SPOTLIGHT TRACKING WITH AUTOMATED RECOGNITION (S.T.A.R.)

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Motivation

- **Problem:** There are currently no tracking spotlights on the market that use a camera with human tracking to automatically follow a subject. Other technologies (RFID tracking chips) are very expensive and inaccurate

- **Proposed Solution:** is a low-cost, human detection based imaging spotlight system designed for performer tracking in live theatrical environments. The system targets a specific use case, allowing reliable performance without the cost or complexity of commercial follow-spot solutions.

Our Goals

- The basic goals are to detect and track a subject at 7.5 meters, control a motorized gimbal to keep the spotlight centered, and ensure smooth, low-latency motion.

- The advanced goals are to enable multi-target detection with single-target spotlight focus, optimize gimbal motion for smooth continuous operation, and add a wireless interface for control and calibration.

- The stretch goals are to network multiple S.T.A.R. units for coordinated coverage and improve performance under challenging conditions such as smoke, fog, and high-contrast lighting.

Our Objectives

- Our basic objectives are to design a multi-lens imaging system using commercial components and implement human recognition algorithms to identify and track a subject, enabling coordinated gimbal control for pan and tilt positioning.

- The advanced objectives are to enhance the vision system for multi-subject detection with user selection, improve motor control to reduce jitter and overshoot, and develop a mobile interface for manual control and override.

- The stretch objectives are to enable DMX/Ethernet integration with existing lighting systems and explore extended sensing capabilities, including far-infrared detection for thermal imaging.

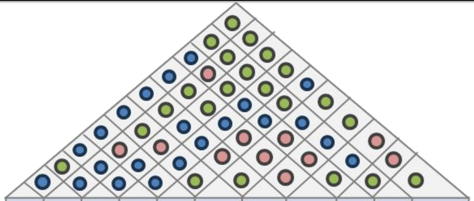
Specifications

Parameter	Description	Target Value & Unit(s)
Tracking Latency	Time delay between performer movement and spotlight response	≤ 500 ms (basic), ≤ 300 ms (advanced)
Tracking Accuracy	Angular error between spotlight center and the selected performer's center of mass	≤ 5° RMS at 10m
Detection Confidence	The confidence score given by the detection system upon first detection of an incident subject	>70%
Field of View (FOV)	The angular viewable area that the sensor can image	> 45°
Depth of Focus	The acceptable focus depth that a performer can move on a stage	> 1m
Tracking Range	Distance at which subject can be reliably detected and tracked	7.5m (± 1m)
Frames Per Second (fps)	How many frames are captured by the camera per second	30 fps @ 1920x1080p
Lighting Conditions	Minimum illumination where tracking is possible	≥ 1000 Lumens

Specifications cont.

Parameter	Description	Target Value & Unit(s)
Spotlight Beam Size	Effective beam diameter at 10m	0.5m - 1m adjustable (>5° half cone)
Pan/Tilt Range	Gimbal rotation coverage	Pan: 180° max, Tilt: 120° min
Pan/Tilt Speed	Spotlight movement speed	≥ 180°/s pan, ≥ 120°/s tilt
Operating Power Consumption	Wattage consumed by system during operation (NOT including illumination source)	~ 611Watts
System Weight	Total weight of system (NOT including illumination source)	≤ 20 lbs
System Cost	Total cost of prototype build (not including redundancies)	≤ $800 prototype

House of Quality



Technical Requirements

Direction of Improvement

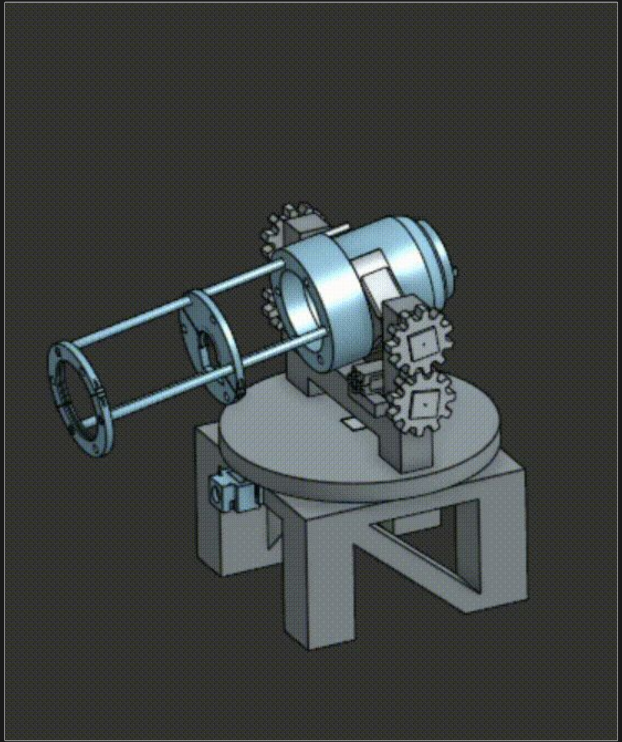
Customer Requirements	Direction of Improvement	Weight	Image Resolution	Size	Spotlight Beam Size	Frame Rate	Tracking Accuracy	Detection Accuracy	Tracking Latency	Tracking Range	Cost	Overall Power Consumption
Direction of Improvement		↓	↑	↓	↑	↑	↑	↑	↓	↑	↓	↓
Reliability	↑	○	●●	○	●	●●	●●	●●	●●	●●	○	○
Ease of Use	↑	○	○	○	○	○	○	○	○	○	○	○
Quiet Operation	↑	●	○	●●	○	○	○	○	○	○	⊙	●●
Brightness	↑	⊙	⊙	○	●●	⊙	●	○	⊙	●	●●	●●
Portability	↑	●●	○	●●	⊙	○	○	○	○	○	●●	○
Optical Scalability	↑	○	●●	●●	●	○	●●	●●	⊙	●●	●	○
Customization	↑	●●	●●	●●	●●	●	●●	●	●	●●	●●	●
Affordability	↑	●●	●●	●●	●●	●●	●●	●●	⊙	●●	●●	●●
Ease of Installation	↑	●●	○	●●	○	○	○	○	○	○	○	○
Product Targets		<20 lbs	≥ 720p	≤ 18" x 12" x 12"	0.5m-1m	≥ 50fps	≤ 5° RMS at 10m	> 80%	≤ 250 ms	7.5m (±1m)	< $800	< 611 Watts

Correlations:
- ● Positive
- ● None
- ● Negative

Relationships:
- ●● Strongest= 10
- ● Strong= 7
- ⊙ Fair= 4
- ○ Weak= 1

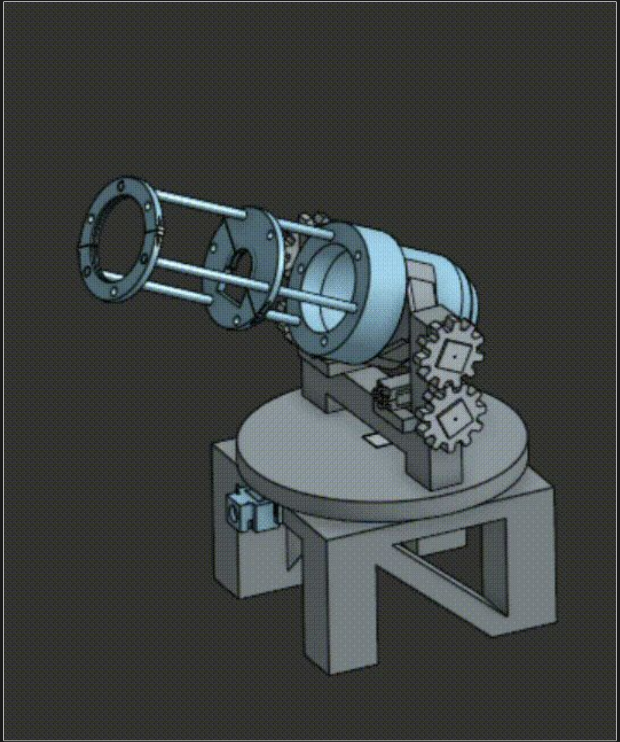
S.T.A.R. Visualization

Tilt Motion



Gear Operated

Panning Motion



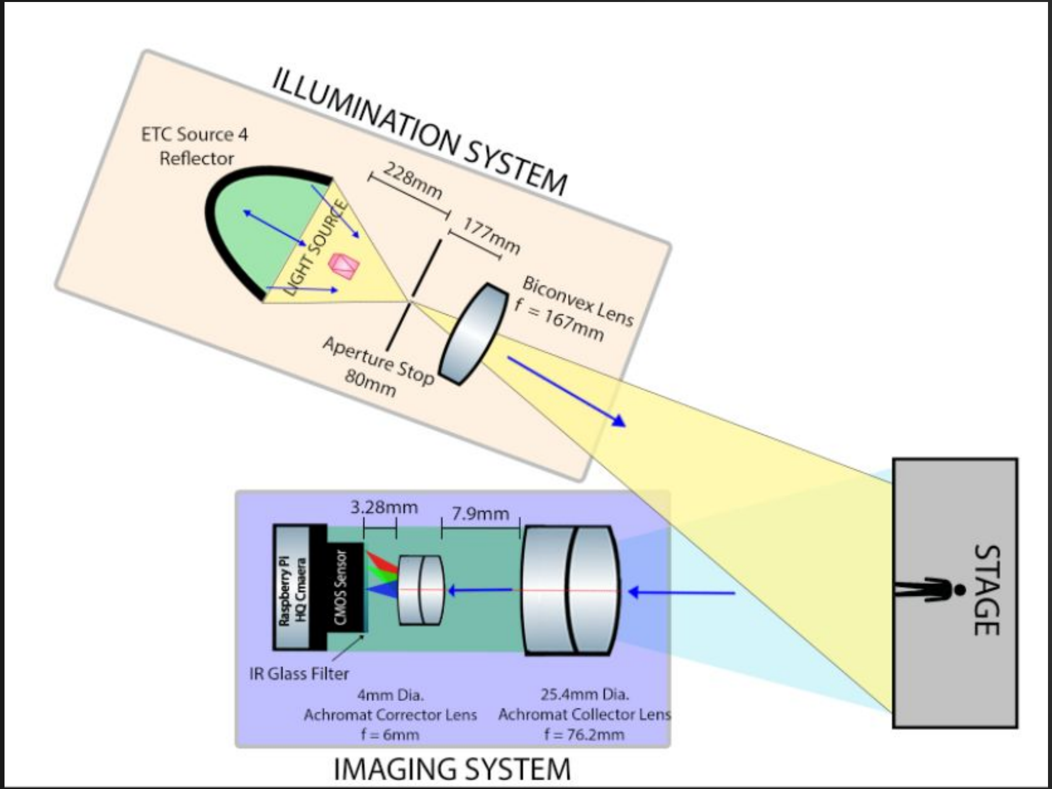
Lazy-Susan Operated

S.T.A.R. operates in a pan and tilt motion

Pan: Operated through a lazy-susan style mount

Tilt: Operated through 1:1
gear ratio

Optical Design



- Illumination system composed of a high power, broadband 3000k LED source
- Reflector absorbs heat (IR radiation) and reflects visible light
- Imaging plane at the gate allows for projection of images/patterns
- BK7 lens after the gate to focus output light

- Imaging system is stationary, placed at the base of the system
- Uses raspberry pi HQ camera
- Double lens system, to ensure accurate, clear imaging

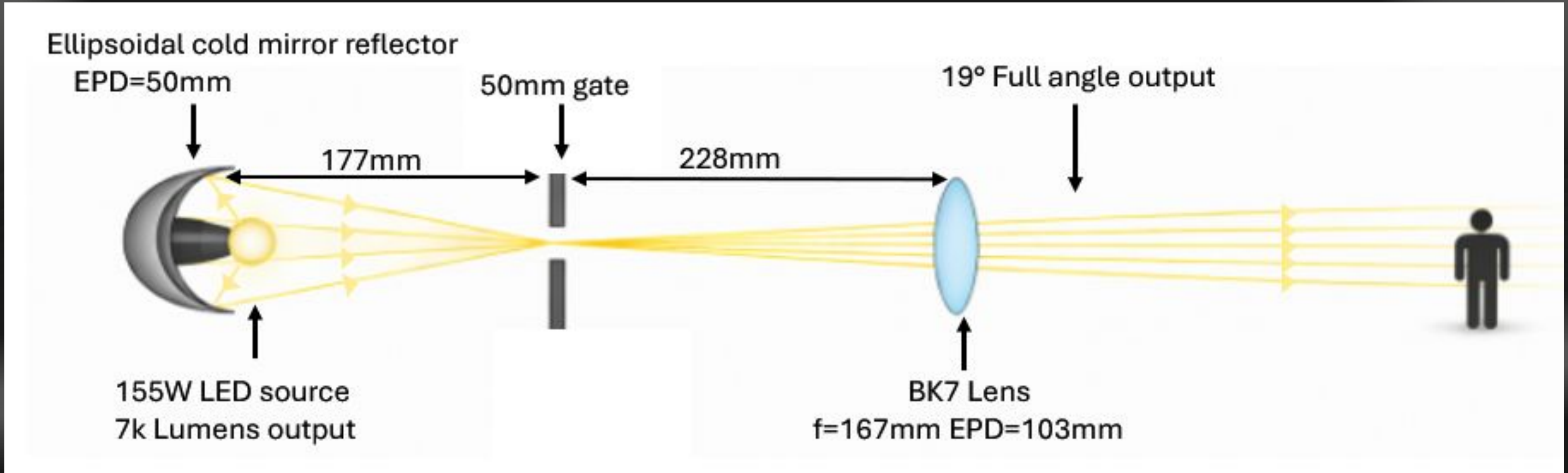
$$tan(\theta) = \frac{1.25}{7.5} = 9.5$$

Illumination System

- Calculations for the illumination system were made around the requirement that the full angle output be 19°. This was determined using basic geometric laws given two requirements: spot diameter=2.5m, and the distance from the source to the subject = 7.5m.

- 50mm gate size is a standard in stage lighting, so it was chosen for compatibility with existing accessories.

