored properly. Although operations have been performed by trained professionals, there is always the presence of human error which leads to inaccurate results and potential hazards to safety.

To find a solution to these problems, the goal of the automated capture and analysis system is to reduce the number of steps involved for the user to avoid damaging equipment and reduce human error. As a result of this, user movement in the lab is reduced which increases user and equipment safety. In addition to reduced steps and movement, the implementation of the design increases efficiency by connecting multiple manual steps of the process and letting a coded finite state machine trigger what to do next and when to do it. Finally, the automatic classification feature allows for less technical knowledge —the program not only retrieves and classifies sample images but stores them in an organized directory containing all possible classification types.

This project uses both software and hardware elements to perform the RHEED capture and analysis process. The capture half of the process involves controlling an electron beam gun, camera shutter using a servo motor, and the kSA 400 camera. A finite state machine consisting of 8 states is downloaded onto a Raspberry Pi Pico microcontroller and is considered the "brain" of the operation. The finite state machine simulates the manual process that would usually be performed by the user with additions such as keeping track of the timer (to protect equipment) and automatic process rerouting (like retaking an image or emergency shut down).

The analysis half of the process involves obtaining the most recent image taken by the kSA 400 camera and displaying it for the user to verify. The user only needs to identify blurry or obstructed views while lighting, streaks, and other detailed features of the image are reduced by the machine learning code. The program waits until a valid image is confirmed before continuing with the classification. As of right now, the model is designed to only consider monocrystalline and polycrystalline structures. Regardless, the model is readily altered with highlighted regions to change if classification types were to change or expand beyond the two listed. Once classified, the program immediately prints the results on the screen and saves them to a specified directory and folder.

In conclusion, implementation of the automated system allows the RHEED capture and analysis process to be executed faster and efficiently while continuously and consistently returning accurate information in real-time. The following is a report on the system designed and implemented that automatically captures and analyzes the reflection of high energy electron diffraction images.

INTRODUCTION

Due to the rapid growth and expansion of technology, previous methods of performing a given task can be replaced with a control system that provides faster results and more benefits. Regarding the analysis done to determine the purity of a crystal structure, a control system with an automated process is more efficient, accurate, and consistent than the manual process as it minimizes human error and eliminates redundant and tedious steps. Electron diffraction is used for conducting molecular beam epitaxy, a key step in monitoring the growth of crystal layers. Dr. Makin is currently conducting thin-film research and would like to enhance the efficiency and precision of this procedure. He is specifically interested in using machine learning to automate the process of analyzing an electron diffraction image to determine crystal purity of a given sample based on the formed crystal structure. Not only will the procedure be executed faster and efficiently, but an automated system will continuously and consistently return accurate information in real-time as well as analyze substantial amounts of data quickly. This project is a designed device that automatically captures and analyzes the reflection of high energy electron diffraction (RHEED) images. A machine learning algorithm was used to help identify if the captured diffraction pattern reflects a monocrystalline or single crystalline structure.

DISCUSSION

DESIGN AND IMPLEMENTATION

This system is designed to imitate the actions that a human would perform during RHEED capture and analysis. Several tasks are performed in order and in a timely manner to not cause any damage. A microcontroller interfaced with a mounted servo motor, stepper motor, electron beam gun, capture camera, custom built control station, and a machine learning algorithm performs this process with the most accuracy and precision.

Regarding the physical design, all flowcharts, components, and design images can be found in the *Appendices* section at the end of this report. This is to ensure detailed information is easily accessible to and all figures are organized in one location. The following *Specifications* section compares the proposed specifications to the final ones.

SPECIFICATIONS

Original Specifications

Below are the specifications that were developed during the proposal stage and prior to any development of the actual design. While these specifications were created to ensure a robust design, it is important to note that not every specification was necessary in the final design. More about any modifications can be found in the proceeding section.

1. *Functionality*
   - 1.1. Autonomously run the RHEED image capture process (requirement)
     - 1.1.1. Control activation of the electron beam
     - 1.1.2. Control movement of the built-in shutter
     - 1.1.3. Trigger camera
   - 1.2. Analyze and classify the sample (goal)
     - 1.2.1. Identify sample and display the classification
       - 1.2.1.1. Either single or poly-crystalline

2. *Hardware*
   - 2.1. Camera (requirement)
     - 2.1.1. kSA 400 Analytical RHEED System
       - 2.1.1.1. Model: k2750-14
     - 2.1.2. Accessories: k2750-T cable
     - 2.1.3. Control Signal: Pi Pico Microcontroller
       - 2.1.3.1. External trigger: input pulse
   - 2.2. Control Box (requirement)
     - 2.2.1. Enable Button
     - 2.2.2. LED Indicators
       - 2.2.2.1. Green = Ready/previous run concluded
       - 2.2.2.2. Blue = New run in progress
       - 2.2.2.3. White = Waiting for user input, cannot continue
       - 2.2.2.4. Blinking Yellow = Waiting for beam timer to equal 5 minutes
         - 2.2.2.4.1. User attempted to start a new run but equipment might get damaged based on the value of the timer
         - 2.2.2.4.2. Only occurs when program is in the *beam rest* (S8) state, the user pushed the enable button, a valid safe continuation code was entered
         - 2.2.2.4.3. User can enter override code if the beam timer <= 7 minutes

2.2.2.4.4. Stops blinking when beam timer <= 5 minutes

2.2.2.4.4.1. The enable button can now be pressed without warnings

2.2.2.5. Solid Yellow = Beam timer is in L2 or [6, 8) minutes

2.2.2.6. Solid Red = Beam timer is in L3 or [8, 9:30) minutes

2.2.2.6.1. Send warning message to user interface

2.2.2.6.2. User must verify it is safe to start a new process

2.2.2.7. Blinking Red = Beam timer >= 9:30 minutes

2.2.2.7.1. Beam will be turned off by the microcontroller in 15 seconds

2.2.2.7.2. User must verify it is safe to start a new process

2.2.2.7.3. Turns off when electron beam turns off (required)

2.3. Raspberry Pi Pico Microcontroller

2.3.1. Input Signals

2.3.1.1. Control Box (required)

2.3.1.1.1. Start

2.3.1.2. In-Lab Computer

2.3.1.2.1. Image validity (preference)

2.3.1.2.2. Safety continuation (required)

2.3.1.2.3. Timer value request (preference)

2.3.2. Outputs

2.3.2.1. Control Box (preference)

2.3.2.1.1. All LED Indicators

2.3.2.2. In-Lab Computer

2.3.2.2.1. Pulse to enable camera to take a picture (required)

2.3.2.2.2. Timer value (preference)

2.3.2.2.3. Error messages to user interface (preference)

2.3.2.2.3.1. WARNING: […]

2.3.2.2.3.2. ATTENTION: […]

2.3.2.2.3.3. Code/Master Key Request

2.3.2.3. Other Components

2.3.2.3.1. Shutter enable to servo motor (required)

2.3.2.3.2. Value of angle (speed/sec) to stepper motor (goal)

2.4. Servo Motor (required)

2.4.1. Connected to shutter knob for automatic opening and closing

2.4.1.1. Clockwise to close shutter

2.4.1.2. Counter-clockwise to open shutter

2.5. Stepper Motor (goal)

2.5.1. Rotate the sample in the vacuum chamber either 30, 45, 60, 90, or 180 degrees

2.5.1.1. Rotation angle is specified by the user

2.5.1.2. Motor operates on machine learning code which uses the initial position of the motor upon start-up as a reference point for maximum accuracy

