ECE 445

Polynomial Texture Mapping Dome

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Team 22

Abstract

This project presents the restoration and redesign of a Polynomial Texture Mapping (PTM) dome system used by the Spurlock Museum to digitally preserve cultural artifacts. The system captures 32 photographs of an object, each illuminated from a unique direction, enabling surface detail analysis. We developed a custom PCB for LED control, integrated camera synchronization, a user-friendly GUI, and a robust 3D-printed enclosure. The final system operates reliably in both manual and automatic modes and includes repair documentation to support long-term use.

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1. Introduction

1.1 Problem

The Spurlock Museum uses a PTM dome to digitally capture surface textures of fragile artifacts through directional lighting. However, their previous dome system had become non-functional due to obsolete components, unreliable LED behavior, and compatibility issues with modern computers. The museum required a robust replacement system that was easy to operate, maintain, and repair without requiring technical expertise.

1.2 Solution

Our team developed a fully functional PTM dome control system with three major components: a custom LED control PCB, a cross-platform graphical user interface, and a modular hardware enclosure. The PCB controls 32 high-powered LEDs and opto-isolates the camera trigger signal for synchronized image capture. The GUI allows for both automatic and manual lighting control. Custom LED units and a heat-resistant, labeled enclosure were designed to simplify future repairs and replacements. The system is reliable, easy to use, and ready for long-term use in the museum environment.

1.3 High Level Requirements

- **Precise LED Sequencing and Control:** The system must be able to turn each of the 32 LEDs on and off in a controlled sequence, both manually and automatically. Each LED should maintain stable illumination without flickering or unintended activation of adjacent LEDs. Also, the user must be able to select and activate individual LEDs on command through the user interface in a separate mode of operation.
- **Accurate Camera Shutter Synchronization:** The camera must be triggered within 50ms of an LED turning on to ensure accurate image capture. The triggering. mechanism (a 3.5mm jack signal sent to the N3 port) must be stable and repeatable, ensuring that the camera does not miss or misfire during the sequencing process. This will require isolating the signal sent to the camera, and properly shielding the attached cable.
- **Long-Term Reliability and Stability:** The system must complete multiple full PTM capture cycles (a cycle includes activating all 32 LEDs and capturing corresponding images) without system crashes or desynchronization. The hardware (microcontroller, PCB, LED drivers) should maintain consistent performance without overheating or signal degradation. The system must function across multiple operating systems and remain compatible for at least a few years with minimal maintenance, ensuring long-term usability for museum staff.

1.4 Block Diagram

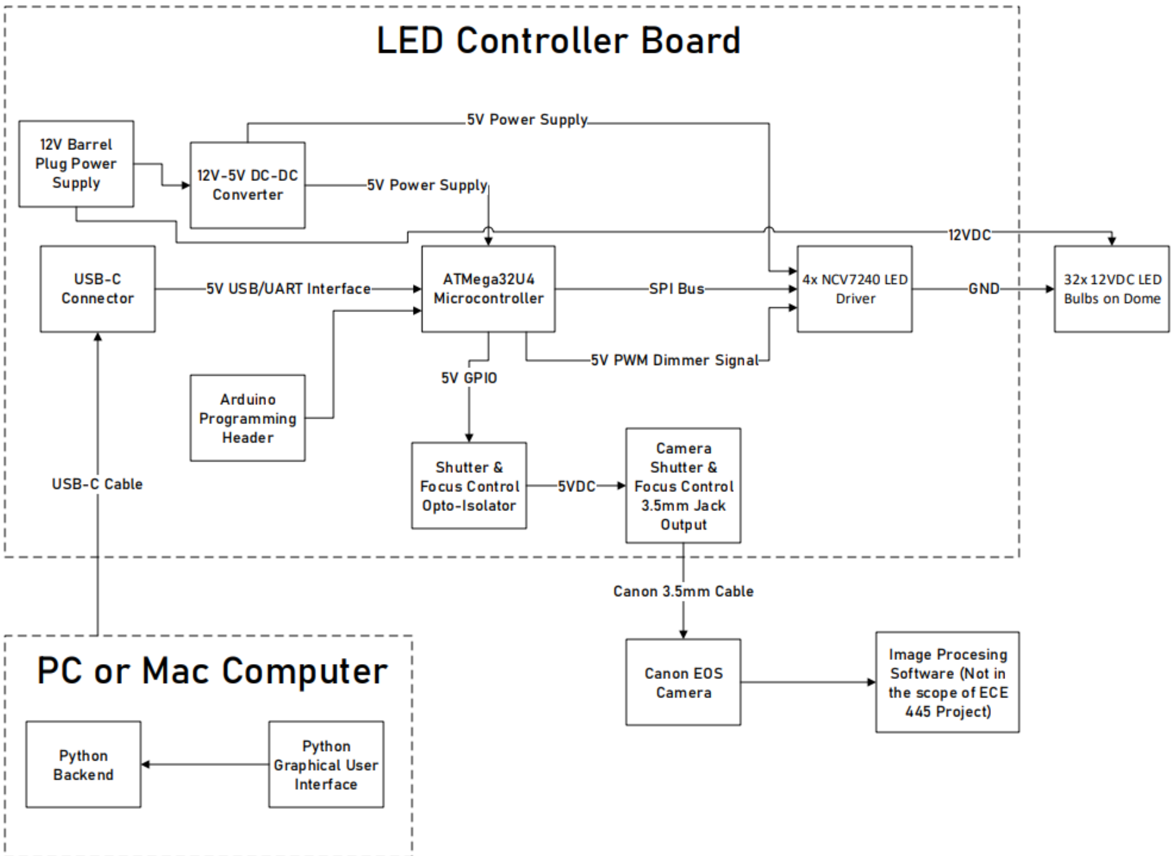

Figure 1 - PTM Dome Block Diagram

2 Design

2.1 LEDs and Wiring

The PTM dome's lighting system consists of 32 high-intensity 12V LED bulbs arranged hemispherically to illuminate an artifact from distinct angles. These bulbs were selected after it was found that the previously installed LEDs contained internal control circuitry that conflicted with our LED drivers. The selected "dumb" LEDs have no built-in regulation, allowing for direct control by our driver chips and ensuring consistent behavior under both manual and automatic operation.

To make the system modular and serviceable, each LED was installed using a custom 3D-printed retainer ring. These rings were tailored to fit the dome's geometry. The electrical connections for each bulb use standard quick-disconnect connectors with the female connector soldered to the dome wire and the male connector soldered to an LED. This allows LEDs to be replaced without tools, soldering, or adhesives. This was a major improvement in usability and maintainability, and the museum has been provided with several pre-assembled spare LEDs.

Wiring from each LED is routed internally and bundled into four groups of eight, corresponding to the four NCV7240 driver ICs on the PCB. Each group is routed to the controller via a keyed 8-pin connector to ensure reliable and error-free wiring during assembly. Cables are labeled with printed tags at both ends to assist with troubleshooting and documentation, and all groups are zip-tied neatly to avoid strain and accidental unplugging.