- The cold mirror reflector that was chosen fit the geometry of our system, so EPD=50mm and an output angle of 36°



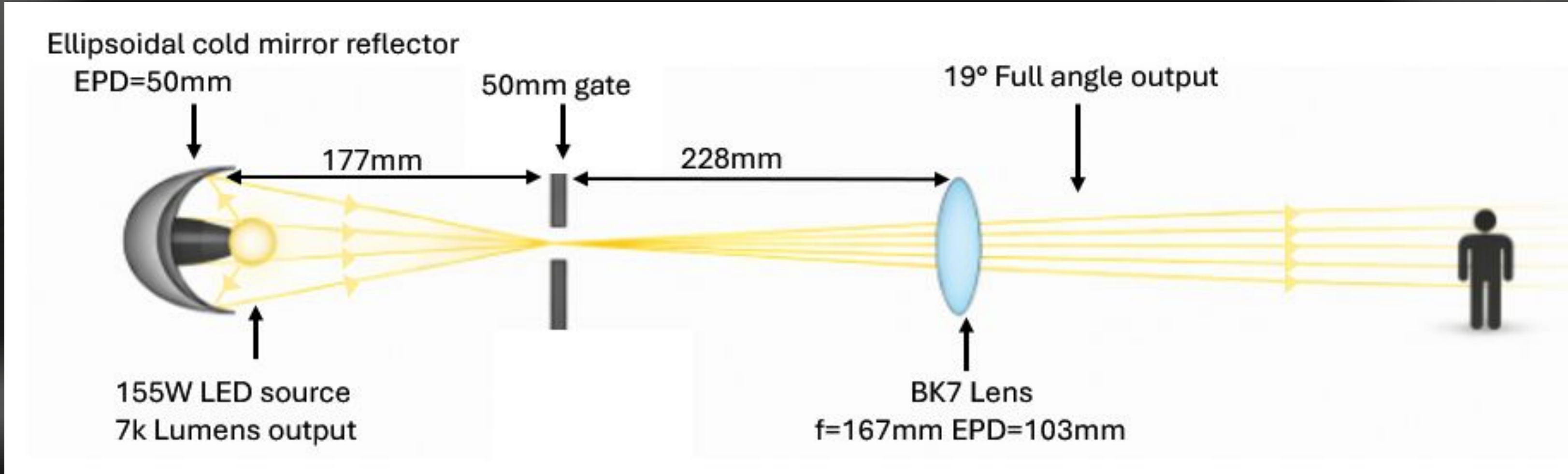
Illumination System

1. $NA = n(sin(\frac{\Theta}{2}))$ → $NA = (sin(18)) = .31$

2. $NA = \frac{1}{2(f/\#)}$ → $f/\# = \frac{1}{2(.31)} = 1.618$

3. $f = \frac{r}{tan(\Theta/2)}$ → $f = \frac{25}{tan(8.5)} = 167mm$

4. $EPD = \frac{f}{f/\#}$ → $\frac{167}{1.618} = 103mm$



Lens selection

Parameter	Calculated	Selected COTS Lens	Unit
Focal Length	167	171	mm
EPD	103	105	mm
Material	BK7	BK7	–

- The lens implemented in the system meets design requirements

Source selection

- Three different styles of light sources were considered for selection:
  - 1. Tungsten-halogen lamp (Incandescent)
  - 2. Integrated RGBW Engine
  - 3. LED COB (Chip-on-board) Module

- Tungsten-halogen lamp provides the most aesthetically pleasing light due to its broadband emission, but produce extreme heat (500C)
- LED arrays are very compact and provide multiple color options, but require significantly more optics for collection, color mixing, and projection.
- Remote-phosphor LED light engine provides high output, and impressive temperature regulation due to the core being a copper heat pipe.

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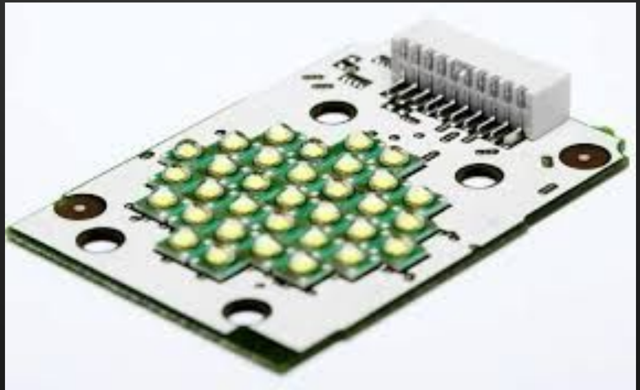

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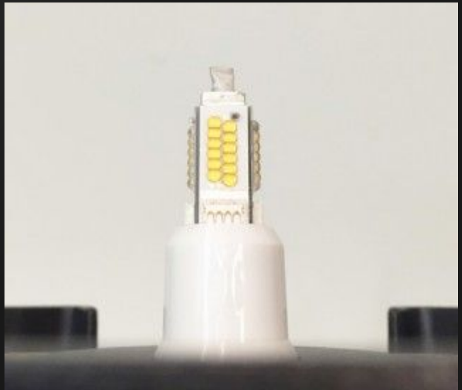


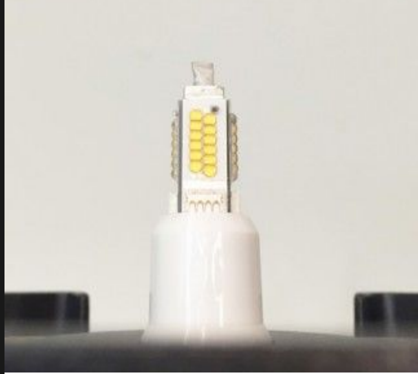
Source selection

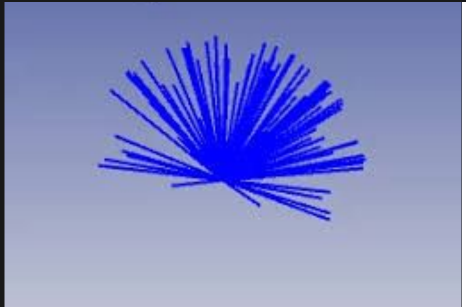
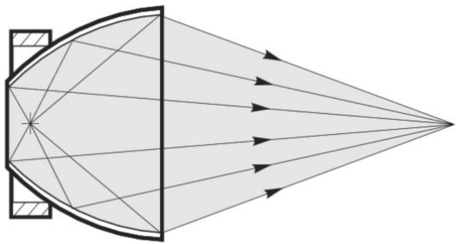
Criteria	HPL 757 Halogen Lamp	High-Power LED COB Module	Integrated RGBW Engine	Unit	Best Option
Luminous Output (lm)	≈ 5000	4500–6000	3500–5000	Lumens (lm)	LED COB Module
Efficiency (lm/W)	≈ 18	≈ 90	≈ 70	(lm/W)	LED COB Module
CRI	> 85	80–90	> 90	Percent	Integrated RGBW Engine
Thermal Load	High	Moderate	Low	-	Integrated RGBW Engine
Lifetime	300–500	25,000+	20,000+	Hours	LED COB Module
Cost	~$20	~$80	~$150	USD	HPL 757 Halogen Lamp
Integration Ease	Direct fit to housing	Requires adapter + driver	Custom driver needed	-	HPL 757 Halogen Lamp

- The LED COB module emerges as the strongest overall option based on these comparisons.

Reflecting vs. Refracting source optics

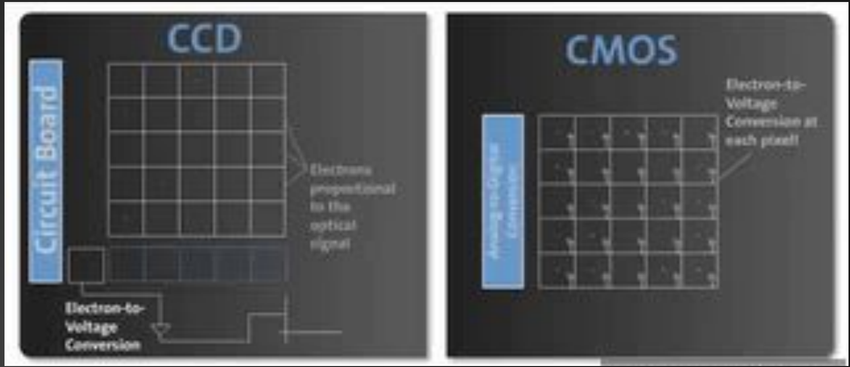
- Using a lens to try to focus light from a lambertian emitter only collects about 5-10% of the output light
- An ellipsoidal reflector collects roughly 50-70% of output light
- Reflector chosen is the ETC Source 4WRD Ellipsoidal Reflector
- Reflector coating absorbs heat, reflects visible light. (cheaper than lens coating)



Sensor Technologies - CCDs vs CMOS

Specification	CCD	CMOS
Frame rate	Slower	Faster
Temperature control	Requires cooling	Does not require cooling
Power consumption	High power usage	Low power usage
Output noise level	Low	High
Cost	More expensive	Less expensive



The chosen technology between the sensors was the CMOS sensor, primarily due to its lower power usage and lower cost.

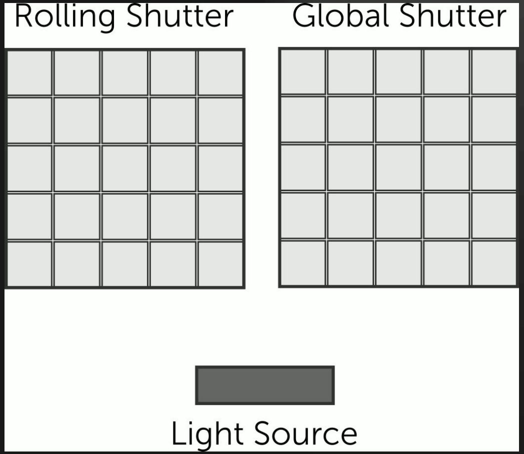
Not requiring cooling is a benefit as other systems within S.T.A.R. may already emit heat, causing an increase in dark current in CCD sensors

Sensor Technologies - Global vs Rolling Shutter

There are two main types of sensor technology that was considered:

1. Global Shutters - capture an entire scene and its pixels in an instant simultaneously
2. Rolling Shutters - reads and exposes images and pixels line-by-line sequentially

Specification	Global Shutter	Rolling Shutter
Sensor Size	Larger	More Compact
Cost	High	Significantly lower
Power Consumption	Higher	Lower
Availability	Limited	Widely available

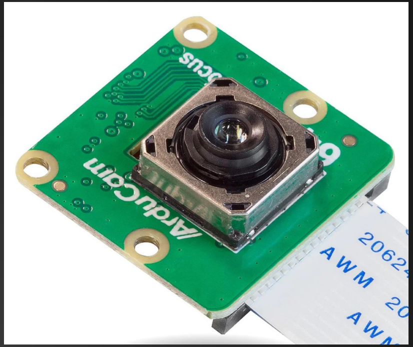


After consideration we ultimately chose for a rolling shutter sensor due to a cost vs performance analysis.

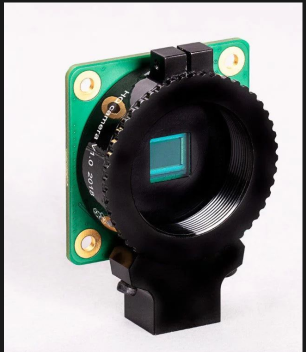
The smaller size and lower power consumption helps support our system despite a small cost in the imaging capabilities.

Sensor Part Comparison

Specification	ArduCam Pi Hawk-eye	Raspberry Pi HQ Camera
Net Price	$65	$50
Shutter Type	Rolling Shutter	Rolling Shutter
Sensor	Sony IMX686	Sony IMX477
Sensor Resolution	9152 x 6944 pixels	4056 x 3040 pixels
Still Resolution	64 megapixels	12.3 megapixels
Horizontal Image Area	Not Specified	6.287mm
Vertical Image Area	Not Specified	4.712mm
Pixel Size	0.8 μm × 0.8 μm	1.55 μm × 1.55 μm
Horizontal Field of View	74 degrees	Lens Dependent
Vertical Field of View	55 degrees	Lens Dependent
Lens Mount	Non-interchangeable	C/CS or M12 Mount



ArduCam Pi Hawk-eye


Raspberry Pi HQ Camera

Ultimately chose Raspberry Pi HQ Camera as cost-effective option with enough pixels to image our target.

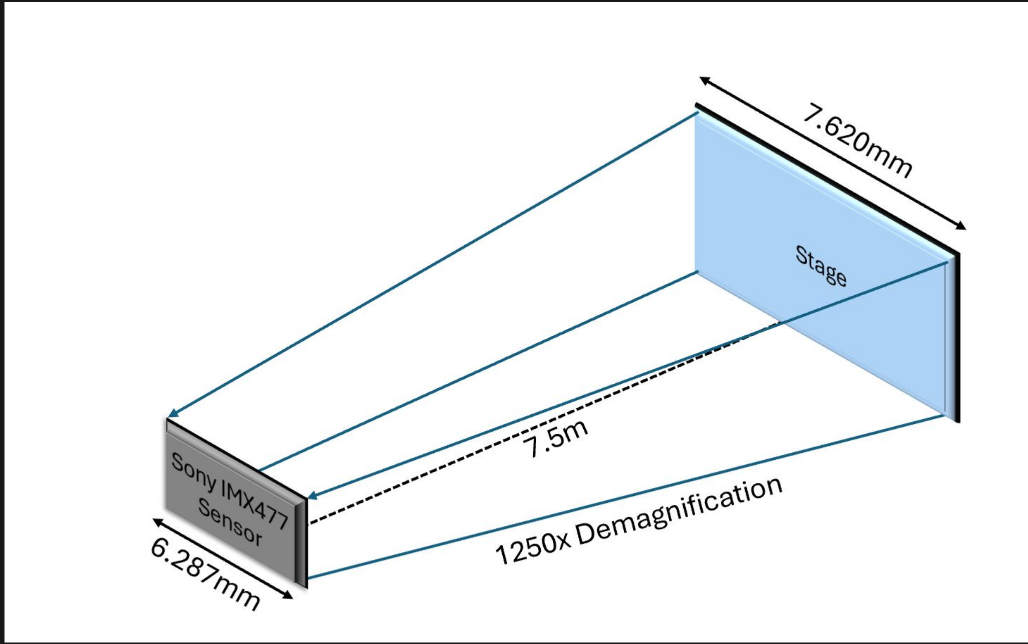
Transmittance in visible wavelength ranges, with filter in the IR region (650nm)

Lens System Parameters Calculations

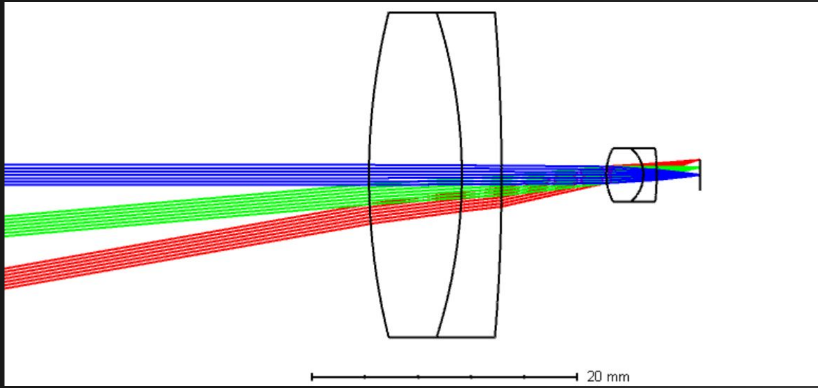
We want to image a stage with length of ~7.62m at a distance of 7.62m

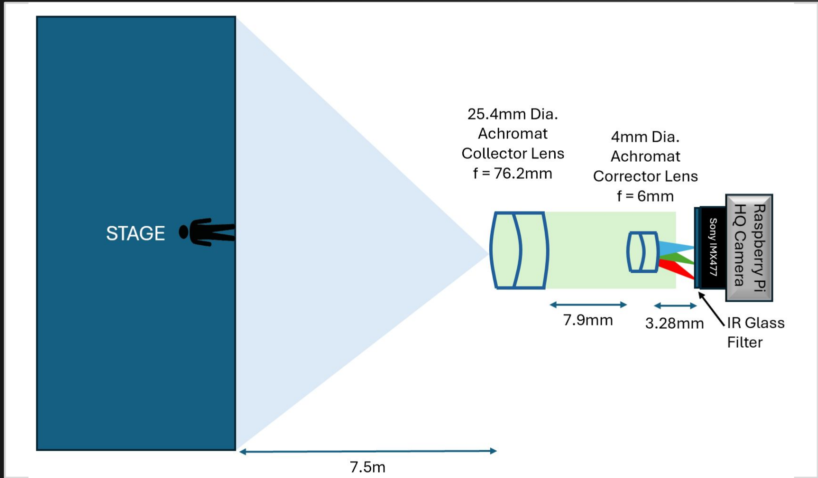
$$M = \frac{h_i}{h_o} = \frac{L_{Sensor}}{L_{Stage}} = \frac{6.287mm}{7620mm} = 0.0008 \approx \frac{1}{1250}$$

The target magnification is a 1250x demagnification to image the entire FOV of the stage, alongside any performers on it to the incident sensor



Lens Design





Achromatic Doublets
Used for every lens to mitigate the amount of chromatic aberration appearing on the sensor.

