Tracking Recyclables Automated Sorting Hand T.R.A.S.H.

Group 7:

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Tristan Koopman
Mechanical Engineer

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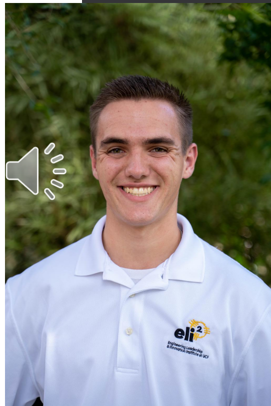
Computer Engineer

Background & Motivation

- **Manual recycling tasks**
- **Labor shortages**



Goals & Objectives

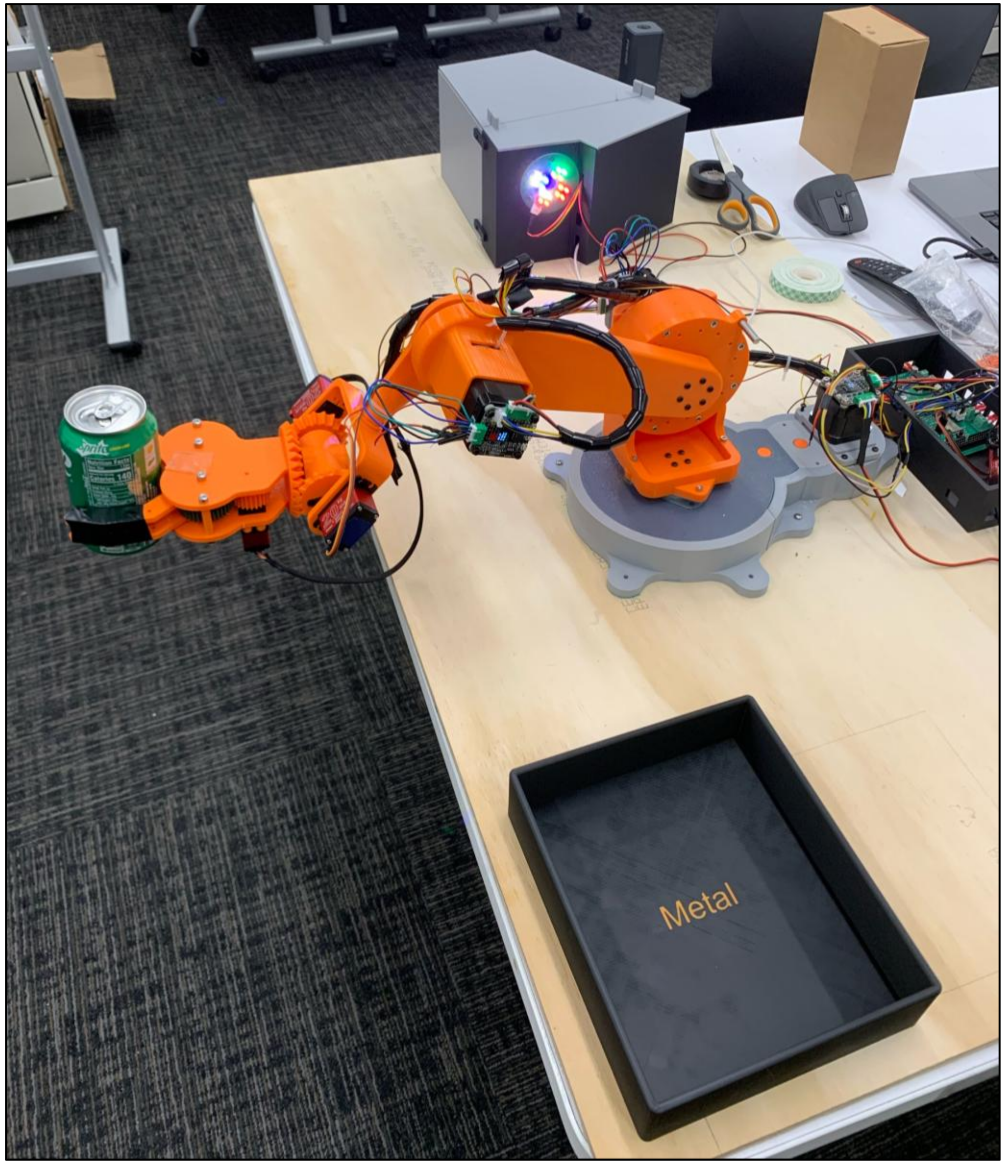
Pick & Sort	Develop an Automated Robotic Sorting System • Build a robotic arm that can pick up and sort recyclable materials like plastic, aluminum, and glass.
Identification	Enable Material Detection and Classification • Use cameras and sensors to identify the type of material without human input.
Automation	Improve Recycling Efficiency • Automate the sorting process to reduce human labor and increase speed and accuracy.
Affordability	Keep the System Lightweight and Affordable • Design with low-cost components and compact parts to make it accessible for small recycling centers.
Scalability	Make the System Easy to Use and Expandable • Create a simple interface and design the system to be easily integrated into existing setups.

Engineering Specifications

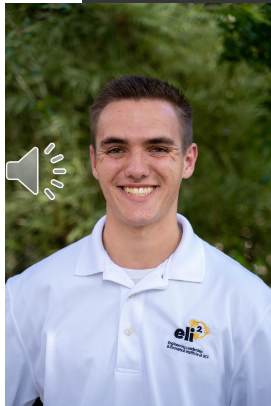
	Specification	Target Value	Units
General Specifications	Object Detection Time	20	sec
	Total Pickup Time	30	sec
	Pickup Accuracy	± 5	mm
	Min. Payload	100	g
	Arm Degrees of Freedom	6	DOF
	Power Consumption	≤ 350	W
	Power Supply	120	VAC
	Computer Vision	1	Camera
	Material Identification	At least 2	Materials

	Specification	Target Value	Units
Optical Specifications	Slit Width	$8 \leq x \leq 40$	μm
	Spectral Resolution	< 20	nm
	Lens Focal Distance	100	mm

Structural Overview

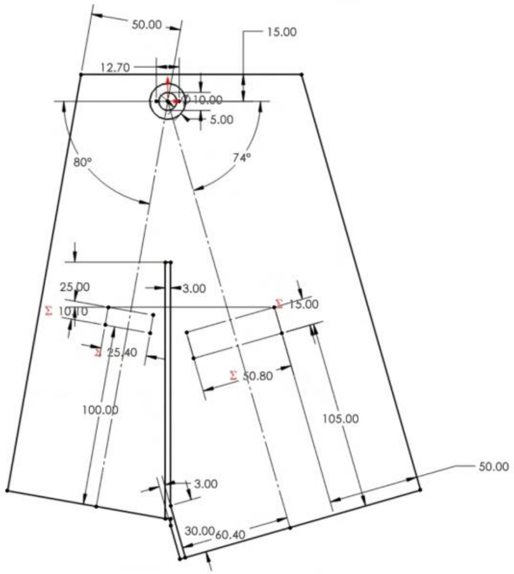


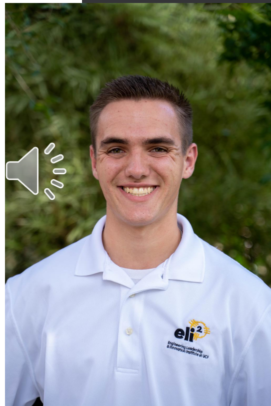
- Spectrometer
  - Adjustability
- Robot Arm
  - ROM
    - T1: 100,-100
    - T2: 45, -90
    - T3: -45, 90
  - DOF
- Electronics Housing
  - Organization



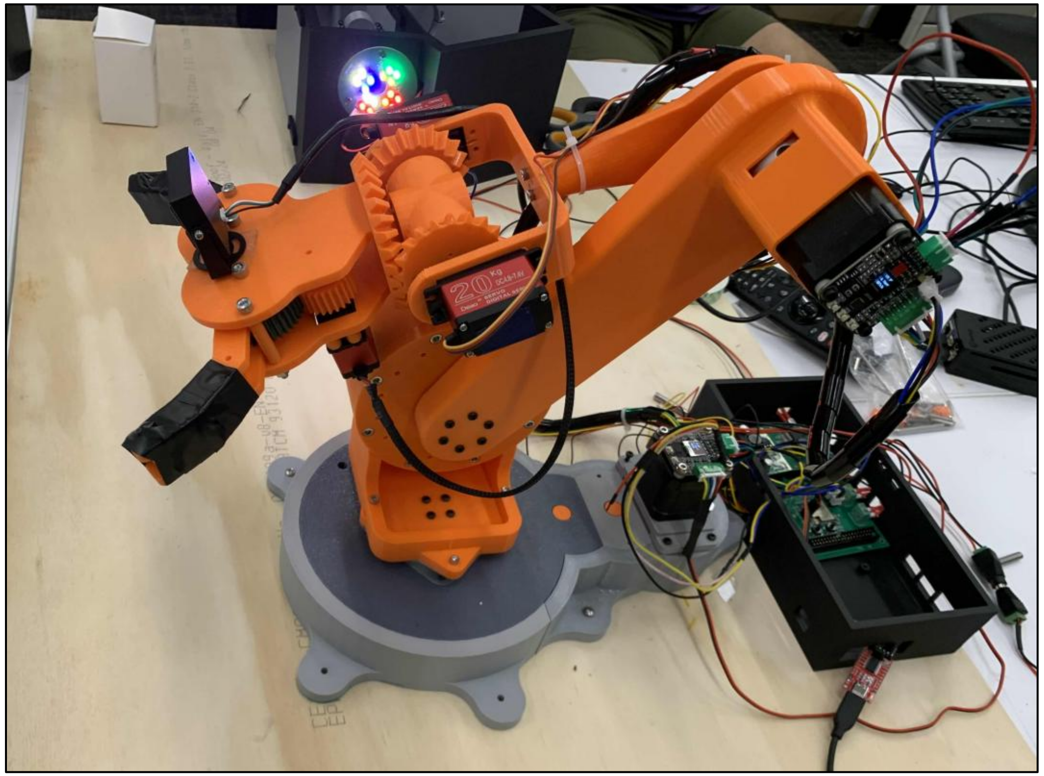
Spectrometer

- Walls
- Lens
  - +-5mm x’, y, z’
  - Yaw 360
- Grading
  - +-5mm y
  - Yaw 360
  - Pitch 360
- Sensor
  - +-5mm y