Finally, each socketed LED unit is removable, and wiring can be serviced without needing to disassemble the dome itself. This modularity was a core design consideration which enables the museum to service the system with minimal technical expertise while preserving the functionality necessary for artifact imaging.

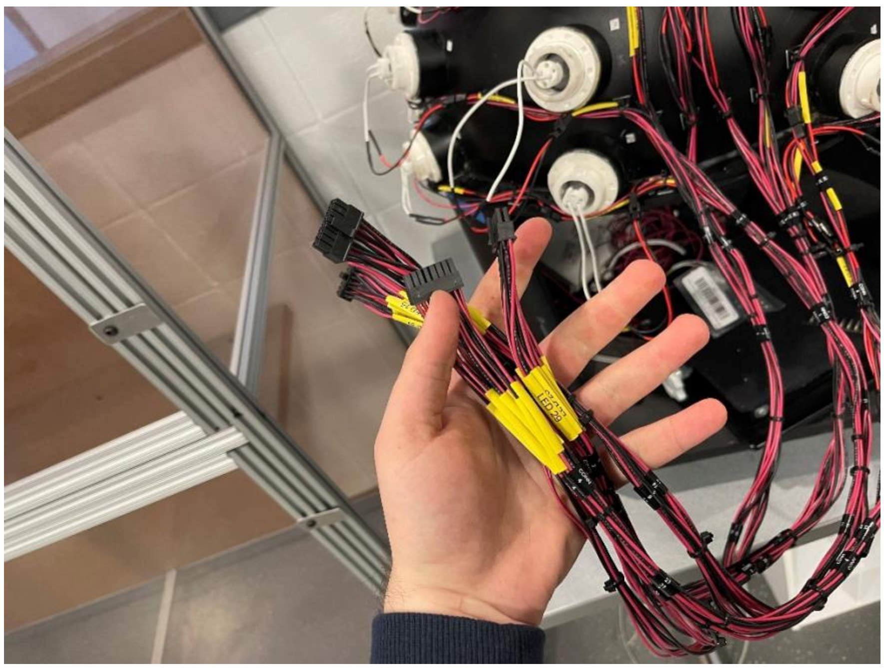

Figure 2 - LED Connectors on PTM Dome

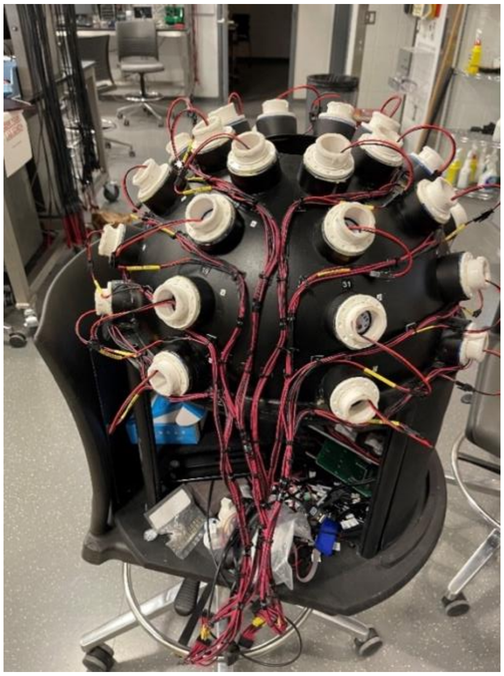

Figure 3 - Completed Wiring on PTM Dome

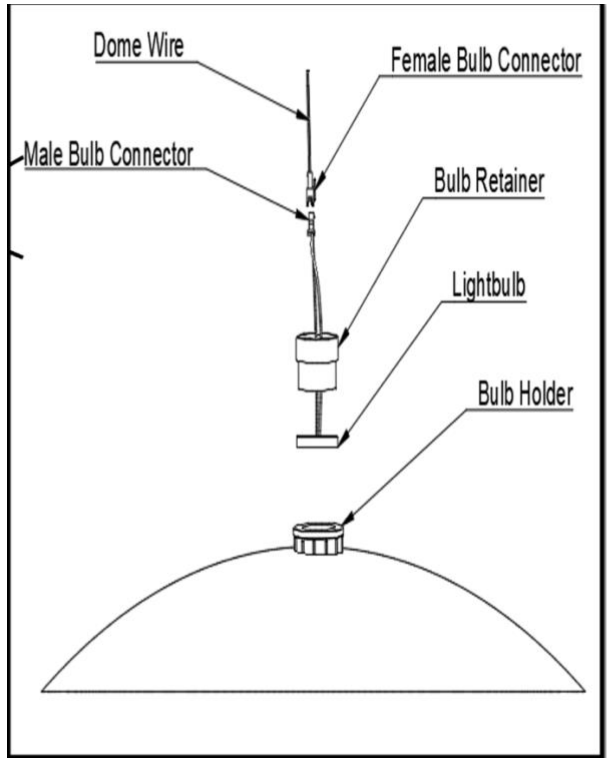

Figure 4 – Structure of a LED unit

2.2 PCB Design

Our PCB was designed by TA Zhongmin, with input from both us and the Spurlock museum staff. Our PCB has two major revisions. The first revision (the prototype) had floating pins on the anode of the input diode on the optoisolators, and used a smaller power jack. To have this board function, we soldered wires from the barrel jack to a larger barrel jack with leads, and scraped the surface of the PCB to expose a ground plane so we could solder zero-ohm resistors from the anode of the input diode on the optoisolators to the ground plane. The final version of the board included the larger barrel jack with the same package type and included internal connections from the anode of the input of the optoisolators to ground (removing the need for those zero-ohm resistors). An image of the dimensions of the board in millimeters is shown in Figure 5, with the connections shown in Figure 6 and Figure 7. Test points on the board, which were added at the request of our team for longevity and repairability, are shown in Figure 8. Finally, each of the integrated circuits on the board are shown in Figure 9 (excluding any simple components like resistors, capacitors, buttons, or connectors).

