Polynomial Texture Mapping Dome for Digitally Preserving Our Past

ECE 445 Team 6 Project Proposal

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Introduction

Problem: The Spurlock Museum has been using a Polynomial Texture Mapping dome to digitally preserve artifacts, enabling researchers worldwide to study them remotely without physical handling. This system, originally built in 2008 using technology from 2001, captures high-detail images of artifacts under varying lighting conditions. Specifically, the dome captures 32 images, each associated with lighting one of 32 LEDs. These images are fed into an external image processing software to generate high-quality 3D renders of the object. However, over time, the original dome became non-functional, halting the museum's digital preservation efforts. To address this, two previous ECE 445 teams attempted to restore the system. They successfully rewired the 32 LEDs and developed a partially working GUI for controlling them. Despite these improvements, the PCB, which is necessary for integrating the lighting system with the camera's shutter and ensuring proper sequencing, is still non-functional.

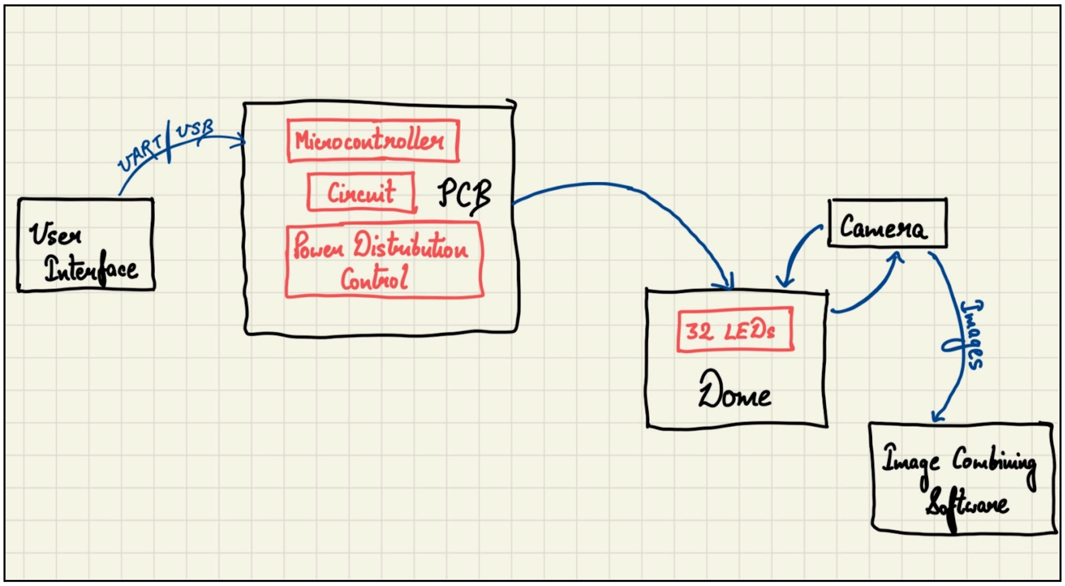
While the foundational work has been completed, the lack of a working control system prevents the system from operating as intended. Additionally, the overall reliability of the dome has not been thoroughly tested, making long-term functionality uncertain. Our project will focus on finalizing the PCB implementation, testing the full system for long-term reliability, and ensuring seamless functionality so the Spurlock Museum can resume its essential digital artifact preservation efforts.

Solution:

This project is rather unique because the solution has mostly been developed previously. Our role is to complete the project to present a functional PTM dome to the museum. This will involve redesigning the PCB to control the 32 LEDs in the existing dome as per the museum's requirements, developing manuals and troubleshooting instructions, and testing the dome to ensure full functionality.

Our PCB will be required to have two modes of operation: (1) individually toggling LEDs for traditional photography of objects within the dome, and (2) taking a sequence of 32 images by controlling the camera shutter and toggling each corresponding LED. The latter mode of operation will require control of the camera shutter through the PCB, as described in our subsystem requirements.