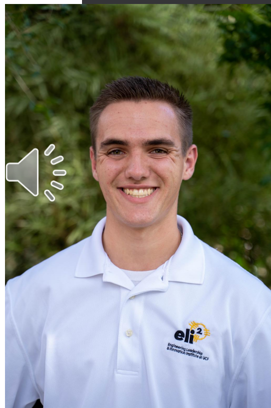




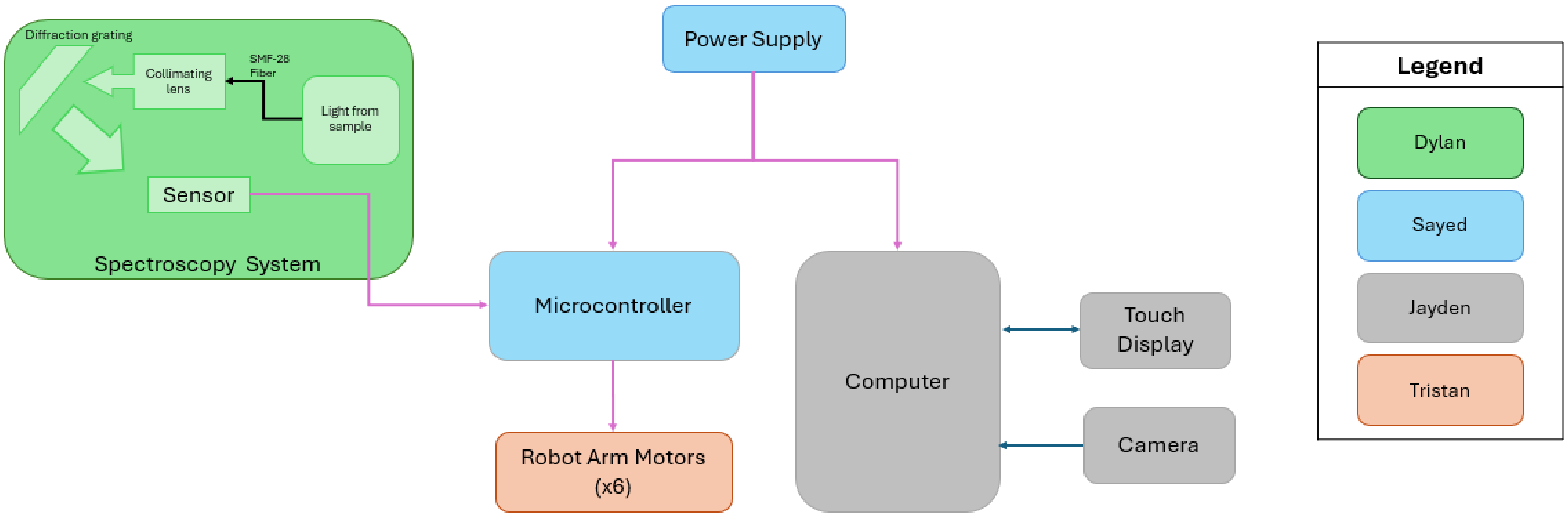
Robot Arm



- Motors
  - T1-T3: Stepper
  - T4-T6: Servo
- Homing Pins
- Differential - 2:1



Simplified Hardware Block Diagram



Microcontrollers

- Required Capabilities For Optical Sensor
  - Fast and accurate ADC
  - Multiple precise timers with advanced controls and triggering functionalities.
  - 32-bit timers
  - DMA support
  - Fast communication protocols

- Required Capabilities For Motor Control
  - Multiple UART interfaces
  - I2C interface
  - Easy programming and debugging

Microcontroller Selection

- Since the CCD sensor is sensitive and has complex requirements, it is on a separate PCB with its own MCU.
- Timer capabilities and ADC accuracy led us to choosing the STM32 for driving the CCD Sensor.
- Availability of CCD sensor project examples using the STM32 online was a key factor.
- The 3xUART, I2C, and ease of programming capabilities of the ESP32-S3 are very useful for our motor control system which is on the main PCB.
- Price was not a main issue since the capabilities were most important for our project to function.

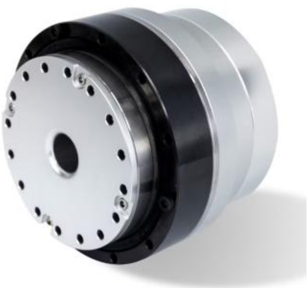
MCU	USB	UART	I2C	Timers	ADC	DMA	Cost
ATmega328P	NA	1	1	2xTimer 8-bit 1xTimer 16-bit	8 channels 10-bit	NA	$1.46
ESP32-S3 WROOM-1	OTG FS	3	2	4xTimer 54-bit (16-bit prescaler)	2xSAR ADC 10 channels 12-bit	YES	$5.71
STM32F401	OTG FS	3	3	2xTimer 32-bit 6xTimer 16-bit	10 channels 12-bit	YES	$5.30

Motor Technology

- Required Capabilities:
  - High torque to handle the payload specifications
  - Closed Loop System for precise control
  - Range of Motion
  - Low Cost

- For the main joints, high torque, precise control, and full range of motion is required.
- Stepper motors meet those requirements.
- End Effector doesn't require such capabilities, so servo motors were chosen to reduce cost.
- BLDC Motors are the perfect choice but very expensive!!

Motor	Position Control	Range of Motion	Holding Torque	Driver	Cost
Servo	Closed Loop (internally)	180°-270°	~0.5 - 3 Nm	PWM Signal	~$2 - $10
BLDC	Open Loop	360°	~0.1 - 100 Nm	ESC (Electronic Speed Controller)	~$10 - $50
Stepper	Open Loop	360°	~0.1 - 8 Nm	Stepper Driver (e.g., A4988)	~$80 - $200



Motor Selection

- Main Joints use stepper motors
- Nema 17s provide enough torque while drawing less current and have a smaller overall dimensions tan Nema 23s.
-

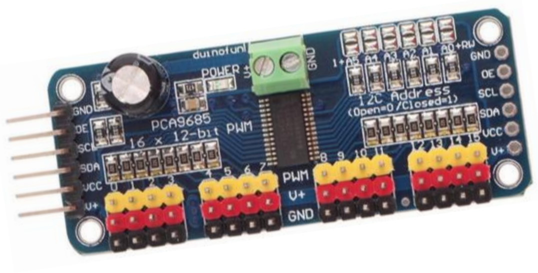
	Motor	Step Count	Current	Holding Torque	Cost
Stepper	**Nema 14**	200 steps/rev (1.8°/step)	~0.4 - 1.0 A/phase	0.08 - 0.12 N·m	$9.07
	Nema 17	200 steps/rev (1.8°/step)	~1.2 - 2.0 A/phase	0.12 - 0.8 N·m	$13.99
	Nema 23	200 steps/rev (1.8°/step)	~2.0 - 3.5 A/phase	1.2 - 4.0 N·m	$25.99

Motor Selection

- End Effector and Gripper joints uses Servos
- MG996R were chosen since they provide better durability and highest torque.

	Motor	Durability	Presicion	Holding Torque	Cost
Servo	**SG90**	~100,000 cycles	±10°	1.8 kg·cm @ 4.8V	$2.38
	MG90S	~150,000 cycles	±8°	~2.2 kg·cm @ 4.8V	$3.5
	MG996R	~200,000 cycles (metal gear)	±5°	~9–11 kg·cm @ 6V	$4.25

Driver Selection



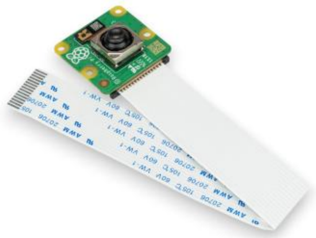
- Evaluated three stepper drivers: A4988, TMC2209, and MKS Servo42C
- A4988: basic, cheap open-loop driver
- TMC2209: adds microstepping and quiet operation, still open-loop
- MKS Servo42C: closed-loop with built-in encoder, mounted directly on motor
- Chosen: MKS Servo42C
  - Simplifies wiring and mounting
  - Enables feedback and tuning using PID
  - Supports UART control for precise, reliable performance
- For Servo Motors, we chose to go with PCA9685 I2C PWM Driver instead of GPIOs to reduce CPU load.

Driver	Control	Interface	Mounting	Size	Features	Cost
A4988	Open-Loop	Step/Dir	External	0.6” x 0.8”	Basic stepper control	$1.74
TMC2209	Open-Loop	Step/Dir	External	0.6” x 0.8”	Quiet stepping, stealthChop	$2.79
MKS Servo42C	Closed-Loop	UART, FOC, Step/Dir	On Motor	1.65” x 1.65”	PID control, auto tuning, feedback	$15.22

Single Board Computer

Feature	Raspberry Pi 5 (8GB)	NIVIDA Jetson Nano	Orange Pi 5 (8GB)
CPU Core	Broadcom BCM2712 Quad-Core Cortex-A76	Quad-Core Cortex-A57	Rockchip RK3588S (4x Cortex-A76 + 4x Cortex-A55)
Clock Speed	2.4 GHz	1.43 GHz	2.4 GHz (A76) / 1.8 GHz (A55)
GPU	VideoCore VII	128-core Maxwell GPU	Mali-G610 MP4
RAM	8GB SDRAM	4GB LPDDR4	8GB LPDDR4X
Storage	MicroSD, PCIe NVMe (optional)	MicroSD	eMMC, NVMe SSD (via M.2 slot) 26
MIPI CSI	Dual 4-lane MIPI CSI	Single 2-lane MIPI CSI	Dual 4-lane MIPI CSI
Networking	Gigabit Ethernet, Wi-Fi 6, Bluetooth 5.0	Gigabit Ethernet (No Wi-Fi or Bluetooth)	Gigabit Ethernet, Wi-Fi (via external module)
AI Acceleration	No (External Module needed)	Yes (CUDA, TensorRT)	Yes (6 TOPS NPU)
Power Consumption	Medium	High	Medium
Availability	High	Low	High
Cost	~$80 (without peripherals)	~$250 (with peripherals)	~$110 (Without peripherals)
Software Support	High (Raspberry Pi OS, Ubuntu, Debian, ROS2)	Medium (JetPack SDK, Ubuntu-based, ROS2)	Medium (Debian, Ubuntu, Android)

Camera



Requirments:

- Chose a high-res autofocus camera for clear, detailed object detection.
- Needed full Ubuntu and ROS 2 compatibility
- Works best in bright lighting, ideal for our controlled environment.

