LED Persistence of Vision Globe

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Abstract

The human visual system retains an image for a brief interval—approximately one-tenth of a second—after the stimulus is removed. This phenomenon, known as persistence of vision, arises from the delayed response of retinal photoreceptors and sensory neural circuits. For centuries, this property has been used to create motion illusions, from early optical toys to modern cinema. In this project, developed for ECE 445, we exploit the same principle to create a dynamic two-dimensional display using a single array of LEDs rotating on a spherical path, producing the illusion of a globe-shaped floating display. The final product's intended use is for UIUC's LabEscape, to display various graphics including clock time and clues through wireless communication in real time.

Contents

1. Introduction

LabEscape at UIUC is a science outreach escape room with the mission of providing rewarding and thrilling experiences that show how science can be amazing, useful, beautiful, and fun. Their puzzles are built around real physical phenomena, giving visitors the chance to see science in action. When an exhibit does not work as intended, it can take away both the educational goals and the entertainment value that are central to the LabEscape experience.

1.1 Problem statement

Recently, the team attempted to create an LED globe that uses Persistence of Vision (**POV**) to display text, images, and animations. The project has run into several problems. The LEDs are not syncing with the motor's rotational speed, the motor seems to run faster than needed, even generating lift which makes the system unstable, and there is uncertainty about whether the correct voltage is being applied. With little documentation to reference, troubleshooting has proven difficult. On top of these issues, the team hopes to add more functionality, including the ability to display images and animations as well as control the globe remotely through Wi-Fi. Solving these problems is important not only for the success of the project but also for maintaining LabEscape's mission of delivering science that both excites and educates.

1.2 Solution

Our solution aims to design and build a stable, Wi-Fi-enabled LED globe that reliably displays text, images, and animations using Persistence of Vision. At a high level, the system will synchronize LED patterns with the rotation of the globe to create clear visuals, while providing a user-friendly interface for uploading and managing content remotely. This approach directly addresses the synchronization, stability, and usability issues that have limited earlier attempts at the project.

To implement this, the globe uses a 12V motor with a maximum output of 6000 rpm, paired with a hall effect sensor to track rotational timings. The ESP32 microcontroller will use this feedback to precisely time LED updates with the goal of eliminating flicker and distortion. A microSD card will store image files allowing for robust image queueing and selection. The ESP32 will additionally provide Wi-Fi connectivity for a web-based control app. Through this app, users will be able to upload content and select desired images in real time. The motor will draw power directly from an outlet, while the control electronics and LEDs will run from a separate USB-C power module to ensure stable performance. Together, these components create a system that not only, when implemented correctly, solves the technical problems of synchronization and instability but also adds new functionality that makes the globe more interactive, engaging, and easy to maintain. By delivering a reliable and visually impressive exhibit, this solution pursues a goal to help LabEscape achieve its mission of creating unforgettable experiences that demonstrate the fun and wonder of science.

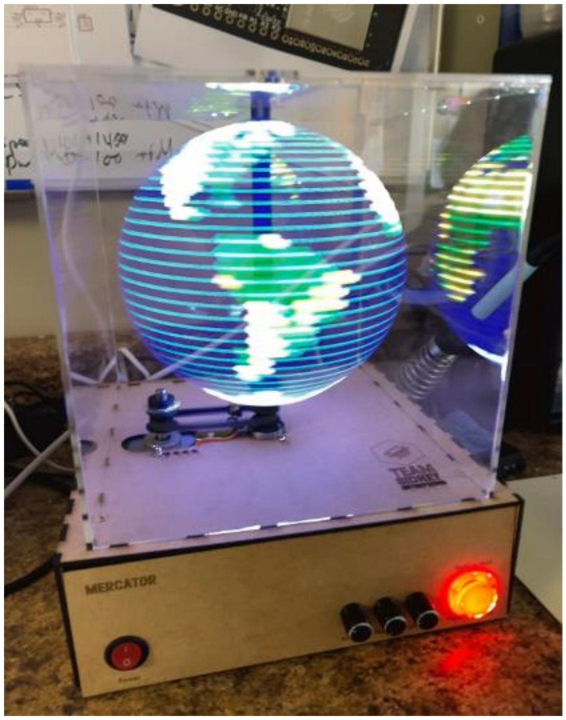

Figure 1. An example of persistence-of-vision globe developed by a hobbyist. Credit: Matt Walsh, Medium

1.3 High level requirements

Our POV Globe will satisfy the following high-level requirements:

1. **Resolution & Color:** The POV globe has the ability to display RGB images with 31x256 pixel resolution and 256x256x256 color. The design is intended to be conducive to the maintenance of stationary and clear images to the viewer as the globe rotates continuously.

2. **Power**: The globe will be powered via a 5V, 2A USB-C power module. The rotating segment containing the LEDs and circuit board will draw power through a slip-ring transformer – i.e. without an on-board battery.

3. **Data Transfer**: The rotating circuit board should wirelessly receive data and store it onto an onboard SD card. The system shall then read and display this data on the LED array in under 10 seconds.

2 Design

The design for the POV globe includes four subsystems, for power delivery, Controller Systems, Display Systems, and Wireless Systems. Our PCB design incorporates all of these subsystems in one cohesive and compact board.