Front Entrance Lens
Large diameter to minimize vignetting and maximize light collection and capture the full field needed to image the stage.

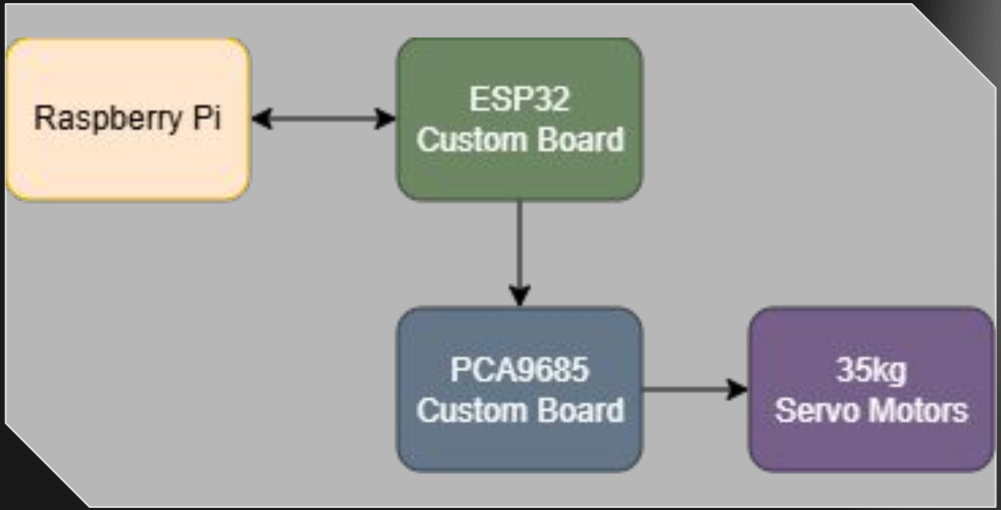
Imaging Corrector Lens
Ensures accurate imaging and accounts for other aberrations (spherical, coma, field curvature).

IR Glass Filter
Provides more mitigation of the IR light, cutting off wavelengths above 650nm

Coatings
Specialized COTS coatings primarily used to transmit solely in the VIS wavelengths optimizing it for the 400-700nm range.

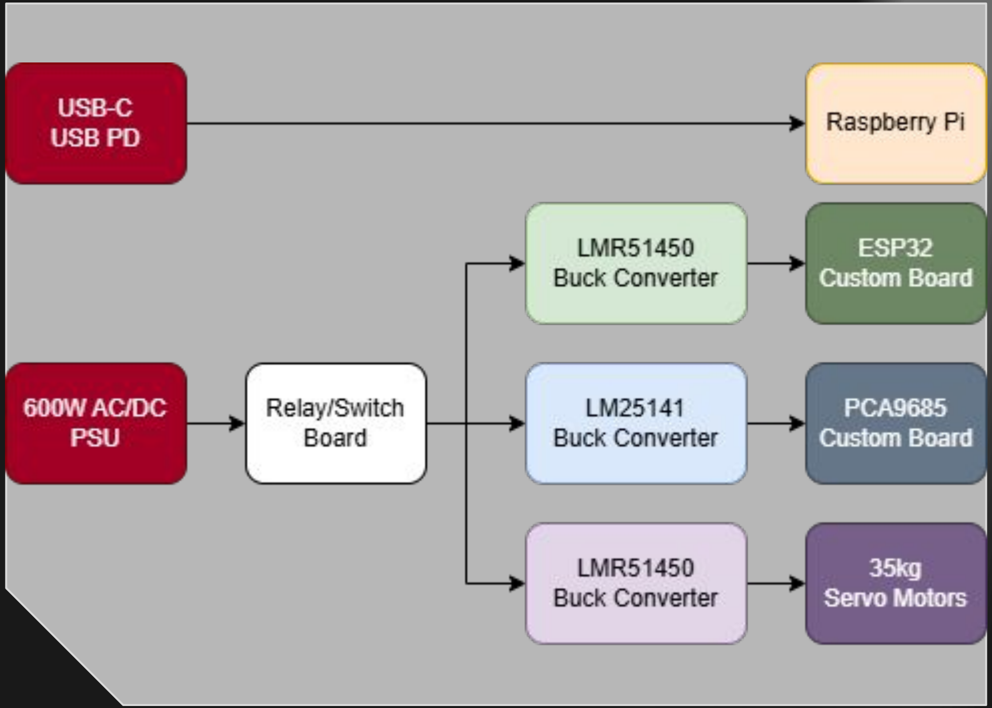
Hardware Block Diagram - High Level

- Raspberry Pi transmits/receives data to/from ESP32 through UART connection
- ESP32 transmits data to PCA9685 through I2C
- PCA9685 controls servo motors using PWM signals



Hardware Block Diagram - Power Delivery

- Raspberry Pi receives power independently through a USB-C power supply
- 600W PSU connects to custom switch board
- Various Texas Instrument LMxx ICs are used to step down the PSU output to rated values for our ESP32, PCA9685, and motors



Hardware Selection - SoM vs SBC

- SoM was chosen over SBC for the ability to design a custom carrier board
- Custom CM5 carrier was initially planned, high-speed PCB requirements made it impractical within our time and cost constraints.

Attribute	System-on-Module (SoM)	Single Board Computer (SBC)
Integration Level	Core computing components only (CPU, RAM, storage, GPU). Requires carrier board.	Fully integrated with I/O ports, power management, and interfaces on a single PCB.
Design Flexibility	Highly customizable—carrier board can be tailored for specific project needs.	Limited customization—fixed I/O layout and hardware configuration.
Scalability	Easier to upgrade by replacing the compute module without redesigning the carrier.	Typically requires replacing the entire board to upgrade hardware.
Manufacturing Cost	Higher initial design cost but scalable for production runs.	Lower cost for prototypes and small projects.
Thermal Management	Can be optimized with custom heat dissipation solutions.	Fixed thermal design based on vendor layout.

Hardware Selection - MCU vs FPGA

- FPGAs require specialized knowledge to develop increasing project risk and design effort.
- An MCU was selected as the most cost-effective, power-efficient, and development-friendly solution for the system.

Attribute	MCU (e.g., ESP32-S3)	FPGA
Programming Complexity	Easy—uses C/C++ or MicroPython.	High—requires HDL (VHDL/Verilog) and synthesis tools.
Development Speed	Rapid—large ecosystem and open-source libraries.	Slower—requires detailed logic design and timing closure.
Power Consumption	Low; ideal for embedded and battery-powered systems.	High; often requires cooling and significant power overhead.
Cost	Very low (<$10 for ESP32-S3).	High ($50–$200+ depending on FPGA).
Reason Chosen for S.T.A.R.	The ESP32-S3 provides real-time motor control, Wi-Fi, and I^2C communication in a compact, low-cost package.	FPGA unnecessary for S.T.A.R.'s moderate control and vision needs.

Hardware Selection - ESP32 vs STM32

- ESP32 was chosen for S.T.A.R. due to ease of development, integrated wireless connectivity, and cost effective pricing for units

Attribute	ESP32-S3	STM32 (e.g., STM32F4/F7)
Wireless Connectivity	Integrated Wi-Fi + Bluetooth 5.0	Requires external modules
I/O Interfaces	I^2C, SPI, UART, PWM, USB, ADC, DAC	Extensive peripheral support
Ease of Development	Excellent—supported by Arduino, ESP-IDF, and MicroPython	Good—requires STM32CubeIDE
Chosen for S.T.A.R.	Offers wireless connectivity, powerful dual-core processing, and efficient servo control via I^2C (PCA9685).	STM32 better for high-precision control but costlier and lacks wireless integration.

Hardware Selection - Servo vs Stepper

- Servos feature a simplified control architecture, allowing direct PWM control.
- Servo motors were selected for S.T.A.R. because they provide smooth, precise motion with integrated positional feedback.

Attribute	Servo Motors	Stepper Motors
Rotation Range	Typically limited (e.g., 180°–270°), suitable for fixed-orientation systems	Capable of continuous 360° rotation
Motion Smoothness	Smooth, continuous motion ideal for fluid pan/tilt tracking	Discrete stepwise motion can cause vibration or “jitter”
External Circuitry Required	Minimal (PWM controller such as PCA9685)	Moderate to high (stepper driver, current regulation, optional encoders)
Torque Characteristics	High torque at low speeds; torque chosen via rated servo strength	Torque drops off rapidly at higher speeds
Suitability for S.T.A.R.	Excellent—supports smooth tracking, stability, and simplified integration	Less ideal due to vibration, complexity, and tracking instability

Hardware Selection - Motor Controller

- Direct PWM generation using the ESP32 deemed impractical for multi-servo control due to processor load.
- The Adafruit PCA9685 selected for its 16-channel capacity and I2C interface, enabling precise and synchronized servo control.

Attribute	PCA9685 (Adafruit)	TLC5940
Control Type	12-bit PWM over I2C	12-bit PWM over SPI
Communication Interface	I2C (addressable up to 62 devices)	SPI (faster, but fewer devices)
Ease of Integration	Very easy—widely supported by Arduino, ESP32, and Raspberry Pi	Moderate—requires more configuration
Power Handling	Separate servo power rail; supports up to 6V	External current sink required
Chosen for S.T.A.R.	Offers high channel count, reliable timing, and I2C compatibility with ESP32-S3 for smooth servo control.	TLC5940 lacks flexibility for multi-servo synchronization.

Hardware Design - Power Budget Table

- The S.T.A.R. system requires a minimum power supply of 17V and 13A.
- A 600W (24V 25A) PSU was chosen to meet the voltage and current requirements for the system

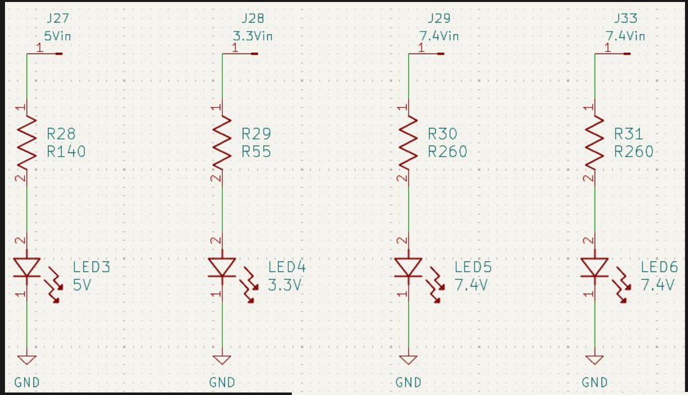
Component	Voltage Requirement	Current Requirement
ESP32	3.3V	1A
PCA9685	5V	400mA
35kg Servo Motors (3x)	~8.4V	3.9A / Each (Stall)
TOTAL	~16.7V	~13A
Our PSU	24V	25A

Hardware Selection - Buck vs LDO

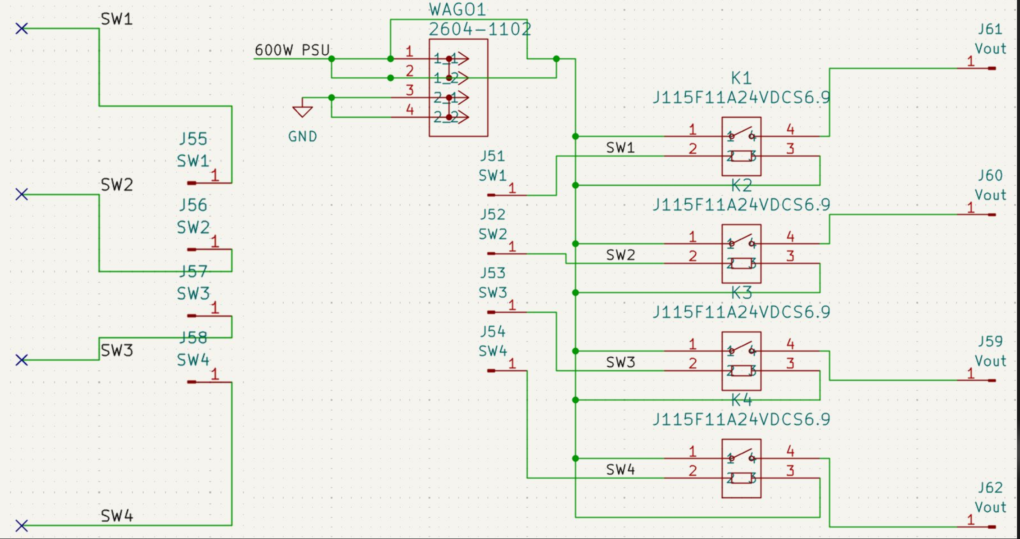
- Buck converters offer high efficiency when stepping down large voltage differences.
- LDOs were not suitable because they dissipate excess voltage as heat.
- TI WEBench was used to select and design regulator schematics

Attribute	Buck Converter (Switching)	LDO (Linear Regulator)
Heat dissipation	Low (most energy converted, small losses).	High (dissipates (Vin−Vout)×I as heat).
Transient response	Good, but requires loop compensation; faster switching designs respond well.	Very fast and clean transient response for small load steps.
Complexity and BOM	Higher: inductor, diode/synchronous FETs, switching IC, output/input capacitors, layout care.	Lower: single component, few external caps.
Transient response	Good, but requires loop compensation; faster switching designs respond well.	Very fast and clean transient response for small load steps.
Efficiency	High (typically 80–95% depending on load and design).	Low when Vin ≫ Vout (efficiency = Vout/Vin).