Feature	RPi Cam V3 and ArduCam 12MP	Arducam 4K 8MP IMX219 Autofocus	ArduCam 16MP
Cost	$25	$40	$25
MP Count	12MP	8MP	16MP
FOV	66	72	66
MOD (cm)	5	5	10
Performance	1080p50	1080p30	1080p30
HDR	Yes	Yes	No
ROS2	Not Official	Yes	Not Official
Support	Excellent	Excellent	Moderate

Linear CCD Sensor Selection

- The Spectral response is identical for both products
- Leaving Sensitivity as the next most important factor
- The TCD1304DG's much larger pixel area (i.e., 8 × 200 μm vs 7 × 7 μm) translates to significantly higher photon collection per pixel, yielding a dramatically greater sensitivity (~160 V/(lx·s) for TCD1304DG

Specification	TCD1501D	TCD1304DG
Number of Elements	5000 elements	3648 elements
Pixel Size	Low: 7 μm by 7 μm	High: 8 μm by 200 μm
Sensitivity	Low: 10.4 to 15.6 V/lx·s	High: 110 to 160 V/lx·s
Dark Signal Voltage	2 mV	Up to 5 mV
Dynamic Range	3000	Up to 300 (no unit specified)
Saturation Output Voltage	3 V	450 to 600 mV
Output Impedance	0.5 to 1 kΩ	0.5 to 1 kΩ
Output Signal Voltage	Not specified	1.5 to 3.5 V
Operating Temperature	-20° C to +60° C	-25° C to +60° C
Package Type	22 pin CERDIP	22 pin CERDIP

Comparison of Illimitation Sources

Light Source	Pros	Cons
Incandescent Source	- Continuous and uniform illumination from 400 nm to 1000 nm - Output light from a single fiber	- High power consumption - High operating temperatures that may damage 3D printed parts - Separate power system
LED Source	- Low power consumption - Flexible with system integration	- Non-uniform illumination across the spectrum - Illumination source's location are separated

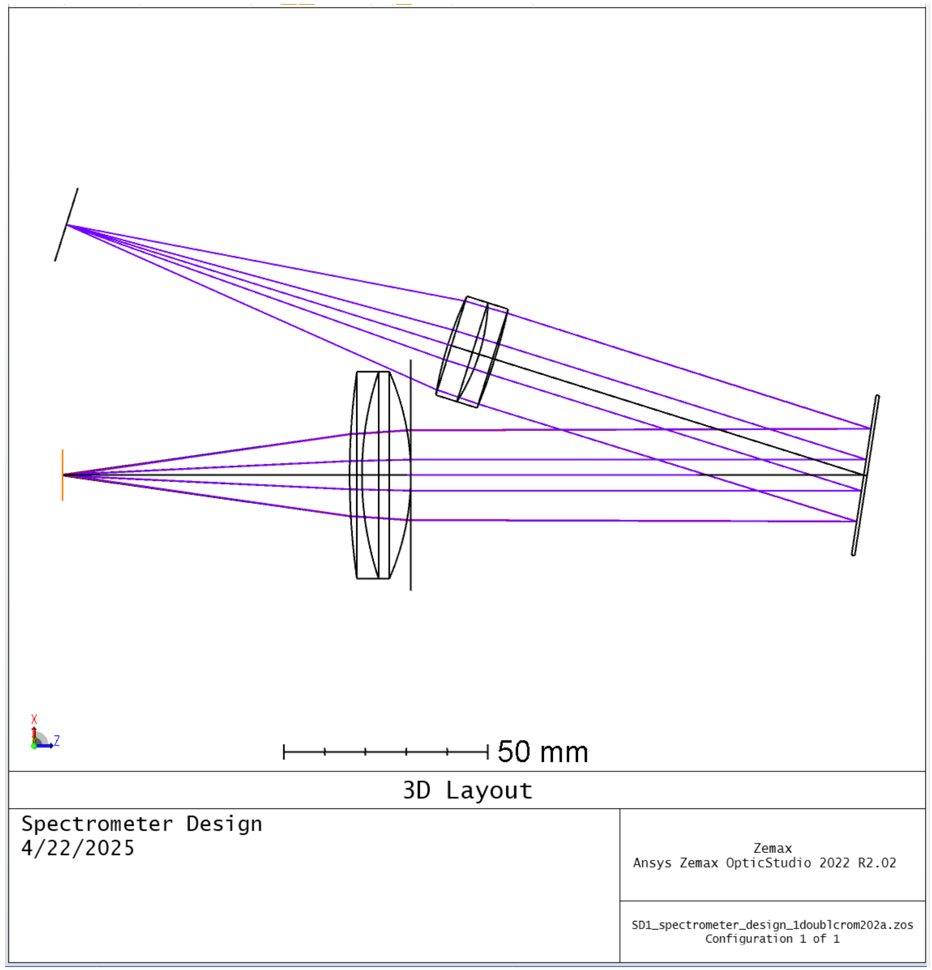
LED Selection

- Since the system is reflected based spectroscopy. The system can only receive the light being illumined onto the object.
- Thus, to get the full visible spectrum of the object. An array different LEDS is required.

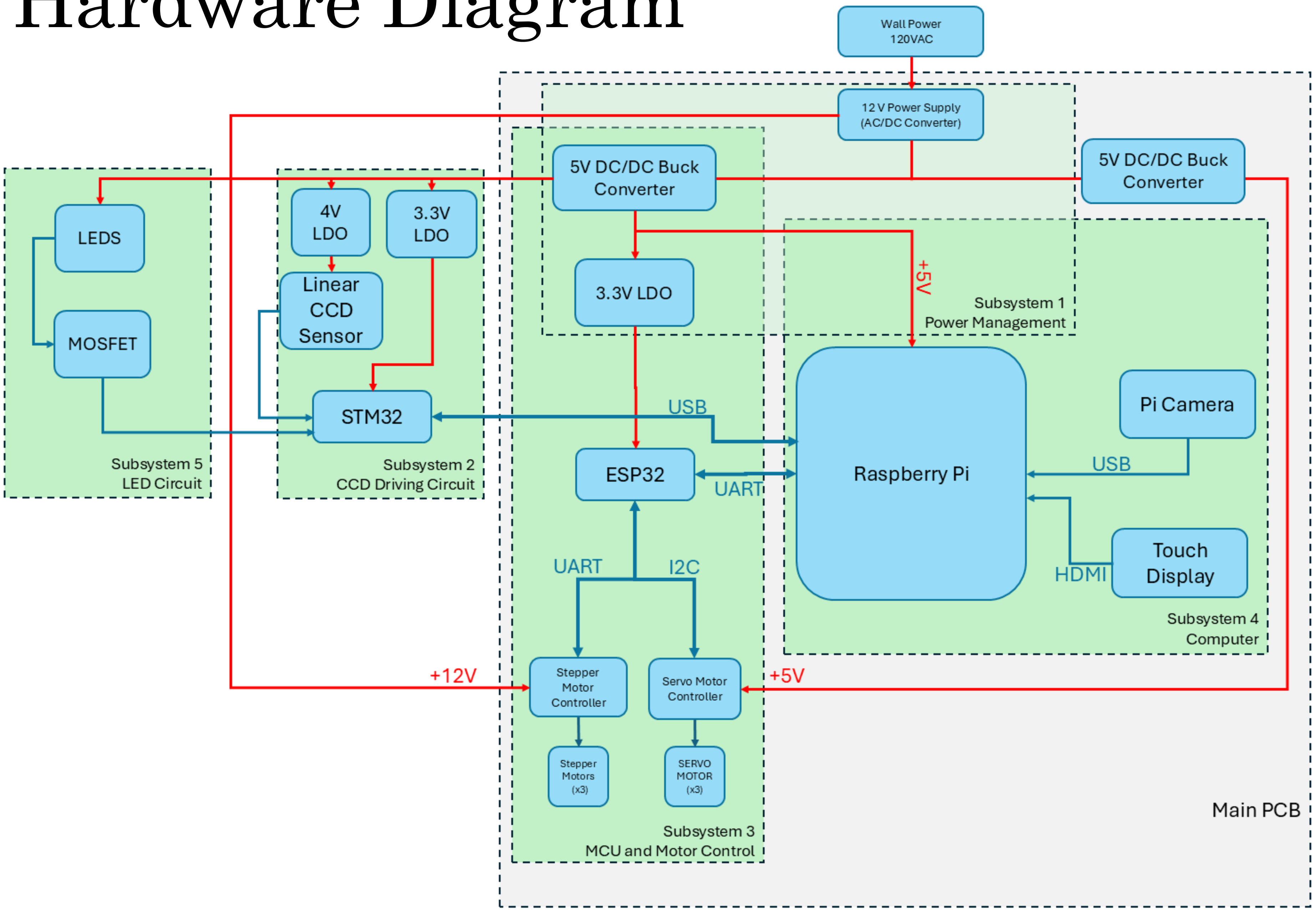
Name	Lambda Range (nm)	Quantity
White	395 to 530	4
Ultraviolet	<400	0
Violet	400 to 450	0
Blue	450 to 500	2
Green	500 to 570	2
Yellow	570 to 590	2
Orange	590 to 610	2
Red	610 to 760	4
Infrared	> 760	0

Hardware Design for Spectrometer

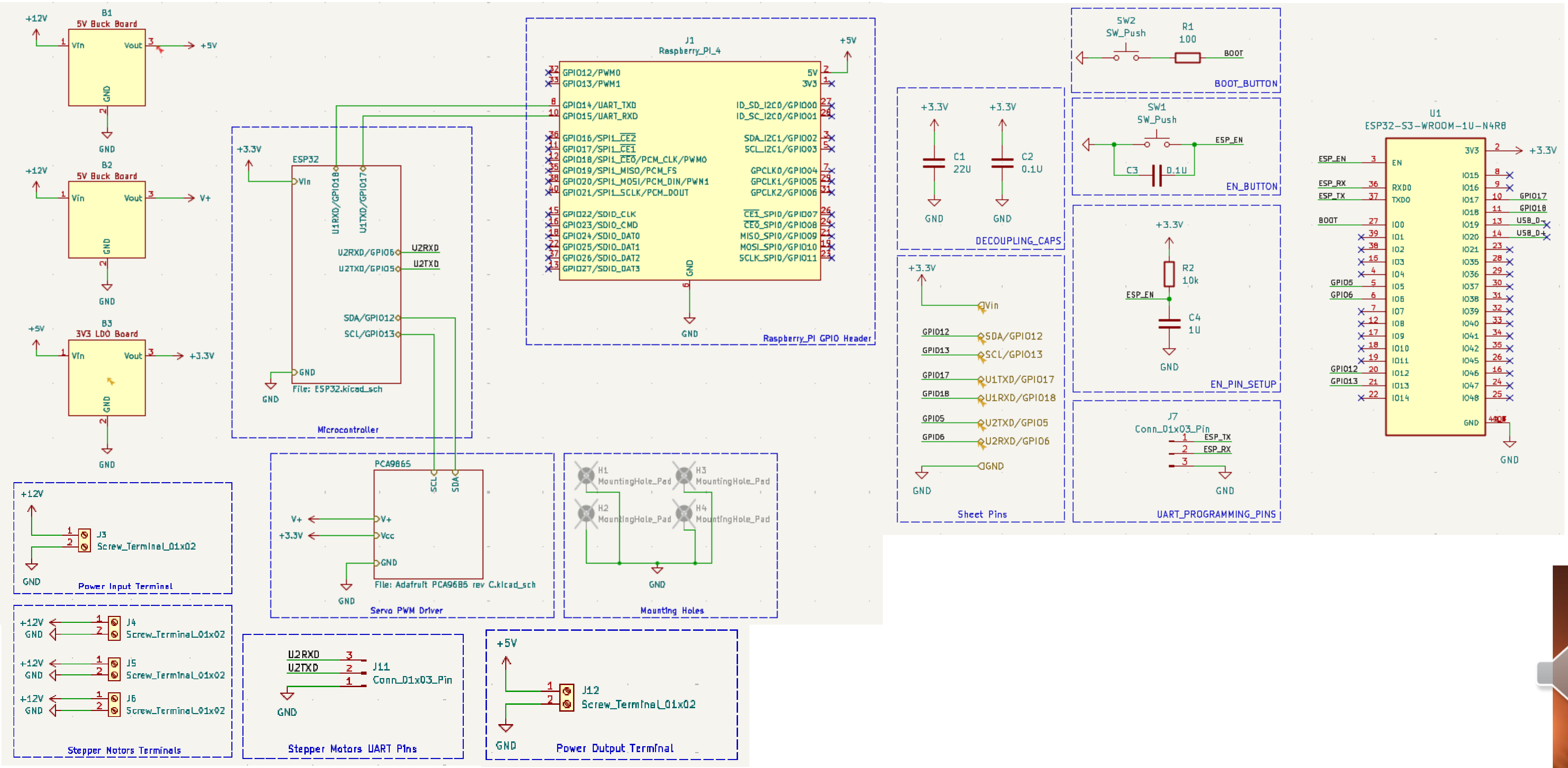
- The goal of this spectrometer design is to focus light from a 1/2" circular entrance aperture onto a single detector pixel (8 µm), optimizing spatial-spectral resolution in an aberration-limited regime.
- A 0.8× magnification is used to match the effective image size.
- The entrance slit was removed to increase the optical throughput and maximize the light incident on the sensor.
- Final optimization focuses on minimizing spot size across all wavelengths to ensure consistent performance over the full spectral range.