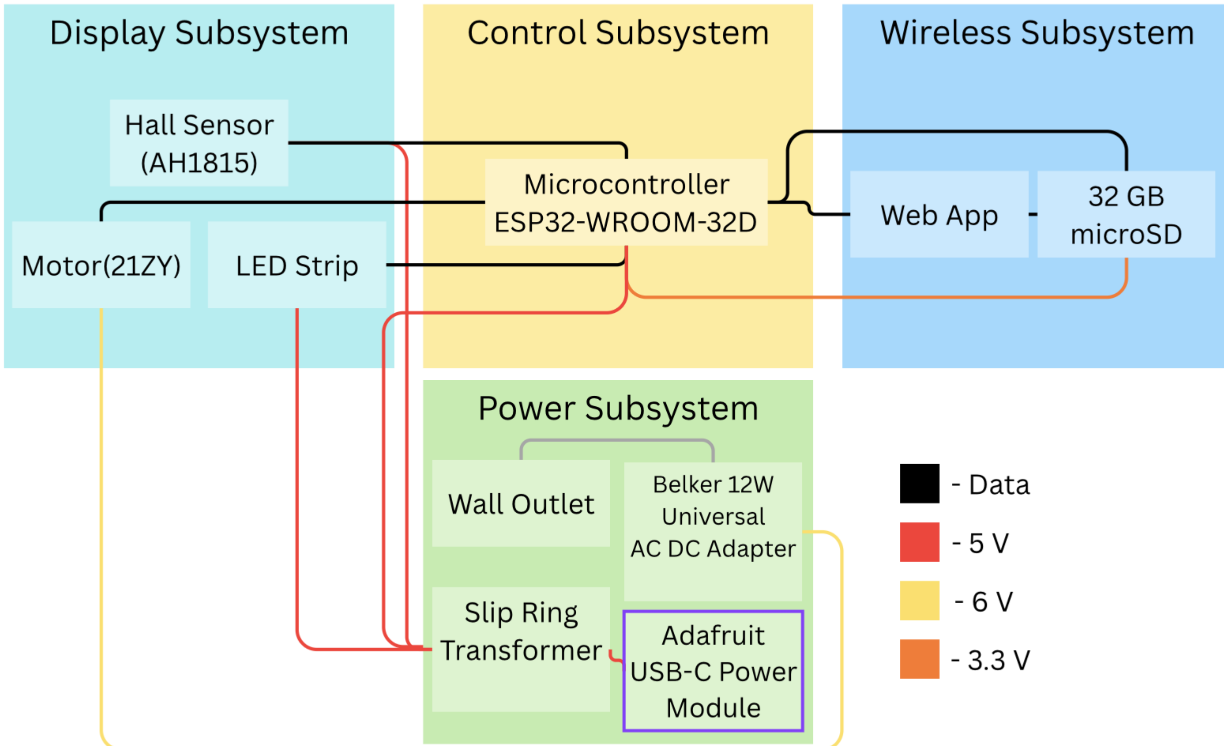

Figure 2: A block diagram indicating connections between components and subcomponents.

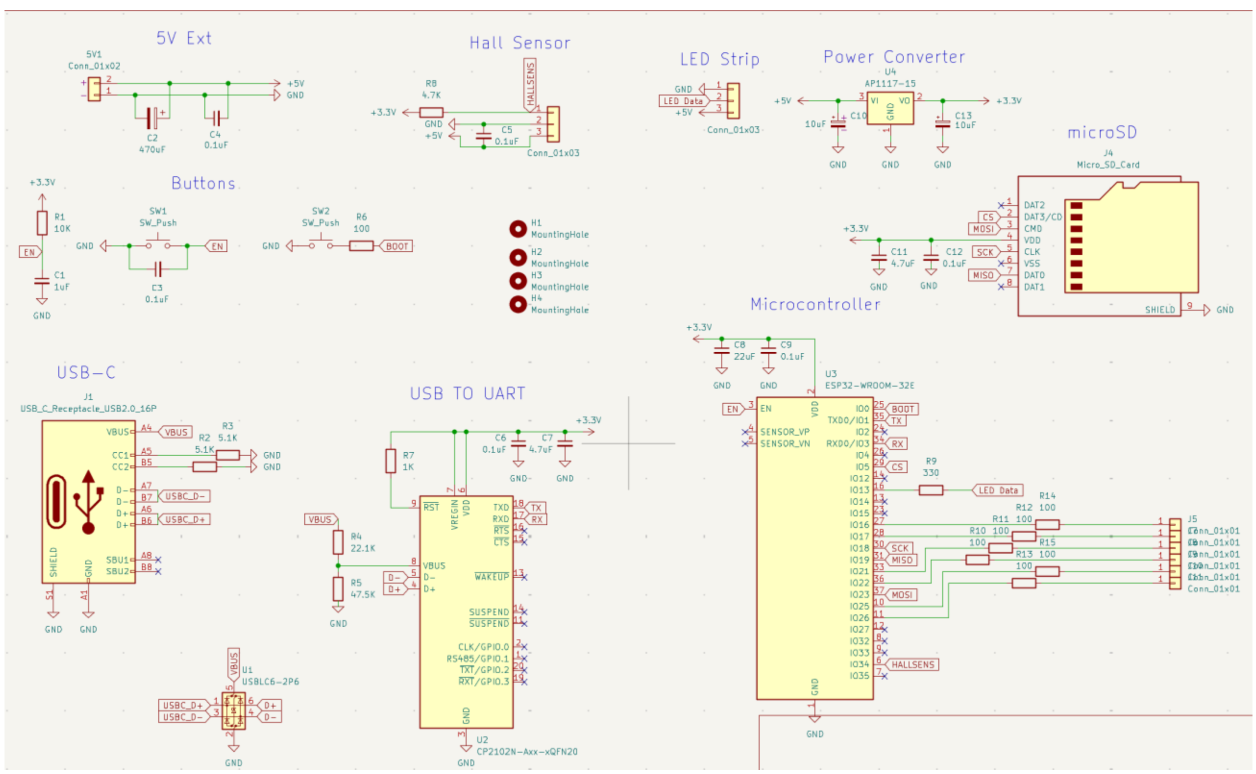

Figure 3: A schematic circuit diagram showing all our connections and components.

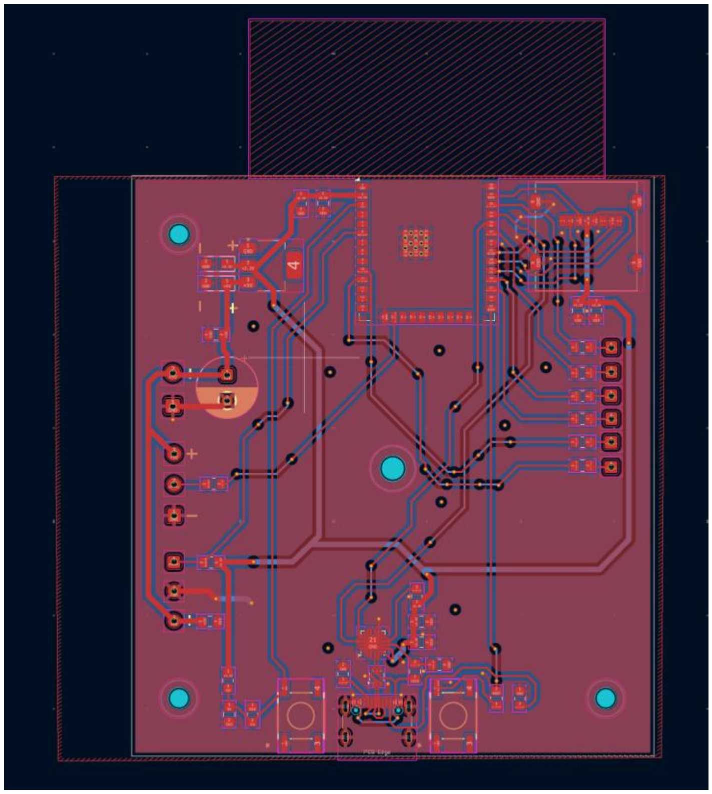

Figure 4: A schematic of our PCB design showing its layout and design

2.1 Display Subsystem

This system consists of a motor[1], hall sensor[2], and LEDs[3]. All of which are necessary to provide the logistical and mechanical needs to allow for a readable display. This subsystem interacts heavily with our microcontroller. An addressable LED strip is utilized to display pixel information buffered from our microcontroller. The motor must spin at 600 RPM and is held in place by a 3D print support structure. Additionally, its stem is modified by a 3D printing stem to both adapt and extend its width/length to fit our slip ring/ extend all the way through the slip ring. The 3D printed extension allows for proper connection to our connection board. The LED's span approximately 2/3rd of the surface of black globe

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[1] Amazon. "31ZY Permanent Magnet Motor, 6V/12V/24V 3500-8000RPM Permanent Magnet DC Motor Electric Brushed Motor CW/CCW." *Amazon.com*, https://www.amazon.com/Permanent-Magnet-3500-8000RPM-Electric-Brushed/dp/B07G5GRKFG?th=1. Accessed 8 December 2025.