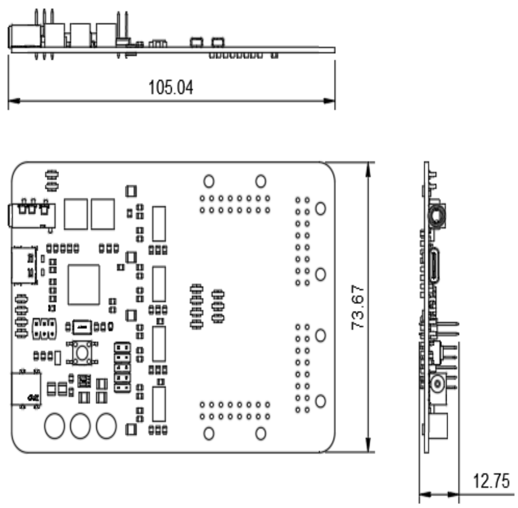

Figure 5- PCB Dimensions

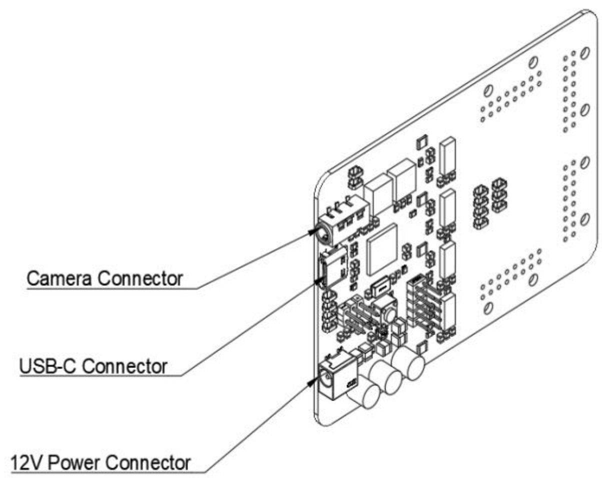

Figure 6 - Interface Connectors

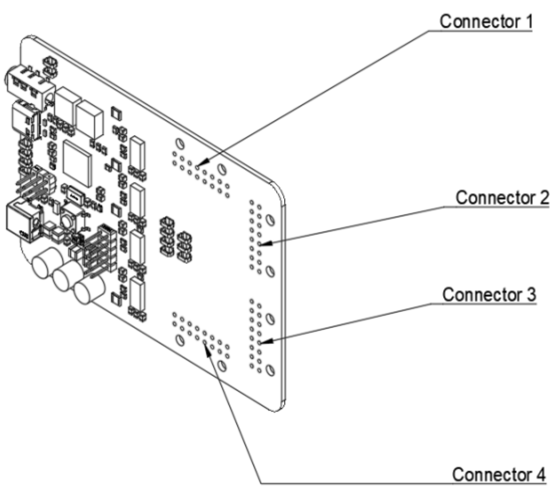

Figure 7 - LED Connectors

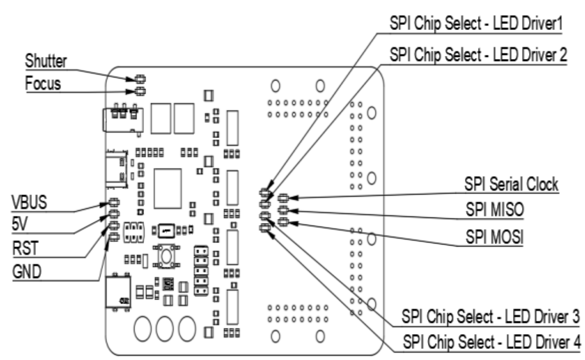

Figure 8 - Test Points

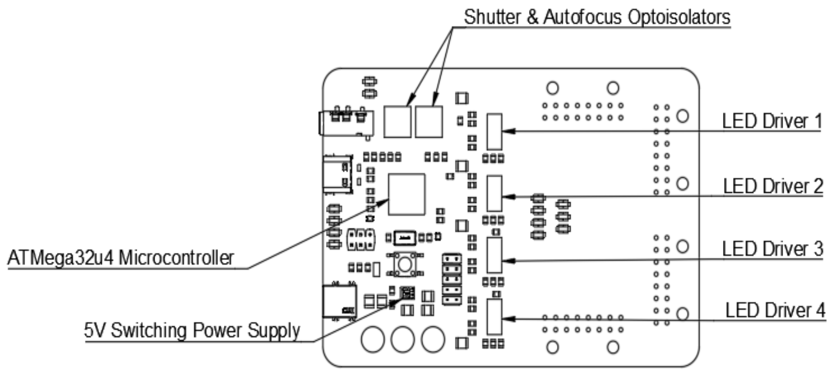

Figure 9 - Integrated Circuits

Below, we will discuss each of the individual components on the PCB and their connections to other components on the PCB.

2.2.1 Microcontroller

The microcontroller we used for this project is an ATMega32U4, which is a low-power, high-performance 8-bit controller with several GPIO pins and a built-in SPI and serial interface. The primary inputs to the microcontroller are the serial lines from the USB-C connector (D+ and D-), the reset pin (RESET), and the MISO (master-input slave-output) signal which is generated in parallel from the four drivers. The primary outputs from the microcontroller are the SPI chip-select signals to each of the four drivers (SPI_CS_1-4, active low), the SPI MOSI (master-output slave-input, SPI_MOSI), the focus signal (active low, MCU_FOCUS), the shutter signal (active low, MCU_SHUTTER), and the four LED PWM outputs (LED_PWM_1-4, unused in our final implementation). The shutter and focus signals are fed into optoisolators to protect the GPIO pins on the ATMega32U4 and reduce noise from the load on the camera pins. Information about the SPI signals is provided in more detail in the LED Drivers subsection of this document. There were also six user-defined signals for debug purposes, PD0-PD3, PD6 & PD7, which we did not use outside of test programs for the Arduino software. An image of the microcontroller schematic is shown in Figure 10.