Hardware Diagram

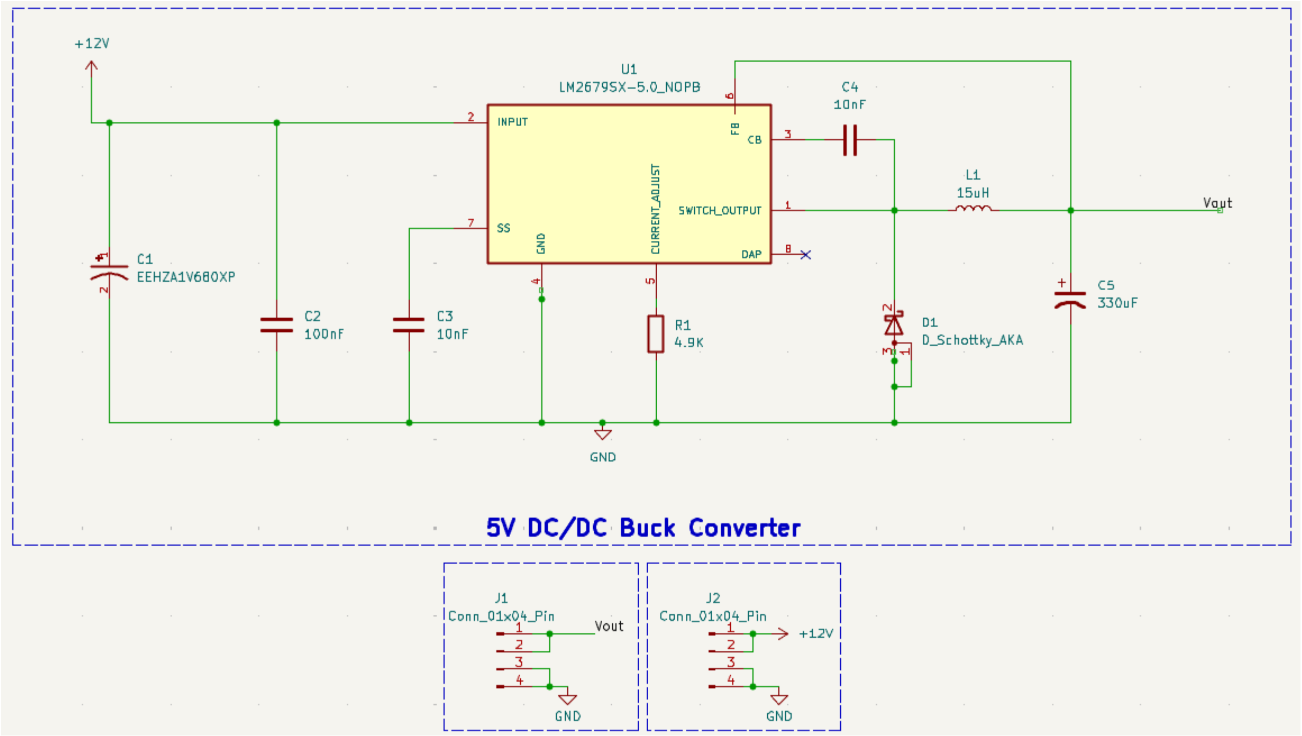


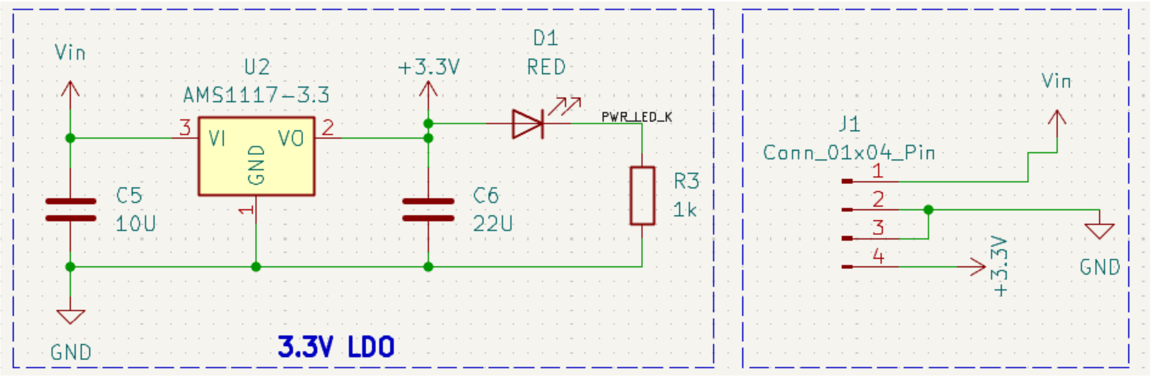
Main PCB Schematic



Power Regulators Schematic

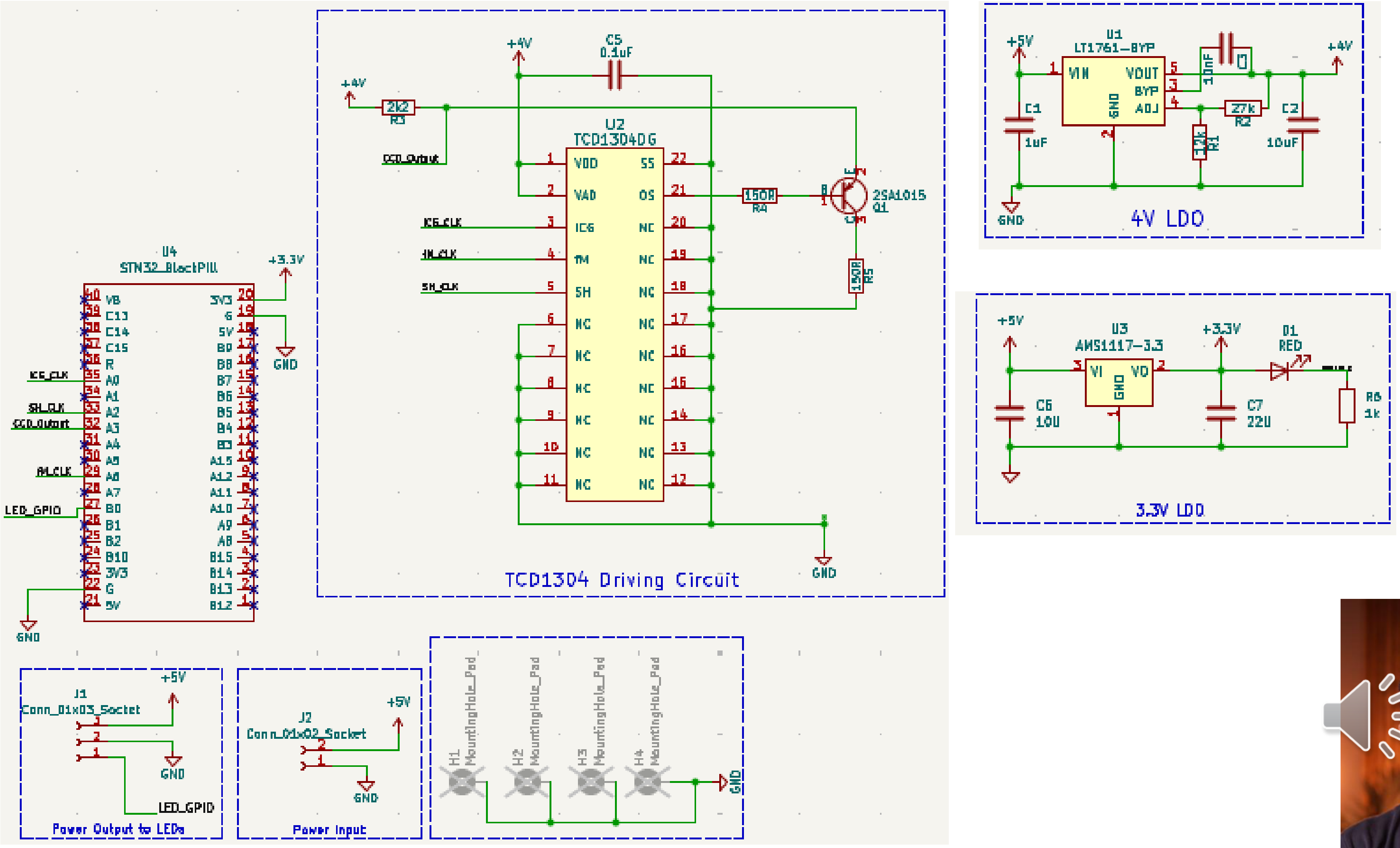
- 12V-5V Buck Converter
  - Designed using TI WEBENCH
- 5V-3.3V LDO
  - Designed according to Datasheet recommendation
  - Added LED to confirm status.