[2] Sparkfun Electornics. "Hall-Effect Sensor - AH1815 (Non-Latching)." *Sparkfun Electornics*, https://www.sparkfun.com/hall-effect-sensor-ah1815-non-latching.html.

[3] Amazon. "BTF-LIGHTING WS2812B IC RGB 5mm Ultra Narrow LED Strip 2020SMD DC5V Individually Addressable 3.2FT 160Pixels/m 160LED Dream Color Tape Light for Home DIY Decoration IP30 (No Adapter or Controller)." *Amazon*, https://www.amazon.com/dp/B0DWXHKYMG?ref=cm_sw_r_cso_cp_apin_dp_ZRW4V97QCWJJVRE0VYTS&ref_=cm_sw_r_cso_cp_apin_dp_ZRW4V97QCWJJVRE0VYTS&social_share=cm_sw_r_cso_cp_apin_dp_ZRW4V97QCWJJVRE0VYTS&titleSource=true&th=1. Accessed 8 December 2025.

that is used to eliminate background noise when viewing the display. Further details regarding the LED's numbers and length will be expanding on in their respective sections.

2.1.3 Motor

The design uses a 31ZY Permanent Magnet Motor rated for up to 12V and 8000 RPM. The motor is setup and intended to spin the globe at any rate from 480 - 1200 RPM. 480 RPM is the minimum speed necessary to achieve satisfactory persistence of vision. 1200 RPM is an arbitrary upper limit on spin speed in order to avoid complications with spinning masses and their tendency to fly apart. For this same reason, the motor will be run at a reduced voltage of 3V yielding a rotational speed of a maximum of 900 RPM. This speed is more than sufficient to provide persistence of vision.

Figure 5: Our motor used attached altogether with our final assembly.

2.1.4 LEDs

For this design, we utilized a BTF-LIGHTING WS2812B LED strip. This LED strip provides 6mm LED spacing, individual LED addressability, and a convenient small profile with convenient methods of power and data input. The strip is addressed via 3 wires, ground, power, and data pin. The data input takes the form of an array for the number of LED's being used. The array contains the RGB values, ranging from 0 to 255 of each LED on the strip allowing for a massive arrangement of colors and brightnesses.

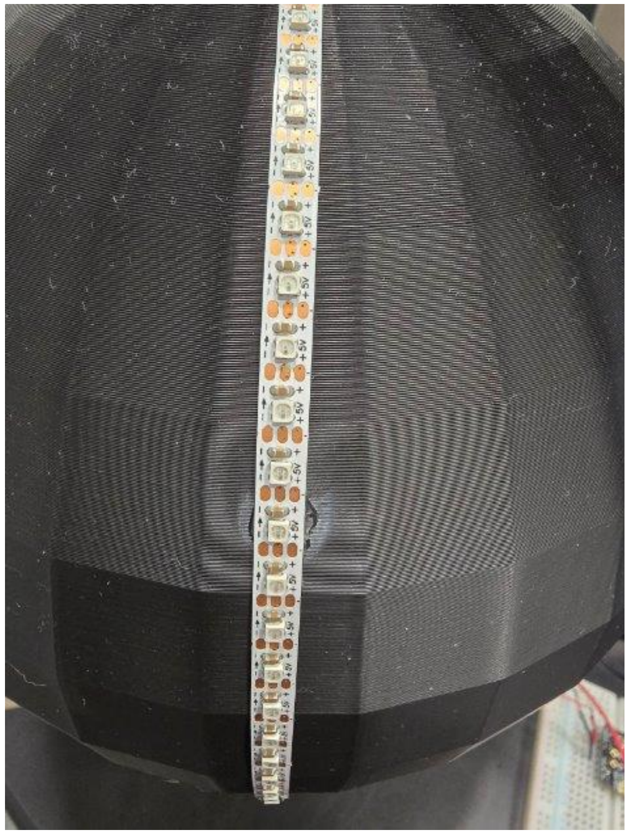

Figure 6: A snippet of how the LEDs are spaced on a portion of the arch mentioned above.

2.2 Control Subsystem

This subsystem consists of our ESP32[4] microcontroller which will hold the logic and do all calculations necessary to display items on our LED display. This system also includes all code structures that were built in order to properly handle image data, pixel data, and synchronization systems. These had to be structured in such a way as not to interfere with one another. Specifically, the synchronization system demands constant authority. To accomplish this, the design utilizes the dual core architecture of the ESP32 to constantly run checks for the hall sensor on one core all the while the second core continues running display systems relying on the previous data collected from the first core.

2.2.1 Microcontroller ESP32

The ESP32 being used has 21 GPIO pins and 2 cores. The two cores are utilized to run synchronization software and LED pattern logic simultaneously. The 21 GPIO pins are utilized for interfacing and power. As mentioned previously, the dual cores allow for a live synchronization system without sacrificing image display quality. The onboard 520 KB of SRAM of the ESP32 also allows for the buffering of image data for easy and fast access speed of 100 Mb/s, for effective display to our spinning LED’s.

[4] ESPRESSIF. “ESP32-WROOM-32U.” *Espressif Systems*, https://www.espressif.com/sites/default/files/documentation/esp32-wroom-32d_esp32-wroom-32u_datasheet_en.pdf. Accessed 12 October 2025.

2.3 Wireless Subsystem

The wireless subsystem enables remote interaction with the globe through the ESP32's integrated Wi-Fi capabilities. The ESP32 is configured to operate as a client on an existing local network (LabEscape's private network or a staff mobile hotspot). This allows authorized users to connect to the globe from any device on the same network without requiring physical access. Through this wireless interface, staff can upload new images, select stored images for display, and prepare new images to be rendered directly on the LED strip. Finally, the wireless connection is stable for the short distances and the elongated times necessary for extended operation, as the globe may be powered continuously during exhibitions.