3. *Software*

3.1. Microcontroller

3.1.1. Hardware system: Raspberry Pi Pico Microcontroller

3.1.2. Code language: Micro Python

3.1.2.1. Beam timer (required)

3.1.2.1.1. Counts up if beam is on

3.1.2.1.2. Counts down if beam is off

3.1.2.1.3. Displays time in "Minutes: Seconds"

3.1.2.2. Input & Output Signals (required)

3.1.2.3. Test program using forced values ('1', '0', etc.) (required)

3.2. Machine learning logic

3.2.1. Code language: Python

3.2.1.1. Analyzes the most recently imported image from camera

3.2.1.2. Coded characteristics of straight lines and arcs

3.2.1.2.1. Test using valid images from previous runs

3.2.2. Hardware system: In-lab computer

3.2.3. Image Identification and Classification (goal)

3.2.3.1. Single Crystalline

3.2.3.2. Poly Crystalline

3.3. User Interface

3.3.1. Located on the in-lab computer with the machine learning program

3.3.2. Loops for valid input (required)

3.3.2.1. Asks for safety code, override code, or master key

3.3.2.2. Asks user to verify captured image

3.3.2.2.1. Continue process if valid, otherwise retake the picture

3.3.2.2.2. Strips whitespaces and insensitive to capitalizations

3.3.2.2.2.1. Ex. "NO" = "no" = "N o" , etc.

3.3.2.3. Ask user to set a rotation angle for the sample

3.3.2.3.1. Reference point aligned with the electron beam

3.3.2.3.2. Step motor has a 0.18-degree error range

3.3.2.3.2.1. Fix with machine learning of reference plane and motor rotation position

3.3.2.3.3. Manual or Preset option

3.3.2.3.3.1. Preset inputs: "0" "30", "45", "60", "90", or "180"

3.3.2.3.3.2. Manual inputs: [0, 180]

3.3.3. Gives output in the same window as the input (required/default)

3.3.3.1. Provides sample classification

3.3.3.2. Provides selected angle of rotation relative to the electron beam.

3.3.3.3. Provides image captured for the current run*

4. Safety

4.1. Control Box

4.1.1. Electrical (required)

4.1.1.1. Non-Inverting buffered input and output signals to protect Components

4.1.1.2. Connected to lab power supply

4.1.1.2.1. Receives the same emergency stop signal as the power supply, and electron beam

4.1.2. Physical (required)

4.1.2.1. All circuits enclosed in protective container

4.1.2.2. Physical shut off switch

4.1.2.3. Visual Warnings

4.1.2.3.1. Various LEDs for indicating where the program is in the run and timer status (see 2.2.2 for description)

4.2. Raspberry Pi Pico Microcontroller

4.2.1. Electrical (required)

4.2.1.1. Non-Inverting buffered input and output signals to protect components

4.2.1.2. Connected to lab power supply

4.2.1.2.1. Receives the same emergency stop signal as the power supply, and electron beam

4.2.2. Physical (required)

4.2.2.1. All circuits enclosed in protective container

4.3. User Interface

4.3.1. Passcode protection (required)

4.3.1.1. New Run Safety Code

4.3.1.1.1. Beam timer during previous run >= 8 minutes at some point

4.3.1.1.2. Accepts safety code or master key

4.3.1.1.3. Loops for 3 attempts

4.3.1.1.3.1. If no valid entry, master key is required

4.3.1.2. Override Code

4.3.1.2.1. Program is in *beam rest* state
4.3.1.2.2. Accepts safety code or master key
4.3.1.2.3. Loops for 3 attempts
4.3.1.2.3.1. If no valid entry, master key is required
4.3.1.3. Master Key
4.3.1.3.1. Loops infinitely until a valid entry is received
4.3.1.3.2. Given to approved faculty
4.3.2. Visual Warnings (goal)
4.3.2.1. Messages displayed on user interface
4.3.2.1.1.1. "WARNING: electron beam has been on for more than 6 minutes"
4.3.2.1.1.2. "WARNING: electron beam has been on for more than 8 minutes"
4.3.2.1.1.3. "ATTENTION: electron beam has been turned off due to prolonged activity."
4.3.2.1.1.4. "WARNING: you have attempted a new run after the previous run (1) reached a critical activity time OR (2) was forced to stop. Please check hardware. Enter a valid safety code to continue:"
4.3.2.1.1.5. "WARNING: the program is still in the *beam rest* state, indicating equipment could be damaged if reactivated. Please check hardware. Enter passcode to override or wait for the green light:"

Final Specifications

While the bulk of the original specs were implemented in the final design, there were some slight changes. Below are several bullet points indicating the exact modifications followed by the final specifications in the correct format.

- For the *Hardware* section- specifically 2.1 *Camera*- specifications 2.1.1 and 2.1.2 were removed because they are parameters, not specifications.
- For the *Hardware* section- specifically 2.3 *Raspberry Pi Pico*- specifications 2.3.1.2.3 and 2.3.2.3.2 were removed. The code automatically displays the timer value after classification, and the sample rotation feature was removed from the project.

- For the *Hardware* section, specification 2.5 *Stepper Motor* was removed as the sample rotation feature was not implemented.
- For the *Software* section- specifically 3.1 *Microcontroller*- specification 3.1.2.1.3 was removed as the microcontroller is not displaying anything.
- For the *Software* section- specifically 3.2 *Machine Learning Logic*- specification 3.2.1.2 was removed and replaced with its sub-specification 3.2.1.2.1. This was due to lack of knowledge in creating machine learning models during the proposal stage.
- Specifications 3.3.2.1, 4.3.1.1.2, 4.3.1.2, and 4.3.1.3 were modified or removed. After speaking with the sponsor, three safety passcodes were determined to be unnecessary. It was reduced to a one single passcode that only the sponsor would have.
- For the *Software* section- specifically 3.3 *User Interface*- specification 3.3.2.2.2 was removed as the user does not need to input anything. Validation of an image is determined by pressing buttons.
- For the *Software* section- specifically 3.3 *User Interface*- specification 3.3.2.3 and 3.3.3.2 were removed since the sample rotation feature was removed the final design.
- For the *Safety* section, specifications 4.1.1.2 and 4.2.1.2 were modified to be connected to its own power supply. As a result, the sub specifications were removed.