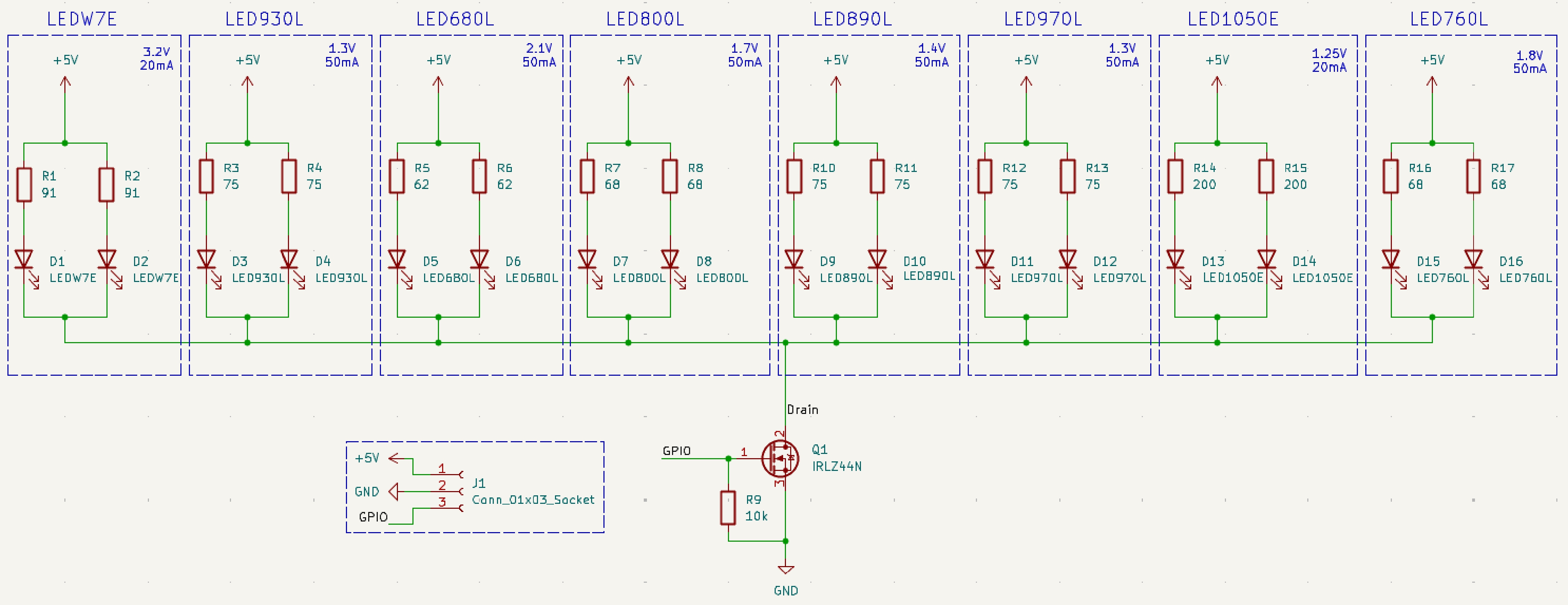


CCD Sensor Board Schematic

- STM32-F401
  - Dev Board attached to the back of the PCB, specifically for controlling the CCD Sensor
  - USB output to RaspberryPi
  - 5V input from main PCB
  - 3.3V LDO used for MCU input.
- TCD1304 Linear CCD Sensor
  - Driving Circuit designed according to the Datasheet recommendation
  - Sensor receives the 4V recommended input using an adjustable LDO
  - Output of CCD routed directly to STM32 ADC

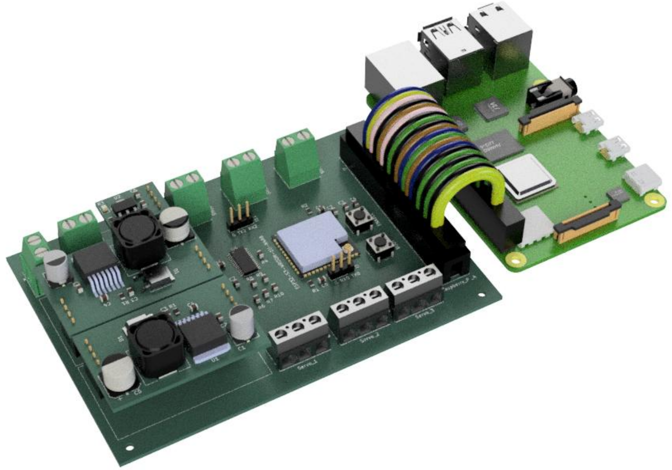


LED Ring Schematic

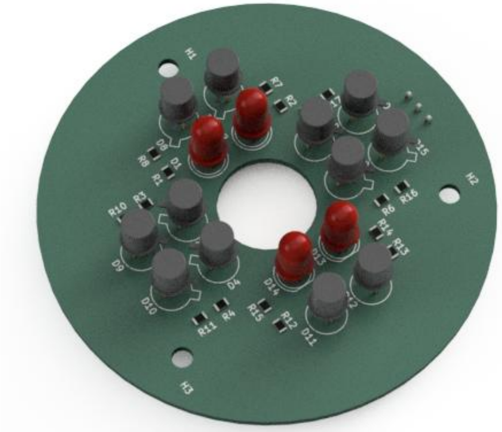


PCB Design

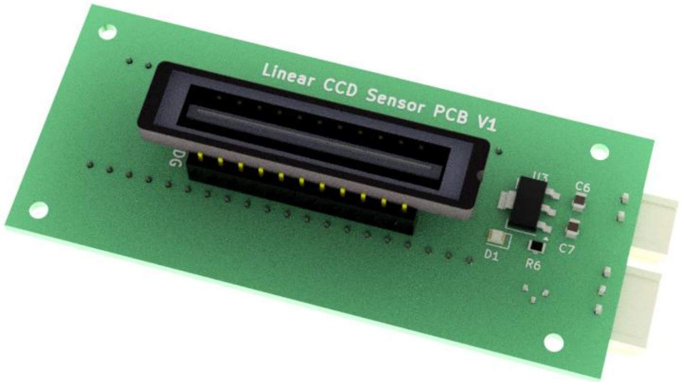
- Main Board
  - Includes all power and regulators circuitry
  - Regulators on Daughter Boards
  - ESP32 for motor control
  - Motor connections
  - Power output to other PCBS
  - Raspberry Pi Connection
  - Servo Driver
- Sensor Board
  - Has its own power regulators required for MCU and sensor
  - 5V power input connector
  - 5V and GPIO connector for LED PCB
  - STM32 DEV Board on the back side
- LED Board
  - Has 16 specific LEDs needed for spectrometer system
  - MOSFET Controlled by the STM32 GPIO pins
  - Circle cutout in the center to fit around spectrometer slit
  - 3-Pin connector for power and control from the sensor board.