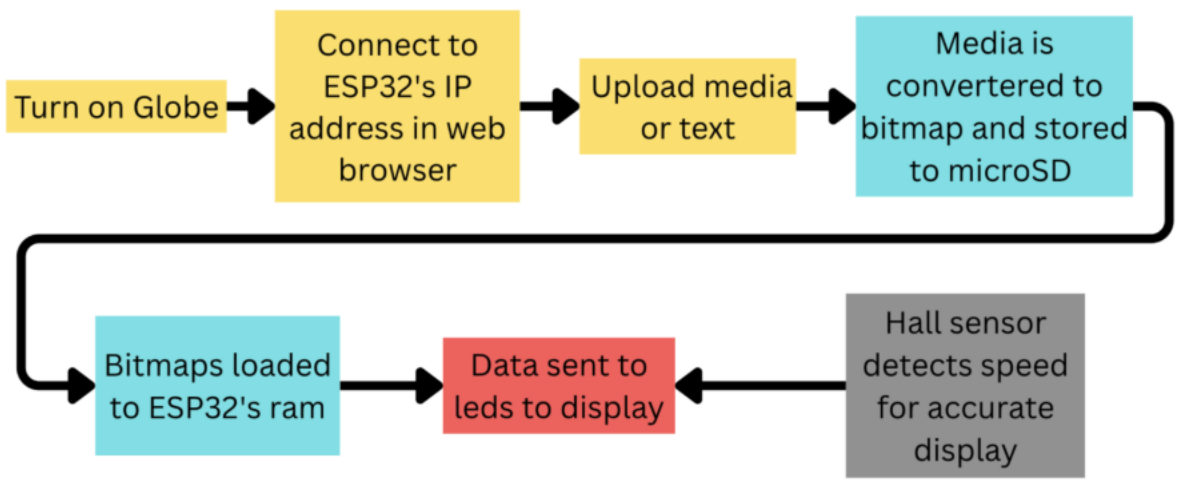

Figure 7: Flow Chart indicating the path our users would take to display media on the globe

2.3.1 Web App

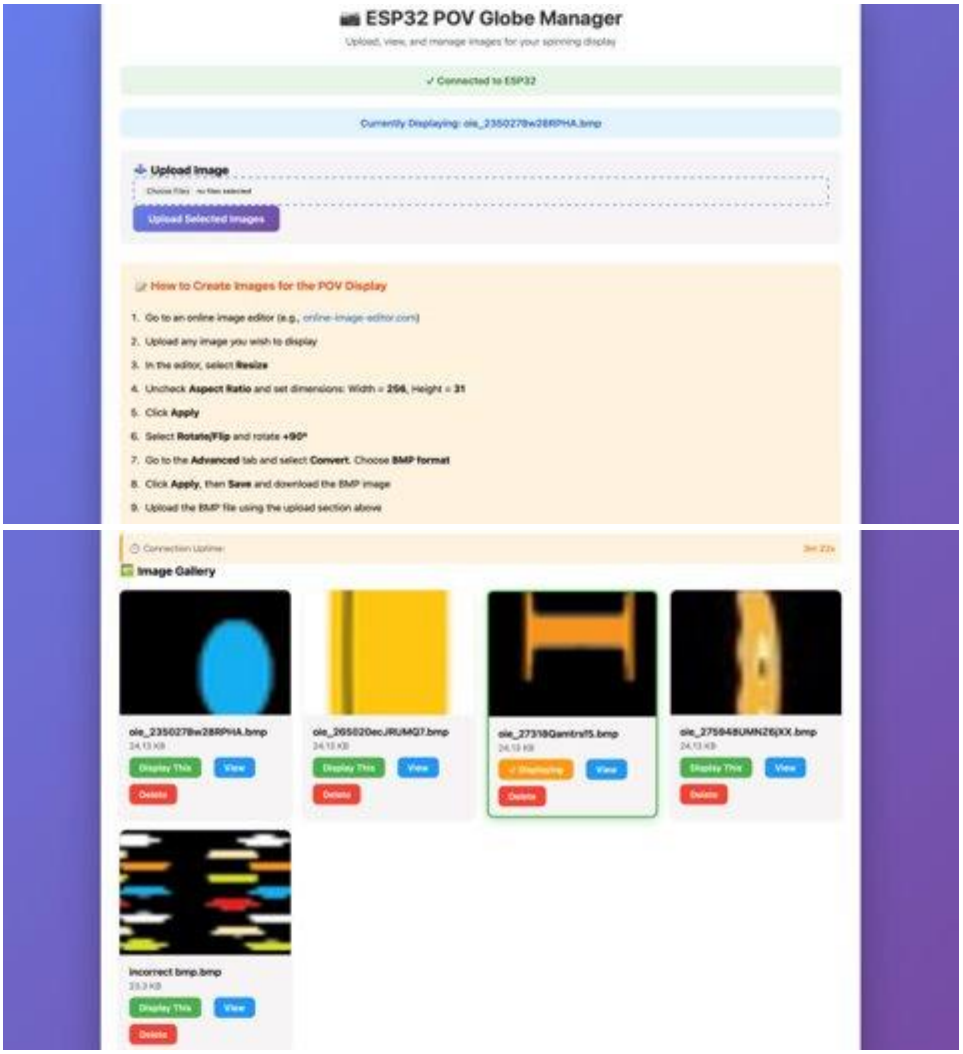

Figure 8: The I/O interface and web application users experience.

The web application provides the primary user interface for managing visual content on the globe. When accessed through a browser, the application displays a list of image files currently stored on the microSD card and allows users to upload new assets. To ensure proper alignment with the physical LED layout, all images must be formatted to 31×256 pixels in BMP format. The web app provides users the instructions to properly convert any arbitrary image for display to the globe. This ensures that every stored file matches the display subsystem's expected pixel mapping and can be rendered without additional processing or visual distortion. Images with text are displayed using the above-mentioned processes and methods.

2.3.2 MicroSD

The microSD card serves as the storage medium for all displayable visual assets. Each stored image is a 31×256 BMP, ensuring a consistent pixel layout for direct mapping to LED positions. When an image is selected for display, the ESP32 loads the BMP data from the microSD card into RAM, allowing the display subsystem to retrieve pixel values at high speed during rotation. This prevents timing artifacts that would occur if the system attempted to stream directly from the SD card while the globe was spinning.

Typical BMP files at this resolution are expected to be under 500 kB, which allows the SD card to store over 60000 static images along with additional multi-frame sequences for simple animations or GIF-style effects. Images are selected by filenames through the web interface.