Visual Aid:

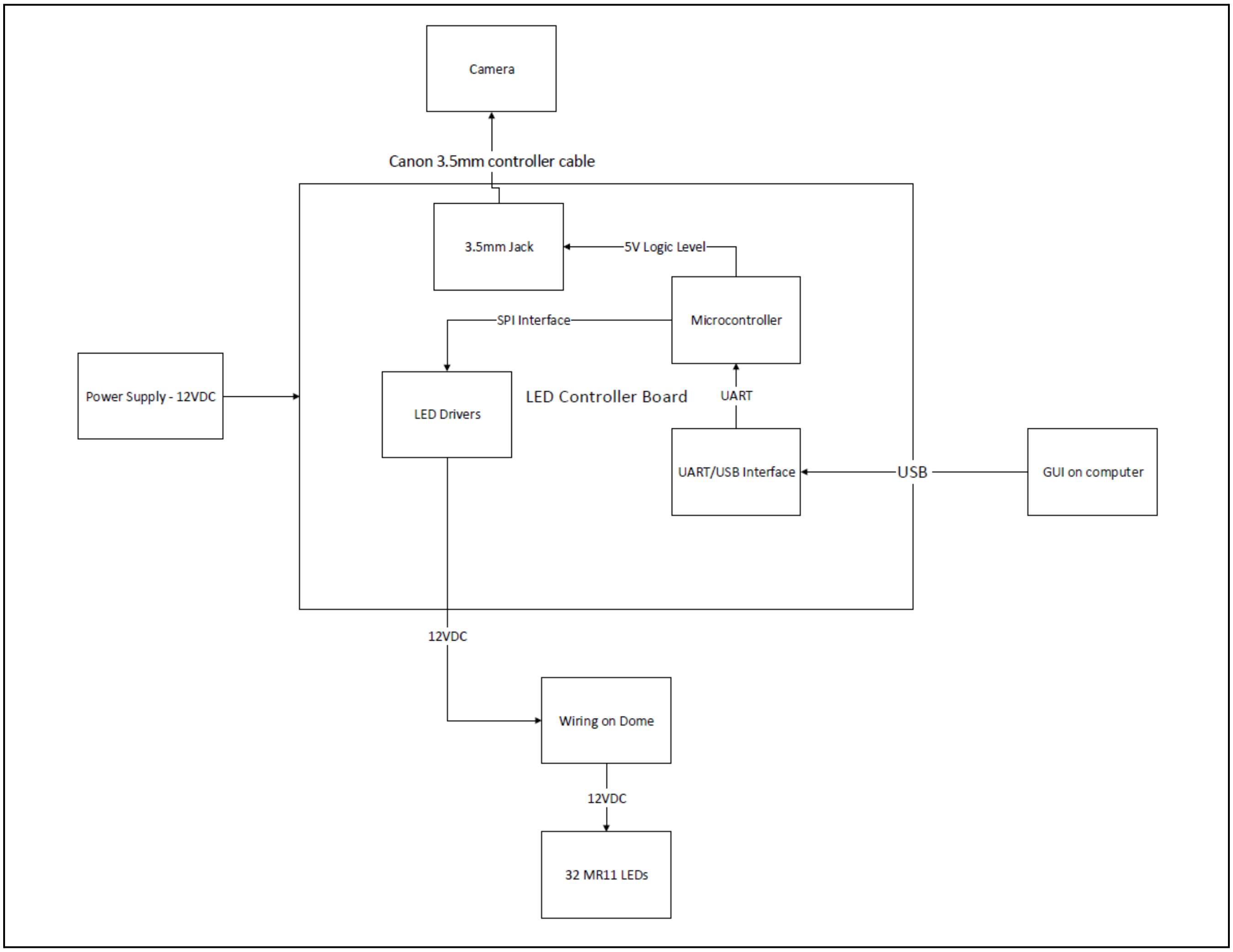


High-level requirements list:

- **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 or automatically, with an accuracy of 1 ms per LED switch. 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 50 ms 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 at least 100 consecutive 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.

Design

Block Diagram:



Subsystem Overview:

Subsystem 1 - LED Controller board

This controller board will have a microcontroller which is capable of controlling 32 12V LEDs individually based on its programming. It will interface with an software-based external controller, and a camera shutter trigger. The timing of the camera shutter and the LEDs should align to ensure proper functionality of photo capture for all 32 images, as well as simultaneous operation of multiple LEDs for traditional photography.

This controller board will build upon the design of past groups. Our intention is to design a new board, but with the assistance of course staff as needed to ensure that we resolve issues encountered in Fall 2024, specifically crosstalk between I/O lines and 12V power.