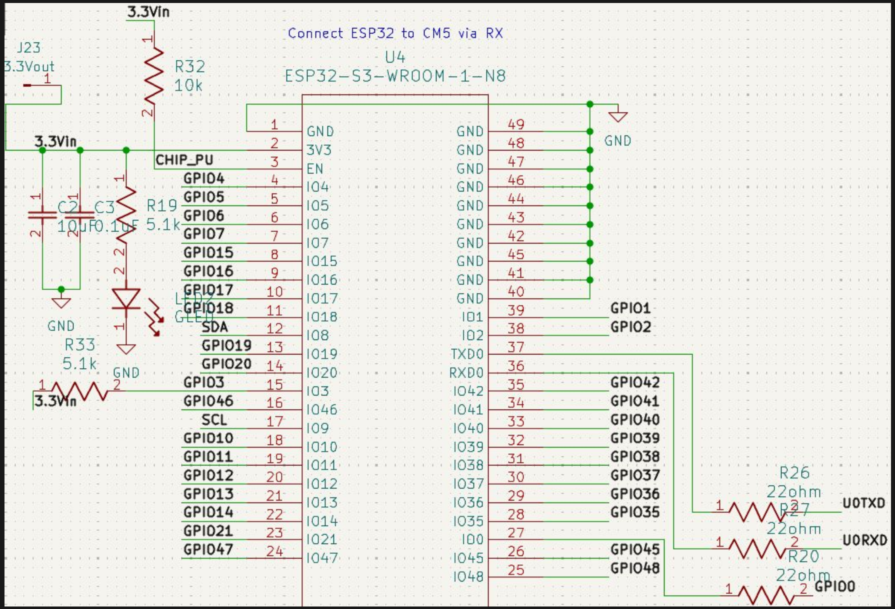
Overall Schematics - Terminal Board



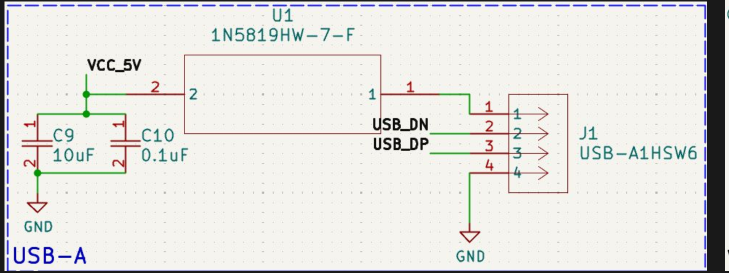
- Custom terminal switch board
- 4x automotive relays used to isolate each power circuit
- Auxiliary status LEDs for each regulator board

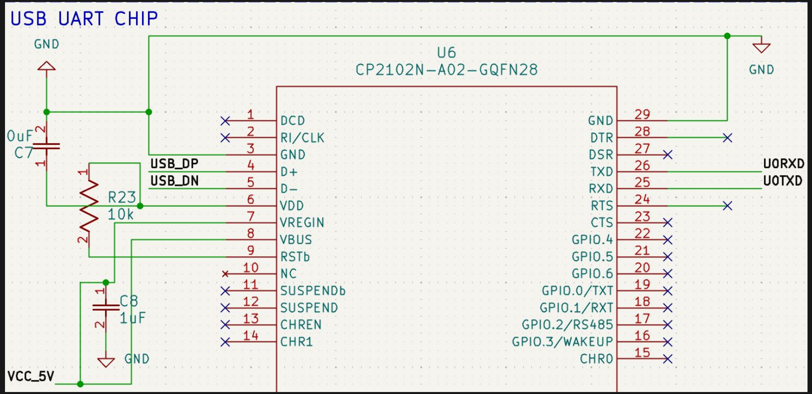


Overall Schematics - ESP32



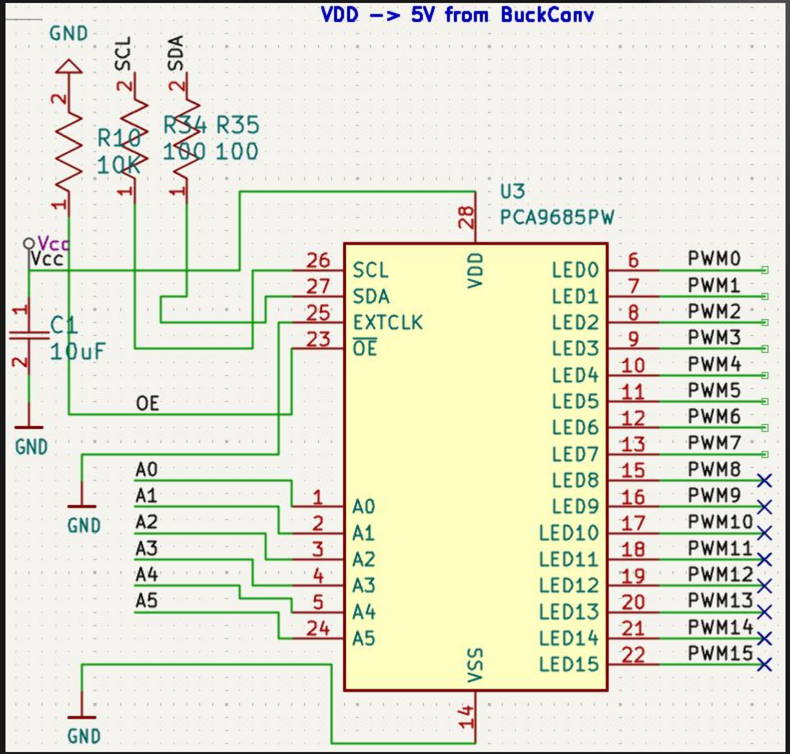
- Custom ESP32 board
- USB-A interface for programing MCU
- Custom board for ESP32 was chosen for S.T.A.R. due to ease of development and readily available documentation

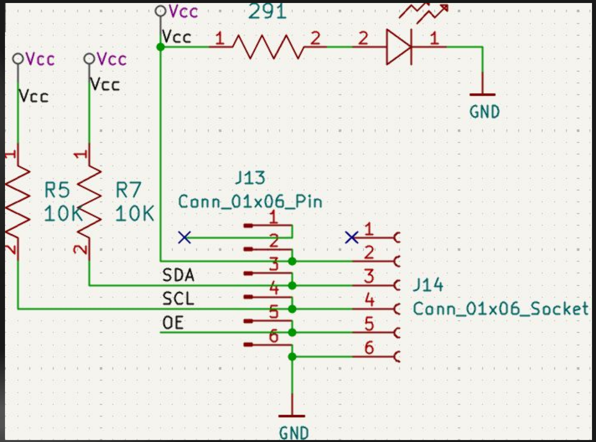




Overall Schematics - PCA9685

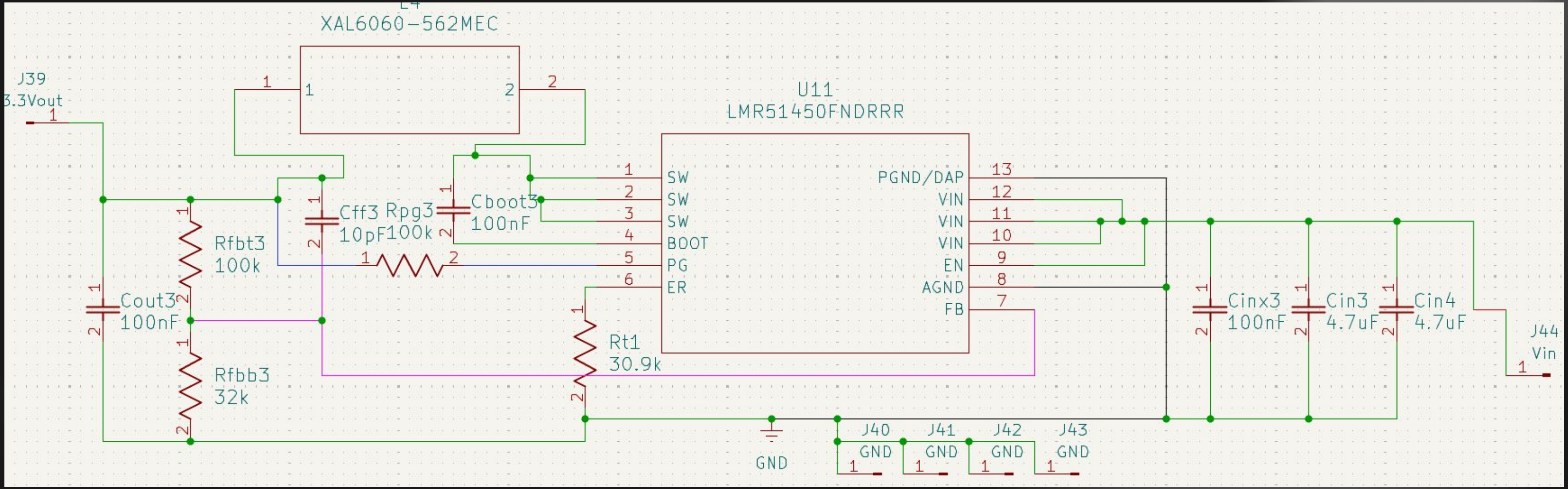
- Custom motor controller board was chosen for S.T.A.R. to meet PCB requirements
- No power rail for motors. External source needed





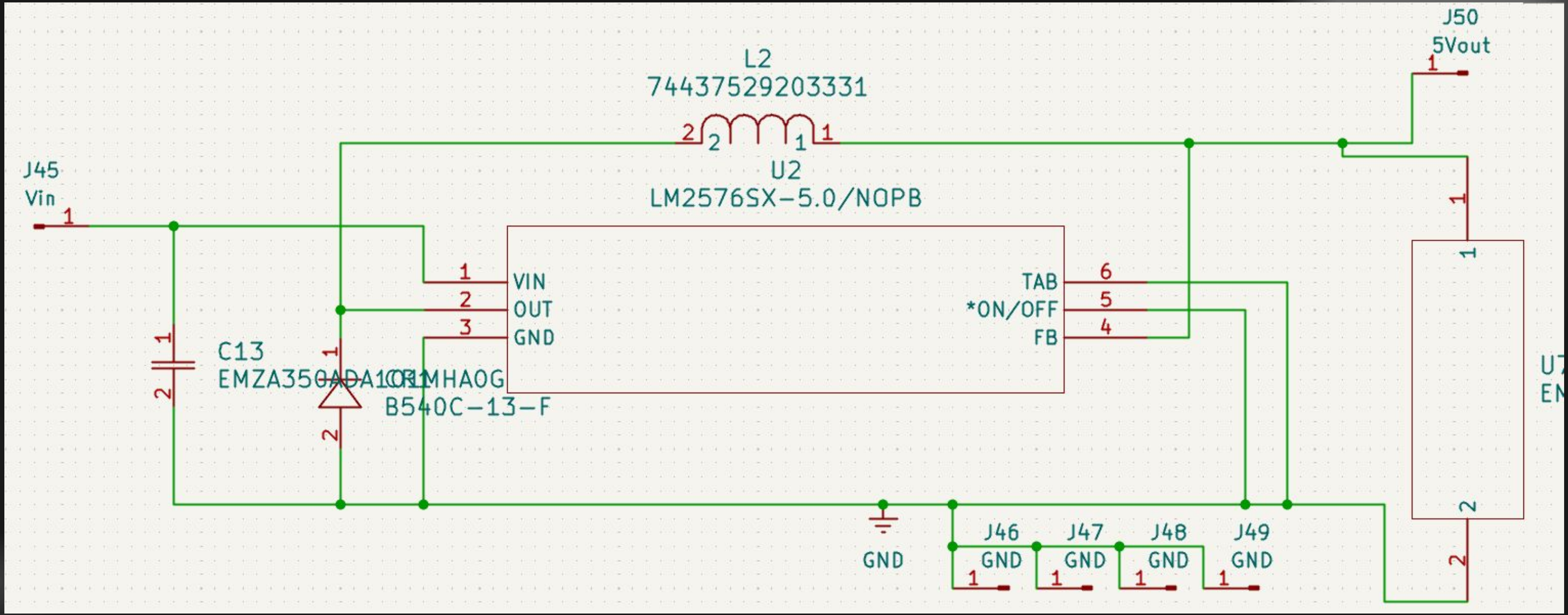
Overall Schematics - 3.3V Regulator

- TI LMR51450 used for its robust (36Vin, 5Aout) ratings
- High voltage rating needed because of 24V PSU
- Circuitry was designed using TI WEBENCH power designer



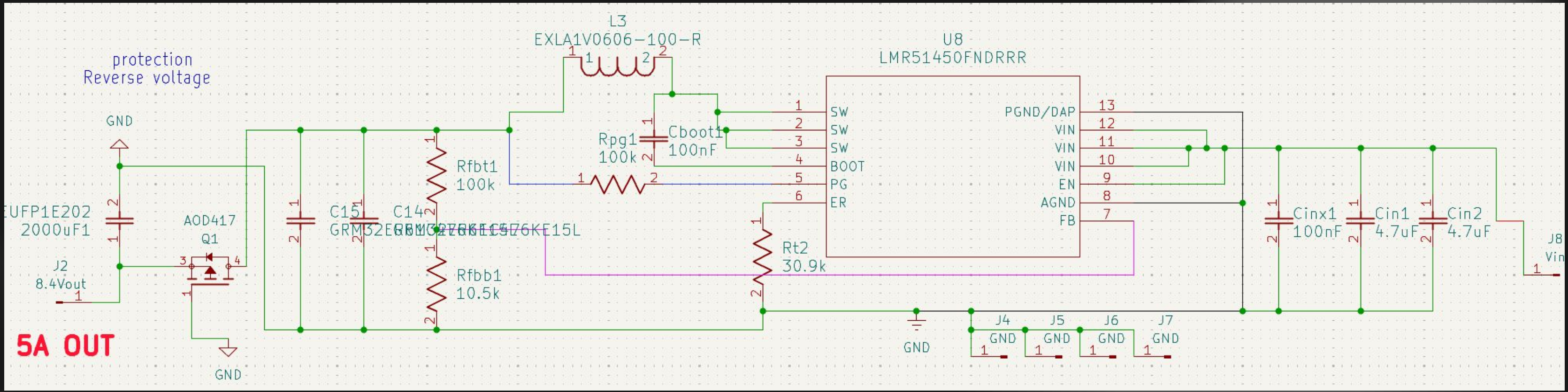
Overall Schematics - 5V Regulator

- TI LM2576 used. Recommendation from Dr. Weeks because of availability and simplicity.
- Rated for 45Vin and 3Aout
- Circuitry was designed using TI WEBENCH power designer