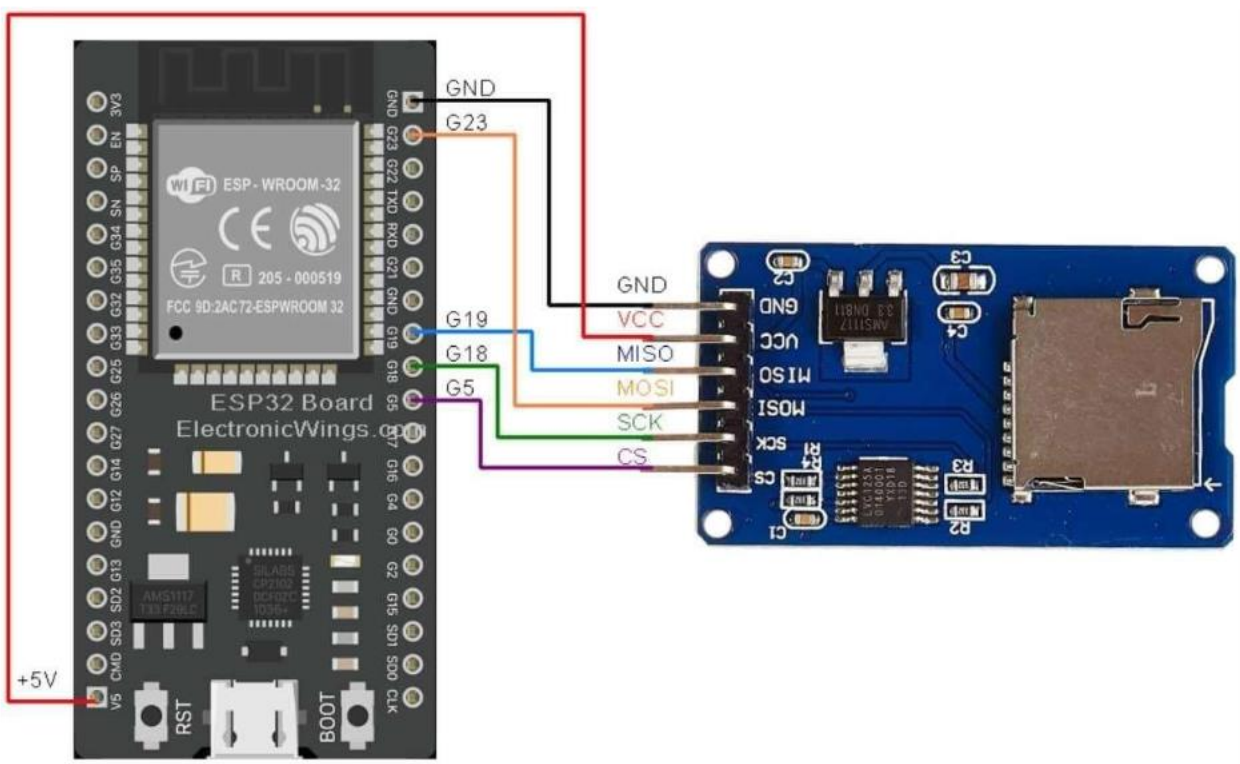

Figure 9: MicroSD module hooked up to ESP32. Credit: ElectronicWIngs

2.4 Power Subsystem

The power subsystem begins at a 120V power supply. Two power converters are utilized to power the motor and LED globe separately. This separation greatly reduces potential heating and power control issues when trying to regulate power to both the board and motor simultaneously. A power converter[5] is used to step down our voltage from 120V to a choice of between 3 – 12 V. This power converter will

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[5] Amazon. “Belker 12W Universal 3V 4.5V 5V 6V 7.5V 9V 12V AC DC Adapter Power Supply for Household Electronics Mp3 Routers TV Boxes LCD Tablets CCTV IP Cameras Max. 1000mA [BB].” *Amazon*, https://www.amazon.com/dp/B013UJAZY8. Accessed December 8 2025.

be used to power our motor. For our LED globe it will utilize a USB C power converter[6]. This converter supplies our globe with a constant 2 amps and 5 volts. This 5V line runs that into a slip ring[7] which will then transfer power to the globe's component board. The 5V will be used to power the part on this board including the microcontroller, SD card unit, and hall sensor. The slip ring is a central component to this design as it ensures that we can provide proper power to the microcontroller and SD card unit that manages all our LED logic and display systems.

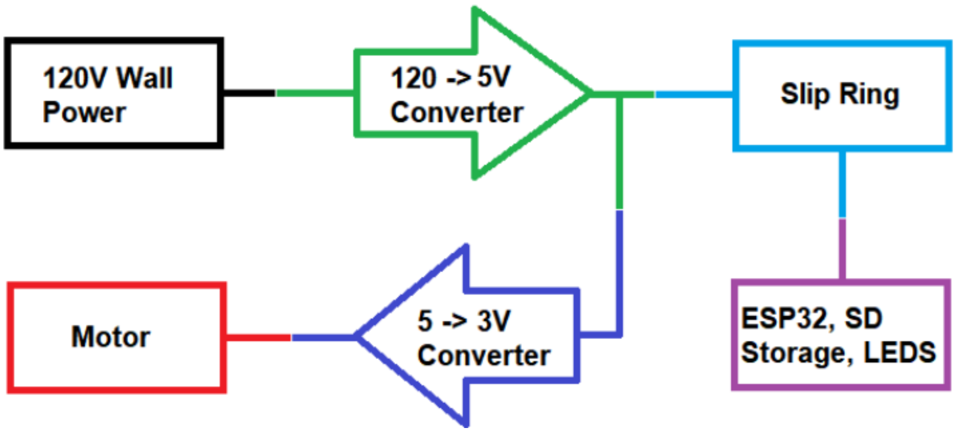

Figure 10: A visual depiction of the flow of power between the different major modules in the design

3. Design Verifications

If all systems are working properly, we will test whether we are able to upload a set of images wirelessly and display those images properly onto our LED display. Properly implies the proper positioning of pixels from our respective images onto our rotating sphere of LED's. Verification for each subcomponent is as follows:

3.1 Display Subsystem

Requirements	Verifications
The motor must spin the globe at a rate of 600 ± 15 RPM	Due to complications in the structure of our support mount, it was inadvisable to attempt to spin up to full speed of 600 RPM. However, we were able to affectively spin our design at 120 RPM.

[6] Adafruit. "Adafruit USB Type C Power Delivery Dummy Breakout - I2C or Fixed." *Adafruit*, 21 September 2023, https://www.adafruit.com/product/5807. Accessed 8 December 2025.
[7] Amazon. "Taidacent Hollow Slip Ring Signal Power Continued 2/4/6/12 Road Collector Ring Conductive Electric Motor Slip Ring Rotating Connector (2 Wire 1.5A Inner Hole 7mm Outer Diameter 22mm)." *Amazon*, https://www.amazon.com/dp/B07XKGFGRC?ref=ppx_yo2ov_dt_b_fed_asin_title&th=1. Accessed 8 December 2025.

Externally powered spinning LED's	We were able to power the LED globe through a slip ring while spinning the design with our motor.
LEDs must achieve 256 distinct colors	By displaying 8 different levels of color for each red, green, and blue, we implicitly can calculate at least 8*8*8 = 512 distinct colors to be available (See Figure 10).

Table 1: Requirements and verification for the display subsystem.

