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

Group 7 Authors

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Chapter 2 - Project Description

2.1 Background and Motivation

Stage productions, concerts, and presentations rely on spotlighting to direct the audience's attention to the appropriate subject and enhance performance quality. Traditionally, this task can be achieved via two options; a trained spotlight operator manning a heavy, large spotlight, or a costly lighting console that needs a programmer to operate [1]. While effective, these methods present limitations: consoles often cost upwards of $20,000, spot operators add to labor expenses, and manual control can introduce inconsistencies in timing and accuracy.

Advances in computer vision and security applications open new possibilities for automated spotlighting systems [2]. By utilizing imaging sensors, real-time subject tracking, and mobile control platforms, an autonomous spotlight can be made both affordable and reliable. There are many applications and systems where precision human tracking is essential for operation; utilizing these systems will be crucial in developing an accurate system.

The S.T.A.R. project aims to address these challenges. The system uses a CMOS camera and real-time human recognition algorithms to track performers on stage. A motorized gimbal directs the spotlight toward the tracked subject, ensuring consistent illumination. In addition, S.T.A.R. integrates wireless control via a mobile app or remote interface [3], eliminating the need for expensive lighting boards. S.T.A.R. demonstrates the feasibility of creating an accessible, user-friendly spotlight system by combining off-the-shelf imaging hardware, embedded processing, and motor control.

2.2 Goals and Objectives

At its foundation, the system aims to detect and track a single moving subject in lit environments, using a CMOS imaging system and real-time recognition algorithms to guide a two-axis motorized gimbal that delivers smooth spotlight tracking with less than 250 ms of latency. Advanced goals build upon this by refining multi-target detection, enabling user selection of subjects, optimizing gimbal motion for silent operation, and incorporating a wireless control interface for calibration and override. Stretch goals further extend the system's functionality by supporting DMX/Ethernet integration for compatibility with professional lighting consoles, networking multiple units for coordinated coverage, and adapting to environmental challenges such as smoke, fog, or high-contrast lighting. Additional objectives include implementing built-in lighting effects, reducing optical distortion through post-processing, and exploring higher-wavelength detection capabilities such as thermal imaging in the far-infrared range. Together, these goals and objectives provide a clear roadmap for developing a robust, real-time, and versatile autonomous spotlighting system.

2.2.1 Goals

Basic Goals:

1. Detect and track a single moving person in a lit environment.
2. Control a motorized gimbal to pan/tilt the spotlight toward the center of mass of the tracked subject.
3. Provide smooth, low-latency spotlight movement (<300 ms total system delay).

Advanced Goals:

1. Enable multi-target detection with single-target spotlight focus.
2. Optimize gimbal motion for continuous and smooth operation.
3. Add wireless control interface (web app or mobile) for calibration and override.

Stretch Goals:

1. Network multiple S.T.A.R. units for coordinated spotlight coverage.
2. Incorporate environmental adaptation, such as handling smoke, fog, or high-contrast lighting.

2.2.2 Objectives

Basic Objectives:

1. Implement a CMOS imaging system to capture real-time video for human detection.
2. Use human recognition algorithms (i.e. computer vision or ML) to identify and track a single subject and communicate to a gimbal system for pan/tilt control.
3. Validate the system for latency through stage test scenarios with one performer.

Advanced Objectives:

1. Refine the vision algorithm to detect multiple subjects and allow selection of which performer to follow by the user.
2. Calibrate the motor control to minimize jitter, noise, and overshoot in gimbal movement.
3. Design and test a mobile/remote app interface for manual override and basic spotlight control.

Stretch Objectives:

1. Implement DMX/Ethernet support to allow for integration with existing lighting systems and console control.
2. Incorporate detection of higher wavelengths including that of the Far-Infrared (9µm - 12µm) range in order to provide thermal imaging.

2.3 Description of Features / Functionalities

Rotating Gimbal

A core feature of the S.T.A.R. system is the motorized gimbal that allows the spotlight to rotate in two separate axes: the horizontal and vertical direction. In professional stage lighting, motorized gimbals are most commonly found in moving head fixtures, such as the MAC Martin Viper. These instruments are some of the most versatile in the entertainment industry, and require the most skill to manipulate. These fixtures use multi-axis gimbal systems not only to provide pan and tilt movement, but also to manipulate other parameters such as zoom, focus, and beam shaping. By contrast, S.T.A.R. aims to simplify the gimbal system by providing only the most essential element: pan and tilt. The gimbal serves as the method for subject tracking, translating the output of the vision system into physical movement of the illumination system. The design incorporates two degrees of freedom (pan and tilt):

- Pan (X-axis rotation): Allows the spotlight to sweep left and right across the stage.
- Tilt (Y-axis rotation): Adjusts the vertical angle to follow performers as they move closer or farther from the camera's elevation.

Human Detection

A key feature of the S.T.A.R. system is the ability to detect and track humans on stage in real time. This function eliminates the need for a dedicated spotlight operator and ensures consistent, automated coverage of performers. Human tracking will be achieved using a CMOS imaging system combined with computer vision algorithms that identify and follow targets as they move [4]. The camera will be mounted onto the rotating gimbal, so the subject will always be in view of the camera system [5].

To be able to track humans, the system will utilize a machine learning model from OpenCV that's trained for object detection. After taking input from the CMOS imaging system, it will communicate it through the MCU, where an application will be used alongside the system to help users select which human in view of the camera will be targeted by the system.The output of the application should then be able to track the selected human, adjusting the camera movement (pan and tilt) as the human moves [5].