1. *Functionality*

1.3. Autonomously run the RHEED image capture process (requirement)
- 1.3.1. Control activation of the electron beam
- 1.3.2. Control movement of the built-in shutter
- 1.3.3. Trigger camera

1.4. Analyze and classify the sample (goal)
- 1.4.1. Identify sample and display the classification
  - 1.4.1.1. Either single or poly-crystalline

2. *Hardware*

2.1. Camera (requirement)
- 2.1.1. Control Signal: Pi Pico Microcontroller
  - 2.1.1.1. External trigger: input pulse

2.2. Control Box (requirement)
- 2.2.1. Enable Button
- 2.2.2. LED Indicators
  - 2.2.2.1. Green = Ready/previous run concluded
  - 2.2.2.2. Blue = New run in progress
  - 2.2.2.3. White = Waiting for user input, cannot continue
  - 2.2.2.4. Blinking Yellow = Waiting for beam timer to equal 5 minutes
    - 2.2.2.4.1. User attempted to start a new run but equipment might get damaged based on the value of the timer
    - 2.2.2.4.2. Only occurs when program is in the *beam rest* (S8)

state, the user pushed the enable button, a valid safe continuation code was entered

2.2.2.4.3. User can enter override code if the beam timer <= 7 minutes

2.2.2.4.4. Stops blinking when beam timer <= 5 minutes

2.2.2.4.4.1. The enable button can now be pressed without warnings

2.2.2.5. Solid Yellow = Beam timer is in L2 or [6, 8) minutes

2.2.2.6. Solid Red = Beam timer is in L3 or [8, 9:30) minutes

2.2.2.6.1. Send warning message to user interface

2.2.2.6.2. User must verify it is safe to start a new process

2.2.2.7. Blinking Red = Beam timer >= 9:30 minutes

2.2.2.7.1. Beam will be turned off by the microcontroller in 15 seconds

2.2.2.7.2. User must verify it is safe to start a new process

2.2.2.7.3. Turns off when electron beam turns off (required)

2.3. Raspberry Pi Pico Microcontroller

2.3.1. Input Signals

2.3.1.1. Control Box (required)

2.3.1.1.1. Start

2.3.1.2. In-Lab Computer

2.3.1.2.1. Image validity (preference)

2.3.1.2.2. Safety continuation (required)

2.3.2. Outputs

2.3.2.1. Control Box (preference)

2.3.2.1.1. All LED Indicators

2.3.2.2. In-Lab Computer

2.3.2.2.1. Pulse to enable camera to take a picture (required)

2.3.2.2.2. Timer value (preference)

2.3.2.2.3. Error messages to user interface (preference)

2.3.2.2.3.1. WARNING: […]

2.3.2.2.3.2. ATTENTION: […]

2.3.2.2.3.3. Code/Master Key Request

2.3.2.3. Other Components

2.3.2.3.1. Shutter enable to servo motor (required)

2.4. Servo Motor (required)

2.4.1. Connected to shutter knob for automatic opening and closing

2.4.1.1. Clockwise to close shutter

2.4.1.2. Counter-clockwise to open shutter

3. *Software*

- 3.1. Microcontroller
  - 3.1.1. Hardware system: Raspberry Pi Pico Microcontroller
  - 3.1.2. Code language: Micro Python
    - 3.1.2.1. Beam timer (required)
      - 3.1.2.1.1. Counts up if beam is on
      - 3.1.2.1.2. Counts down if beam is off
    - 3.1.2.2. Input & Output Signals (required)
    - 3.1.2.3. Test program using forced values ('1', '0', etc.) (required)
- 3.2. Machine learning logic
  - 3.2.1. Code language: Python
    - 3.2.1.1. Analyzes the most recently imported image from camera
    - 3.2.1.2. Test using valid images from previous runs
  - 3.2.2. Hardware system: In-lab computer
  - 3.2.3. Image Identification and Classification (goal)
    - 3.2.3.1. Single Crystalline
    - 3.2.3.2. Poly Crystalline
- 3.3. User Interface
  - 3.3.1. Located on the in-lab computer with the machine learning program
  - 3.3.2. Loops for valid input (required)
    - 3.3.2.1. Asks for safety code
    - 3.3.2.2. Asks user to verify captured image
      - 3.3.2.2.1. Continue process if valid, otherwise retake the picture
  - 3.3.3. Gives output in the same window as the input (required/default)
    - 3.3.3.1. Provides sample classification
    - 3.3.3.2. Provides image captured for the current run

4. *Safety*

- 4.1. Control Box
  - 4.1.1. Electrical (required)
    - 4.1.1.1. Non-Inverting buffered input and output signals to protect components
    - 4.1.1.2. Connected to separate power supply
  - 4.1.2. Physical (required)
    - 4.1.2.1. All circuits enclosed in protective container
    - 4.1.2.2. Physical shut off switch
    - 4.1.2.3. Visual Warnings
      - 4.1.2.3.1. Various LEDs for indicating where the program is in the run and timer status (see 2.2.2 for

description)

4.2. Raspberry Pi Pico Microcontroller

4.2.1. Electrical (required)

4.2.1.1. Non-Inverting buffered input and output signals to protect components

4.2.1.2. Connected to separate power supply

4.2.2. Physical (required)

4.2.2.1. All circuits enclosed in protective container

4.3. User Interface

4.3.1. Passcode protection (required)

4.3.1.1. New Run Safety Code

4.3.1.1.1. Beam timer during previous run >= 8 minutes at some point

4.3.1.1.2. Only accepts case sensitive safety code

4.3.1.1.3. Loops for 3 attempts

4.3.1.1.3.1. If no valid entry, master key is required

4.3.2. Visual Warnings (goal)

4.3.2.1. Messages displayed on user interface

4.3.2.1.1.1. "WARNING: electron beam has been on for more than 6 minutes"

4.3.2.1.1.2. "WARNING: electron beam has been on for more than 8 minutes"

4.3.2.1.1.3. "ATTENTION: electron beam has been turned off due to prolonged activity."

4.3.2.1.1.4. "WARNING: you have attempted a new run after the previous run (1) reached a critical activity time OR (2) was forced to stop. Please check hardware. Enter a valid safety code to continue:"

4.3.2.1.1.5. "WARNING: the program is still in the *beam rest* state, indicating equipment could be damaged if reactivated. Please check hardware. Enter passcode to override or wait for the green light:"

STANDARDS

Metadata

Regarding metadata, this system involves communicating with a machine learning program through an internet connection and a custom user interface. Therefore, the information we provide to it must be sent in a readable format. Additionally, the information compiled together at the completion of this project should be accessible across various other platforms and systems. Thus, compliance with metadata standard of Dublin Core (Dublin Core Metadata Initiative, 2012) will guarantee that necessary information will be easy to read and use by the user and the systems that communicate with it. This will also ensure that our data can be preserved and archived in various locations for future use. Compliance with this standard involves the establishment of the following elements: title, date, subject, description, publisher, contributor, type/genre, format, identifier, source, language, relation, coverage, and rights.

Electrical Usage

As this design involves the use of sensitive and high-voltage equipment, adherence to electrical safety standards is of the utmost importance. This system will be compliant with the electrical safety standards set forth by the Occupational Safety and Health Administration (OSHA), specifically OSHA 29 CFR 1910.33 – Electrical Safety-Related Work Practices. The implementation of several emergency cut-off systems as well as thorough system checks contribute to making a safer environment for operation. Compliance with these standards will mitigate damage to the equipment and those working with it.