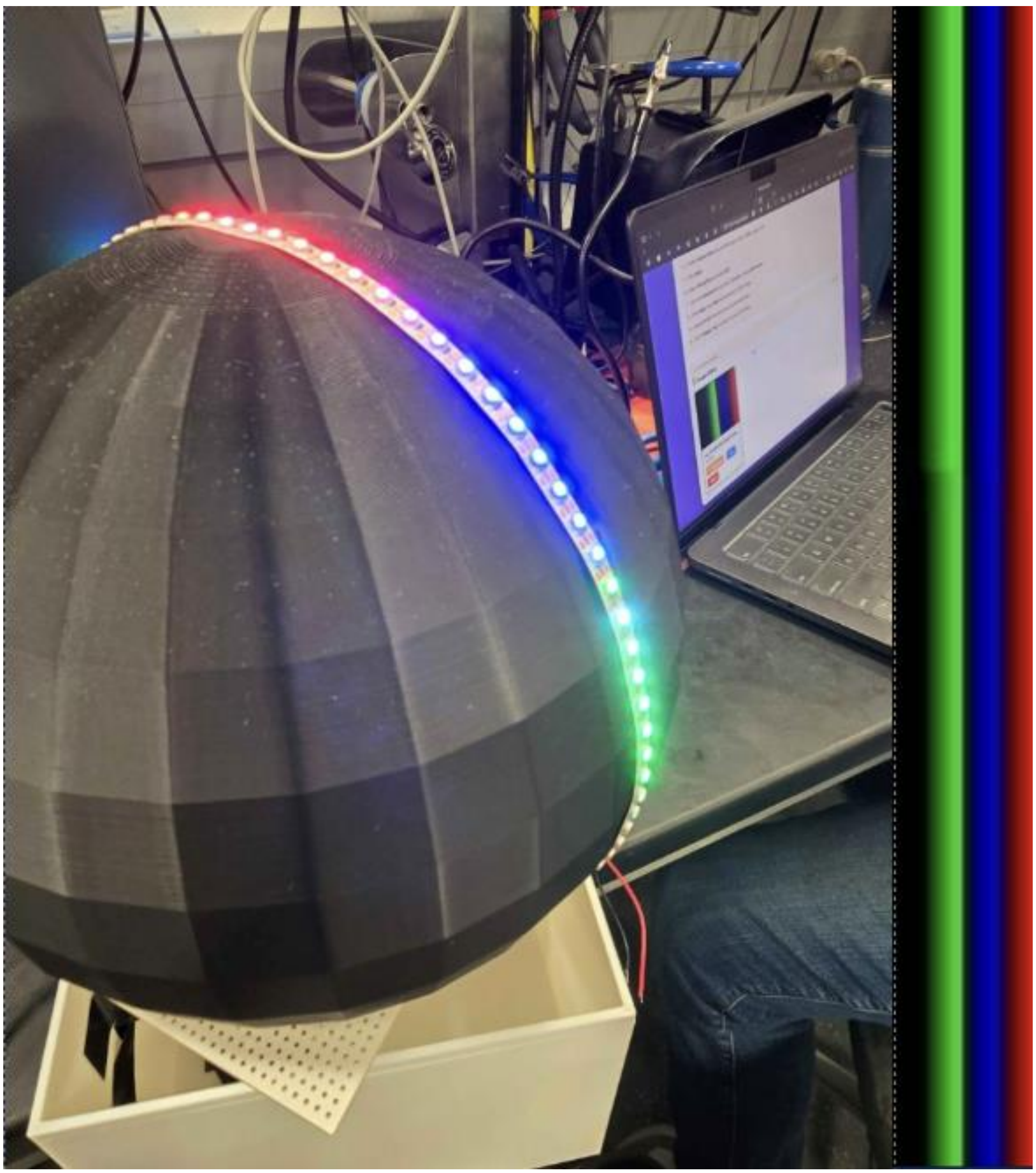

Figure 11: An image showing 8 different colors of RGB each and its display on the globe.

3.2 Controller Subsystem

Requirements	Verifications
LED control loop must complete in less than 0.2 ms per iteration	As will be discussed in the Tolerances section, our LED strip was incapable of addressing our LEDs fast enough. Our column addressability was about 2ms, 10x greater than our needs (See figure 11).
RPM adaptability	The hall sensor on our device successfully registers every rotation and documents time of rotation even when images are processing.

Table 2: Requirements and verification for the Controller Subsystem.