Illumination System

The most critical component of the S.T.A.R. system is its illumination system, which is based on the ellipsoidal reflector spotlight (ERS) design (see Fig. 5). Ellipsoidal reflector systems have been a pillar of stage lighting for decades, with the release of the Source Four ERS by Electronic Theatre Controls (ETC) in 1992, setting the industry standard. The ERS illumination system is unique in that it utilizes a combination of lenses and mirrors - an ellipse shaped mirror focuses the light to a point, and lenses are used to collimate past the focal point. Traditionally, these fixtures use a tungsten-halogen four-filament lamp, which provides a very high output, but also generates significant heat and requires frequent replacement. In contrast, the S.T.A.R. system adopts an LED emitter. Unlike filament lamps, the LED produces a large number of lumens in all directions with far greater efficiency, lower heat generation, and an extended operational lifespan.

2.4 Existing Products & Related Work

Follow-Me 3D
Follow-me 3D is a tracking and control system used in large-scale productions. Unlike a standalone automated spotlight, Follow-Me is a software platform that integrates with existing moving head fixtures. It works by using cameras placed around the venue to track performers in three dimensions, then translates that data into a DMX signal which is sent to multiple moving lights. Operators can assign fixtures to specific performers, adjust beam parameters, and manage complex stage environments in real time. The system supports multi-fixture tracking, allowing one operator to control dozens of spotlights following several performers simultaneously. This product displays the effectiveness of tracking systems with automated lighting instruments, but its complexity and price make it not suitable for small-scale usage. S.T.A.R. will fill this gap by utilizing the same camera tracking, while delivering a smaller scale system that can be used by anyone.

MAC Viper Profile
The Viper Profile is a powerhouse in the moving light industry. Its mechanical system is a proven model for moving head lighting instruments. It utilizes a motorized yoke design, where stepper motors control both the pan and tilt directions. While it does not utilize any human tracking systems listed above, its mechanics will be utilized in the S.T.A.R. design.

2.5 Specifications

Table 1.0: Component Specifications

OPTICAL COMPONENTS			
Component	**Parameter**	**Specification**	**Unit**
Spotlight System			
Ellipsoid Reflector	1. Efficiency 2. Cone Angle 3. Focal Length	1. 90 2. 19 3. 237	1. % 2. Degrees 3. mm
Light Source	1. Brightness 2. Color Quality 3. Emitter	1. 5000 2. 85 3. LED	1. Lumens 2. CRI
Focusing Lens	1. Focal Length 2. Spot Size 3. Material	1. 479 2. 4 3. BK7	1. mm 2. ft
Imaging Camera Lens System			
Positive Meniscus	1. Radii 2. Focal Length 3. Coating	1. 12.7 2. 100 3. N/A	1. mm 2. mm
Plano-Concave Lens	1. Radii 2. Focal Length 3. Coating	1. 12.5 2. -50 3. N/A	1. mm 2. mm
Achromatic Doublet Lens	1. Radii 2. Focal Length 3. Coating	1. 12.5 2. 100 3. MgF_2	1. mm 2. mm
Sensor (Sony IMX477 sensor)	1. Pixel Size 2. Megapixels 3. Wavelength Range	1. 1.55 x 1.55 2. 12.3 3. 400 - 700	1. µm 2. Mp 3. nm
ELECTRICAL COMPONENTS			
Component	**Parameter**	**Specification**	**Unit**

MCU (ESP32-S3)	Operating Voltage	Runs motor control	3.3V
SoM (Raspberry Pi Compute Module 5)	Operating Voltage	Runs Computer Vision and MCU programming	5V
Motor (Pan/Tilt)	Speed, Standing Torque, Operating Voltage, Stall Current	2-axis servo system	0.12sec/60° @ 14V, 50kg-cm @ 14V, 10-14V, 5500 mA
Motors (Shutter Mechanism)	Standing Torque, Operating Voltage, Stall Current	Illumination shutter system for blacking out light source	21.5kg-cm @ 6.8V, 5-6.8V, 2200 mA
PWM Motor Controller (PCA9685)	Max PWM Outputs, Operating Frequencies	Maximum number of servos that can be controlled, PWM frequency output range	16, Up to 1.6KHz
Power Supply (Raspberry Pi)	Power Output	DC power supply, USB-C connector	5.1V, 15W
Power Supply (ESP32 and Motors)	Power Output	DC power supply	24V, 25A
WAGO Connector (2606-1102)	Rated Voltage, Rated Current	For connecting 24V power supply to PCB	300V, 31A
Housing	Material	Material for housing motors, PCB, etc. (3D printed)	PETG

Table 1.1: Overall System Specifications

Parameter	Description	Target Value & Unit(s)
Tracking Latency	Time delay between performer movement and spotlight response	≤ 250 ms (basic), ≤ 150 ms (advanced)
Tracking Accuracy	Angular error between spotlight center and center mass of selected performer	≤ 5° RMS at 10 m
Tracking Range	Distance at which subject can be reliably detected and tracked	10 m (± 2 m)

Frames Per Second (fps)	How many frames are captured by the camera per second	50 fps @ 2028x1080p
Lighting Conditions	Minimum illumination where tracking is possible	1000 Lumens
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
System Power Source	Source of power for system	AC wall power (~120V)
Operating Power Consumption	Wattage consumed by system during operation (NOT including illumination source)	~ 611Watts
System Weight	Total weight of system (NOT including illumination source)	≤ 14 lbs
System Cost	Total cost of prototype build (not including redundancies)	≤ $800 prototype