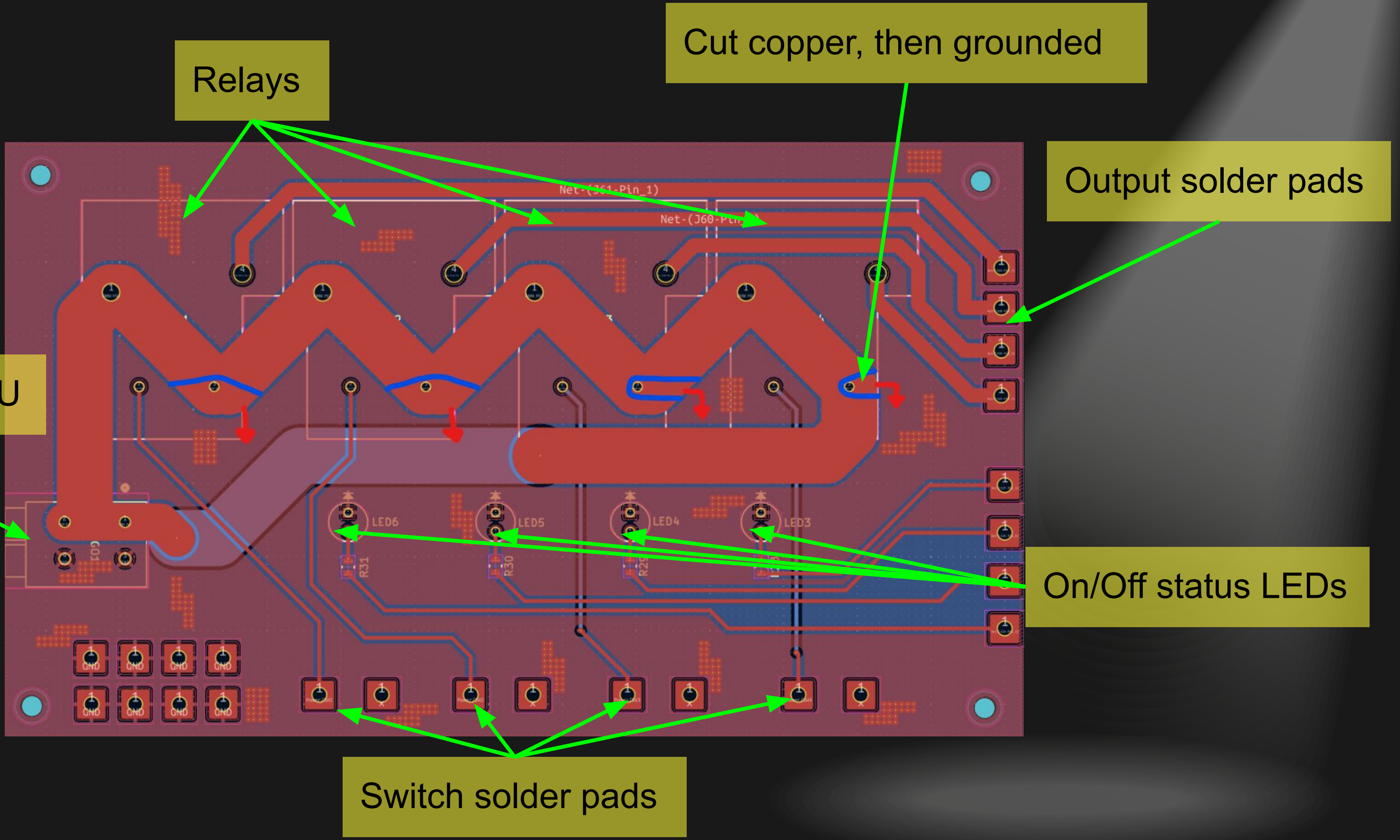


Overall Schematics - 8.4V Regulator

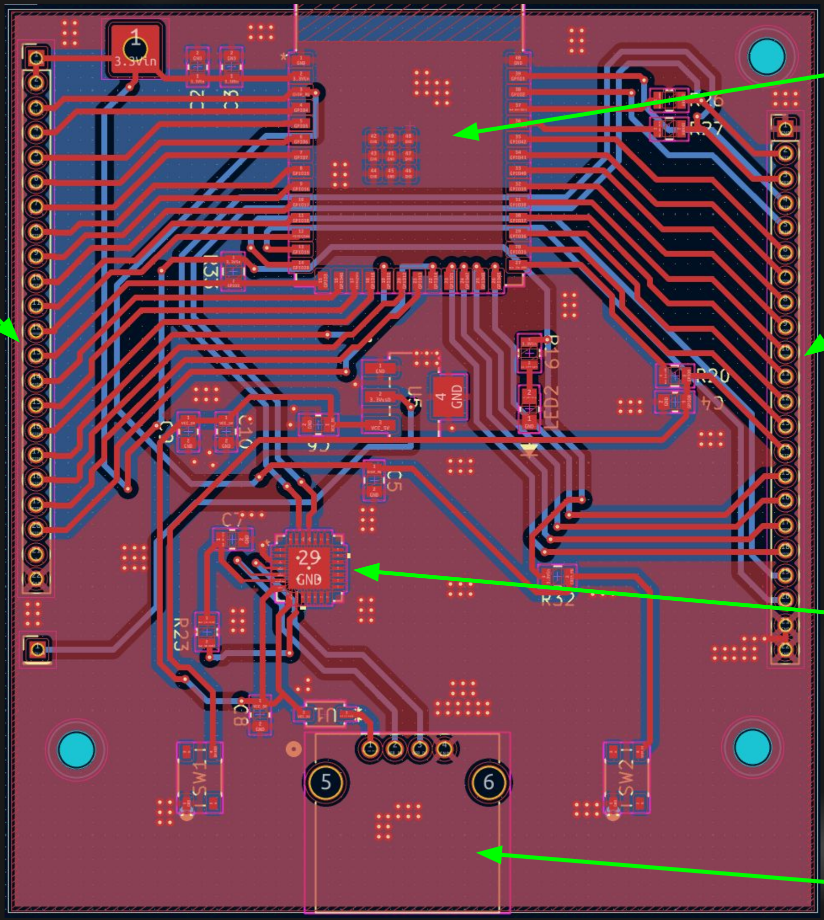
- TI LMR51450 used. Rated for a constant 5Aout.
- Output current has to be high to support the combined stall current of our motors
- AOD417 and 2000uF cap used at output for reverse voltage protection