Subsystem 2 - User Interface
The User Interface subsystem is responsible for providing the graphical user interface (GUI) for the PTM Dome project. We have adopted the GUI from last semester's group which was primarily built using Python's tkinter library. This interface allows users to control the dome's LED lighting system, providing both manual and automatic options for controlling the 32 LEDs options. The UI also displays the connection status of the RTI device which ensures users are informed of the system's current state. It also offers a clear and intuitive layout that makes controlling the LEDs straightforward for museum employees. This approach also prevents motion in the dome during use.

The UI subsystem communicates with Subsystem 1 through serial communication. User commands, such as starting lighting sequences or toggling individual LEDs, are sent from the UI to the microcontroller, which processes these commands and controls the LEDs. The UI also receives real-time feedback from the microcontroller, such as the connection status and the current state of the LEDs, and updates the interface accordingly. The software-based control system offers flexibility, as it can be easily modified if issues arise. This also makes it easier for the museum staff to use, because the system is adaptable. This software-based approach also also reduces the number of components that can fail in the resulting PCB, since there are no longer buttons and associated physical connectors that can wear and degrade. In this control type, the user interface will need to send UART signals through an attached connector which will interface a user's computer with the PCB/microcontroller.

Subsystem 3 - LED Lights & Dome
This subsystem consists of a dome fabricated by the machine shop with 32 integrated MR11 LEDs operating at a maximum power of 2.5 Watts apiece at 12V. It connects directly to Subsystem 1, which controls the power and lighting sequences. We will evaluate the wiring for compatibility with the LED controller board and verify its functionality to ensure that it can handle the required power draw. This subsystem is essential for the visual output of the PTM Dome, translating control signals from the LED drivers on the PCB into physical lighting effects.

Subsystem 4 - Longevity
We are calling this a "subsystem" because it is an important component of the project, even if it is not a specific component of the design itself. The Longevity subsystem ensures that the PTM dome system remains functional and reliable for an extended period, meeting the high-level requirement of long-term stability. This subsystem focuses on durable design, ease of maintenance, and future-proofing against technological changes.

Subsystem 5 - Control Enclosure
The control enclosure will house all essential components including the PCB, microcontroller and LED drivers, ensuring they are protected from environmental factors such as dust, moisture, and electrostatic discharge (ESD). This enclosure is essential to the overall design because it safeguards the internal hardware from physical damage and external interference, contributing to our design's high-level requirement of long-term stability and reliability. The enclosure will also include proper ventilation to allow for heat dissipation, ensuring internal

temperatures remain below 120°F (322K) at all times. External connectors for power, camera control, and LEDs will be securely mounted with EMI shielding to prevent signal interference. The enclosure will interface directly with the LED Controller Board.

We plan to 3D print the enclosure in-house using ABS or PETg filament, chosen for its thermal resistance, durability, and ease of modification. This option allows for rapid prototyping and adjustments during the design phase. As a backup, the ECEB machine shop will be used to construct a custom enclosure from metal or durable plastic, ensuring precise cutouts for connectors, ventilation, and fastening points. This dual-plan approach ensures we have flexibility in fabrication while maintaining high standards for durability and protection.

Subsystem Requirements:

Subsystem 1 - LED Controller board

This subsystem is derived from the previous groups' work and will be worked on heavily by course staff as well. The controller board must be able to control 32 MR11 LED bulbs independently, taking inputs from a GUI on a computer. It will be designed with longevity in mind as well as modularity. The following is a list of potential improvements over the previous designs:

- Different LED driver setup. Previous groups used an LED driver designed for an LED Matrix display, which may be unnecessary for simple applications of LEDs. The previous design's LED driver also required a dedicated crystal clock which was not provided on the board; we will use drivers that do not require an external clock for the sake of reliability. Additionally, the previous LED drivers required a GPIO input for each output. By using drivers that are intended for automotive applications (e.g. headlights) that are SPI-controlled, we can reduce the number of traces and utilization of the microcontroller's GPIO.
- More stable microcontroller with fewer GPIOs - The chip that we will be using (ATMega88) has support for Arduino using MiniCore, which would make designing the software component simpler.
- Improving the wattage of the on-board power supply for reliability. This was a major constraint in the Fall 2024 team's budget, with the 5V output regulator (LM1117MPX-50NOPB, https://www.onsemi.com/pdf/datasheet/lm1117-d.pdf) current-limited to a maximum of 1 Amp, and the 12V jack (PJ-102AH, https://www.sameskydevices.com/product/resource/pj-102ah.pdf) current-limited to 5 Amps. We intend to increase the current limit for both the 12V jack and 5V regulator on the board, to provide more overhead for operation of up to 5 LEDs at once, in addition to a higher-powered microcontroller.
- Better routing of traces on the PCB to reduce crosstalk. We are working on this problem with TA Zhongmin.