2.6 Hardware Block Diagram

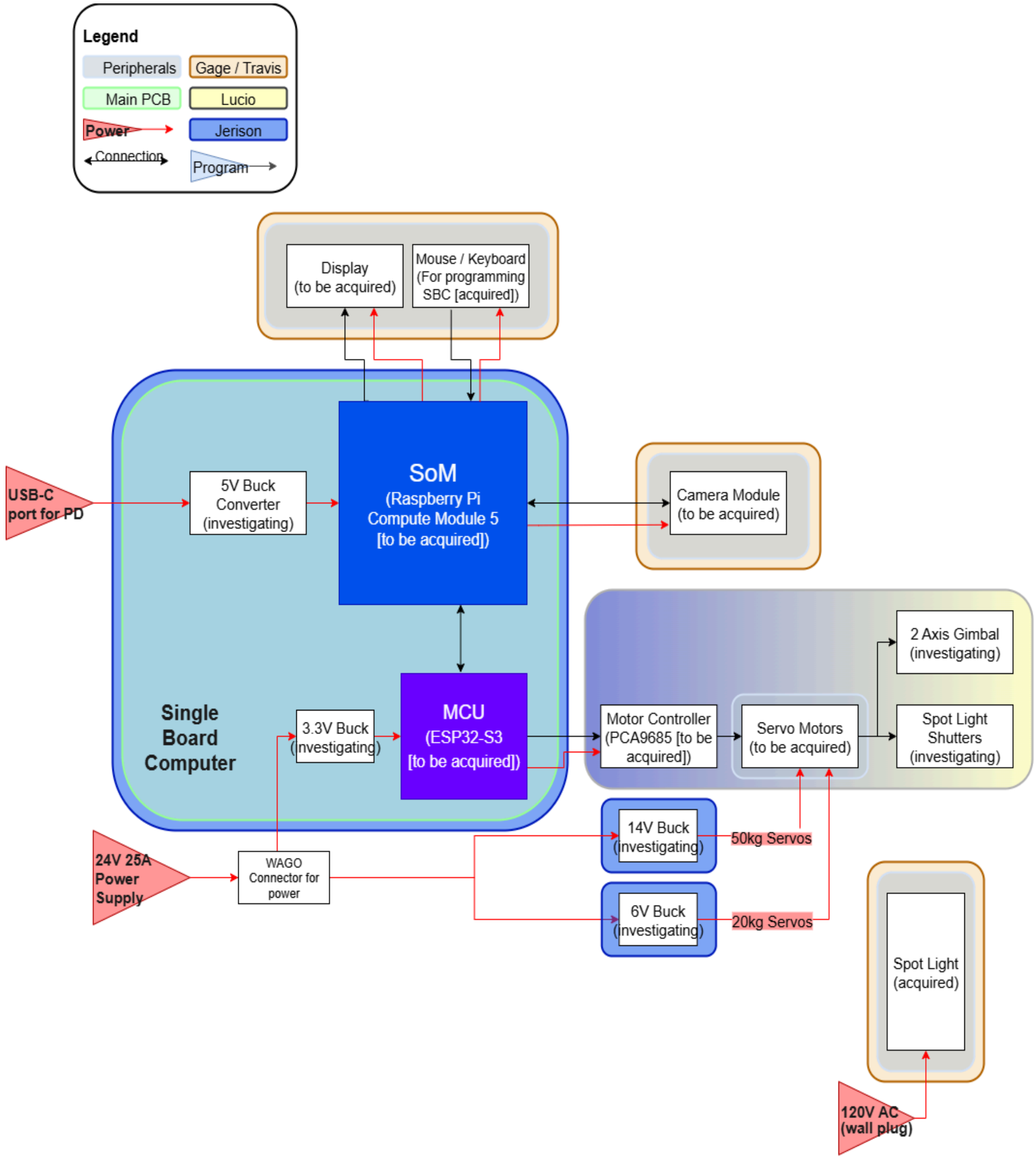


Figure 1.0: Hardware Block Diagram - Does NOT include lens system. Please refer to section 2.9 for diagrams of optical components.