PCB Layout - Terminal Board



PCB Layout - ESP32



GPIO Pins

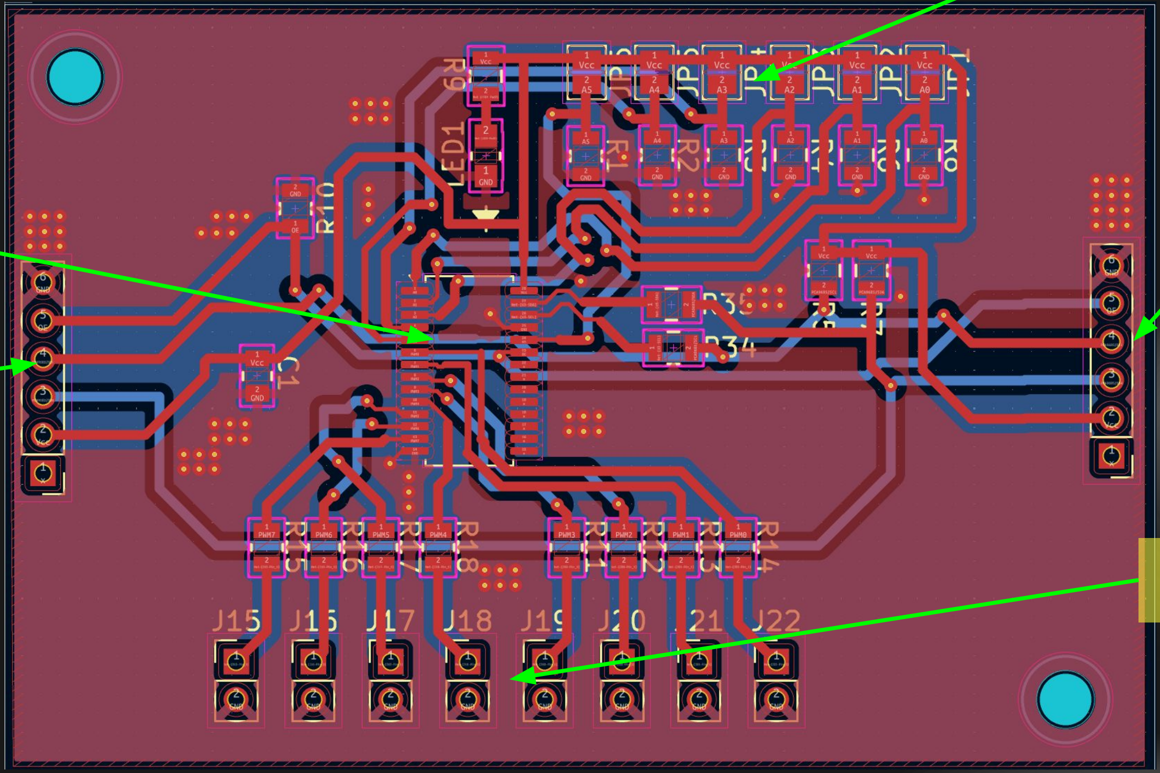
ESP32 Chip

GPIO Pins

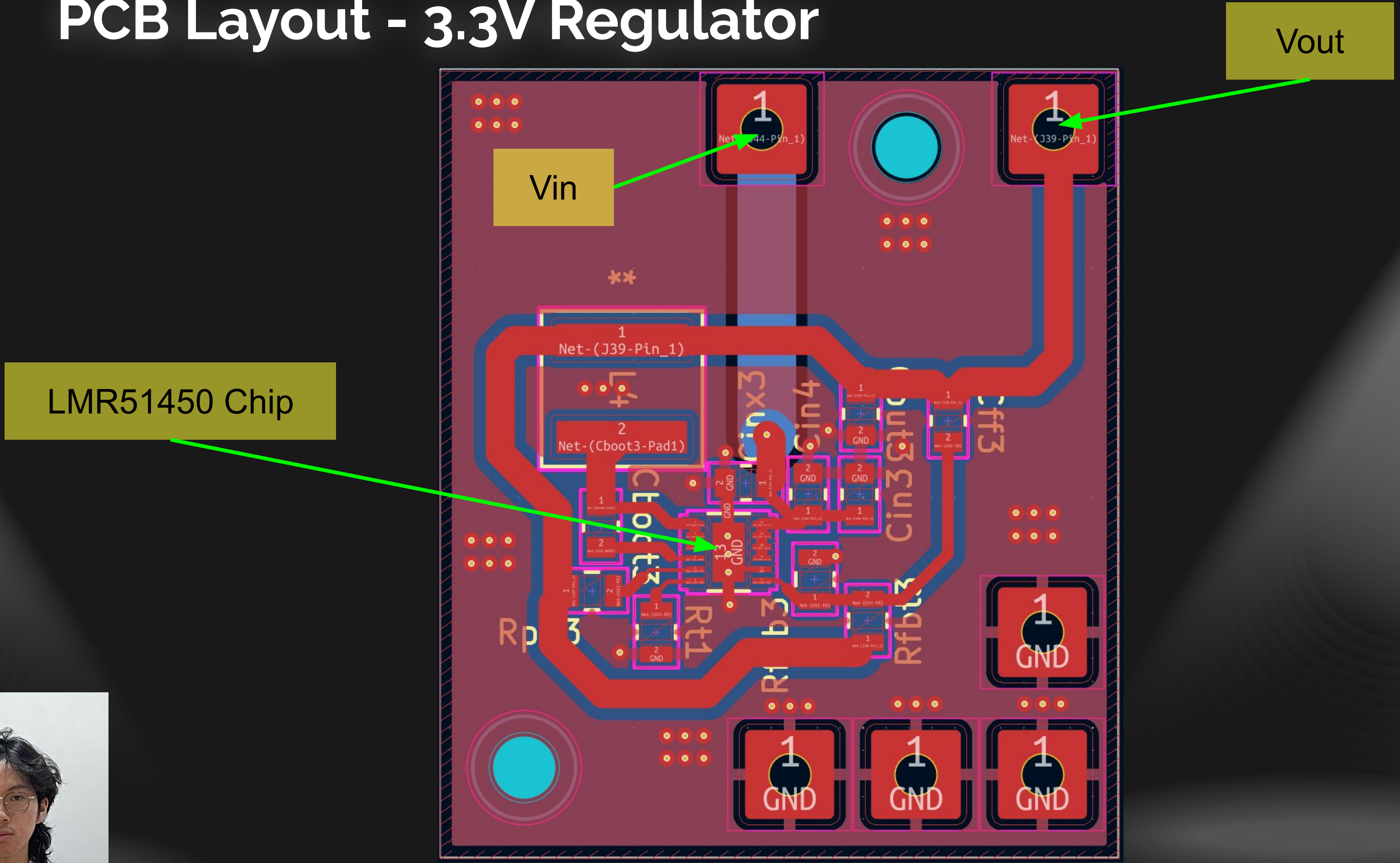
CP2102

USB-A Connector

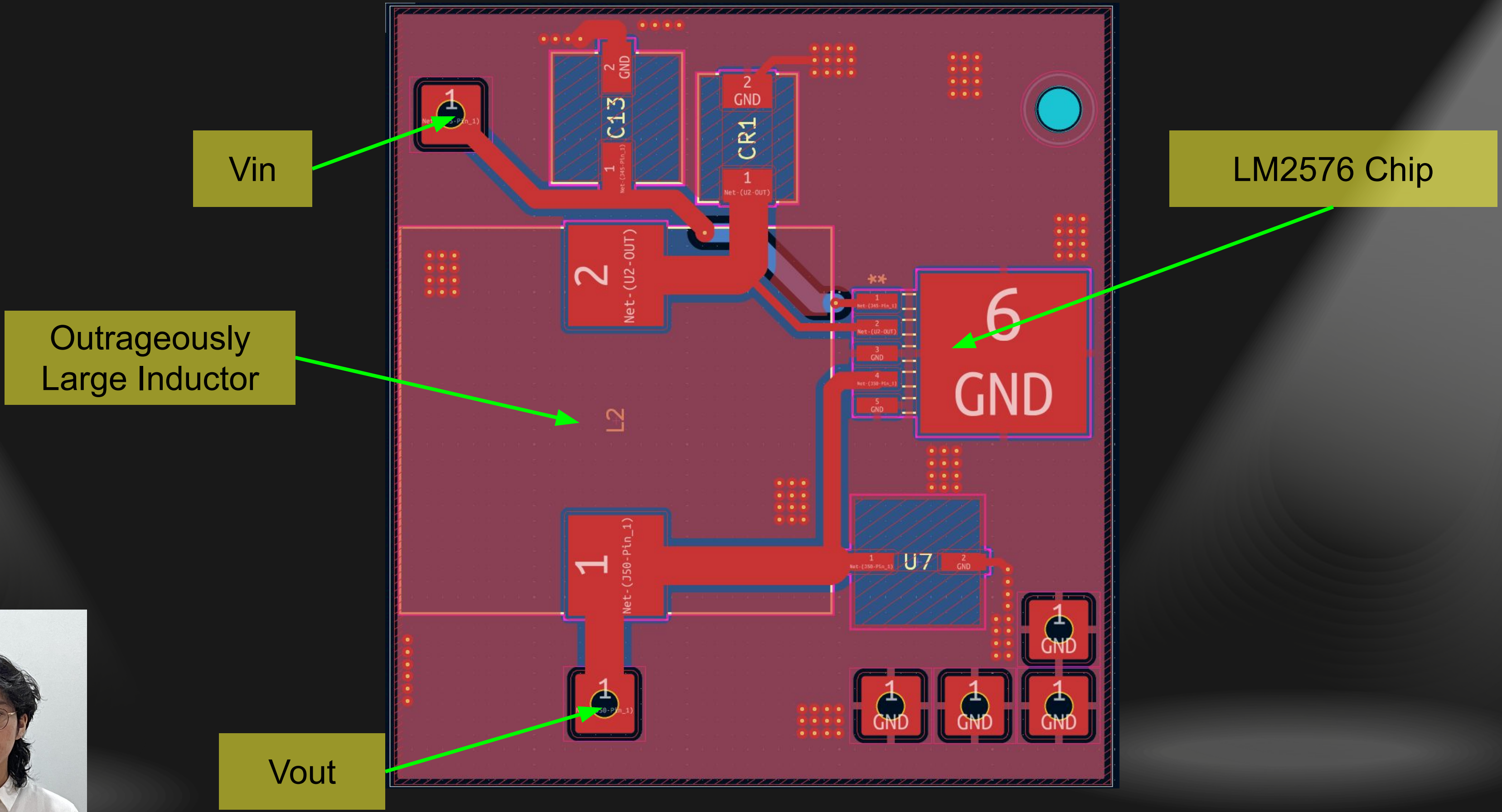
PCB Layout - PCA9685



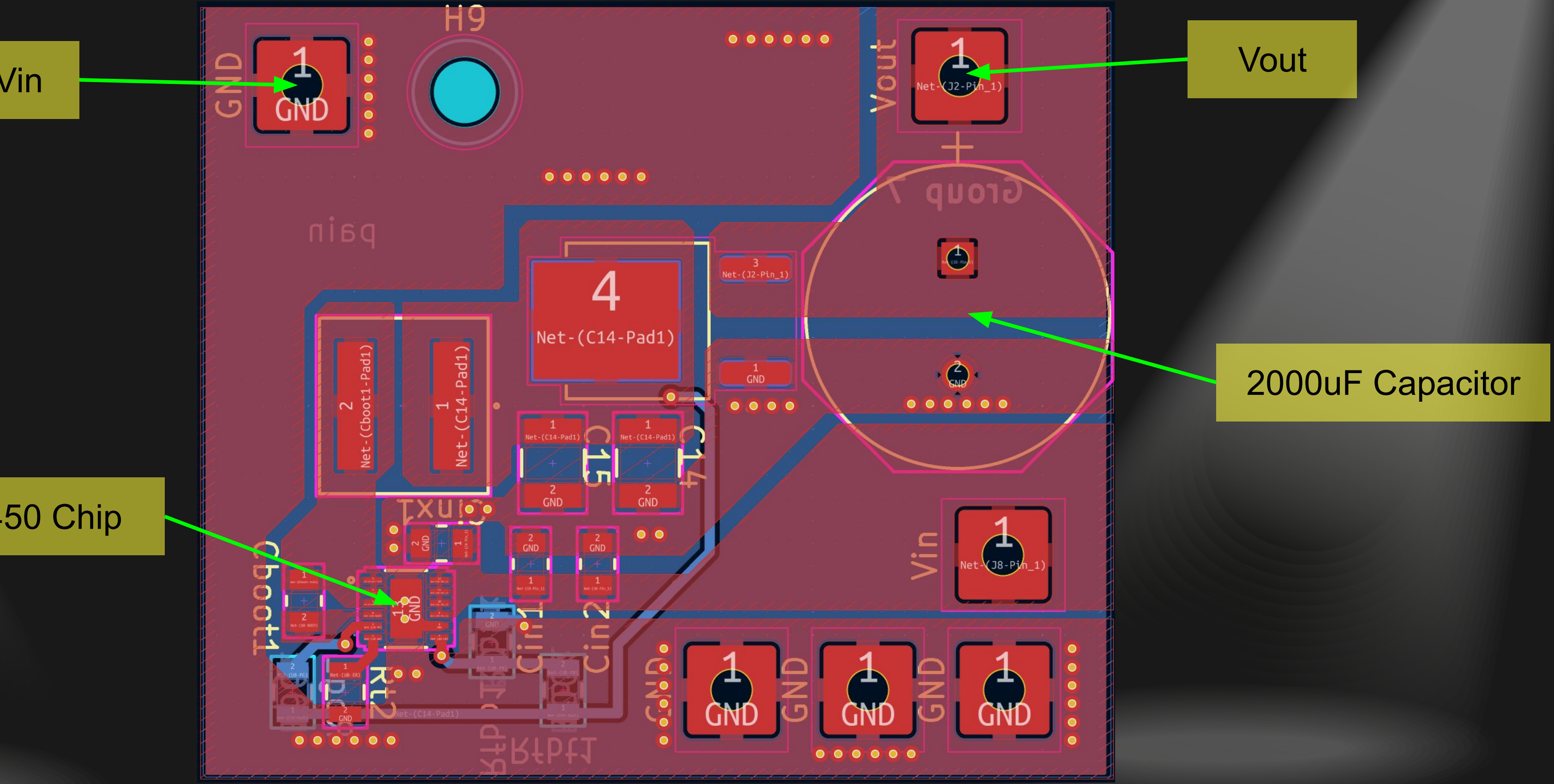
PCB Layout - 3.3V Regulator



PCB Layout - 5V Regulator



PCB Layout - 8.4V Regulator



Communication

Role:

- Communication between ESP32 and Raspberry Pi CM5

UART

- Simple, point-to-point serial communication protocol
- Low and predictable latency for real-time data exchange
- Well-suited for reliable MCU-to-processor communication in embedded systems

Method	UART	I2C	SPI
Wires	TX, RX, GND	SCL, SDA (+pull-ups), GND	SCLK, MOSI, MISO, CS, GND
Clocking	Asynchronous	Synchronous (open-drain)	Synchronous (push-pull)
Practical Rate	115.2 kbps–1 Mbps	100 kHz/400 kHz/1 MHz	1–20+ MHz
Determinism & Jitter	Good with framed packets and acks	Bus arbitration; moderate jitter under load	Very good, clocked

Communication

HTTP/REST

- Stateless request–response communication model
- Simple and reliable for configuration and system commands
- Higher overhead per message due to headers

WebSocket

- Persistent, bi-directional communication channel
- Enables low-latency, real-time data streaming
- Reduced overhead after initial connection

Criterion	HTTP/REST	WebSocket	MQTT
Setup cost	Request per action; keep-alive helps	One upgrade; then steady state	Broker + client connects
Push capability	No (client-pull only)	Yes (bi-directional)	Yes (publish/subscribe)
Per-msg overhead	High (headers)	Low (frame header)	Low (tiny header)
Backpressure	Ad-hoc	Event-loop awaits/queues	Broker buffer + QoS acks
Reconnect	Per request	Heartbeats & fast resume	Retained messages + QoS
Best use here	Config, logs	Primary real-time control	Future multi-client/IoT

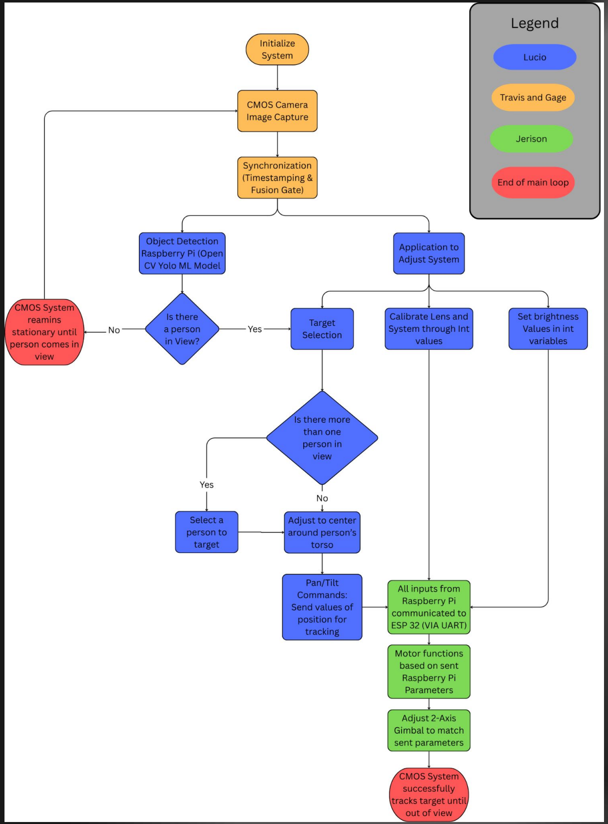
Software Design

Objectives

- Detect and track a single performer in real time
- Drive pan/tilt gimbal toward performer center
- Maintain smooth spotlight motion
- Communicate target error data to MCU in real time

Pipeline

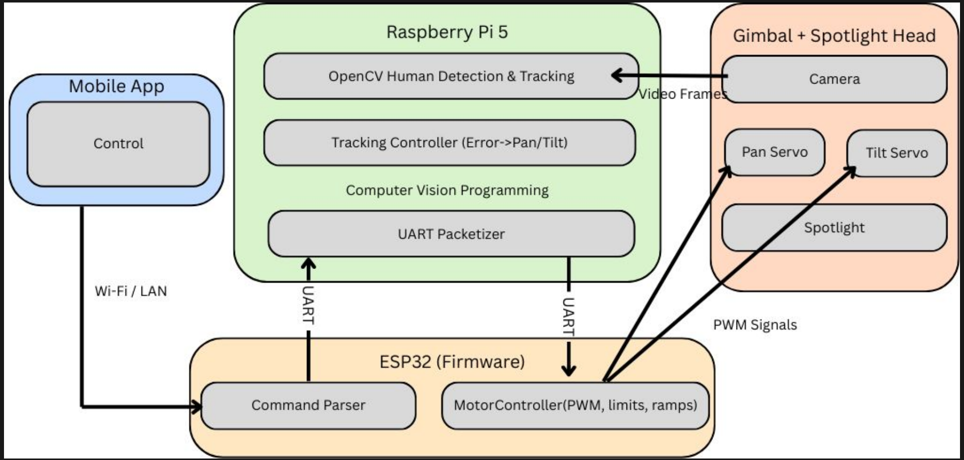
- Camera -> Detection -> Tracking -> Target Coordinates



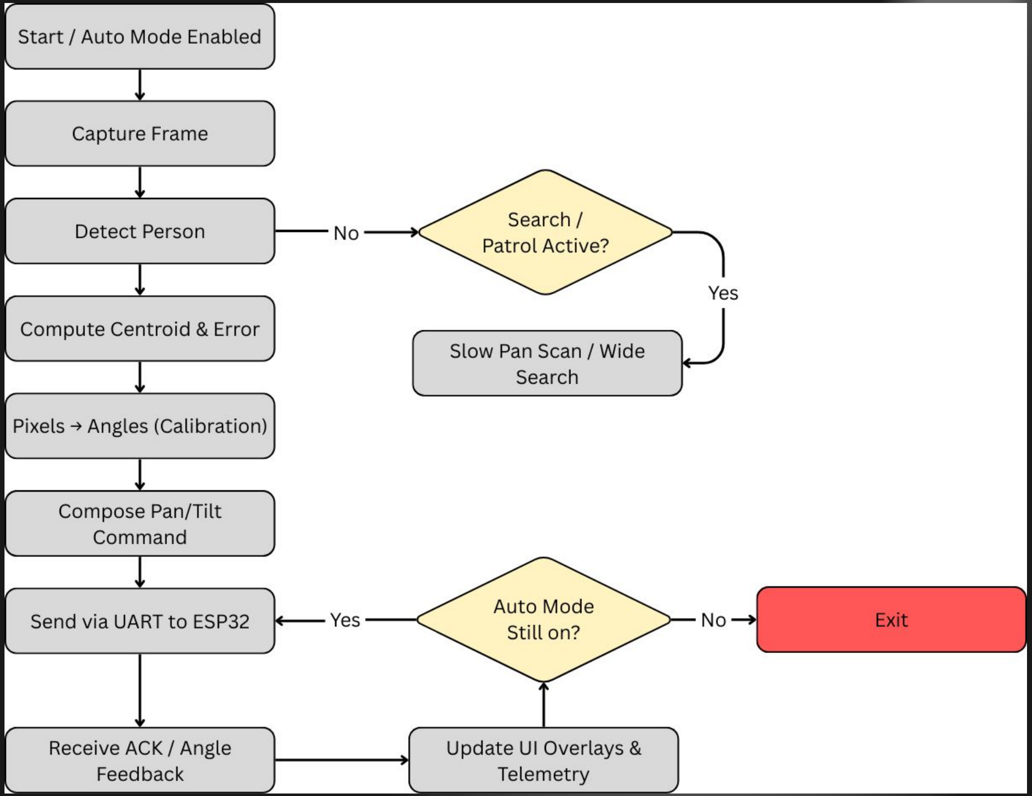
Software Design

Components

- Computer Vision - Detection
- ESP32 - Motorization
- Mobile App - Control



Computer Vision



Role:

- Capture live video from camera
- Detect and track performer
- Output target position data for motor control

Computer Vision

Raspberry Pi CM5

- Linux Based Embedded Computing
- Supports Native Camera interfaces
- Compatibility with Machine Learning Frameworks

Criterion	Raspberry Pi CM5	Nvidia Jetson Nano
Primary Role	Embedded Vision Programming	GPU-accelerated edge AI
Compute Capability	Quad-Core ARM Cortex-A76	Quad-Core ARM Cortex-A57
Compute Capability	Moderate-High (CPU + GPU)	High (CUDA GPU)
Power Consumption	4 - 8 W	5 - 10 W
Embedded Suitability	High	Medium
Cost Efficiency	High	Medium

Computer Vision

OpenCV

- Computer Vision Library
- Supports camera Input, object tracking, and image preprocessing
- Optimized for ARM-based systems