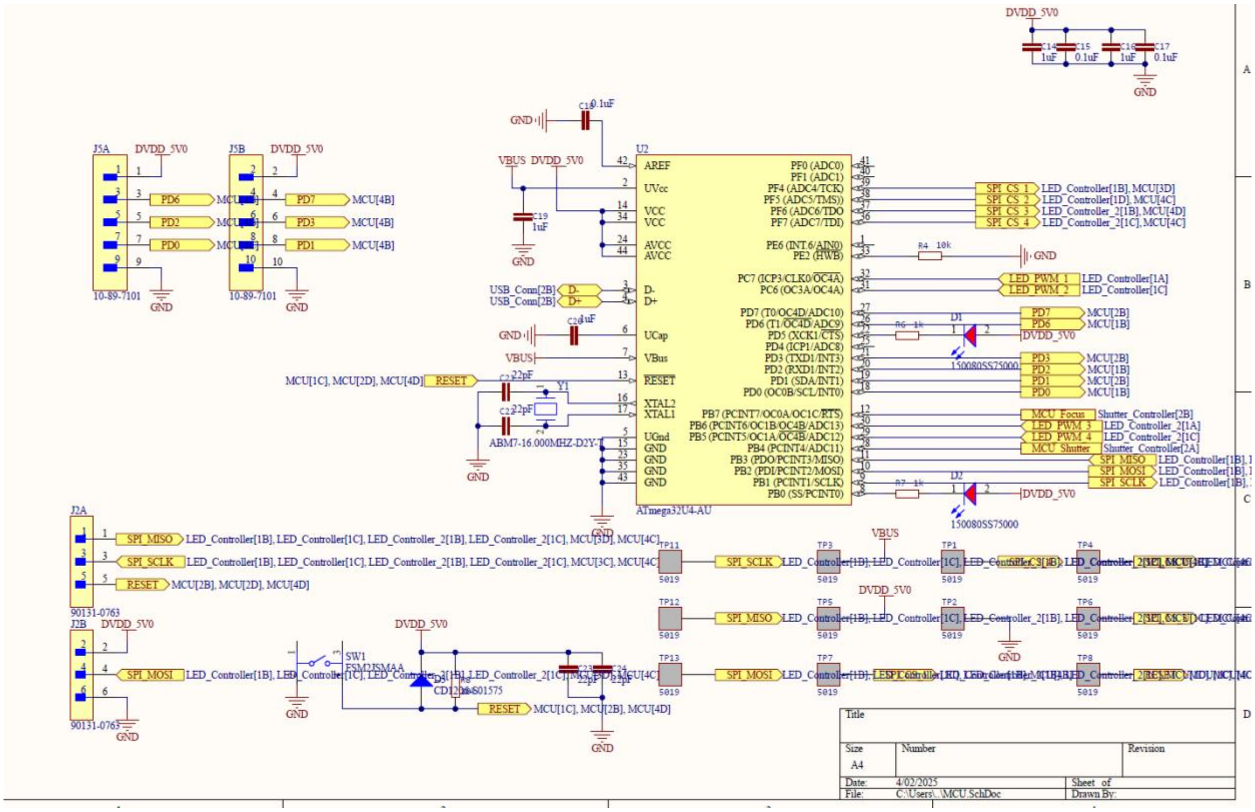

Figure 10 - Microcontroller Schematic

2.2.2LED Drivers

The LED drivers that we used were a set of four octal low-side relay drivers with SPI control and PWM inputs. The microcontroller sent instructions to the LED drivers via an SPI interface, with one chip select pin for each driver and parallel MOSI, MISO, and SCLK lines. Each driver input, output, and power signal had an associated capacitor bank to reduce noise from the internal circuitry of the driver and the power supply. PWM controls were not used for the purpose of our project, since they were not requested by the Spurlock staff. The circuitry was included because it was low-cost in terms of routing on the PCB (all LEDs on a driver are set using a single PWM signal) and would work in the eventuality of overly bright LEDs (that would overexpose the image) to reduce LED brightness by a fixed amount (e.g. 50%). We did not require the PWM controls since our LEDs were the proper brightness for PTM imaging.

The LED drivers have four possible modes—OFF (driver pin is off but uses a small quiescent current to check diagnostics), GLOBAL STANDBY (driver pin is off, with no diagnostics), INPUT (using the PWM input pins), and ON (driver pin is on with diagnostic current enabled). The input signal is a set of 16 bits sent over SPI, two bits for each LED, with the following codes: 00 is global standby, 01 is input, 10 is on, and 11 is off. For the self-test mode, the LEDs use the OFF and ON settings to test diagnostics for whether the pin has an open circuit fault (01 in the output results), a closed circuit fault (10 in the output results), or overtemperature/overload (11 in the output results) [2]. Errors are returned from the Arduino microcontroller and converted into relevant error messages in the Python GUI—e.g. “Open fault on LED

X." On the other hand, both the automatic and manual modes use the GLOBAL STANDBY and ON modes, since we don't want any current leaking to the LEDs during normal operation. This leakage current caused all the LEDs to light up slightly on the dome (at a much lower brightness than ON mode), which would ruin the PTM photography which relies on a high and consistent directionality to the light source in each of the 32 images. In addition, we disabled diagnostic current for normal operation to reduce power consumption in idle mode. Since the serial polling operation on the ATMega32U4 is a blocking instruction, the ATMega32U4 goes into IDLE mode when no data is sent over the serial connection. Then, the only components drawing power are the drivers drawing quiescent power (40uA per driver, 200uA or 2.4mW total) [2] and the idle power from the microcontroller (6mA at 5V, or 30mW) [3]. Total, our system draws less than 50mW power from the wall when left plugged in for an extended period of time. On the other hand, the microcontroller draws 27mA at 5V or 135mW when active. On the other hand, we measured the LEDs drawing ~80mA of power each on the 12V line, or ~1W of power per active LED. Then each LED draws roughly 20 times the amount of power that the system draws at IDLE, or 7 times the amount of power the rest of the system draws when active. The LEDs comprise the vast majority of power usage on the PCB, which makes the driver traces to the MOLEX connector the most susceptible to overload and overheating. An image of the drivers, MOLEX connectors, and associated capacitor banks is shown in Figure 11.