2.7 Software Diagram

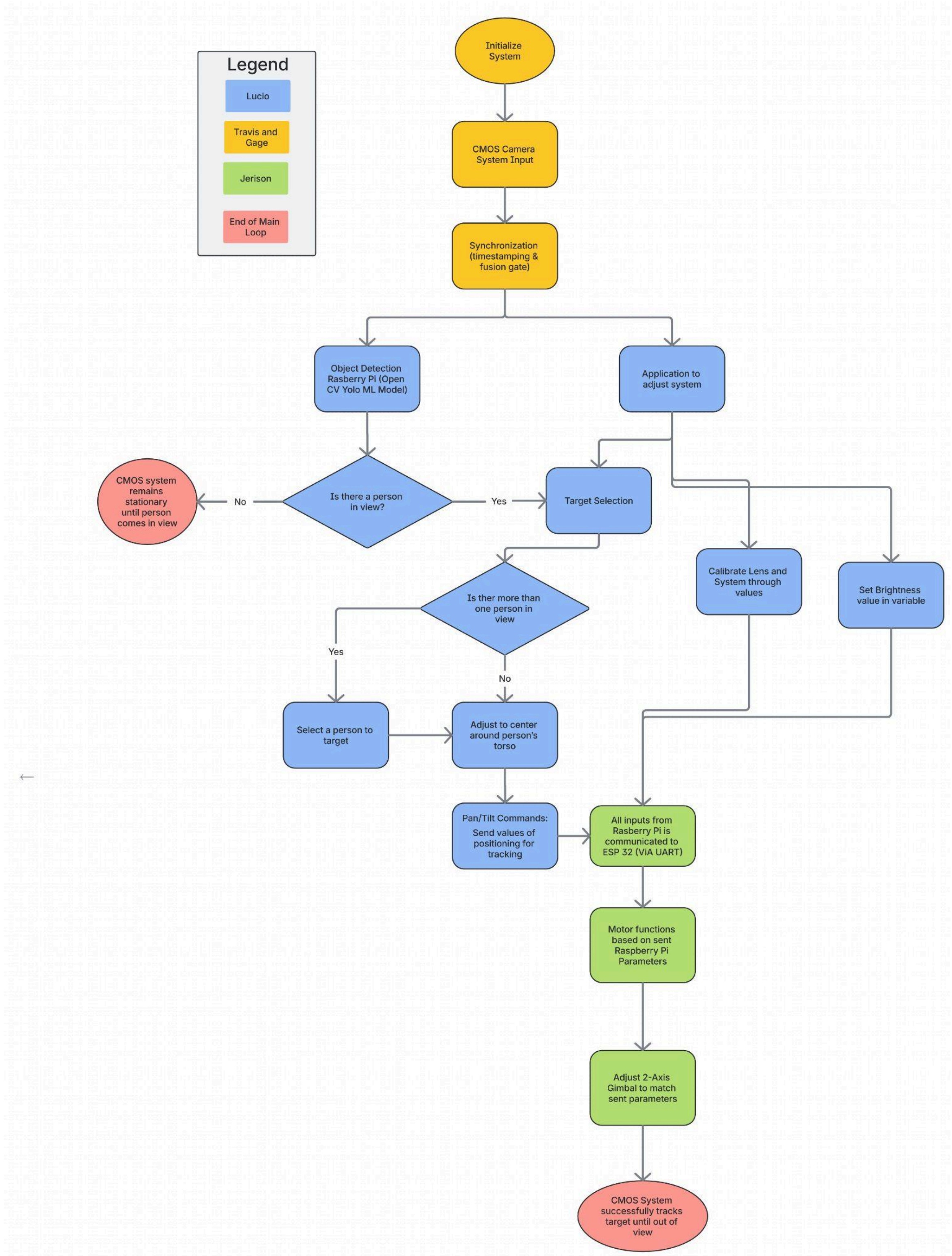


Figure 2.0: Software Block Diagram

2.8 Prototype Illustration

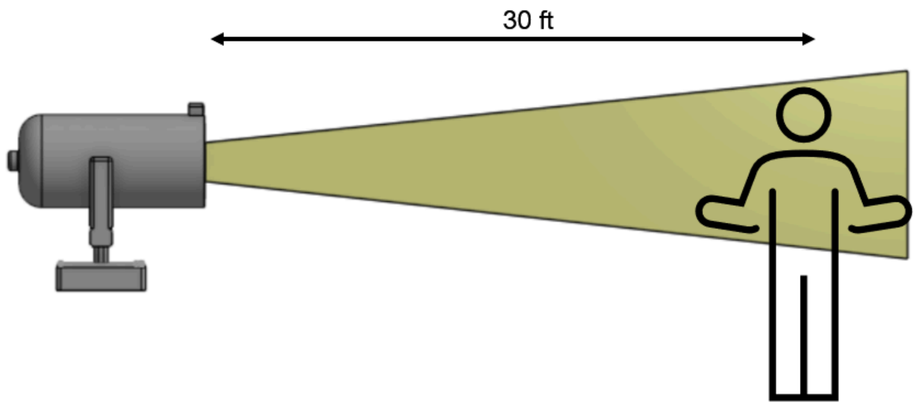


Figure 3.0 Prototype model of S.T.A.R.

The prototype shown above displays the S.T.A.R. motorized spotlight system capable of autonomous human tracking. The goal is to illuminate the entire upper half of the subject from 30ft to allow for hand motions/actions to be seen by the audience. The cylindrical housing contains the light source, reflector, and lens system. Inside the gimbal are servo motors for two-axis movement (pan and tilt), The base houses the control electronics, including the microcontroller, motor drivers, PCBs, and power sources. Our CMOS sensor system is mounted at the top of the output of the system. The system operates as a standalone unit, requiring only power and a simple user interface (remote or mobile app) rather than a traditional lighting console.