Criterion	OpenCV (Selected)	TensorFlow Lite	PyTorch/Torch Script	MediaPipe
Primary Role	End-to-end CV toolkit	Edge inference for TF models	Research DL; scripted deployment	Prebuilt perception graphs
Edge Readiness	High (CPU/NEON; broad backends)	High (quantization, delegates)	Medium (heavier runtime)	High (mobile/edge focused)
Pipeline Breadth	Wide (capture → inference → tracking)	Narrow (inference only)	Narrow → Medium	Medium (task-focused)
Integration Effort	Low	Medium	Medium–High	Medium

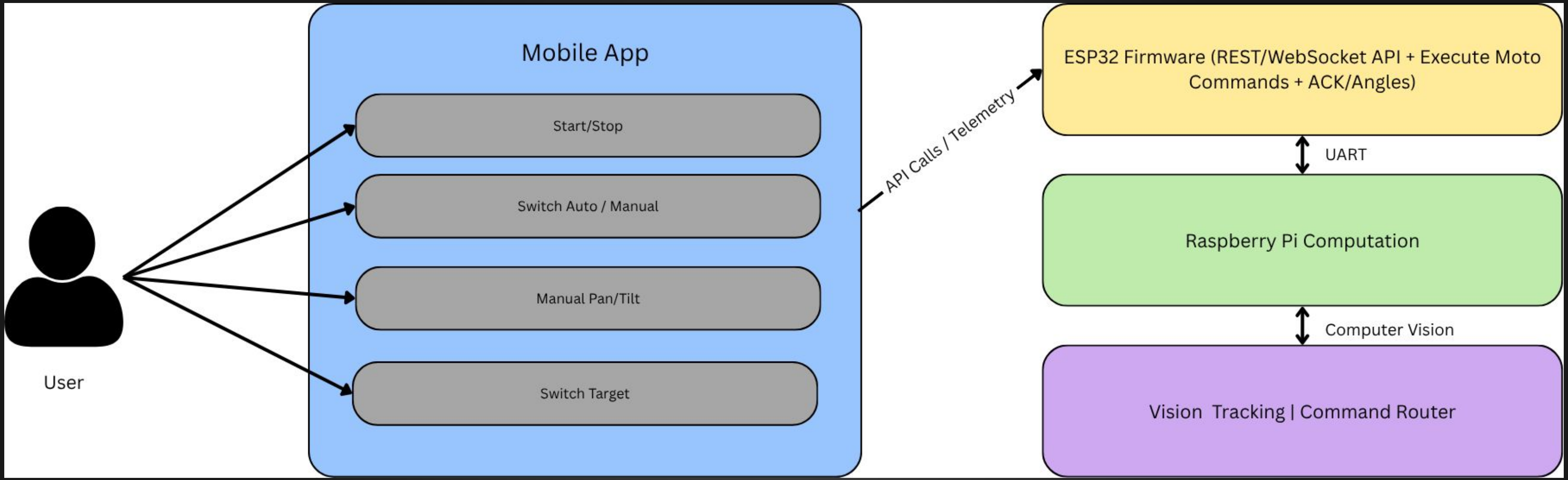
Computer Vision

YOLO (You Only Look Once)

- Performs object localization and classification in a single forward pass
- Delivers high detection accuracy with low end-to-end latency
- Well-suited for real-time inference on embedded platforms

Criterion	YOLO (Selected)	MobieNet-SSD	HOG + SVM
Detection Accuracy	High	High	Very High
Inference Latency	Low (~33–66 ms / frame)	Very Low (~25–50 ms / frame)	Medium (~100–200 ms / frame)
Throughput	15-30 FPS	20-40 FPS	5-10 FPS
Robustness	High	Medium	Low
Resource Usage	Moderate(~300-500 MB)	Low (~200-350 MB)	Moderate (~150-250 MB)
Modern Relevance	State of the art	Widely Used	Legacy

Mobile App



Role:

- Provide a user interface for system control
- Allow mode switching and manual override
- Display system status and feedback

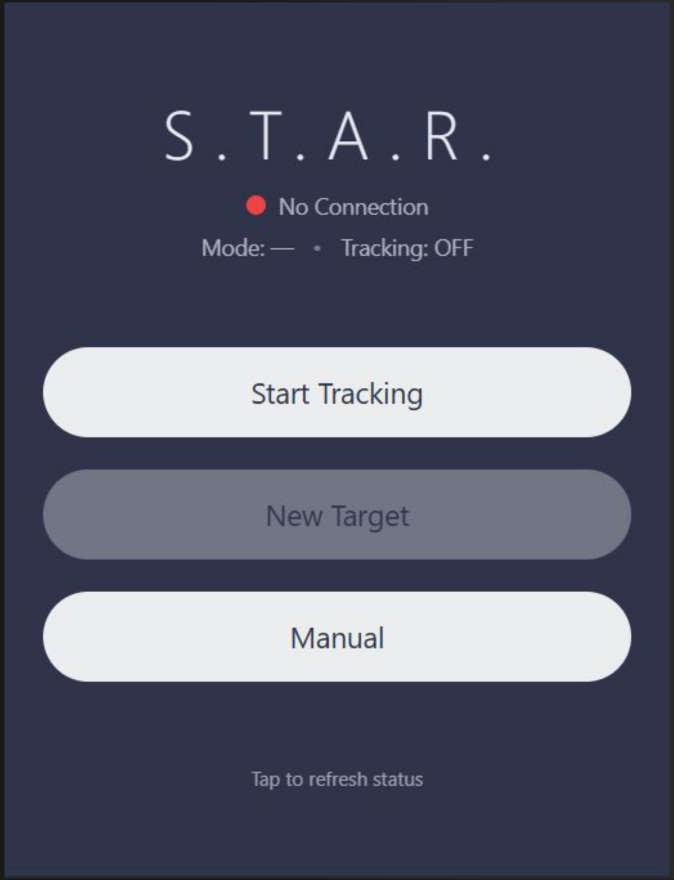
Mobile App

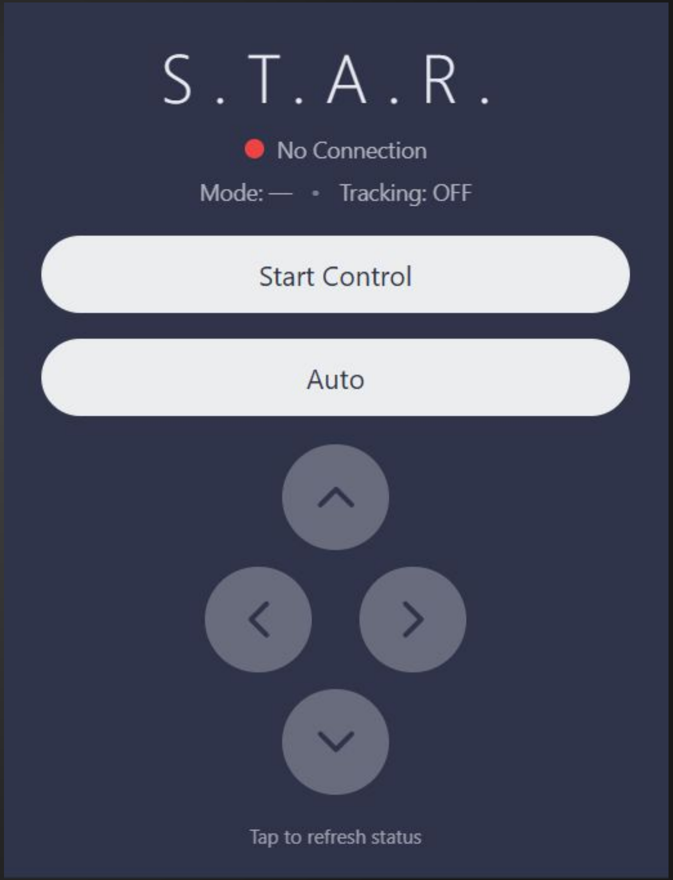
React Native

- Cross Platform Development
- Javascript / Typescript
- Single codebase
- Provides need for minimal stack App
- Able to help with HTTP Rest and Websocket

Criterion	React Native (Selected)	Flutter	Native Android / iOS
Performance	High	High	Very High
Codebase Count	Single	Single	Multiple
Development SPeed	High	Medium	Low
Ecosystem Support	Very Large	Medium	Platform Specific

Mobile App Layout

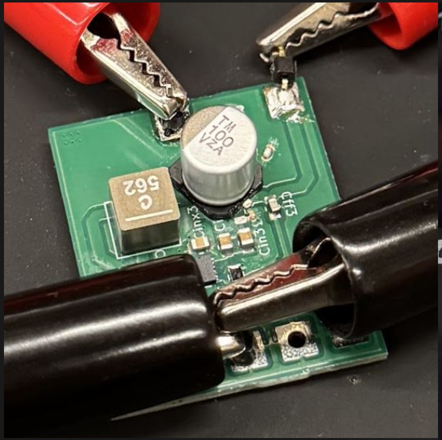




PCB Testing

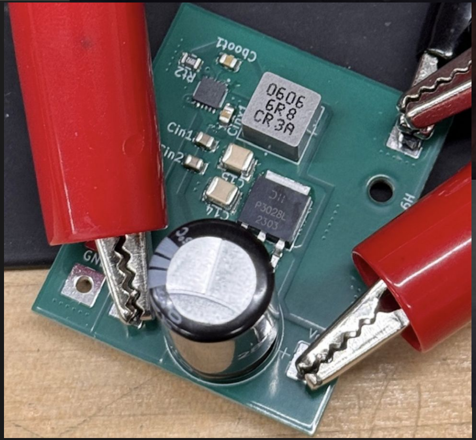
- PCB testing was conducted multiple ways.
    - Lab Tests (Oscilloscope, Multimeter, Electronic load etc.)
    - Connectivity Tests (UART, I2C, etc.)
    - Operational Tests (Full motor control, Terminal board operation, etc.)
- Successful and unsuccessful tests were noted and revisions were made to improve the functionality of the system
- Tests were conducted multiple times to ensure system reliability and robustness