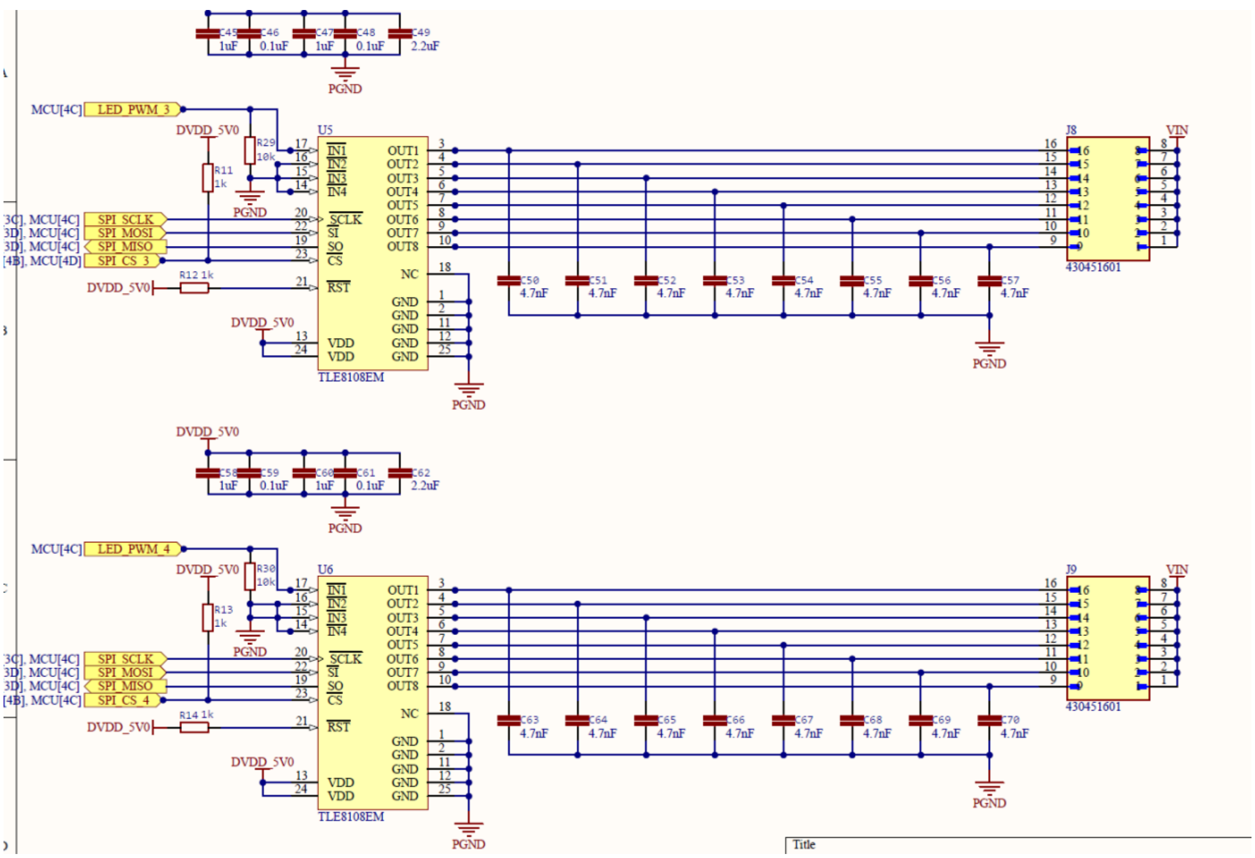

Figure 11 - LED Driver Schematic

2.2.3 Power Supply

Our power supply is an external wall-powered 12V supply at 3A, although any 12V power supply above 1.5A and below 5A can be used safely at the maximum number of LEDs (16). This power supply is connected to the barrel jack on the PCB, which can handle up to 5A, shown at the bottom left of Figure 12 [4]. This 12V power is fed directly to one end of the MOLEX connectors to form a circuit with the low-side relay drivers, and is also fed into a 12V-5V DC-DC converter, shown at the top of Figure 12 [5]. The input and output of the power supply have capacitor banks to reduce noise from the input 12V power and the internal circuitry of the DC-DC power converter. There are also further protection mechanisms, such as a separate set of capacitors between the 12V and ground (on the bottom right of Figure 12), and a set of 0 Ohm resistors between the relay drivers' ground (PGND) and the other common ground (GND, shown at the bottom center of Figure 12).

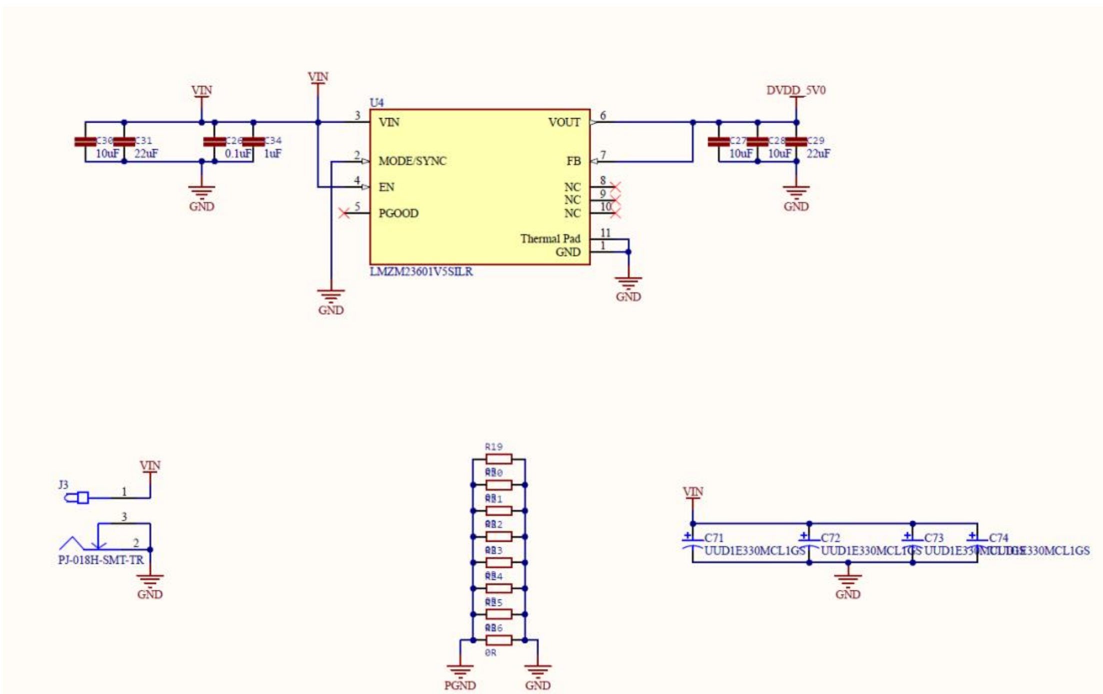

Figure 12- Power Supply Schematic

2.3 Software & GUI

The software for this project was written in two components-- (1) the graphical user interface on the target laptop, which was written in Python using several standard libraries, and (2) the microcontroller software written in the Arduino IDE, using the default Arduino Leonardo bootloader.

The graphical user interface was written in Python using the following standard libraries: **tkinter** for the GUI windows, **threading** to set up listening and sending threads from the GUI to the PCB microcontroller, and **sys** to safely exit python windows. It also included the **pyserial** module, which needs to be installed on the machine using **pip** or a similar Python package installer, and allows for simple serial communication over USB-C. Figure 12 shows the flowchart for the Python GUI, and the full code is attached on the course website.

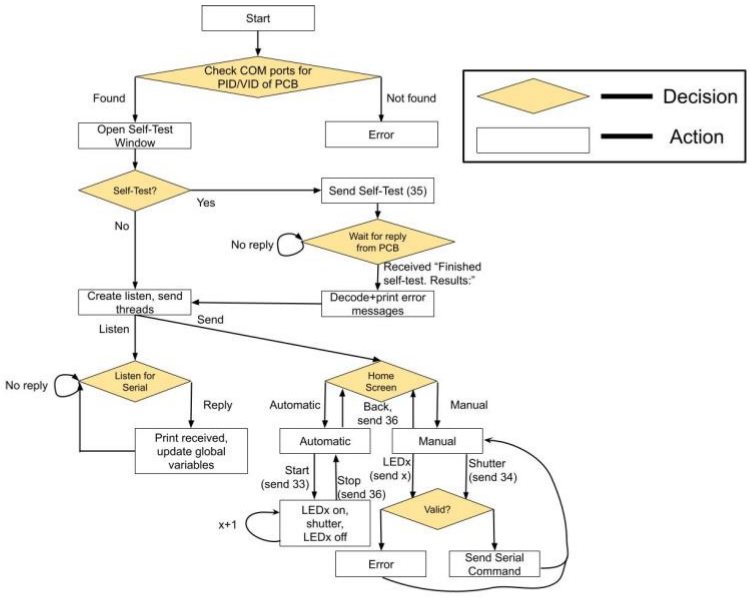

Figure 13: Python GUI flowchart. Arrows from decisions are labeled with the relevant received button commands from the GUI or replies from the PCB.

There are three primary functions of the GUI: the self-test, the automatic mode, and the manual mode. On the self-test window, the user can decide whether or not to initiate a self-test, which turns on and then off each LED in quick succession. The automatic mode allows the user to start or stop a run of 32 images, one for each associated LED, for use in PTM photography. On the other hand, the manual mode allows the user to select up to 16 LEDs and up to four LEDs per driver, turning any LEDs on or off at will using a toggle. Manual mode also allows the user to manually trigger the shutter from the GUI.