2.9 Optical Components

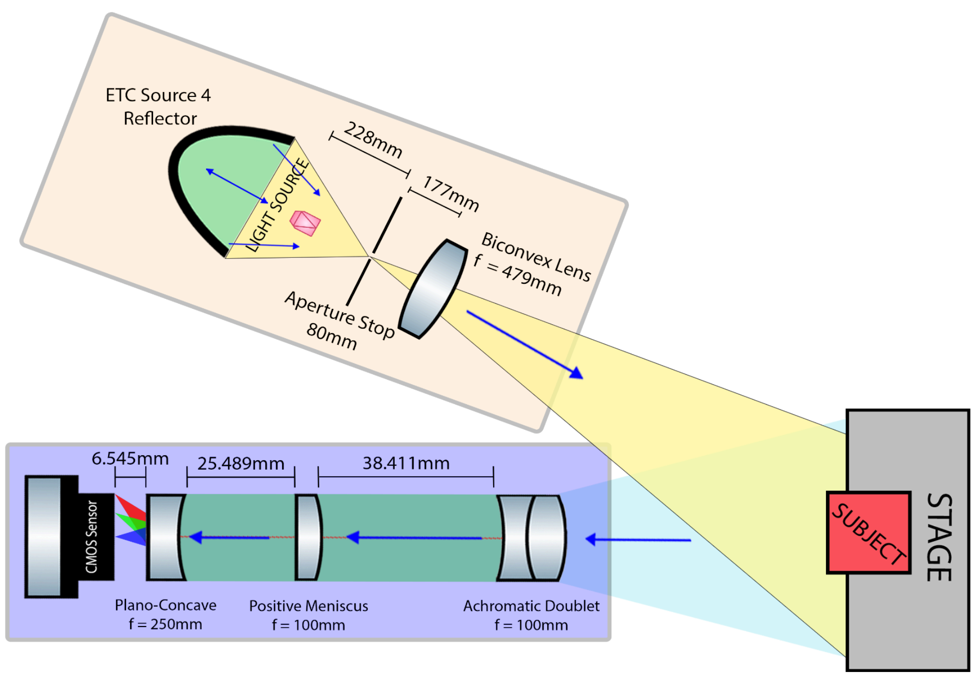


Figure 4.0 Optical Schematic

Illumination system
The illumination system is composed mainly of two components: the source and reflector, and the focusing lens.

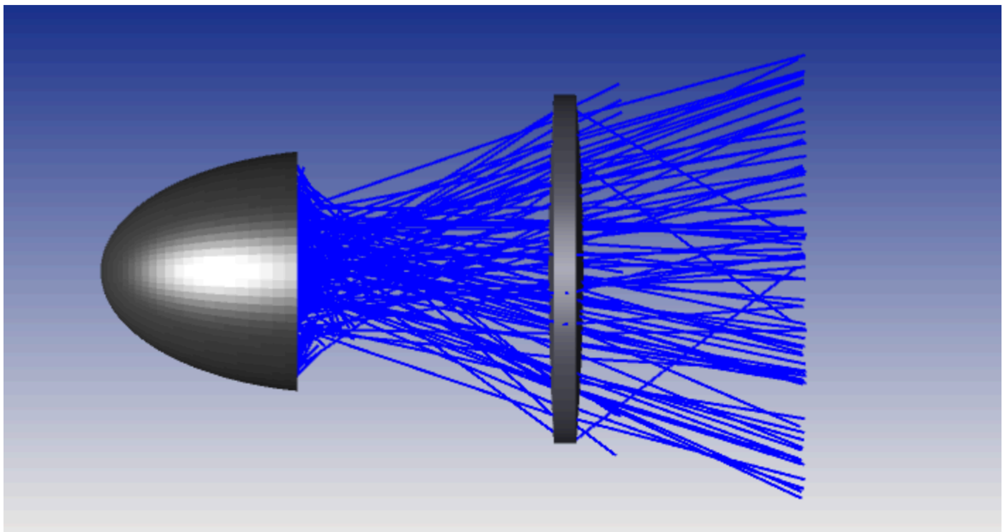


Figure 5.0 Illumination source, reflector and lens design

The reflector is modeled after the ETC Source Four design, which is an elliptical housing coated with a reflective material to maximize light collection and projection efficiency. The lighting source can vary, as long as it is small enough to fit in the housing. For S.T.A.R., the Source Four lamp will be used. For the S.T.A.R. prototype, a Source Four lamp has been selected due to its high lumen output and strong overall efficiency. The primary drawback of this lamp is its heat generation, so a further investigation and testing of LED sources will be appropriate.

	Surface Type		Comment	Radius	Thickness	Material	Coating	Clear Semi-Dia	Chip Zone	Mech Semi-Dia	C
0	OBJECT	Standard		Infinity	400.000			40.000	0.000	40.000	0.0
1	STOP	Standard		Infinity	0.000			46.548	0.000	46.548	0.0
2	(aper)	Standard		482.000	21.000	BK7		64.000 U	0.000	64.000	0.0
3	(aper)	Standard		-476.250	1500.000			64.000 U	0.000	64.000	0.0
4	IMAGE	Standard		Infinity	-			209.141	0.000	209.141	0.0

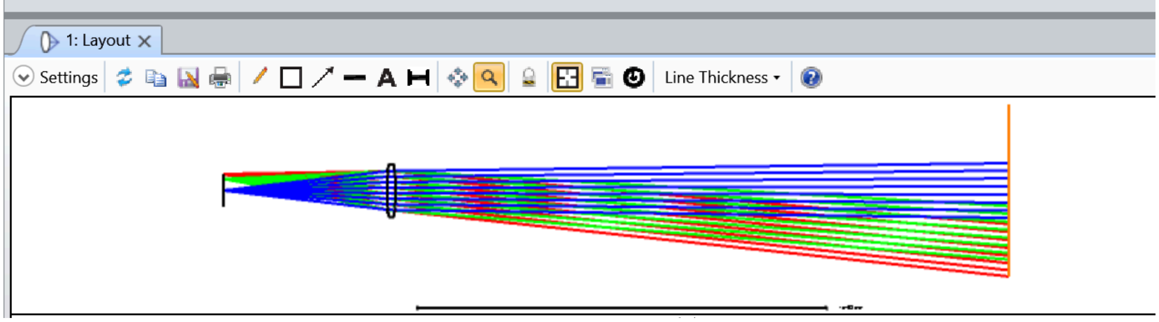


Figure 6.0 Prescription for output lens of S.T.A.R.