Main PCB

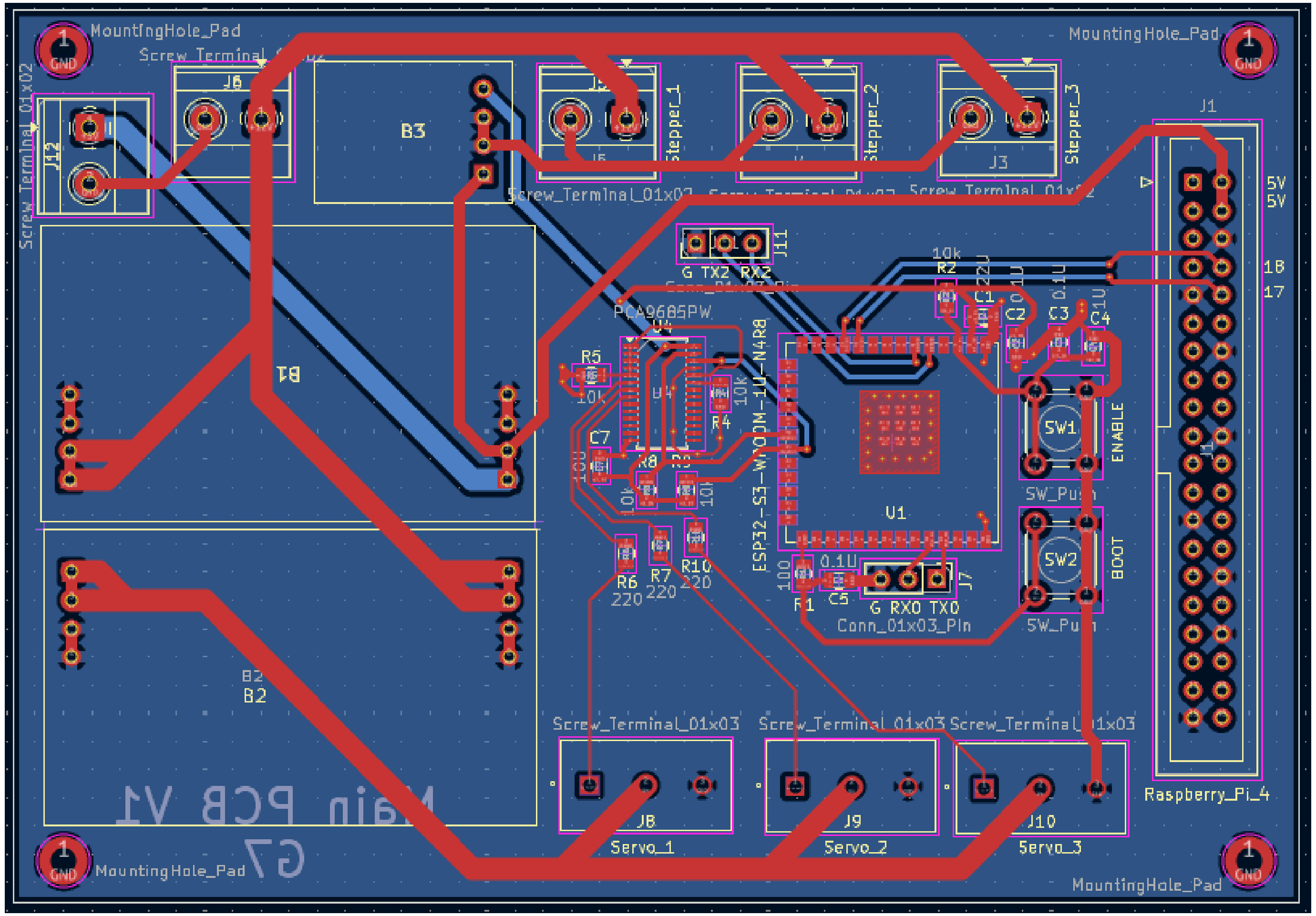


LED Ring PCB

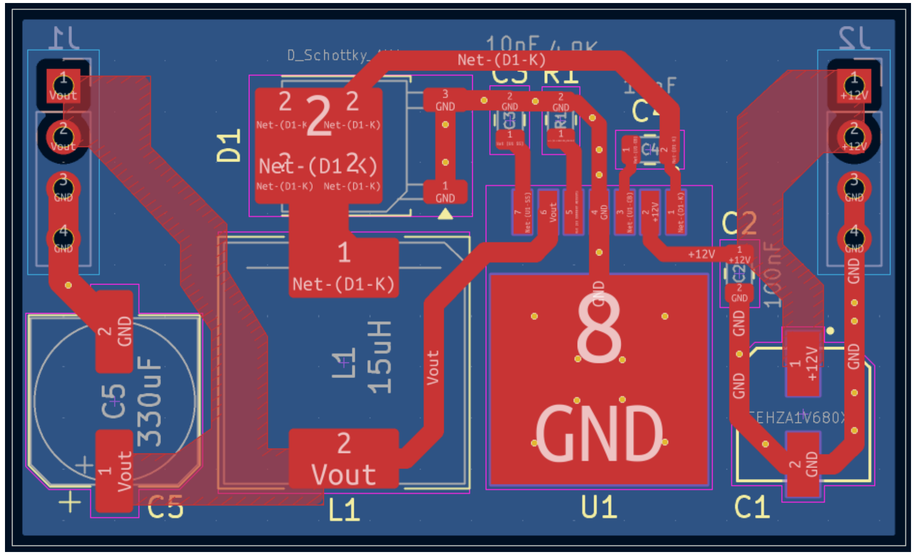


CCD Sensor PCB

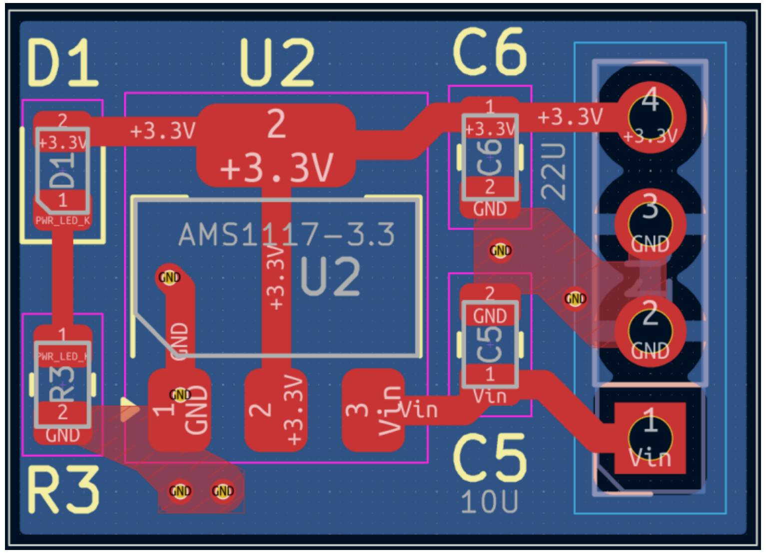
Main PCB Layout



Main PCB

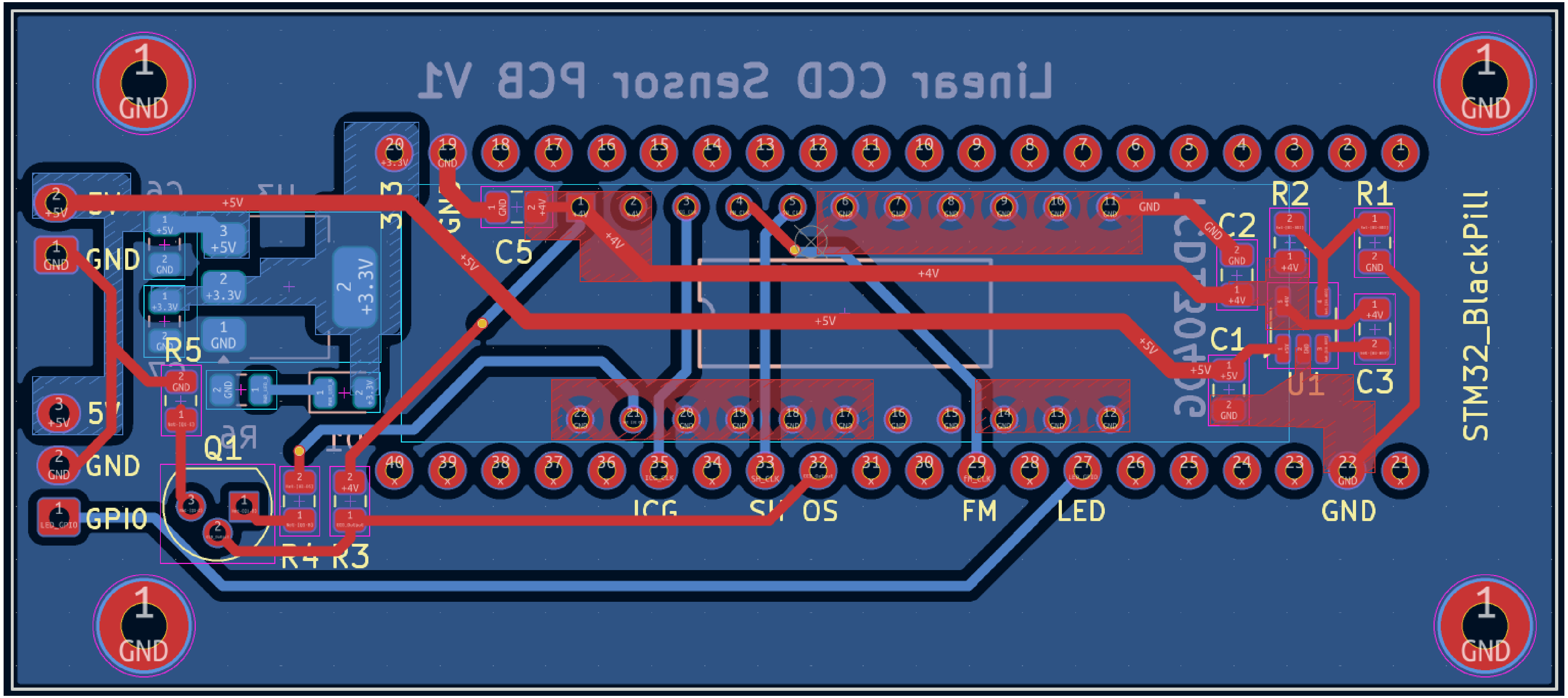


5V Buck Converter PCB

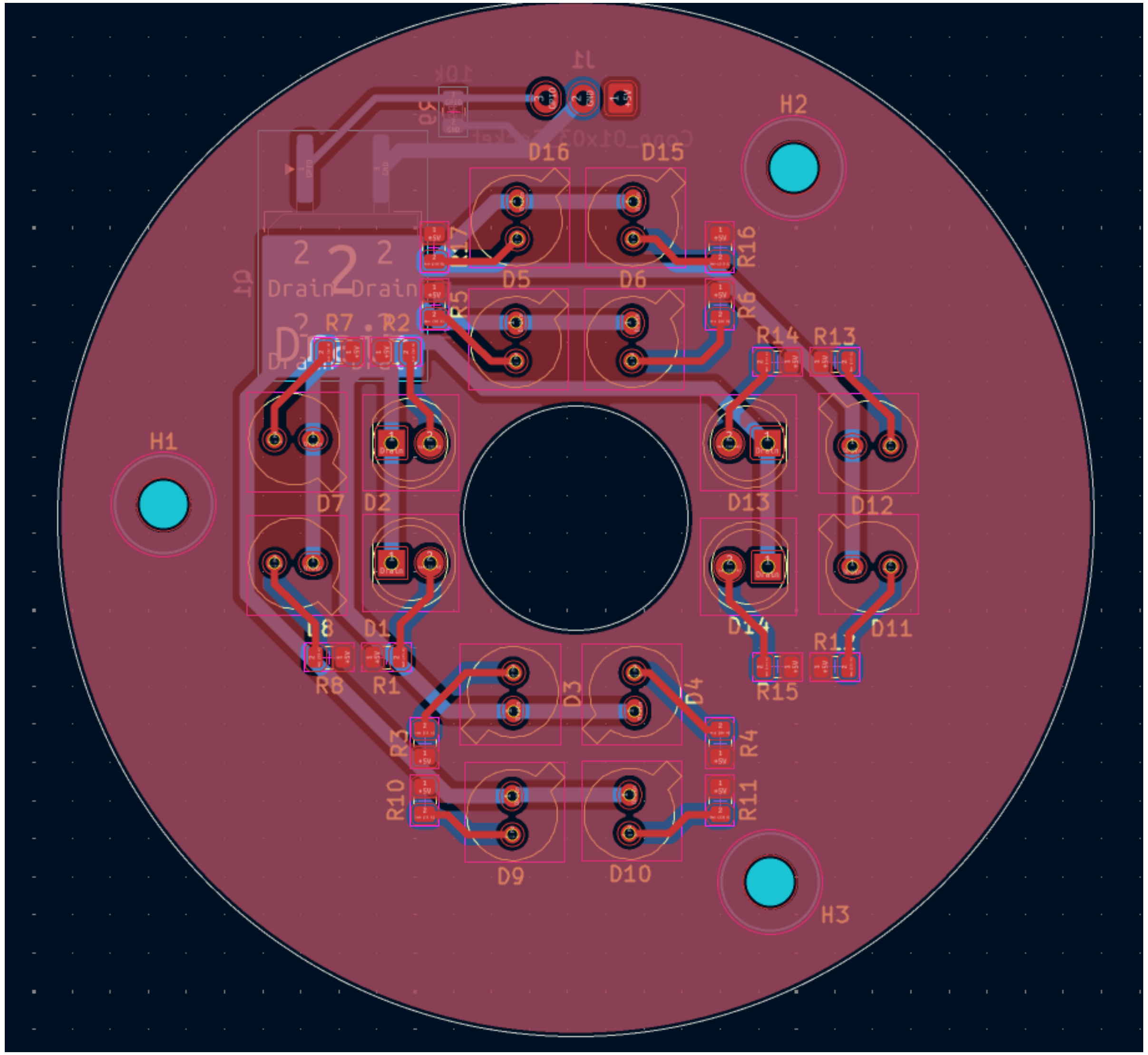


3.3V LDO PCB

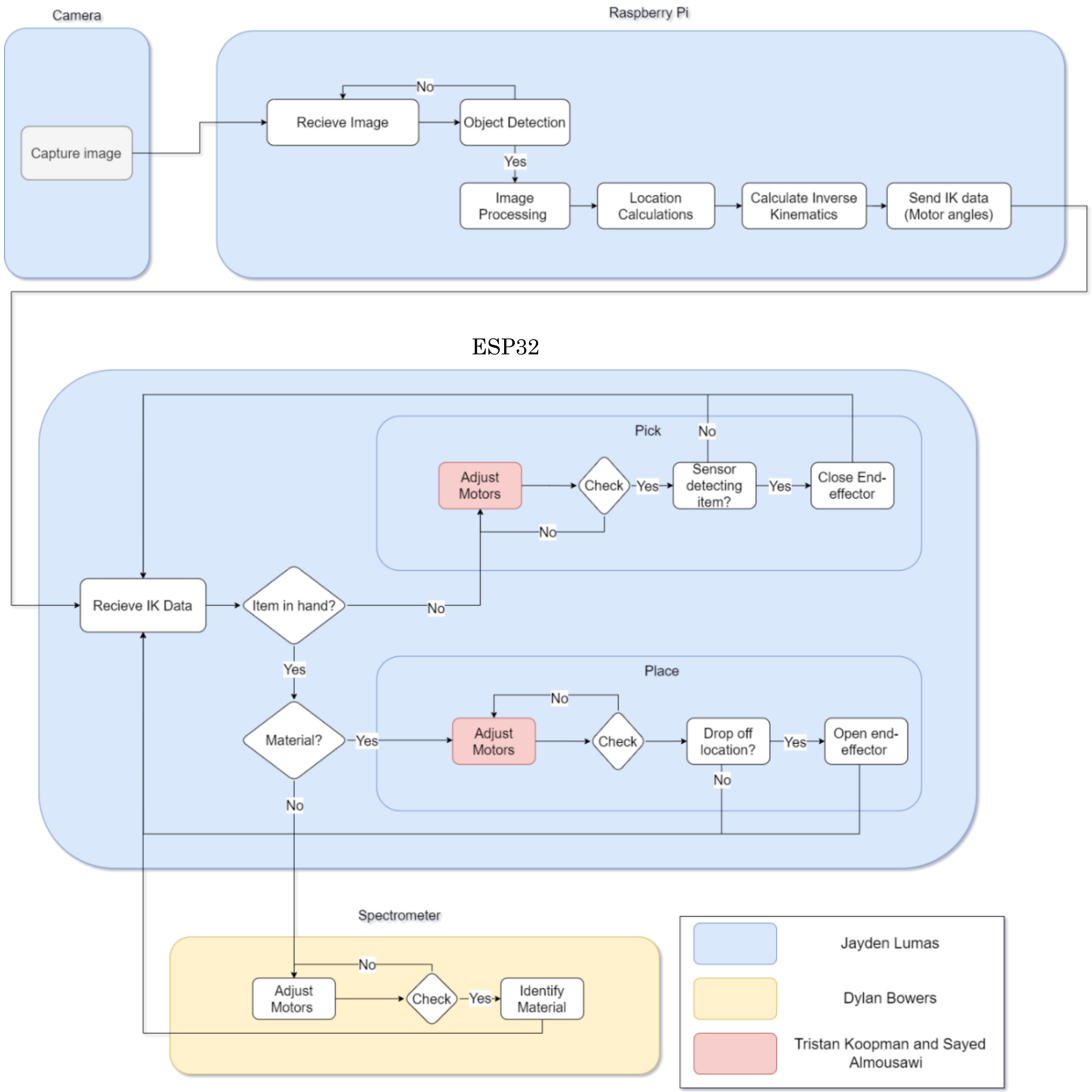
Sensor PCB Layout



LED PCB Layout



Software Flowchart

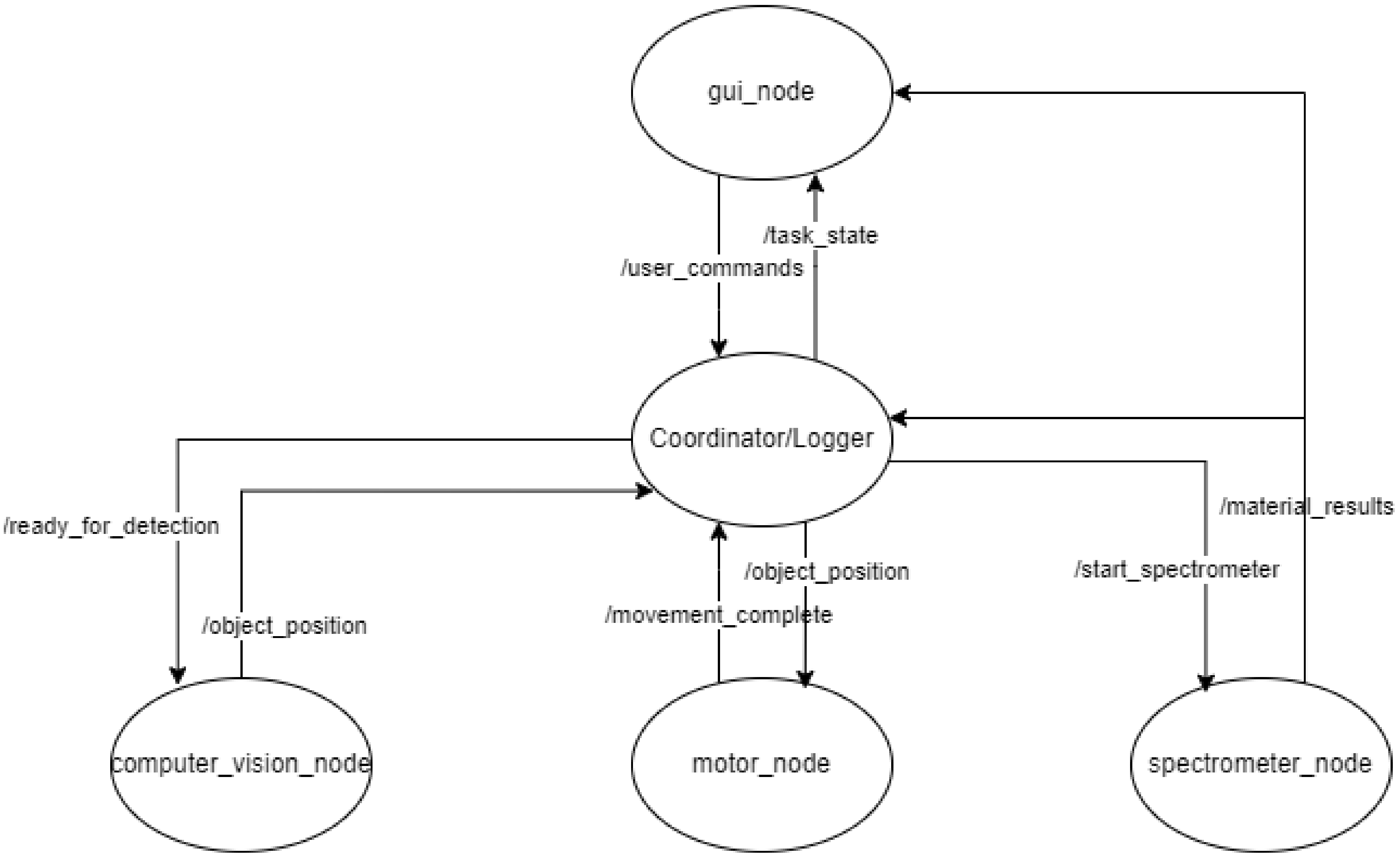


Robot Operating System Overview

- Leveraged ROS for its **mature ecosystem**, **rapid prototyping tools, and broad package support.**
- Adopted ROS2 for its **real-time capabilities**, secure communication, native multi-robot integration, and **Industry Standard**.
- Combined, they enabled a scalable, high-performance framework tailored for complex system development.

Feature	ROS	ROS2
End Of Life	May 31st, 2025	Actively Supported and being Developed
Middleware	Centralized ROS Master	Decentralized DDS (Data Distribution Service)
Real-Time Performance	Not designed for real-time applications	Improved execution timing and scheduling
Multi-Robot & Distributed Systems	Limited support	Built-in support for multi-robot and distributed applications
Security	Minimal security features	Encrypted communication and authentication