Electrical Installation

Since this system will perform its actions within an environment of considerable risk, standards for installing the electrical equipment must be taken into consideration. Therefore, our project will be compliant with Article 500 of the National Electrical Code (NEC) which describes these necessary requirements. As our environment falls under Class I (Areas with flammable gases or vapors) and Division 1 (Hazardous materials are present continuously or intermittently under normal operating conditions) we are required to use equipment that is intrinsically safe, explosionproof, purged and pressurized, and non-incentive. Our equipment must also be properly grounded, sealed with explosion-proof and compound fittings and wired using metal conduits or mineral-insulated cable. Compliance with this article will also help mitigate damage to the equipment and those working with it.

DESIGN VALIDATION

Table 1. *Evaluation table for meeting specifications*

SPECIFICATION	MET?	COMMENT
FUNCTINOALITY (1)		
1.1	YES	Code and physical connections control the camera and shutter
1.2	YES	Classifies with altered ResNet50 model
HARDWARE (2)		
2.1	YES	Toggles camera for capturing images
2.2	YES	Interactive buttons and LEDs on control box
2.3	YES	Contains all inputs and outputs required and preferred
2.4	YES	Connects to knob and is removable as requested
SOFTWARE (3)		
3.1	YES	Required components were implemented
3.2	YES	Uses altered ResNet50 to satisfy requirements
3.3	YES	Required components were implemented
SAFETY (4)		
4.1	YES	Control box encloses circuitry with buffered connections and separate DC power supply
4.2	YES	Microcontroller circuitry is enclosed by the control box with buffered connections and a separate DC power supply
4.3	YES	Several messages were implemented as automated warnings based on the beam timer and if the user restarts the process.

BILL OF MATERIALS

Below in *Table 2* is a list of the components bought for the project. It is important to note that the table only includes purchased materials. There are several components that were not bought but obtained in one of two ways: donated materials from individuals and the university or made using university machinery and equipment. These additional components include the mounts and connection pieces, the control box container, power supplies and wiring, the breadboard for the circuit, screws, additional switches, and software.

Table 2. *Detailed Parts and Cost List of the Final Design*

Component	Manufacturer	Part Number	Quantity	Cost
1-1M Ω Resistors	BOJACK (Amazon)	N/A	1 kit	$9.99
Breadboard Wires	AUSTOR (Amazon)	N/A	1 kit	$11.99
Buttons	VINGVO (Amazon)	N/A	1 kit	$6.80
Jumper Wires	EDGELEC (Amazon)	N/A	1 kit	$13.99
LED Indicators	BOJACK (Amazon)	N/A	1 kit	$3.95
NAND Gate	Texas Instrument	SN74HC00N	2	$1.38
Non-Inverting Buffer	Texas Instrument	SN74HC541N	2	$2.80
Servo Motor	Hobbyporter RC	N/A	1	$16.39
Switch	E-Switch	100SP1T1B4M2QE	1	$2.82
Grand Total				**$70.11**

DESIGN CONSIDERATIONS AND IMPACTS

Economical

Economically, the design saves time and company money as the system can function on its own. While operating the design only requires the user to start the process and verify the image, it decreases the need for skilled or knowledgeable personnel. As a result, this reduces costs by eliminating the need to hire a person with more advanced skills and cuts down training time and expenses. It also saves time, increases safety, and reduces error.

Environmental/Sustainability

Implementation of the design reduces environmental impacts by optimizing energy consumption and controlling electron emissions. The process in general consumes a lot of energy. The equipment operates only when necessary, reducing energy usage and minimizing waste. Specifically, the electron beam timer is a safety feature that is implemented not only to protect the equipment. As a byproduct of this new feature, consumption of resources and emissions are controlled, ultimately making the lab more sustainable.

Global Impact

Globally, this design allows companies and universities to allow a wider range of candidates to operate a molecular beam epitaxy process and RHEED analysis. The design is more efficient than the manual process as everything is controlled by a coded finite state machine opposed to user knowledge or familiarity with the process. The design also removes required skills such as navigating Linux or directories in general, use of kSA software, and the difference of monocrystalline or polycrystalline features in a diffraction pattern image.

Health, Safety and Welfare

The entire process happens within encapsulated or closed off containers, so all parties involved are safe from any potential hazards as far as implementing and testing our prototype goes. All our project implementations happen outside of these containers. As a byproduct of our prototype functionality, we do turn on the electron beam for some amount of time within one of the containers (a vacuum chamber). Without the container, the exposed electron beam while on will not only damage other lab components but cause lethal electric shock. While it is always important to be mindful of the process happening, there are several easily accessible safety features and layers of protection within the lab and project design to keep everyone and the environment safe.

Social Impact

There are a few sociological constraining factors related to this project design. The literal purpose of the project is to convert a predominantly manual process into a predominantly automatic one. The duties of the user are replaced with a robot that does the tedious work. Though less work on the user’s end increases comfort, there is a larger scale impact. The qualifications of users for the automated design will be lowered and if implemented in a factory or workplace, the pay of individual could be lowered as they are required to do and know less than before.

Notice

There are no cultural impacts that result from the development of this design.

CONCLUSIONS

This project not only assisted the molecular beam epitaxy lab with their work, but also to the students who worked on this project. Having implemented concepts such as machine learning, electronics, control systems, and programming into this design has provided long term benefits to these students in their pursuit of engineering excellence.

DELIVERABLES

Table 3. *Deliverables for the final design which were approved by the sponsor*

Deliverable	Description	Status
Microcontroller + Circuitry	The supplied microcontroller combined with the developed circuit	PROVIDED
Control Box	Physical box with removable lid. Contains wiring for the power supply and the microcontroller circuit	PROVIDED
Microcontroller Code	Code containing the state machine that automates the process with comments	PROVIDED
User Interface + Machine Learning Code	The classification code combined with interactive features for the user with comments	PROVIDED
Custom Model + Test Code	Model trained and used in the user interface/machine learning code in addition to the test file that validated the model	PROVIDED
User Manual	In depth details for the user explaining the components, features, and procedures of the implemented design	PROVIDED
Additional Parts	Request rotation angle from user and rotate sample using a stepper motor	PROVIDED

RECOMMENDATIONS

As many types of data can be measured from RHEED capture analysis, it is recommended for those undergoing a project like this one to do more with the machine learning code. Not only classifying between single crystalline and polycrystalline, but other structures (amorphous) and potentially sample quality (defective monocrystalline). It is also recommended to implement the sample rotation feature. While the software end was an easy addition, the designers ran out of time to implement the physical components. The automated rotation feature reduces the steps required by the user and increases angle accuracy of the knob being turned- all of which increase comfort. Finally, duplicating the design in the Western Michigan University Molecular Beam Epitaxy Lab (B113) is encouraged so that both systems are automated. This can be applicable for any environment outside of Western Michigan University that may also have more than one molecular beam epitaxy system setup, increasing comfort for not just one person, but a field of scientists and researchers.

REFERENCES

Safety and Standards

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[2] "Hazardous (Classified) Locations, Classes I, II, and III, Divisions 1 and 2 | UpCodes," *UpCodes*, 2020. https://up.codes/s/hazardous-classified-locations-classes-i-ii-and-iii-divisions-1-and-2 (accessed Dec. 11, 2024).

[3] DCMI Usage Board, "DCMI: Dublin core™ metadata element set, version 1.1: Reference description," *www.dublincore.org*, Jun. 14, 2012. https://www.dublincore.org/specifications/dublin-core/dces/

[4] U.S. Department of Labor, "Selection and use of work practices," Jan. 31, 1994. https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.333 (accessed Dec. 11, 2024).