To be as cost efficient as possible, a biconvex lens is used to achieve a roughly 8.5 degree output half cone angle. Considering the variety of scenarios that S.T.A.R. will be used in, 8.5 degrees seems to be an optimal angle for varying distances. The lens will be placed at the end of the assembly. If we find that this angle is too wide for large distances, an iris will be placed at the gate of the optical assembly to reduce spot size.

Imaging System

The imaging system consists of a lens system and a CMOS sensor. This is a crucial optical element for the system as it determines the efficiency of the spotlight tracking. Glass choice is vital for building an optical setup to meet the parameters scoped for the resultant image. For this scope we are aiming to reduce as many aberrations as possible, leading to the design choice of using two types of glass: a crown lens and a flint lens. To maintain cost efficiency we explore the option of Commercial Off the Shelf Lenses (COTS) which provide a low cost alternative in comparison to a custom built lens.

The objective is to build a lens system that focuses light to a focal plane equivalent to the sensor size used. In this case we are using the **Raspberry Pi High Quality Camera 12.3 megapixel Sony IMX477 sensor**,

Table 2.0 Specifications of tracking camera

Raspberry Pi High Quality Camera 12.3 megapixel Sony IMX477 sensor	
Sensor Size	Horizontal: 6.32mm Vertical: 4.74mm
Pixel Size	1.55μm × 1.55μm
Megapixels	12.3
Wavelength Range	~ 400nm - 700nm
Lens sensor format	1/2.3” (7.9mm) or larger
IR Cut Filter	Integrated

For the crown lens, the glass of choice considered is a N-BK7 which when uncoated provides a transmission wavelength in the visible light spectrum to the near infrared wavelengths.

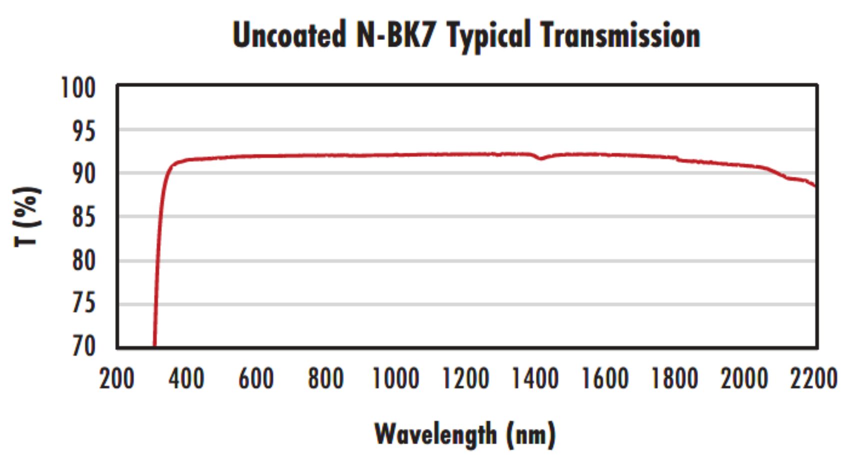
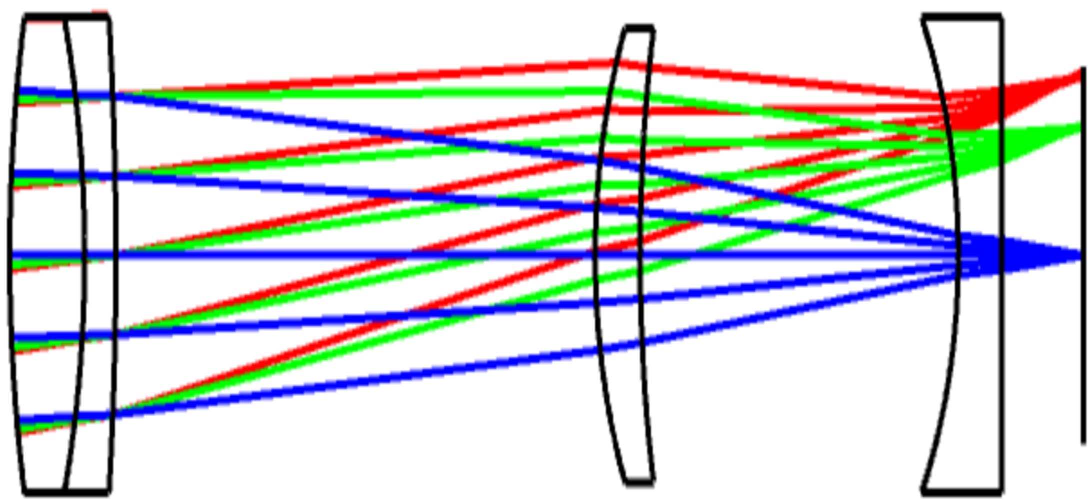


Figure 7.0: Typical Wavelength Transmissions of an Uncoated N-BK7 per Edmund Optics

For the Flint Lens, a substrate of N-SF5 is considered for cost effectiveness, and provides a low dispersion. Put together with a BK-7 Lens to create an Achromatic Doublet, this allows for some minimization of chromatic aberrations. Shown in *Figure 8.0***,** the Zemax Model represents the lens specifications modeled with test rays in the object and image field. The achromatic doublet is coated with MgF_2 and starts as the first lens within the system. This is followed by a positive meniscus Crown lens, which is used to alter the focal length of the system to be focused at the sensor. The last lens used in this design is the Plano-Concave lens, used to serve as a field-corrector for warping distortions. The lenses selected are commercial off the shelf (COTS) lenses, making them cheaper than optimizing a system using custom built lenses. Although this does cause trade-off in image aberration, the cost-effectiveness remains of higher priority.