The Python GUI is run on a laptop or desktop that is connected to the PCB via an onboard USB-C connector. The PCB is running its own software from the Arduino-capable ATMega32U4 microcontroller. Code was written in the Arduino IDE using a modified form of C code with included libraries such as the SPI library, Serial commands, and commands for setting the modes and logic levels of GPIO pins. We used the bootloader from the Arduino Leonardo, which is a development board including an ATMega32U4 microcontroller. Comparing the pinouts, none of the pins needed to be changed or remapped from their default values, and the bootloader included microcode for updating the TX/RX LEDs on our PCB [6]. The flowchart for the Arduino software is shown in Figure 14, with the **setup()** (code that runs after the bootloader) and **loop()** (code that runs repeatedly after setup) constructors that are included in the Arduino IDE labelled. Codes 1-32 represent toggling the relevant LED, with an error message thrown if too many LEDs are on already. Code 33 represents automatic imaging, 34 represents manually triggering the shutter, 35 is for running the self-test once, and 36 is for resetting all LEDs. The full Arduino IDE code is attached on the course website.

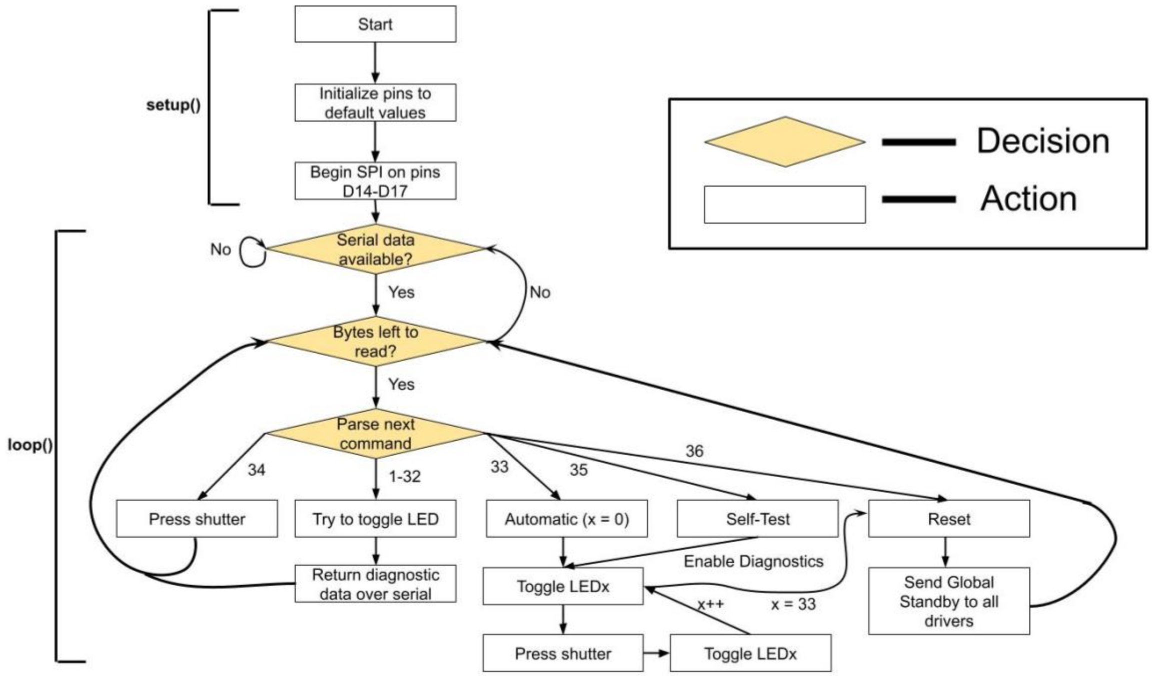

Figure 14: Arduino code flowchart. Arrows from decisions are labeled either from the relevant Boolean value or the command number received from the Python GUI via serial connection.

2.4 Longevity & Repairability

A major goal of our design was to ensure that the PTM dome system would remain functional and serviceable over time, even by users without deep technical expertise. To that end, we incorporated several key features and strategies to support long-term reliability and ease of repair. All mechanical components including fasteners, connectors, and mounts were selected based on availability, durability, and adherence to common industry standards. For example, we used standard M3 machine screws and heat-set inserts to secure the enclosure. This allows users to open and service the enclosure repeatedly without damaging the threads. Likewise, our use of quick-disconnect crimp terminals for LEDs enables simple, solderless replacement of individual units.

All connectors are keyed and labeled clearly, both in hardware and on the GUI, to prevent wiring errors. The PCB includes exposed test points for all major signals which allows for easy debugging with a multimeter or oscilloscope. We also made a full User Manual and Repair Manual, which walk through system setup, operation, troubleshooting, and component replacement. These documents are designed to make the system accessible to Spurlock Museum staff without requiring engineering knowledge. Finally, we also provided a full set of pre-assembled spare parts (including LED units, extra connectors, and fuses) to ensure that the museum has the resources on hand to keep the dome operational for many years.

This emphasis on modularity, documentation, and standardized components aligns directly with our project goals and ethical responsibilities: the dome system is not just functional but built to last and be independently serviceable by Spurlock Museum.

2.5 Control Enclosure

The control enclosure is a custom 3D-printed case designed in Fusion 360 to house and protect the PTM dome's main PCB. Its internal layout is tailored precisely to the shape, mounting hole pattern, and connector layout of the board, minimizing wasted space while providing secure mechanical support and accessibility. The enclosure consists of a lid and a base, both printed in high-infill PLA for strength and rigidity. Although PETG was preferred for its improved thermal and impact resistance, it was not available on the lab printers. The base features integrated cylindrical standoffs that allow the PCB to be secured using standard M3 screws. This isolates it from movement and reduces the risk of connector fatigue or trace cracking during transport or operation.

Each external interface is routed to a clearly labeled cutout on the enclosure. These cutouts are not only dimensioned for a snug fit but also engraved directly on the surface of the print. This labeling makes it easy for non-technical users to identify connection points quickly, reducing the risk of incorrect wiring. The lid and base of the enclosure include ventilation slots to promote airflow and reduce internal heat buildup during extended use, especially when the system runs continuously through all 32 LEDs.

The enclosure is mounted on the dome base using a custom-designed bracket. This bracket lifts the enclosure 4 inches off the surface of the wooden base, providing vertical clearance and cable routing space while also protecting the case from accidental impact. The bracket is secured to the base of the dome using L-brackets and wood screws, allowing it to be detached easily if maintenance is required. All components are held together using standard M3 fasteners and heat-set inserts, ensuring the enclosure can be opened and closed repeatedly without damaging the threads.