PCB Testing - Regulators



24Vin

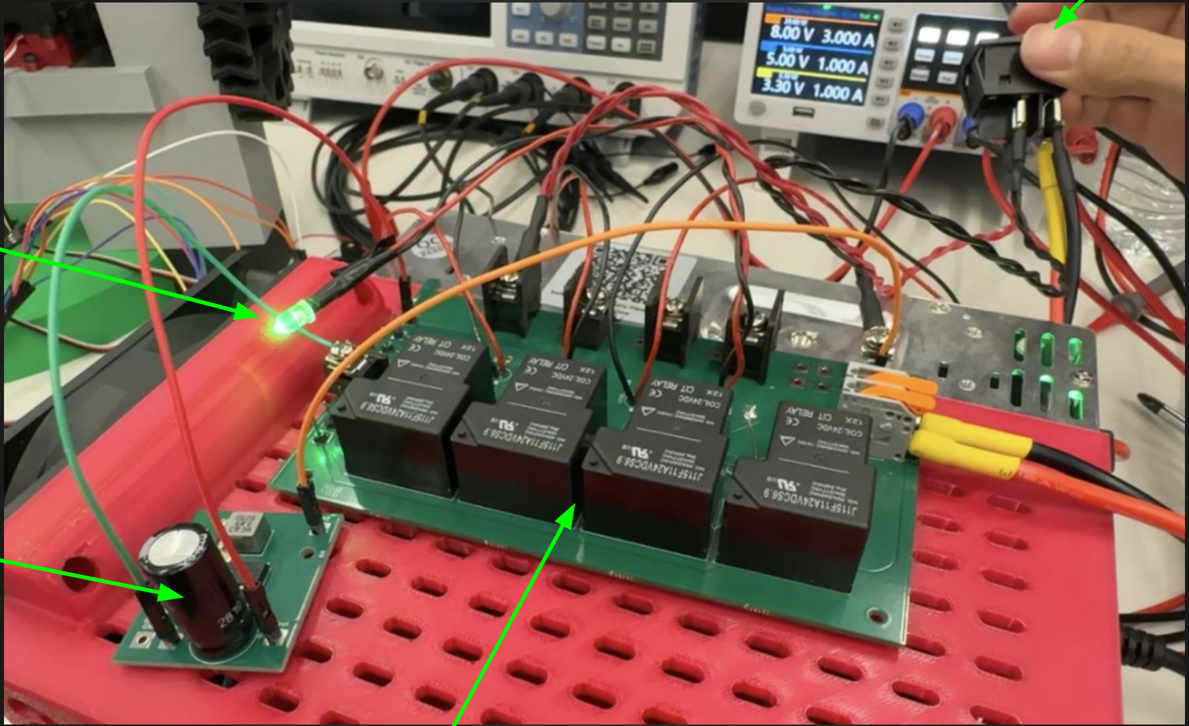
DC Load



PCB Testing - Terminal Board

Rocker Switch

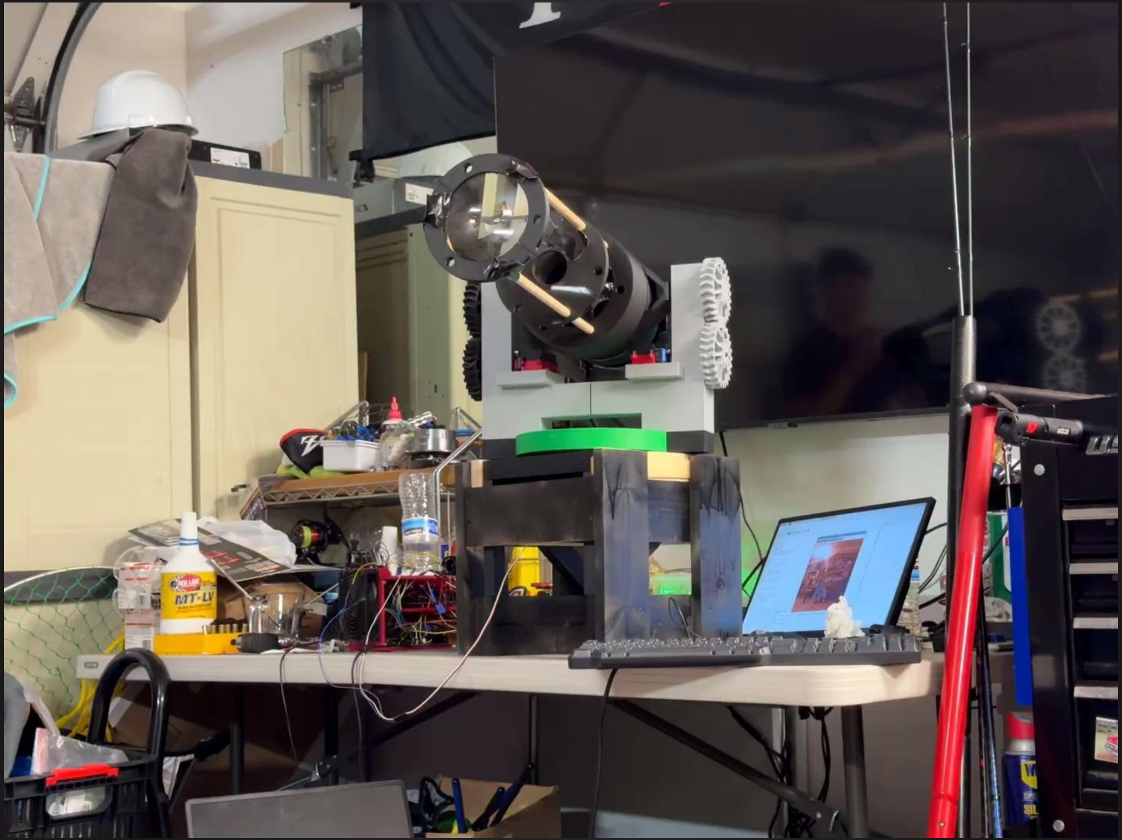
Status LED



8.4V Regulator

Terminal Board

PCB Testing - Full System



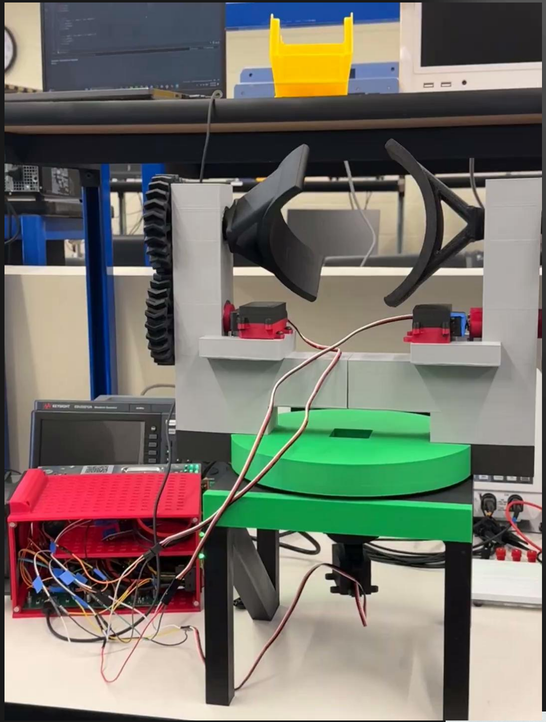
Gimbal Testing

- A full-scale gimbal was designed and 3D printed to validate the mechanical concept.

- High-torque servo motors were used to demonstrate pan and tilt motion and confirm control logic.

- The testing verified axis alignment, range of motion, and structural feasibility under dynamic movement.

- Results from the gimbal testing informed design refinements for the motor system.



Gimbal Latency Testing

- The system latency was evaluated by recording synchronized videos of subject motion and corresponding spotlight movement.

- Frame-by-frame analysis was performed to measure the delay between detected motion and gimbal response.

- The measured frame differences were converted to time (ms) to quantify total system latency.

- These results validate the system's ability to provide smooth and responsive spotlight control during live operation.

Latency Test Results

Average
396.2

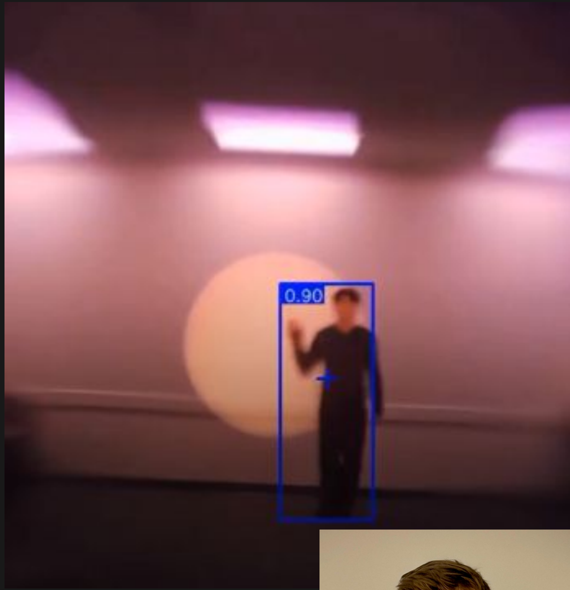
Trial	Change in Frame	Latency (ms)
1	92	383.64
2	120	500.4
3	73	304.41
4	83	346.11
5	99	412.83
6	86	358.62
7	66	275.22
8	111	462.87
9	123	512.91
10	97	404.49

- Through optimization and control improvements, the system achieved an average latency of 392 ms.

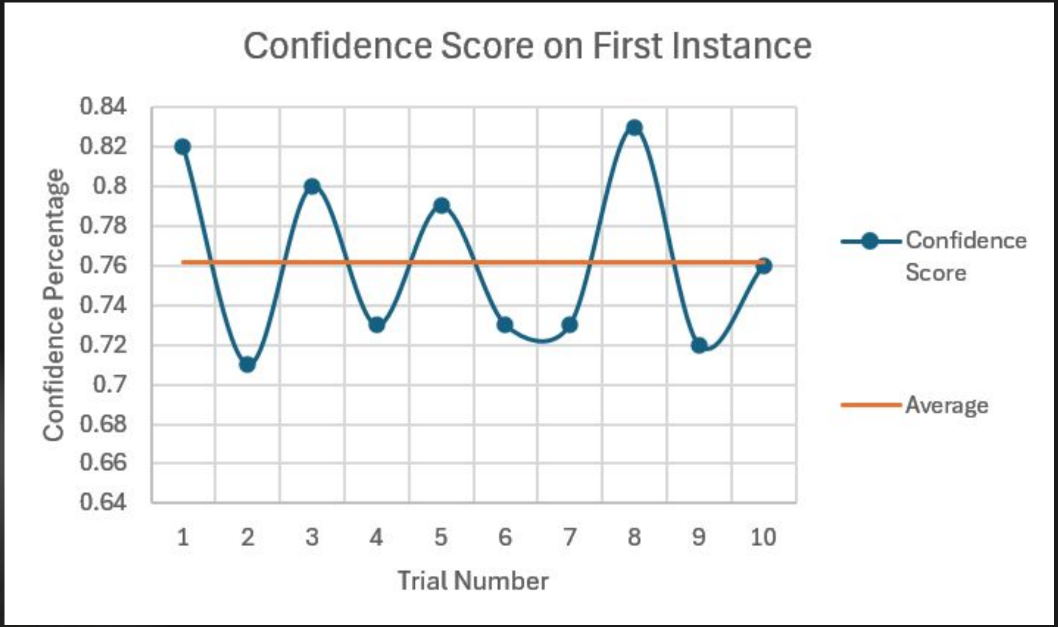
- Performance demonstrates responsive tracking behavior suitable for real-time spotlight control.

Confidence Testing

- The human detection algorithm was tested using live camera input under representative lighting conditions.
- The system successfully identified members
- Detection results demonstrated reliable human detection with a high confidence rate
- These results validate the software's suitability for integration with real-time tracking and control.



Confidence Testing Results



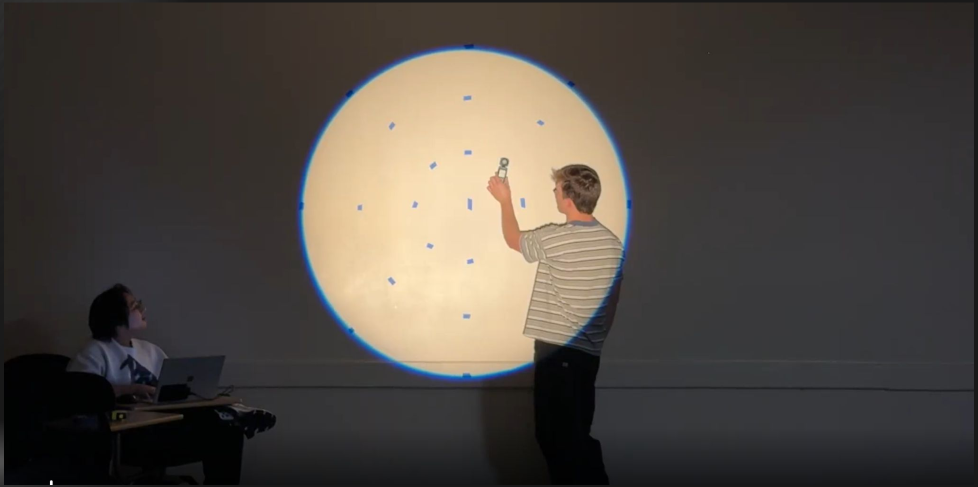
Trial	Detected	Confidence
1	☑	0.82
2	☑	0.71
3	☑	0.8
4	☑	0.73
5	☑	0.79
6	☑	0.73
7	☑	0.73
8	☑	0.83
9	☑	0.72
10	☑	0.76

The detection system held up very well during testing. We had an average confidence of 77% through all 10 trials.

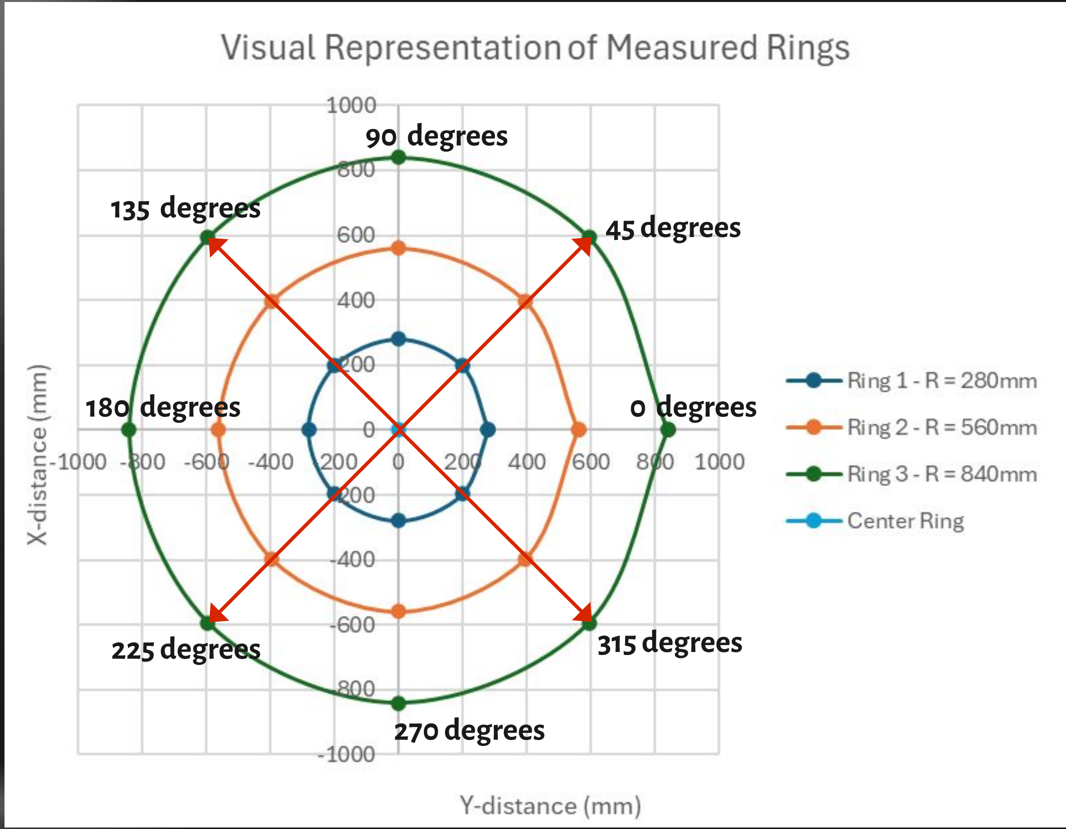
Illumination System Testing

Plotted 4 rings along the spotlight and measured lux using lux reader at various degrees along the circle

- Center - Radius 0mm
- Ring 1 - Radius 280mm
- Ring 2 - Radius 560mm
- Ring 3 (Outer edge) - Radius 840mm



Illumination System Testing - Graphical Visualization



- For each ring, a measurement was taken in 45 degree increments

- The lux for each point was then recorded, tabulated, then averaged for all iterations

Illumination System Testing - Results

Center	
Degree	**Lux**
0	571.9

Ring 3	
Degree	**Lux**
0	323.6
45	326.4
90	338.2
135	344
180	344.4
225	309
270	312.8
315	281.9
360	323.6
Radius:	840mm

Spot Uniformity	
Degree	**Efficiency**
0	57%
45	57%
90	59%
135	60%
180	60%
225	54%
270	55%
315	49%
360	57%

- By dividing the average outer edge lux (Ring 3) by the average center lux we can find the uniformity efficiency along each degree
- Overall, the edge intensity meets our benchmark of 50% of the center

Illumination System Testing - Results

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- By dividing the average outer edge lux (Ring 3) by the average center lux we can find the uniformity efficiency along each degree
- Overall, the edge intensity meets our benchmark of 50% of the center

Problems and Solutions

- **Mechanical Load Integration:** The illumination source experiences high temperatures, so active cooling using a fan will be implemented to improve heat dissipation.

- **Accurate Tracking:** The human tracking software would overshoot the position of the spotlight despite detecting the person. Adjustments to the backend code for optimization was done.

- **Housing Design:** The overall housing for the spotlight faced stability issues when in motion. A more robust wooden casing was built to allow more stability in the movements.

- **Imaging System IR Filter:** The built-in IR filter of the HQ camera was too thick for the distance needed between the last imaging lens and the sensor. That filter was removed and a separate filter was mounted on a flat 3D printed surface to permit that spacing.

Problems and Solutions cont.

- **PCBs:** A new regulator board had to be designed for the motors. The old TI IC was not functioning properly because of incorrect PCB layout. A new IC with simpler layout specifications was designed and assembled. Terminal board traces were improperly placed. Copper needed to be cut, exposed, and soldered to the correct planes.

- **Illumination System:** The housing for the illumination source had to be redesigned for the gimbal to properly support the system's center of mass.

Budget

Part Name	$/unit or lot
ESP32 & RPi 5	$152.47
Raspberry Pi Camera and Lenses	$166.48
Servo Motors & Peripherals	$303.44
Filament	$96.83
Housing Hardware	$81.33
Lens System	$268.37
PCB Components & Boards	$633.31
TOTAL COST	**$1702.23**

Work Distribution

Photonics Engineer	Responsibilities
Gage	Illumination Lens design
	Source Selection
	Illumination Gate System
	Gimbal Design
Computer Engineer	**Responsibilities**
Lucio	Computer vision algorithms
	System UI
	System logic coding
	Motor command code
	Senior Design website

Photonics Engineer	Responsibilities
Travis	Imaging Camera Selection
	Imaging lens design
	Imaging Housing Design
	Magnification and lens calculations
	Administrative Work
Electrical Engineer	**Responsibilities**
Jerison	PCB Design
	Subsystem Integration
	Administrative Work
	3D Design and Printing
	Circuitry and Electrical Components