	Surface Type		Comment	Radius	Thickness		Material	Coating
0	OBJECT	Standard		Infinity	Infinity			
1	(aper)	Standard	Achromatic Doubl...	61.470	6.000		N-BK7	EO_MGF2(550NM)
2	(aper)	Standard		-44.640	2.500		N-SF5	
3	STOP (aper)	Standard		-129.940	38.411	V		EO_MGF2(550NM)
4	(aper)	Standard	Positive Meniscus	28.670	3.600		N-BK7	
5	(aper)	Standard		61.628	25.489	V		
6	(aper)	Standard	Plano-Concave	-25.840	3.500		N-BK7	
7	(aper)	Standard		Infinity	6.545			
8	IMAGE	Standard	Sensor	Infinity	-			

Figure 8.0: Zemax Model

2.9 House of Quality

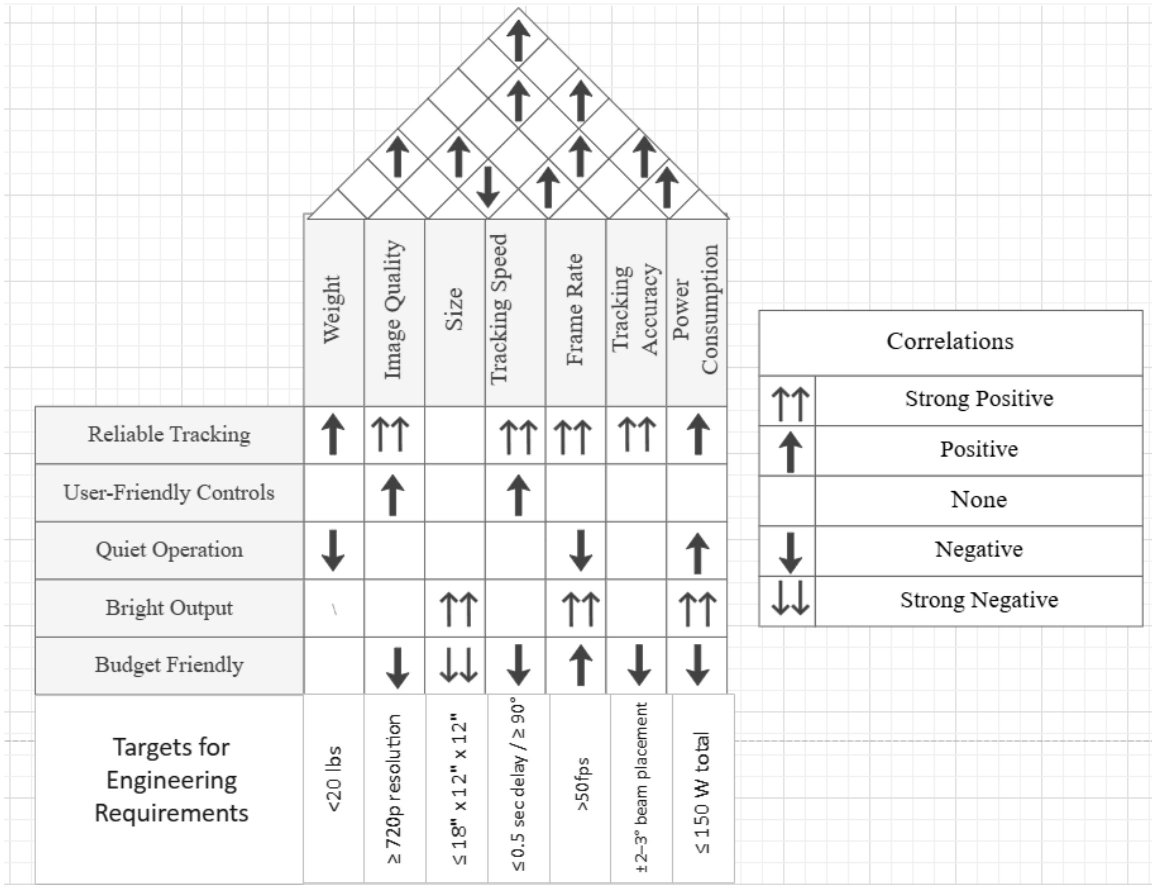


Figure 9.0: House of Quality

2.10 Budget and Financing

The projected budget for this project is $1,700, which reflects both the technical complexity and the specialized hardware requirements necessary to achieve reliable real-time spotlight tracking. A significant portion of this cost comes from PCB manufacturing, as custom-designed boards are required to integrate the MCU, ICs, etc. into a compact, stage-ready system. Not to mention the cost of international shipping. Additionally, the optical components, including a high-quality LED emitter, reflector, and focusing lenses, contribute heavily to the expense, since precision glass optics and lighting elements for professional-grade illumination are costly. The motorized gimbal system also represents a major investment, as it must use high-torque, low-noise servo motors to provide smooth, precise, and silent operation suitable for performance environments. Beyond hardware, funds must also be allocated for testing, prototyping, and iteration, as initial prototypes may require redesigns or component replacements. Compared to off-the-shelf lighting systems, this budget remains reasonable, as it accounts for both performance-level functionality and the flexibility of a custom-engineered design. The group has agreed to split the total cost of this project equally between all 4 members.