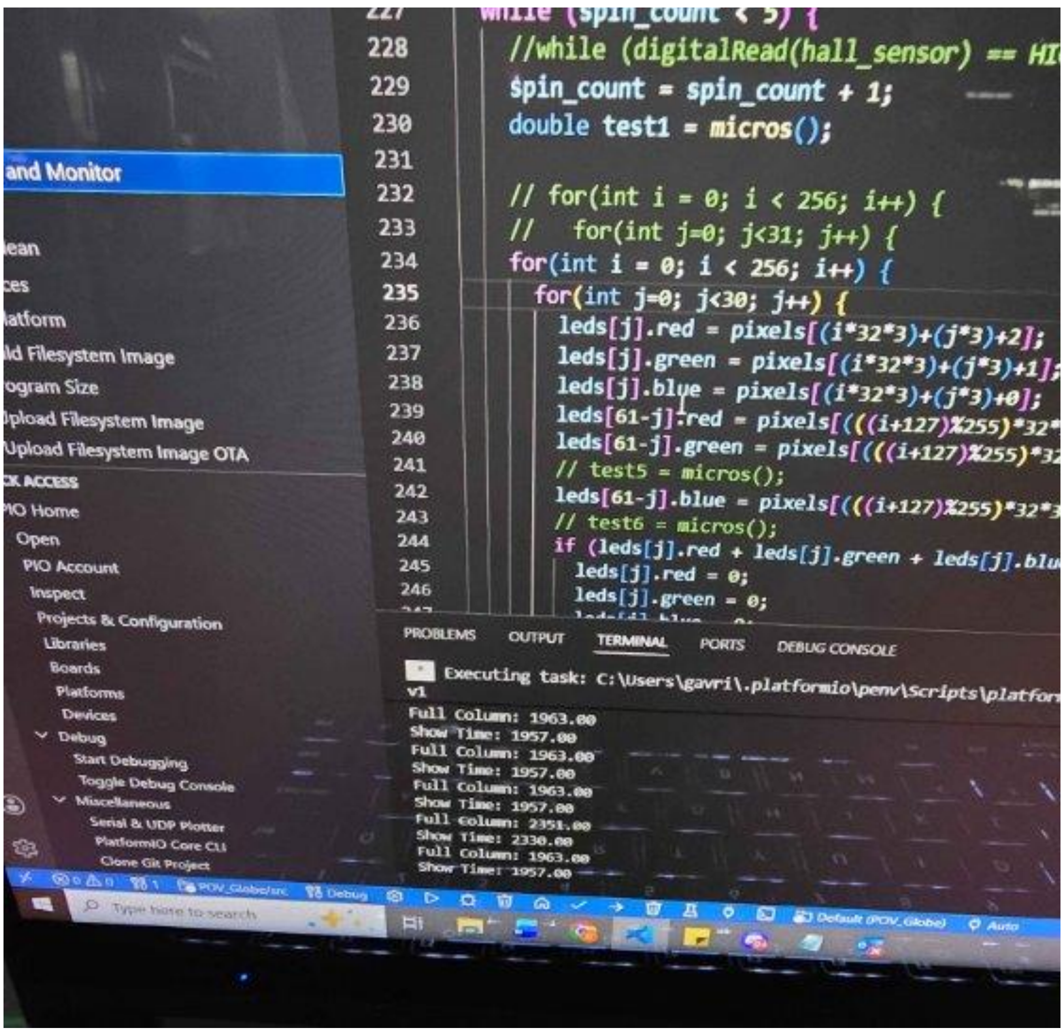

Figure 12: The time it takes to process one column of LED data in microseconds

3.3 Wireless Subsystem

Requirements	**Verifications**
The time from a Wi-Fi command (e.g., image change) being sent until the first pixel is updated must be ≤ 3 seconds.	A combination of methods was used to accomplish this. Firstly, the time of upload to our web app is timed (Figure 12) and then, utilizing the data from our previous test, we see the time to write the full first column of data is 2ms (Figure 11).
Microcontroller must hold a steady connection for at least 2 hours	A simple addition to our HTML code introduced a timer that would display the time the web app has been connected to the MCU (Figure 13).

Table 3: Requirements and verification for the wireless subsystem.

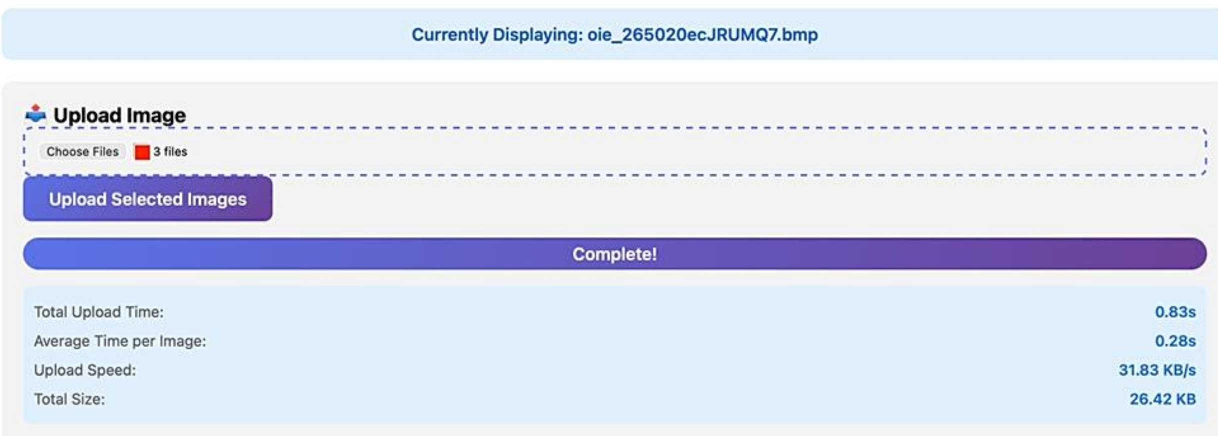

Figure 13: A demonstration of the time it takes to upload images to our device.

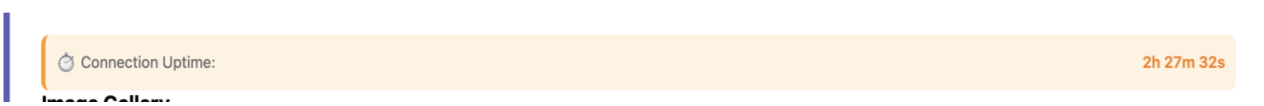

Figure 14: An instance displaying the time the ESP32 was connected to our web app.

3.4 Power Subsystem

Requirements	**Verifications**
Voltage for logic board must be 5V ± 0.2 V	Measurements indicated that through the slip ring 5V was being supplied to our logic board.

PCB must draw less than 6 A as the total current	Our logic board utilized a converter that limited amperage to 2 Amps. Therefore, our design functioned on less than 6 Amps.

Table 4: Requirements and verification for the power subsystem.

4. Tolerance Analysis

The breaking point of our project is the speed at which we can write information to our LEDS relative to our spin speed. The fastest location we can draw pixel data from is our ESP32's onboard memory where it can be accessed at fast enough speeds relative to the rotation of our board. See math below.

We anticipate a maximum spin speed of 1200 RPM. This results in an RPS of…

$$20 \text{ RPS} = 1200\text{RPM} / 60\text{s}$$

This results in a 1 rotation every 0.05 of a second. Our ESP32's memory can be read at a safe value of 100 Mb/s. Our images will be formatted to 256x64 pixels. Therefore, we will want to be updating our color information for pixels every…

$$\text{Seconds per Image Column} = 0.05\text{s} / 256 \text{ columns}$$

The maximum size of our images is roughly, as determined by experimentation via the creation and analysis of multiple 256x31 BMP files, 48 KB large. We will need to read at a maximum of 48000/256 bytes of information each time as only one column is relevant per segment. As long as the time to read required information is less than the amount of time available to read the information (0.05/256), we will be able to read all necessary data from onboard memory and display it in a timely manner.

$$\text{Time to Read New Data} = (48000/256)/100000000$$

$$\text{Available Time to Read Data} = (0.05/256)$$

$$\text{Time to Read New Data} < \text{Available Time to Read Data}$$

Additionally, this math yields the information needed to display any 256x31 image. By timing which LEDS map to which pixels at a given relative time on their revolution, we can map all 16384 pixels to an LED per rotation. However, this assumes the use of 62 individual nonaddressable LED's which have no relevant delay when considering speed of writing data. Our design, on the other hand, uses an addressable LED strip. This causes issues as the strip itself has its own restrictions as shown below.

24 Bits per LED and a bit rate of 800kHz

Each bit needs 1/800000 1.25us

Each LED needs 24*1.25 = 30us

Time to Read New Data to LED strip needs 62*30 = 1860us = 1.860ms

Time to Read New Data to LED strip > Available Time to Read Data

We can therefore see that our tolerance is not satisfied when utilizing the LED strip we selected for this project. Notably, this issue was observed when the device was tested in its entirety, as reflected by some of the requirements and verifications. Also of note is that this issue arises from an improper bit rate of the LED strip we selected. Possible other alternatives are mentioned in the alternatives section below.

Another aspect of our project to consider is the support structure of our design. In our final assembly, our design contained several 3D printed support structures designed to ease assembly and structurally support it. All of the utilized items worked without fail and continue to function. However, it was an oversight on one crucial support that led to many complications.

Figure 15: Highlighting a crucial weak point in our assembly’s design.

As highlighted in figure 14, our design had a crucial weak point that resulted in oscillations and wobble. The reason for this oversight was an oversight in any method to properly support the top board without a direct connection between a rotating reference frame and a non-rotating reference frame. The preemptive assembly of the design without such a support made after the fact implementation difficult to the point that alternate solutions were explored. The solution pursued was high support walls on the motor mount. These walls were meant to serve as supports for the board to eliminate dangerous wobble in the design. While the walls did achieve this purpose, they also massively increase the contact area between the spinning reference frame. This would inevitably cause issues with impacts and outright inconsistency of spin speed.