Circuit Diagram/Design

[5] Max, M. (2020, March 19). Ultimate Guide to Switch Debounce (Part 5). Electronic Engineering Journal. Ultimate Guide to Switch Debounce (Part 5) – EEJournal

APPENDICES

Figure 1. *Flowchart detailing manual operation of the reflection high-energy electron diffraction capture and analysis process*

Figure 2. *Flowchart detailing the automated operation of the reflection high-energy electron diffraction capture and analysis process*

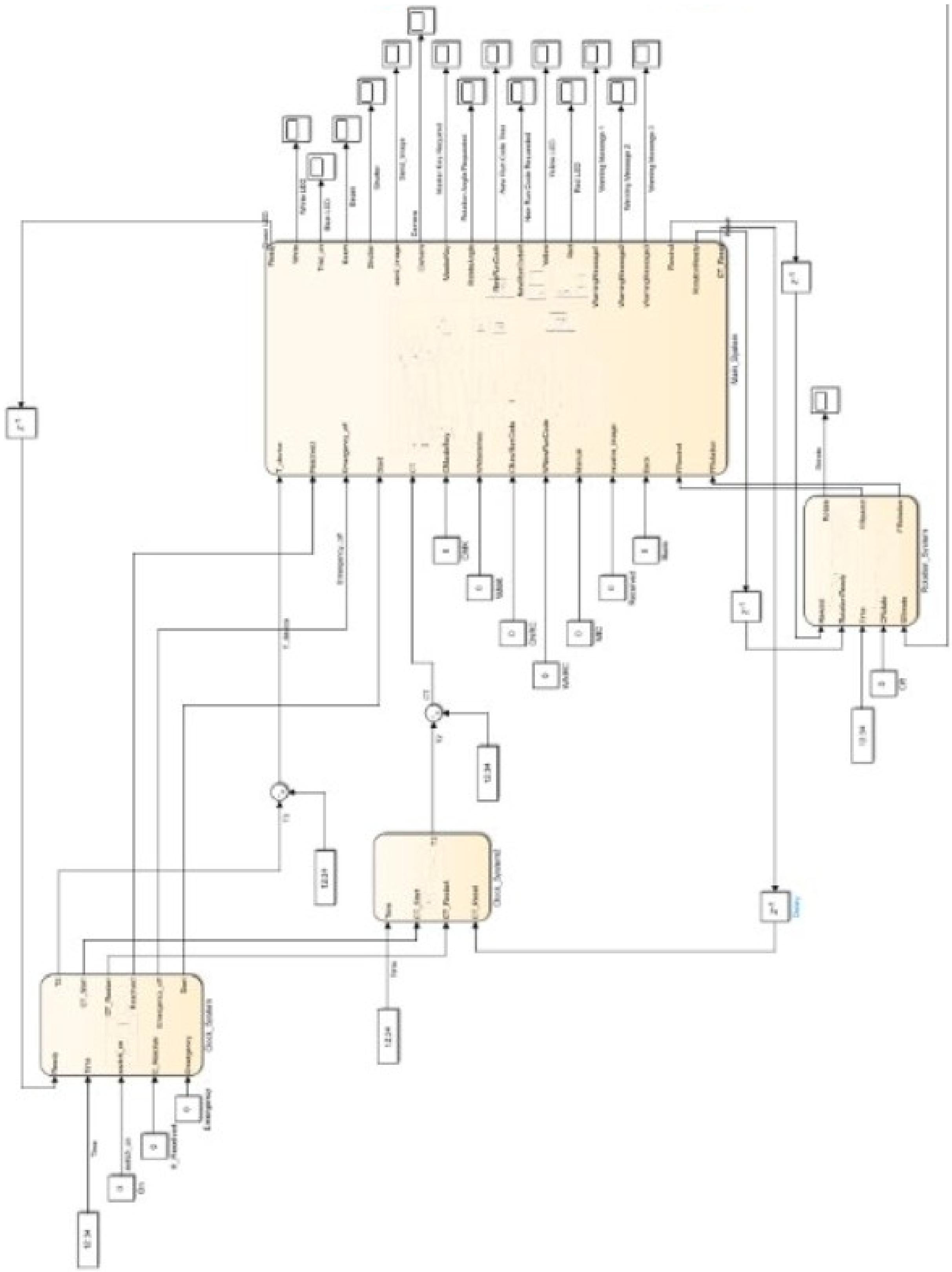

Figure 3. *Connection diagram for the completed automated system*

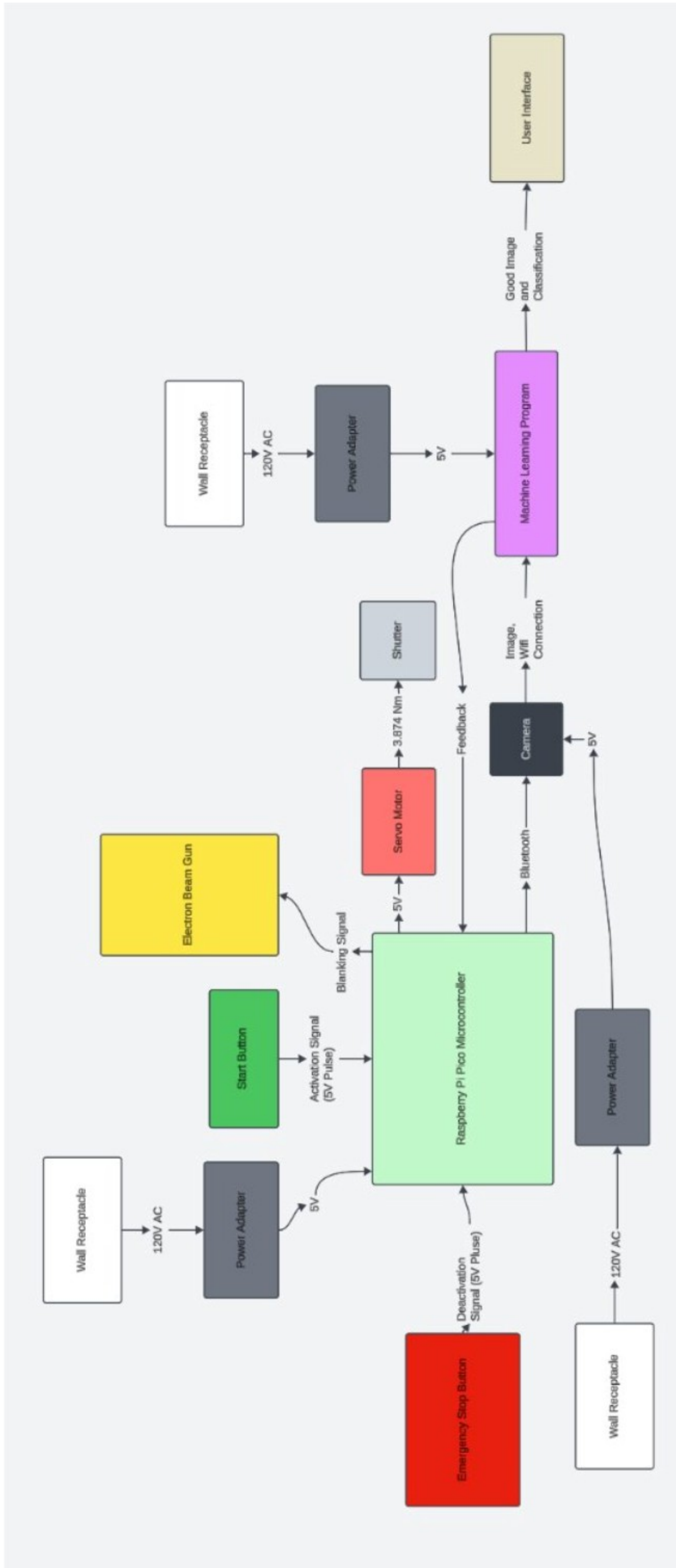

Figure 4. *Block diagram for the completed automated system*

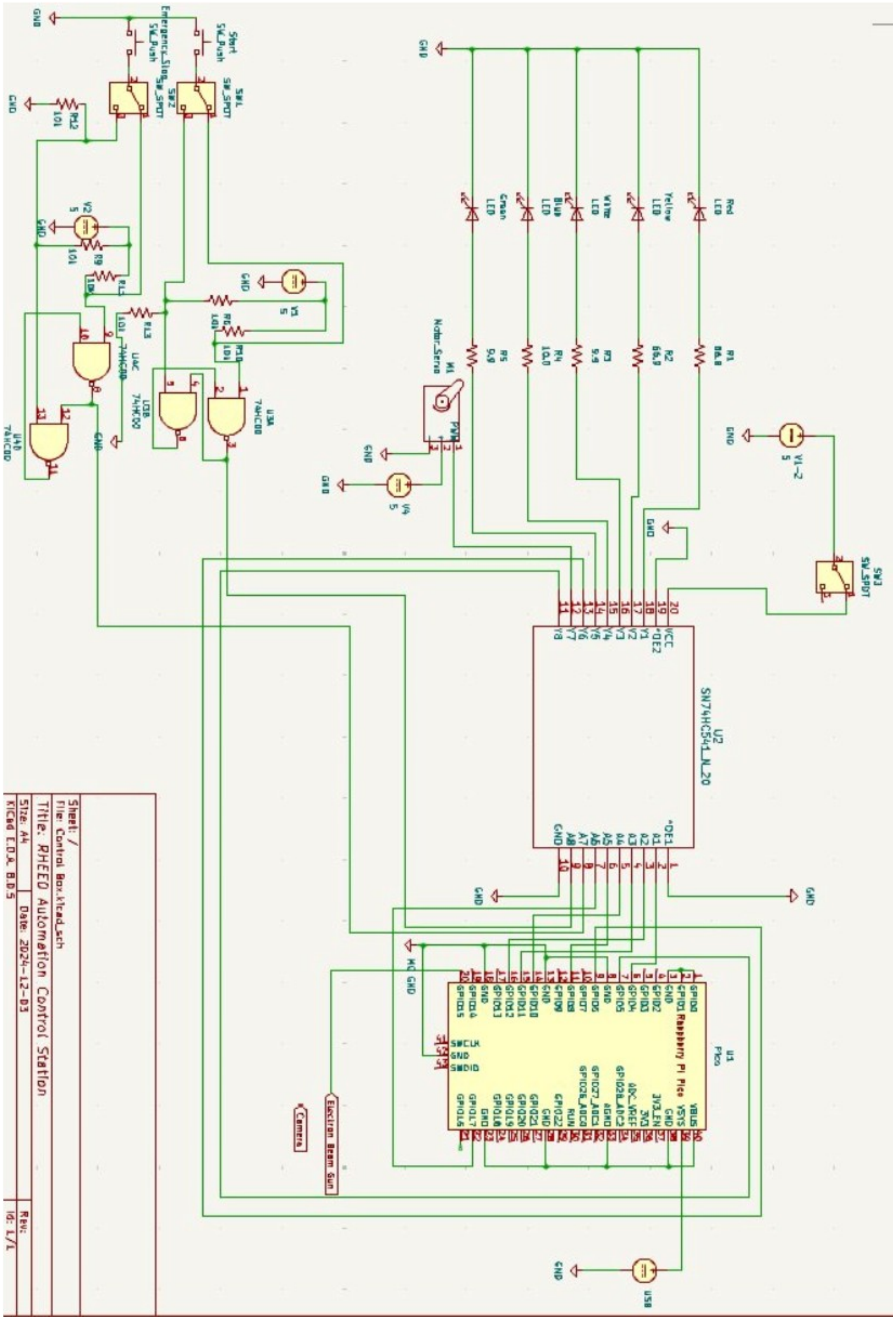

Figure 5. *Schematic for the final circuitry the physical design can be found in Figure 6* [2]

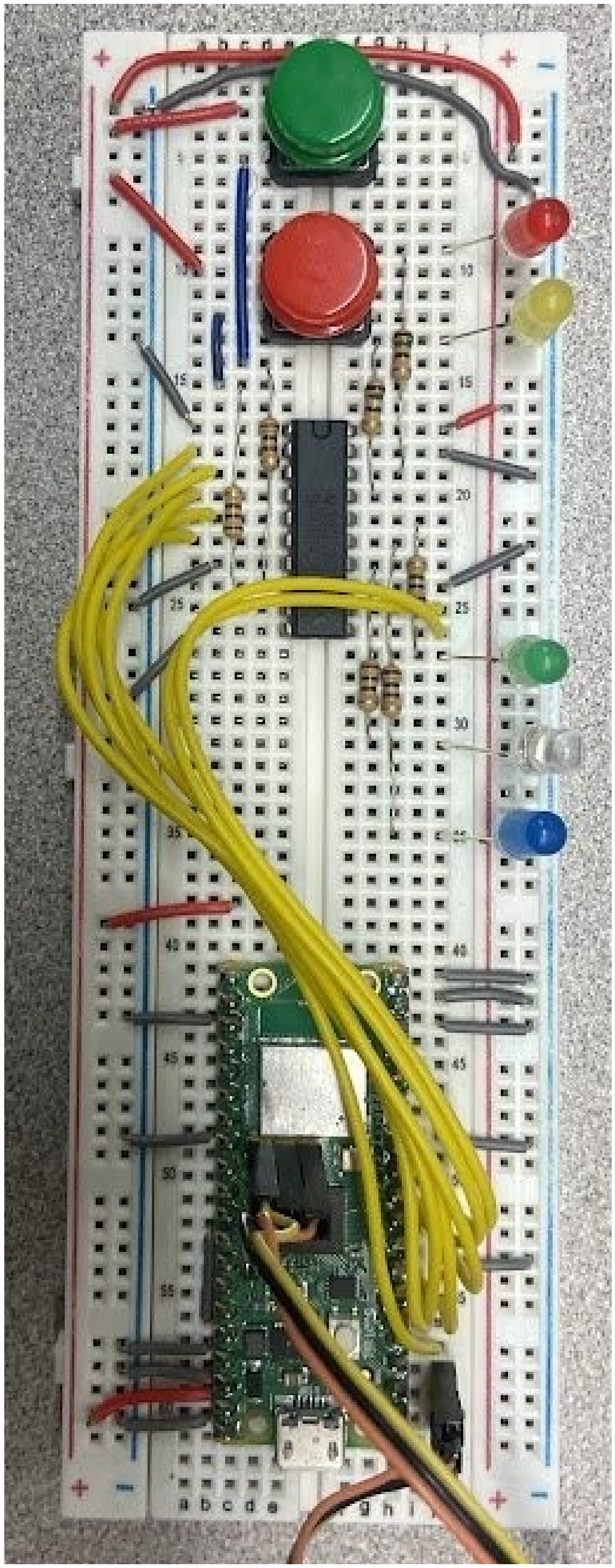

Figure 6. *Final circuitry based on Figure 5- excess wires are removed to see the design more clearly*