Figure 15: CAD Drawings of the Enclosure

3. Design Verification

When the LEDs were in the ON state from the GUI, we identified a voltage on the MOLEX output pin of 12V, while when the LEDs were in the GLOBAL STANDBY (off with no diagnostic current) state, we identified a voltage on the MOLEX output pin of 0V. For the OFF state (including a diagnostic current), we identified a lower voltage on the output pin of ~6.6V. These values were all expected, since in regular operation (with no diagnostic current) the LEDs run on 12V power, while in self-test mode (with diagnostic current) the LEDs run on a lower voltage. We performed testing in two stages, first verifying basic operation of the device and then stress-testing the device. Basic operation of the device involved running the automatic mode from the Python GUI and verifying that the camera takes a set of 32 images, with the images taken with a buffer of time between LEDs switching. We also checked to make sure that the automatic mode switched through all 32 LEDs, before stopping. We also tested diagnostics by selecting two LEDs at random from each driver and disconnecting them, to check for an open fault, and then selecting two LEDs at random from each driver and connecting a wire between the pins to simulate a closed fault. We performed this test four times with the final board, selecting different LED pairs each time. With the final board, Python GUI design, and Arduino code, we observed consistent standard operation of the PCB, with all faults reported through the Python GUI console. The reason why we selected random LED pairs rather than testing all sets of LEDs is because there are far too many sets of pairs from each driver to select from (choosing 2 LEDs from each set of 8 for four drivers, $({}_8C_2)^4 =$ 614656).

After testing the standard operation of the device along with error checking, we stress tested the final PCB using the Self-Test program for progressively smaller intervals of time, and by turning on the maximum number of LEDs for a long period of time. Switching the LEDs quickly would be affected by the volatility of the microcontroller's GPIO pins and the speed at which the LEDs themselves can switch. Since our SPI connection was set to 1MHz, the theoretical maximum transfer speed is 62.5 kips or 16ns per instruction, since each SPI instruction is 16 bits [2]. This would be well below the physical speed at which the LEDs could switch, so we set a reasonable lower limit of 50ms per LED switch which is near the limit of smooth switching per the human eye (20 switches per second). We started at 500ms per LED switch, lowering it to 200ms per switch, then 100ms per switch, then 50ms per switch, checking the diagnostic information from the LED drivers for faults. We found no faults even when running the self-test at 50ms per switch three times in a row, or 1.6 seconds for each entire run of 32 LEDs. At this speed, the reception of data from the PCB buffer and printing to the console took longer than the run itself. Based on the observation of fast LED switching without closed, open, or overload faults, we believed that our PCB was robust with respect to fast switching and repeated trials. We also stress tested the final PCB by turning on the maximum number of LEDs (16, or four per driver) for 20 minutes, simulating a high sustained load that would potentially increase temperatures on the PCB traces and LED drivers. We then tested with the other set of 16 LEDs to make sure that all LEDs were tested. At the end of these tests, the LED status remained the same (all ON LEDs were on, and all GLOBAL STANDBY LEDs were off). At the end of the tests, the drivers and PCB itself felt warm but not hot, with the inside of the dome being somewhat hot due to the many LEDs shining for an extended period of time. This load was designed to simulate someone leaving the PCB with lights on for a long time, or long-term use of the drivers for several imaging sessions in a row. By our metrics (no failure or dangerously hot temperatures on the PCB), the PCB was a success. The formal requirements and verification table is shown in Appendix A.

4. Costs

4.1 Parts

Table 1 – Parts Cost Table

Component Type	Value/Part Number	Description	Quantity	Unit Price	Extended Price
Board	1uF	Generic 0805 SMD capacitor	13	0.1	1.3
Board	0.1uF	Generic 0805 SMD capacitor	12	0.1	1.2
Board	2.2uF	Generic 0805 SMD capacitor	4	0.1	0.4
Board	4.7nF	Generic 0805 SMD capacitor	32	0.08	2.56
Board	22pF	Generic 0805 SMD capacitor	4	0.04	0.16
Board	10uF	Generic 1210 SMD capacitor	3	0.172	0.516
Board	22uF	Generic 1210 SMD capacitor	2	0.112	0.224
Board	UUD1E330MCL1GS	Aluminum Electrolytic Capacitor, UD Series, Low Impedance, 33 uF, 25 V, + / - 20%, -55 to 105 degC, Chip Type, 6.3 x 5.8 mm D x L, Pb-Free, Reel	4	0.53	2.12
Board	150080SS75000	Led, Red, 630 Nm, 1.9 V, 30 Ma, 60 Mcd Rohs Compliant: Yes	2	0.17	0.34
Board	CD1206-S01575	75 V Small Signal Switching Diode, 150 mA, 2.5 uA, 1026 Molded Package, RoHS, Tape and Reel	1	0.053	0.053
Board	4N26-X009T	Transistor Output Optocoupler, 1-Element, 5300V Isolation	2	0.528	1.056
Board	105450-0101	USB Connector, 24 Contact(s), Female, Right Angle, Surface Mount Terminal, Receptacle	1	2.55	2.55
Board	90131-0763	90131-0763 Conn Unshrouded Header HDR 6 POS 2.54mm Solder ST Top Entry Thru-Hole C-Grid III™ Tray	1	0.5	0.5
Board	54-00165	CONN JACK R/A SMT 5.5X2.5MM	1	0.91	0.91
Board	SJ2-3574A-SMT-TR	AUDIO JACK, 3.5 MM, RT, 4 CONDUC	1	0.87	0.87
Board	10-89-7101	CONN HEADER VERT 10POS 2.54MM	1	0.5	0.5
Board	430451601	CONN HEADER R/A 16POS 3MM	4	3.87	15.48
Board	1k	Generic 0805 SMD Resistor	10	0.1	1
Board	22R	Generic 0805 SMD Resistor	2	0.1	0.2
Board	10k	Generic 0805 SMD Resistor	8	0.1	0.8
Board	220R	Generic 0805 SMD Resistor	2	0.1	0.2

Board	0R	Generic 0805 SMD Resistor	2	0.1	0.2
Board	0R	Generic 1210 SMD Resistor	8	0.1	0.8
Board	CG0603MLC-05E	ESD Protector, 5 V Supply, -40 to 85 degC, 1.6 x 0.8 x 0.55 mm SMD, RoHS, Tape and Reel	2	0.307	0.614
Board	FSM2JSMAA	SWITCH TACTILE SPST-NO 0.05A 24V	1	0.201	0.201
Board	5019	Phosphor Bronze Contact Miniature Silver Plated Surface Mount Test Points	13	0.26	3.38
Board	TLE8108EM	Smart 8 Channel Low Side Relay Driver with SPI Interface with Limitation Over-Current Protection, -40 to 150 degC, PG-SSOP-24-4, Reel, Green	4	3.31	13.24
Board	ATmega32U4-AU	8-bit AVR Microcontroller, 2.7-5.5V, 16MHz, 32KB Flash, 1KB EEPROM, 2.5KB SRAM, USB Controller, 44-pin TQFP, Industrial Grade (-40°C to 85°C), Ext Osc	1	5.29	5.29
Board	LMZM23601V5SILR	DC DC CONVERTER 5V	1	5.17	5.17
Board	ABM7-16.000MHZ-D2Y-T	Crystal 16MHz ±20ppm 18pF SMD-2 6mm x 3.5mm	1	0.66	0.66
Dome	Wire	Dome Wiring -1 ft	100	0	0
Dome	430251600	CONN RCPT HSG 16POS 3.00MM	4	1.05	4.2
Dome	430300051	Molex Female Micro-Fit 3.0 ™ Crimp Terminals Pins Wire Diameter: 20-24awg, 1.85 mm	64	0.141	9.024
Bulb	B09N3PC1RR	G4 Bi Pin Base 10W 15W Halogen Replacement Bulb 24-2835SMD LED - 3000K Warm White	32	1.16	37.12
Dome/Bulb	4330128506	22 AWG JST SM 2 Pin Plug Male and Female Connector Adapter with 135 mm Electrical Cable Wire for LED Light	32	0.37	11.84
Power Supply	GST60A12-P1M	AC/DC DESKTOP ADAPTER 12V 60W	1	20.61	20.61
Power Supply Cable	AC30UNA	CORD NEMA5-15P - IEC 320-C13 6'	1	6.36	6.36
			Total		$151.64