Subsystem 2 - User Interface

Block Description: The User Interface subsystem is essential for ensuring user-friendly control and monitoring of the PTM Dome's LED lighting system. It provides an accessible way for museum staff to operate and manage the lighting system, meeting the high-level requirement of user accessibility and reliability. By providing a flexible software-based interface, it enhances the system's maintainability and reduces potential hardware failures, aligning with the project's goal of long-term operational stability.

This subsystem communicates with Subsystem 1 through serial communication (UART). User commands, such as starting lighting sequences or toggling individual LEDs, are sent from the UI to the microcontroller, which processes these commands and controls the LEDs. The UI also receives real-time feedback from the microcontroller, such as the connection status and the current state of the LEDs, and updates the interface accordingly.

Critical Requirements:

- The GUI must support manual and automatic control of all 32 LEDs.
- The GUI must display the real-time connection status of the RTI device.
- The GUI must not cause any dome motion during operation.
- The system must provide clear visual feedback for each LED state and connection status.

Subsystem 3 - LED Lights & Dome

Block Description: This subsystem meets the project's high-level requirements by delivering programmable and dynamic lighting which is essential for the dome to function. The most important part of this subsystem is the LED wiring. Currently, it is set up with a common ground for all of the LEDs, which may or may not work depending on the LED driver that is used (whether it is a current sink or source). Additionally, in the interest of modularity, we will redesign the wiring to ensure each wire and LED socket can be swapped independently without needing to cut through heat shrink tubing or electrical tape.

Critical requirements:

- All 32 LEDs must be independently replaceable
- Sockets must be standard and replaceable, with standard connectors
- Connections to PCB must be robust enough to withstand 100+ cycles of removal/installation, and easily replaceable with standard tools. Ideally, connectors will be chosen where the point of failure is more likely to be on the wire than the PCB.
- Wires should be neatly organized and labeled to ensure easy identification
- Diagrams showing the wiring of the dome will be provided

Subsystem 4 - Longevity

Block Description: The Longevity subsystem contains all components that contribute to the system's durability, including hardware design, software maintainability, and component replaceability. It ensures that the dome can withstand frequent use without performance degradation. The subsystem also guarantees that museum staff can maintain and repair the system without extensive technical expertise.

This subsystem interfaces with the LED Controller Board by ensuring a reliable power supply and durable PCB design to prevent crosstalk and signal degradation. It connects with the User Interface by supporting software updates and ensuring compatibility with various operating systems. It also integrates with the Control Enclosure by maintaining environmental protection, shielding internal components from dust and moisture, and ensuring stable operating conditions.

This subsystem contributes to the overall design by providing repair manuals, spare components, and design documents. It ensures that the system remains operational even if individual components fail, thus avoiding disruptions in artifact preservation.

Critical Requirements:

- All components must be replaceable with basic tools and knowledge (e.g., a YouTube video).
- Custom PCB must be designed with widely available components.
- The microcontroller must support embedded Arduino programming for long-term flexibility.
- The system must operate without overheating, and well within power constraints
- Spare parts and detailed design documents for custom components must be provided.

Subsystem 5 - Control Enclosure

Block Description: The Control Enclosure protects key components from environmental factors like dust, moisture, and ESD. It ensures the system's reliability by managing heat dissipation and shielding external connectors (power, camera control, LEDs) from EMI interference. The enclosure interfaces with the LED Controller Board, ensuring secure connections and stable operation.

Critical Requirements:

- The enclosure must provide ventilation to maintain internal temperatures below 120°F (322K) at all times. Overheating could lead to system instability and component failure.
- The material used must protect internal components from environmental factors like dust, moisture, and ESD.
- External connectors must be equipped with EMI shielding to prevent signal interference.
- The enclosure must be made from durable materials like ABS, PETg, or metal/plastic for thermal resistance and long-term durability.
- The enclosure must include precise cutouts for external connectors to ensure secure connections.