The important fact to know is that when creating a support structure to protect against wobble it will be need as close to the rotational axis as possible while still supplying sufficient wobble support.

5. Costs

The cost of our project includes the many components we will have to purchase as well as the cost of PCB orders and labor costs.

5.1 Parts

Table 5 Parts Costs

Part	Manufacturer	Retail Cost ($)	Amount	Actual Cost ($)
Hall-Effect Sensor - AH1815 (Non-Latching)	Sparkfun	$1.05	1	$1.05
LED Strip - WS2812B RGB LEDs	BTF-LIGHTNING	$13.99	1	$13.99
MicroSD Card Reader Module	Adafruit	$7.50	1	$7.50
USB-C Power Delivery Module	Adafruit	$5.95	1	$5.95
Neodymium Magnet Disk Sensor N35 D6mm(A) x 3mm	Radial Magnet	$1.00	1	$1.00
31ZY Permanent Magnet Motor, 6V/12V/24V 3500-8000RPM Permanent Magnet DC Motor Electric Brushed Motor CW/CCW (12V 8000RPM)	Robot Shop	$16.91	1	$16.91

ESP32-WROOM-32 Dev Board	AITRIP	$8.99	1	$8.99
12 V, 5 A AC-DC Power Jack	Belker	$12.90	1	$12.90
SanDisk Ultra PLUS 32GB microSD Memory Card[6]	SanDisk	$14.99	1	$14.99
Hollow Slip Ring – 240 V @ 2A	Taidacent	$23.16	1	$23.16
Total				$ 106.44

5.2 Labor

According to the Grainger College of Engineering[8] graduates with a computer engineering degree earn on average $57.09/hr. Assuming that we spend a maximum of 70 hours working on this project we get a total cost of labor of:

$$70 \times \$57.09 = \$3996.30$$

6. Conclusion

6.1 Accomplishments

We have accomplished quite a few exciting feats so far in our testing. Namely, we have accomplished proper persistence of vision, multicore control via the ESP32 allowing for proper image synchronization, algorithm to translate pixels from an image onto our spherical design, and remote storage of images. However, most of these accomplishments were on previous test designs. On our most recent implementation, our main accomplishment centers on the implementation of image to pixel translation and mapping. Additionally, we implemented a working I/O interface in the form of a webapp that allowed for the creation, upload, selecting, and deletion of desired images.

6.2 Uncertainties

While most of the issues encountered during design and final testing of the project have reached conclusions on their answers, there are still some concerns regarding the use of a magnet as our synchronizing part. During testing we found that precise positioning is required in order for our hall sensor and magnet pair to work properly. Additionally, since many parts in the design are magnetic, the presence of a strong magnet inherently introduces an ever-present wobble into a rotation reference frame. This is concerning as although supporting structures should support against minor wobble, a constant force present within the design is likely to degrade part positioning and structural stability which can cascade into the dispositioning of our hall sensor to a degree such that it can no longer detect the magnet. This would effectively brick the device.

6.3 Ethical Considerations

6.3.1 Ethics

The development of our LED globe project involves several ethical considerations. We prioritize the safety, health, and welfare of the public by ensuring that the device is electrically safe, mechanically stable, and responsibly designed. The purpose of the globe is to serve as an engaging and educational demonstration of Persistence of Vision, which supports LabEscape's mission of using science to inspire curiosity and learning.

A key ethical concern is privacy and security, since the device can be controlled remotely over Wi-Fi. Without safeguards, unauthorized individuals could connect to the globe and display inappropriate or misleading messages during public demonstrations. To prevent this, we advise using a mobile hotspot as the source of Wi-Fi. People will not have access to this network as long as the hotspot is password protected so that only LabEscape staff can update the display. By being transparent about how the system works, documenting our security measures, and providing clear guidelines for responsible use, we reduce the risk of intentional misuse.

6.3.2 Safety

- **Electrical Safety**
  The globe relies on a high-speed 6V motor powered from an outlet, a microcontroller, LEDs, and a Wi-Fi module. To minimize electrical risks such as overheating, short circuits, or accidental shock, the system uses proper voltage regulation and insulation. All wiring and connections are securely enclosed, and the power supply is housed inside the globe's base enclosure. During development, we followed standard lab safety practices, including the use of insulated tools and protective eyewear when soldering.
- **Mechanical Safety:**
  Because the motor could spin at hundreds or even thousands of revolutions per minute, mechanical stability is a priority. The globe is securely mounted and balanced to avoid vibrations that could damage components or cause parts to detach. A protective housing added around the rotating assembly is a component we still want to implement to reduce the risk of accidental contact during operation. The mounting system has been tested to ensure stability even during extended demonstrations.
- **End-User Safety:**
  Since the project is intended for public demonstrations, the device will always be operated under supervision. Users do not have direct access to the motor or electronics, and clear instructions and warnings will be provided to minimize risks. Security measures such as the usage of a password protected mobile hotspot will ensure that only authorized staff can change the display. Additionally, flashing lights and animations can trigger seizures in individuals with

photosensitive epilepsy, so visible warnings should be posted near the exhibit to alert visitors before use. Together, these precautions ensure the globe remains both safe and reliable in an educational setting.

6.4 Alternatives

As expounded upon in tolerance analysis, this LED globe design utilized an LED strip that lacked proper data rate requirements. Due to its bit rate of 800 kHz our 62 LED strip was unable to update fast enough. Therefore, it is logical to seek out alternative LED strips that possess the required specifications.

One such item is the SK9822 LED strip[8]. With its bitrate of 20 MHZ each led would only need 1.6us to be addressed. With a total of 62 LEDs the total time needed to address a pixel column would total about 99.2us, which finally, would be more than sufficient to satisfy our need of a column per 0.2ms.

The other issue which needs addressing is that of proper stem support. This will be easily resolved by the 3D printing of an additional part that will be attached to the top of our slip ring during assembly. It would serve to support just around the rotational axis and rest just touching the underside of the rotational board. While this will add friction and resistance to the motor, it will be much less than the current implementation, truly accomplish the desired goal of the current solution, and not interfere with device accessibility or utility space.

[8] Amazon. "BTF-LIGHTING SK9822(Similar to APA102C) Individually Addressable 3.3ft 1m 144 Pixels/LEDs Non-Waterproof Black PCB Data and Clock Separately DC5V Full Color." *Amazon.com*, https://www.amazon.com/BTF-LIGHTING-Individually-Addressable-Non-Waterproof-Separately/dp/B07BPX2KFD?th=1. Accessed 8 December 2025.

References

[1] ACM. ACM Code of Ethics and Professional Conduct. Association for Computing Machinery, 2018, https://www.acm.org/code-of-ethics. Accessed 19 Sept. 2025.

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