4.2 Labor

Labor costs were estimated based on an hourly rate of $40, reflecting the skill level of ECE program graduates. A multiplier of 2.5 was used to account for overhead costs such as benefits and administrative expenses. Each team member contributed approximately 80 hours to the project. At 80 hours per person, the total adjusted labor cost per team member was $3200 x 2.5 = $8,000, resulting in a total estimated labor cost of $24,000. This reflects the time and effort dedicated to system design, prototyping, testing, and documentation.

5. Conclusion

5.1 Accomplishments

Our project successfully delivered a fully functional PTM dome system that meets all core functional and reliability goals. We designed a custom PCB capable of controlling 32 high-power LEDs with precise timing and opto-isolated camera synchronization. A cross-platform Python GUI was developed to offer both manual and automatic imaging modes, and the entire system is housed in a custom 3D-printed enclosure engineered for thermal management, physical protection, and long-term serviceability. The system was tested, and it performed consistently. A complete set of user and repair documentation was also produced. The Spurlock Museum now has a working, maintainable system ready for artifact digitization.

5.2 Uncertainties

Although the final system is functional, there were elements that remain either untested or incomplete due to time/resource limitations. One such area was LED PWM dimming; while the PCB supports PWM output lines, the signals on the first print of the PCB were routed together and did not allow for individual brightness control. The re-printed version of the PCB should, in theory, be able to support LED dimming but we weren't able to test it because it arrived in the last few weeks of the semester. This change would require using the PWM lines as analog outputs form the microcontroller, and adjusting the Python GUI to allow for local dimming control. Additionally, while our project is designed for ease of use, usability testing with museum staff was not completed before submission. Finally, although we printed the control enclosure in PLA, we had originally planned to use PETG for better thermal and impact resistance but were limited by material availability.

5.3 Ethical considerations

In accordance with the IEEE Code of Ethics [1], we ensured the system is safe, enclosed, and user-friendly to minimize electrical and mechanical risks to users. All connectors are clearly labeled, physical access to circuitry is restricted through enclosure design, and comprehensive documentation supports safe, long-term use and maintenance. These considerations align with our ethical obligation to hold paramount the safety, health, and welfare of the public, and to disclose promptly factors that might endanger the public or the environment, as stated in Sections I.1 and I.9 of the IEEE Code of Ethics.

5.4 Future Work

Recommendations for Improvements include separating PWM control lines on the PCB for independent dimming, coating the enclosure in ESD-resistant paint for added static protection, reprinting the enclosure in PETG for better thermal and impact performance, extending GUI functionality to support brightness control, and testing and tuning enclosure thermals under full load for better reliability.

References

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Appendix A Requirement and Verification Table

Table 2 - System Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
1. LED Controller Board		
a. Must maintain stability with up to 8 LEDs on simultaneously.	a. Turn on 8 LEDs simultaneously using PC software and verify that current draw on the 12V circuit does not exceed 80% of the rating of the AC Adapter and the LEDs stay illuminated for at least 1 minute without causing damage or excessive heat.	Y
b. Camera ground must be electrically isolated from system ground	b. Measure resistance between camera ground and PCB ground using a multimeter. Confirm "OL" or resistance greater than 1MΩ.	Y
c. Control 32 12V LED Outputs individually through Arduino software.	c. Test signal sent from PC User Interface enables each LED individually.	Y
d. Connect to PC via USB-C Cable	d. PC can successfully communicate with the MCU firmware via the USB-C cable.	Y
2. User Interface		
a. Manual LED control must function correctly.	a. Use GUI manual mode to turn LEDs on and off individually. Confirm correct operation visually.	Y
b. The system must provide clear visual feedback for LED states and display real-time connection status. It must also display error messages when communication fails	b. UI correctly updates based on microcontroller feedback. Simulate communication failure and verify the correct error message appears	Y
c. The GUI and PCB must not cause any dome motion during operation.	c. The dome does not move during operation. The PCB is attached to the dome base to prevent any movement.	Y
3. LED Lights and Dome		

a. LEDs and sockets must be replaceable without tools.	a. Replace an operational LED and a socket with a provided spare without tools. Confirm system operates normally.	Y
b. Single LED must draw less than 300mA at 12V.	d. Measure current draw for a single LED.	Y – 92mA
4: Longevity and Repairability		
a. A user manual shall be provided which encompasses all aspects of normal device operation.	a. User manual will be provided to a person unfamiliar with the project. They will be able to fully execute all instructions.	Y – Edits with input from Spurlock in progress
b. The system must provide clear visual feedback for LED states and display real-time connection status. It must also display error messages when communication fails	b. The troubleshooting & repair manual will be provided to a person unfamiliar with the project. They will be able to fully execute all instructions.	Y
c. All components shall be assembled using standard fasteners. No glue shall be used in the assembly, except for the dome structure or for any pieces which are not reasonably expected to fail.	c. Disassemble and reassemble the system three times using only screwdrivers. Confirm no mechanical failure or cracks.	Y
d. Spare parts will be provided to ensure system longevity.	d. At least one spare of each replaceable component provided	Y
e. The microcontroller must support embedded Arduino programming for long-term flexibility.	e. ATMega32u4 supports Arduino.	Y
5: Control Enclosure		
a. Enclosure must survive minor impacts.	a. Drop the enclosure from a height of 1 foot onto carpet and inspect for cracks, connector loosening, or cosmetic damage.	Y
b. Connectors must be clearly labeled.	b. Visually inspect the system and verify that all external ports are labeled and	Y

	readable from a normal operating distance.	
c. Components inside the enclosure can be replaced several times without damage to the enclosure	c. Ensure all standoffs are metal.Install/remove control board three times and ensure no wear on the enclosure.	Y
d. Enclosure can be disassembled with a standard screwdriver.	d. Verify all connections are made with standard fasteners.	Y