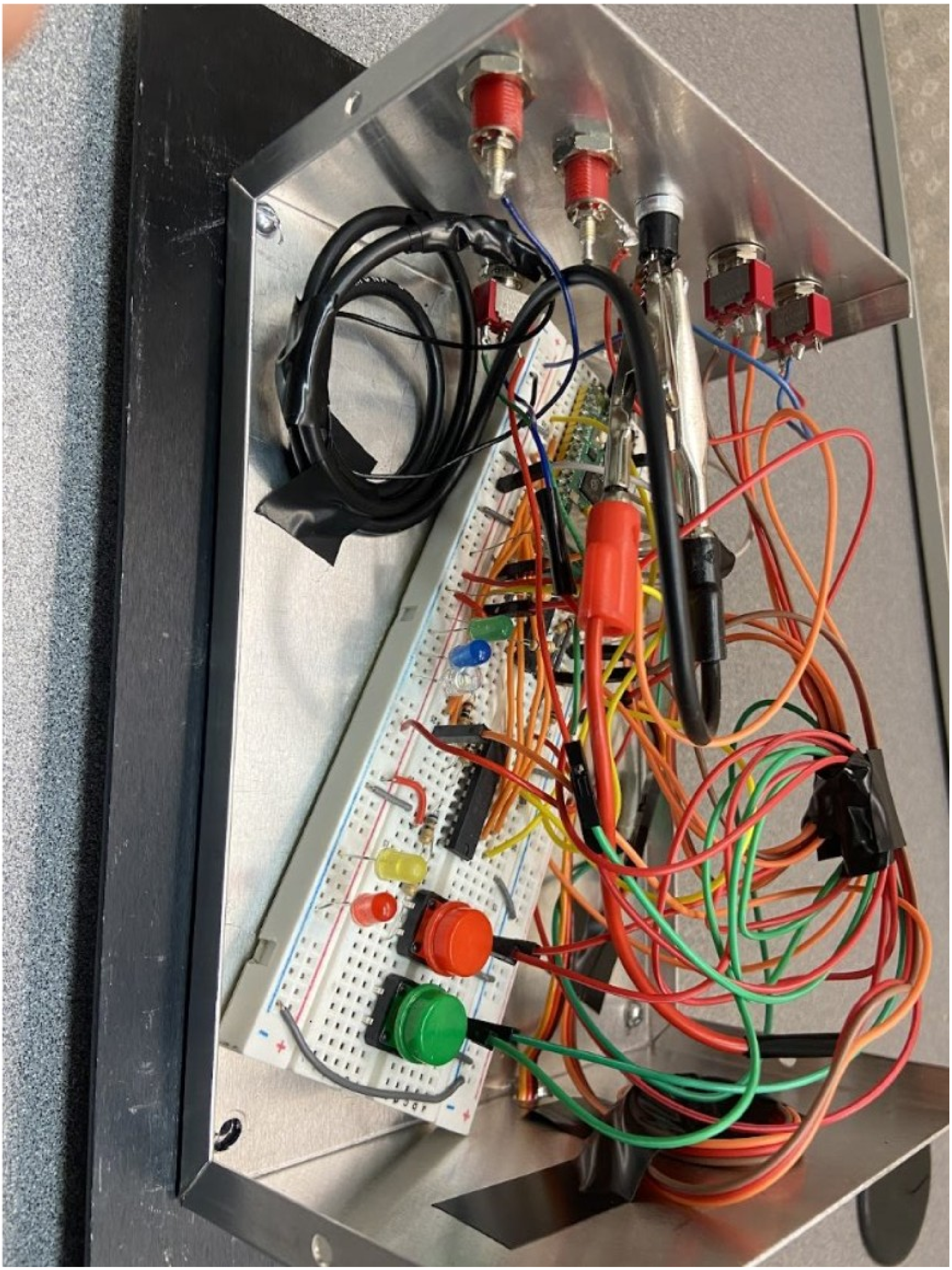

Figure 7. *Inside the final control box design- covering is removed for visual purposes*