Cross-Platform Support	Primarily Linux-based	Supports Linux, Windows, and macOS
Community & Package Availability	Large community with many legacy packages	Growing community with most major ROS1 packages ported over

ROS2 Design



gui_node
/task_state
/user_commands
Coordinator/Logger
/material_results
/ready_for_detection
/object_position
/start_spectrometer
/movement_complete
/object_position
computer_vision_node
motor_node
spectrometer_node

Object Detection Overview

- Chosen for its wide-area visual coverage, allowing detection and classification of multiple objects.
- Seamlessly integrates with ROS2 and machine learning pipelines for real-time decision-making.

Feature	Ultrasonic Sensor	Computer Vision	LiDAR
Cost	About $5	$20-$100; Depends On Camera	+$150
Material Detection	No	Yes	Yes
Enviromental Sensitivity	High; temp/humidity	Moderate; Lighting	High; Reflectiviy
Resolution	Single Point	High; Depends On Camera	Very High; 3D mapping
FOV	Narrow; Single Point	Wide; Depends on Camera	Very Wide
Ease of integration	Easy; Gpio	Medium; Python, ML, OpenCV	High
Real-Time Performance	No	Yes	Yes; High Power Required

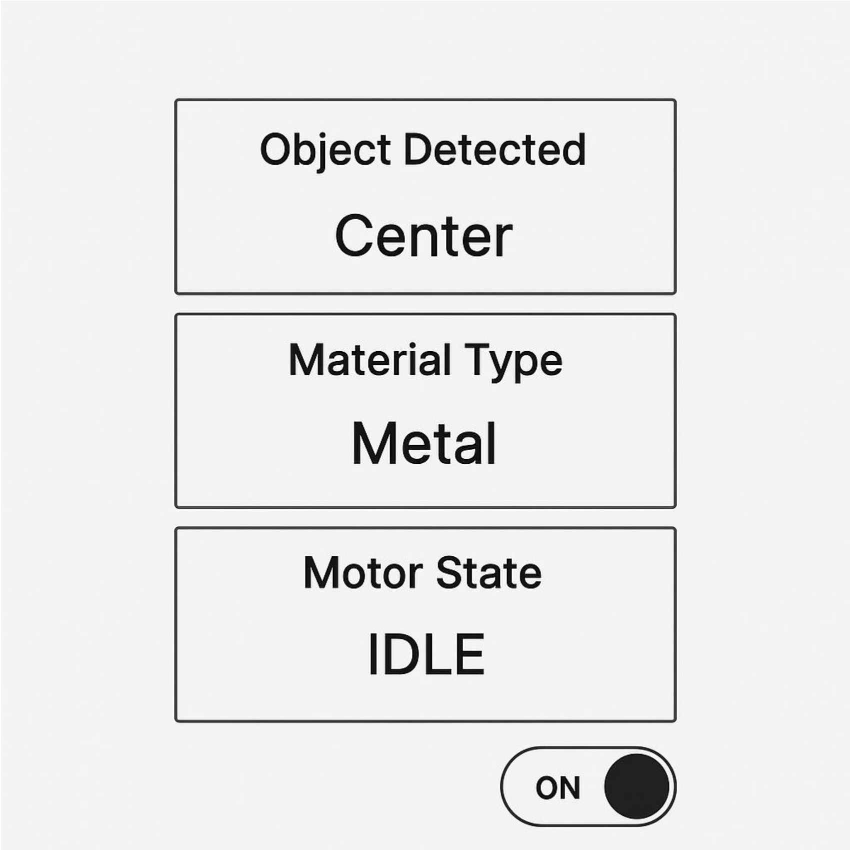
Machine Learning Overview

- Supports custom training, enabling accurate classification of diverse recyclable materials.
- Compatible with ROS2, allowing efficient inference in a compact system.