Tolerance Analysis:

One area of improvement that was identified was the power supply. The previous group used a 2.5A power supply, which is capable of comfortably driving a few LEDs at a time, but has the potential to be overloaded when adding a few more LEDs. We do not want this to be a constraint, and adding additional power capacity is not difficult, so we will have at least a 5A power supply, considering these calculations:

The LEDs operate at 2.5W apiece on the 12V rail, so each LED consumes 0.208 Amps of current. The Darlington source drivers for the LEDs used in the previous project consumed only 3uA of additional current (1uA input current and 2uA leakage, per https://www.ti.com/lit/ds/symlink/tlc59213.pdf?ts=1739421836590&ref_url=https%253A%252F%252Fwww.mouser.fr%252F) which is negligible. Active at maximum operating frequency, the ATMega88 consumes 25mA of current at 5V (https://ww1.microchip.com/downloads/en/DeviceDoc/Atmel-9365-Automotive-Microcontrollers-ATmega88-ATmega168_Datasheet.pdf, pg. 253). CTR for the optoisolators ranges up to 200% with the audio jack drawing likely 1mA or less, yielding 3mA current draw on a 5V output rail. High powered onboard USB to I^2C UART chips like the MCP2221A draw a maximum of 100mA (https://ww1.microchip.com/downloads/aemDocuments/documents/APID/ProductDocuments/DataSheets/MCP2221A-Data-Sheet-20005565E.pdf, pg. 56) across all pins. This gives a very generous estimate of 25mA+3mA+100mA ≅ 150mA total power for all components other than the LEDs. With 50% overhead on this estimate, this implies that the maximum total power from all components excluding the LEDs is roughly equivalent to the average draw from one active LED (225mA). Using a 5A power supply at 12V, this gives us 4.8A of current for the LEDs. With 50% overhead on the maximum current draw for each LED (yielding 300mA), this power supply would provide enough wattage for up to 16 LEDs to be turned on simultaneously, well beyond the required 5 simultaneous LEDs requested by the Spurlock team.

For the most part, tolerance of response times for the LEDs and the camera shutter will be dependent on the ICs used for the LED drivers and the optoisolators on the 3.5mm jack, in addition to any processing delay on the part of the microcontroller. Time is not a major constraint in regular PTM operation of the dome, however it is important that LEDs are responsive to control signals for smooth user operation of the device. Our requirement for 1ms tolerance for toggling LEDs and 50ms tolerance on the shutter are fairly arbitrary, given the ICs have hold and delay times in the microsecond to nanosecond range. The primary source of delay in the circuit would be processing times for commands on the microcontroller, which will be dependent on our software implementation of the control system. Given that 1ms switching delay (1000Hz) is within the limits of perceptibility for the human eye, we felt it was a good standard for evaluating the perception of smooth LED toggling (without lag). Tolerance for the shutter is less important since only a few pictures can be taken per second regardless.

Ethics and Safety

- **Public Safety and Welfare (IEEE Code of Ethics #1 & #9):** We will ensure that our system is electrically safe by properly insulating the 12V LED circuits and incorporating overcurrent protection to prevent short circuits or overheating. We will also keep sensitive electronics in an ESD-safe enclosure to prevent static discharge, following IEEE safety standards for electrical design. We will also ensure that the enclosure for the electronics is protected from dust and other environmental hazards.
  Additionally, we will ensure that light pulses used for artifact scanning remain below 100 lux for highly sensitive items (e.g., textiles, paper, photographs) and below 200 lux for less sensitive items (e.g., wood, undyed leather). The power supplied to LEDs will remain within rated specifications to prevent damage to artifacts and system components. We will provide an instruction manual to guide users in safe operation, troubleshooting, and equipment replacement to avoid electrical injury.
- **Honesty and Transparency (IEEE Code of Ethics, #3 & #7):** We will clearly document our system, ensuring museum staff can use and maintain it without risk of misuse.
- **Avoiding Harm and Misuse (IEEE Code of Ethics, #5):** The system will be designed to prevent accidental misfiring of the camera by ensuring the trigger signal is precisely timed. We aim to comply with FCC regulations on electromagnetic interference and UL safety standards for electrical components.