Figure 8. *Front view of the final control box design with the covering on*

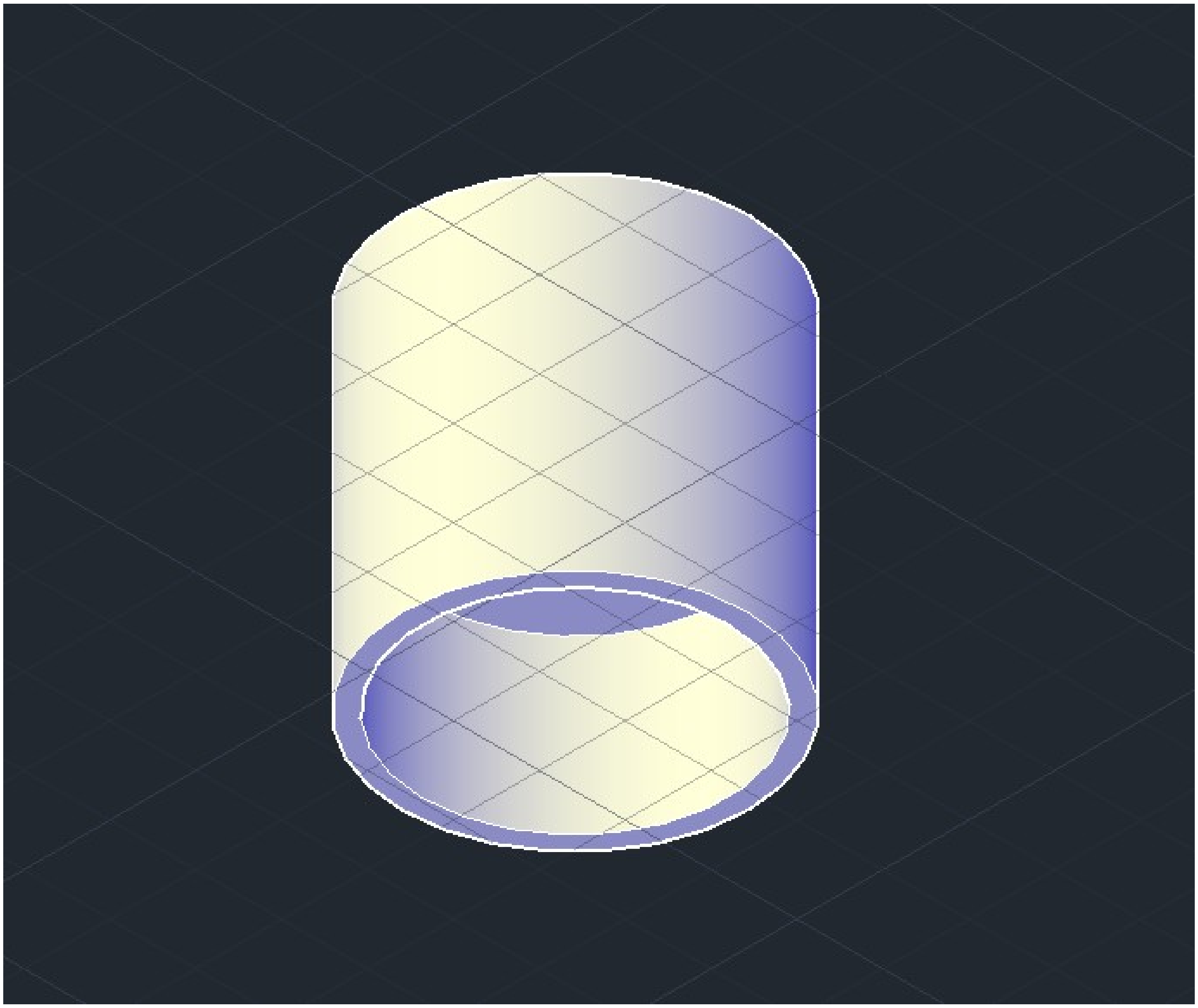

Figure 9. *3D design of the motor-to-knob connector*

Table 4. *Parameter table for the 3D printed piece seen in Figure 9*

Component	Measurement (in)	Measurement (mm)
Height	2	50.8
Inner Diameter	1.77	44.958
Outer Diameter	2	50.8
Depth of Hollow Region	1	25.4
Total Connection Height	2.105	53.467
Minimum Screw Length	0.138	3.5

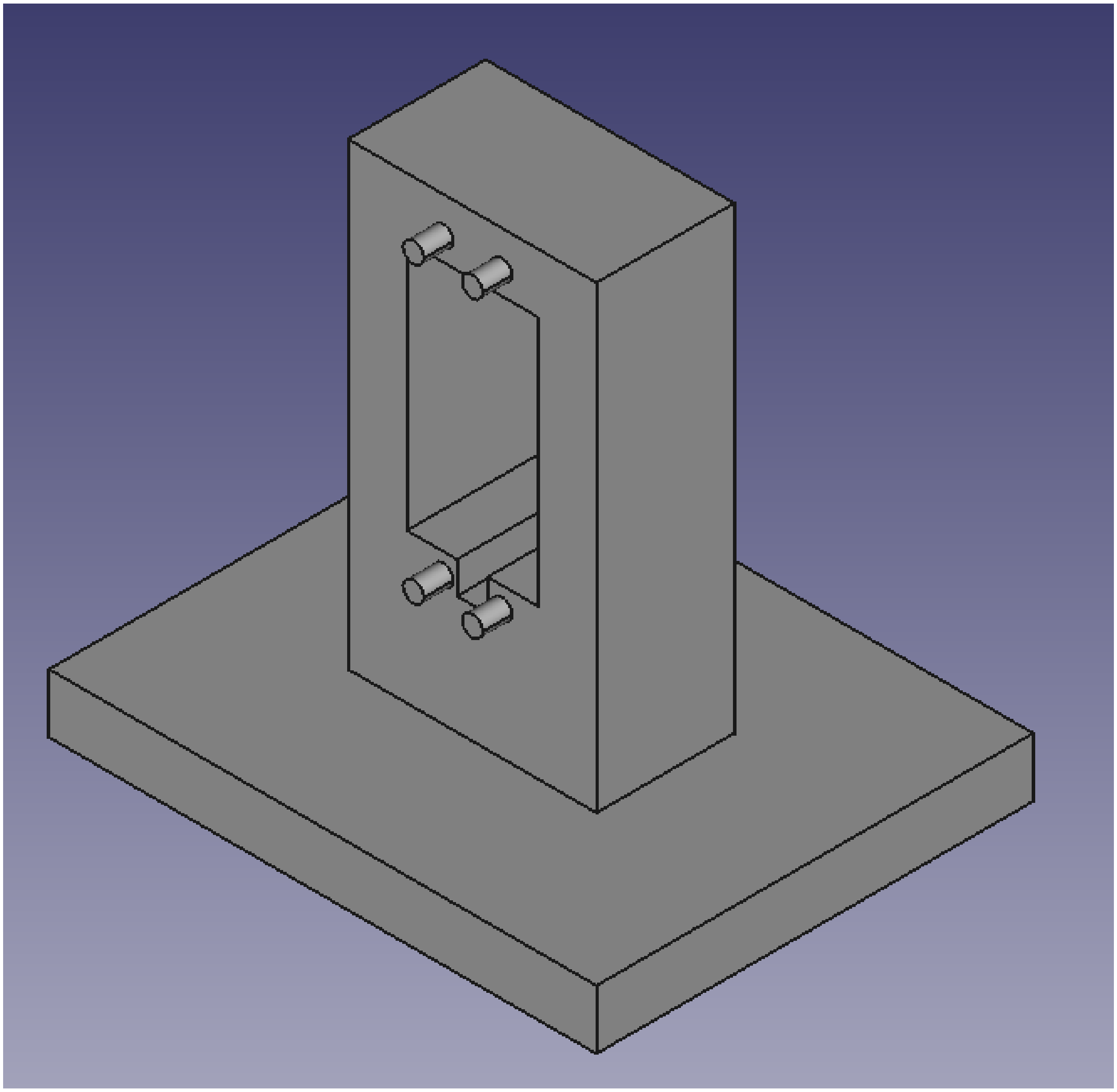

Figure 10. *3D design of the servo motor mount*

Table 5. *Parameters for the 3Dprinted piece seen in Figure 10*

COMPONENT	MEASUREMENT (in)	MEASUREMENT (mm)
Base Length	3.66	93.00
Base Width	2.92	74.20
Base Height	0.39	10.00
Central Column Length	1.66	42.20
Central Column Width	0.92	23.40
Central Column Height (above base)	3.07	77.90
Column Slot Length	0.87	22.20
Column Slot Width	0.92	23.40
Column Slot Height	1.67	42.50
Slot Distance from Top	0.39	10.00
Slot Distance from Base	1.00	25.40
Slot Distance from Sides	0.39	10.00
Slot Divot Length	0.20	5.20
Slot Divot Width	0.92	23.40
Slot Divot Height	0.21	5.40
Slot Divot Distance from Sides	0.73	18.50
Servo Peg Diameter	0.14	3.48
Servo Peg Length	0.20	5.00
Servo Peg Center Distance (1-2), (3-4)	0.39	10.00
Servo Peg Center Distance (1-3), (2-4)	1.96	49.85
Servo Peg Center Distance from Sides	0.63	16.10
Servo Peg Center Distance from Top (1-2)	0.24	6.11
Servo Peg Center Distance from Base (3-4)	0.86	21.94


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Figure 11. *Full system assembly once mounted to the vacuum chamber in lab B113 in Floyd Hall*