Table 3.0: General BOM

Part Name	Vendor	$/unit or lot	QTY	Note
ESP32-S3 Chip	Digikey	$5.00	1	
Raspberry Pi Compute Mod. 5	Digikey	$65.00	3	65-80 depending on model
Servo Motors (shutter mech.) 4x	Amazon	$20.00	1	
Servo Motors (high torque)	Amazon	$60.00	3	50-110 depending on model
Portable Monitor	Amazon	$60.00	1	
RP Camera HQ	Digikey	$50.00	1	
HPL757 Lamp	ETC	$19.00	1	
Illumination lens	ETC	$60.00	1	
Source Four Reflector	ETC	$65.00	1	
VIS-NIR Achromatic Lens	Edmund Optics	$79.38	1	
Uncoated Plano-Concave Lens	Edmund Optics	$28.62	1	
Misc. PCB components	Digikey	$150	1	Rough estimate
PCB Fabrication	JLCPCB	$300	1	Rough estimate
EST. TOTAL		**$1,104.00**		Will most likely exceed est. total due to unforeseen costs

2.11 Project Milestones

Table 4.0: Milestones Fall 2025

Senior Design I - Fall 2025			
Week	Milestone	Dates	Deliverable
1-2	Group Formation and Project Idea	8/18-8/29	Finalized Project Idea with Required Components
3	D&C Document	9/1 - 9/5	Finished D&C Document
4	D&C Revision	9/8	Revised D&C Document
5-6	Research on CMOS Camera and MCU	9/9 - 9/21	Selection of CMOS and MCU
5-6	Research on ML model for	9/9 - 9/21	Demo application of of object

Senior Design I - Fall 2025			
	object tracking and how to interface it with MCU		tracking
7-8	Research motorized GIMBAL, PTU, and PCB Design	9/22 - 10/5	Demo application of Spotlight Tracking Person
9	Research on lowlight optimization	10/6 - 10/19	Demo application of Spotlight Tracking Person in near dark
10	Research on Wireless and UI Interface	10/20-10/26	App/web control demo
11-15	Integration testing	10/27 - 11/17	Prototype built
16	Final Report and Demo Video Due	11/25	Full Report Due

Table 4.1: Milestones Spring 2026

Senior Design II - Spring 2026			
Week	Milestone	Dates	Deliverable
TBD	PCB Testing	TBD	Test PCB
TBD	Integrated Code testing	TBD	Have working application for PCB
TBD	PCB Assembly	TBD	Assembled Prototype
TBD	PCB Testing and Debugging	TBD	Assemble Device
TBD	Final Presentation	TBD	Present final product

Table 5.0: Work Distribution Table

Photonics Engineers	Responsibilities
Travis and Gage	Lens design
	Optical calculations
	Image sensor / Camera module

	System display output
	Illumination shutter system
	Demo video production
Computer Engineer	**Responsibilities**
Lucio	Computer vision algorithms
	System UI
	System logic coding
	Motor command code
	Senior Design website
Electrical Engineer	**Responsibilities**
Jerison	PCB design
	Motor logic for gimbal
	Illumination shutter system
	3D design & printing
	Circuitry & electrical components

Appendices

Appendix A – Reference

[1]Greenslade, Thomas B, and Steven G Heisler. “Stage Lighting Instruments.” *The Physics teacher* 13.9 (1975): 548–551. Web.

[2] Kshirsagar, Aniruddha Prakash, and H Azath. “A Comprehensive ATM Security Framework for Detecting Abnormal Human Activity via Granger Causality-Inspired Graph Neural Network Optimized with Eagle-Strategy Supply-Demand Optimization.” *Expert systems with applications* 272 (2025): n. pag. Web.

[3] R. Holzer, “YOLO — object detection,” *OpenCV tutorial*, 2019. [Online]. Available: https://opencv-tutorial.readthedocs.io/en/latest/yolo/yolo.html

[4] “The Ultimate Guide to Lens Design Forms: The types of optical systems in a lens designer’s toolbox.” https://www.pencilofrays.com/lens-design-forms/

[5] Kaur, Manjinder et al. “Security Camera with Frame Detection.” *2024 International Conference on Emerging Smart Computing and Informatics (ESCI)*. IEEE, 2024. 1–5. Web.

Appendix B – Tables and Figures

Table 1.0: Component Specifications
Table 1.1: Overall System Specifications
Table 2.0 Specifications of tracking camera
Table 3.0: General BOM
Table 4.0: Milestones Fall 2025
Table 4.1: Milestones Spring 2026
Table 5.0: Work Distribution Table

Figure 1.0: Hardware Block Diagram
Figure 2.0 Software Block Diagram
Figure 3.0 Prototype model of S.T.A.R.
Figure 4.0 Optical Schematic
Figure 5.0: Illumination source, reflector and lens design
Figure 6.0: Prescription of output lens of S.T.A.R.
Figure 7.0: Typical Wavelength Transmissions of an Uncoated N-BK7 per Edmund Optics
Figure 8.0: Zemax Model
Figure 9.0: House of Quality

Appendix C – Patents

[5] “SECURITY CAMERA AND MOTION DETECTING METHOD FOR SECURITY CAMERA.” 2020: n. pag. Print.