Feature	**Yolov8**	**Yolov11**	AWS Rekognition	TensoreFlow Lite
Performance	Fast, Accurate	Fast, Improved Accuracy	Cloud-based, Scalable	Optimized for edge devices
Offline Support	Yes	Yes	No	Yes
Ease of Training	Moderate	Moderate	N/A Pretrained Models	High
Integration with ROS2	High	High	Low; API Based	Low; Out-of-Date Drivers
Cost	Free	Free	Paid; Depends on the Model	Free
Documentation	High	Medium	High	Medium

Graphical User Interface

- Displays detected object type, material, and robot state live.
- Integrates with ROS 2 topics from CV, spectrometer, and motor control nodes.
- ON/OFF toggle publishes to `/gui_toggle` for manual override or system shutdown.

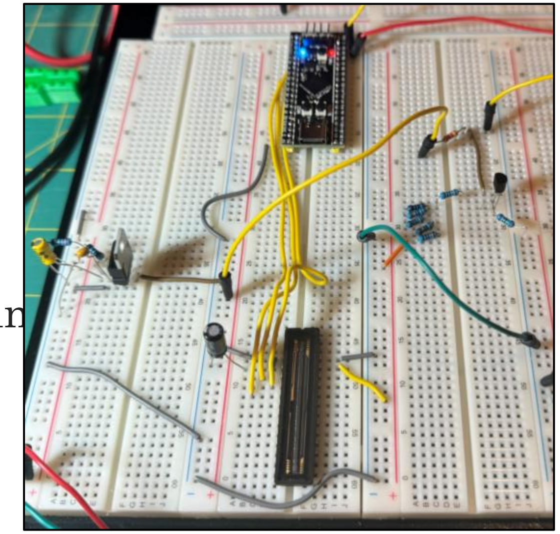


Spectrum Compare Software

- Procedures for code to resolve the object with spectrum information

Receive unknow spectrum → Take the difference between the unknown and control spectrum to eliminate background noise → Compare the unknown spectrum to the spectrum library → Last print out the material type

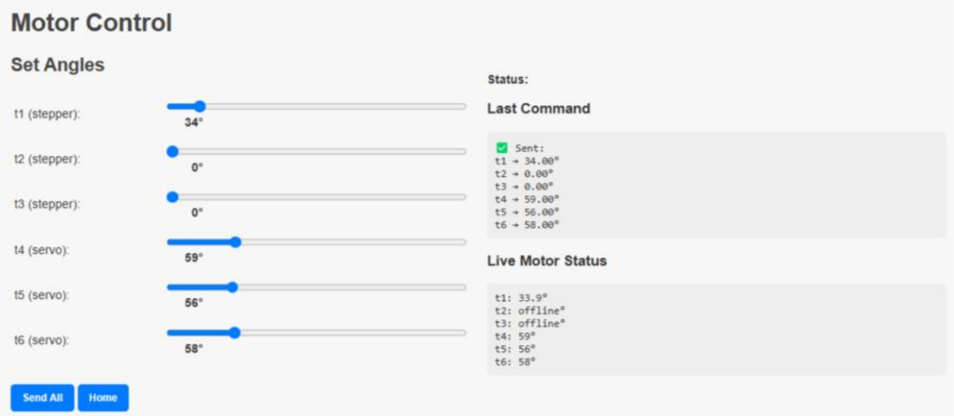
Testing – Hardware

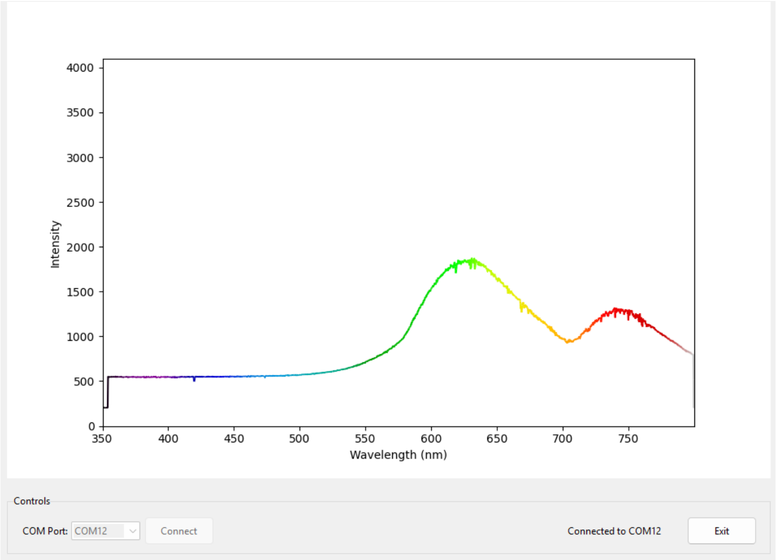


- Servo Motors
  - Tested with direct ESP32 PWM control.
  - Verified smooth movement and holding angles.
  - Upgraded to PCA9685 driver for multi-servo control testin
  - Solved MCU resetting issues by adding a second buck converter.
- Stepper Motors
  - Used MKS Servo42C with UART commands.
  - Verified movement, direction, speed via manufacturer GUI
  - PID tests showed reliable position holding under load.
- CCD Sensor
  - Breadboarded driver circuit using STM32 timers.
  - Adjusted analog signal amplification with 2N3906.
  - Synced ADC timing; verified output with oscilloscope.

Testing – Software

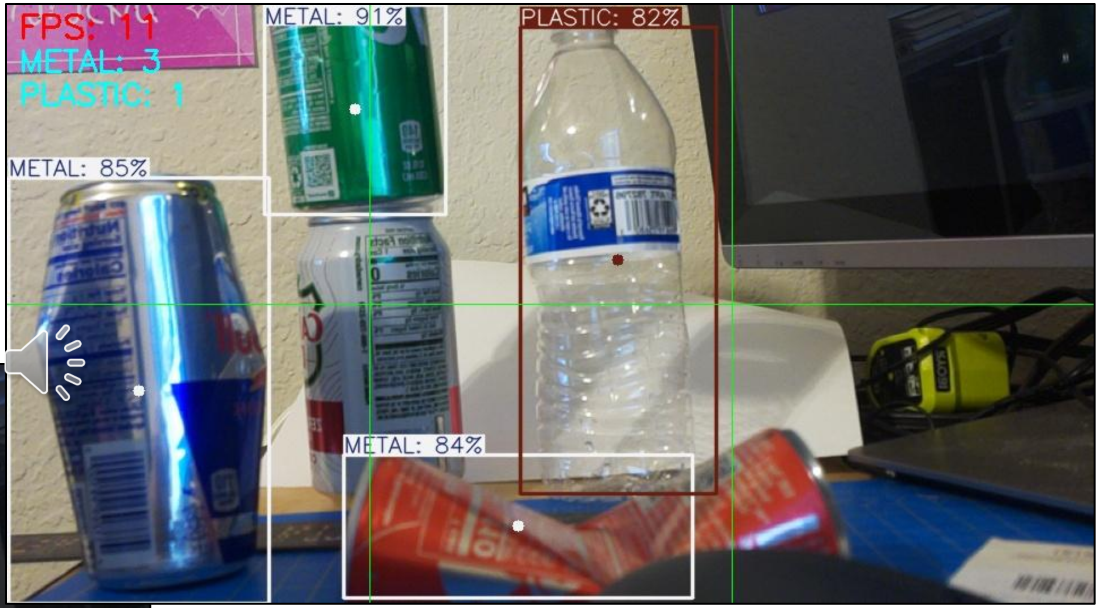
- Motor Control
  - Custom UART protocol for stepper motor commands.
  - ESP32 sends angle/speed; verified feedback from encoders.
  - Developed a web-based GUI for motor control Testing and Demo.
- Spectrometer Firmware
  - STM32 ADC + DMA handles CCD output.
  - Developed Python plotting tools for debugging.
  - Synced sampling timing for clean signals.





Testing – Software

- Computer Vision
  - Real-time classification using YOLOv11 detects plastic and metal recyclables with high confidence.
  - Visual output includes bounding boxes, object type, and certainty for precise robotic sorting.
  - Integrated with ROS 2 for automated decision-making and coordinated arm movement.



BOM and Budget

Sub-system	Projected Cost	Item	Total Price	Sub-System Actual Cost
Optics and Sensors	$700	LEDs	$193.36	$620.08
		Slit	$137.08	
		CCD Sensor	$6.95	
		Lenses	$282.69	
Motor System	$220	Stepper Motors	$66.00	$140.97
		Servo Motors	$41.97	
		Stepper Drivers	$33.00	
Computer Vision System	$140	Raspberry pi 5 kit	$135.99	$210.99
		Mouse and Keyboard	$20.00	
		Camera	$40.00	
		USB-A to Serial Adaptor	$15.00	
PCB and Electricals	$120	PCB	$60.00	$162.47
		ESP32	$2.95	
		STM32 Dev Board	$14.99	
		Electronic Components	$65.54	
		Power Supply	$18.99	
Frame/Robotic Arm	$180	PLA Filament	$80.00	$157.59
		Bearings Pack	$17.59	
		Assorted Hardware	$60.00	
Total:	$1360	Total	$1292.10	

Work Distribution

<table>
<tr><th>Task</th><th>Primary Member</th><th>Secondary Member</th></tr>
<tr><td>Circuit Design and PCB</td><td rowspan="6">Sayed</td><td></td></tr>
<tr><td>Hardware/Motors selection</td><td></td></tr>
<tr><td>Motor Control Software</td><td>Jayden</td></tr>
<tr><td>Website Design and Mangament</td><td></td></tr>
<tr><td>CCD Sensor Low level Software</td><td>Dylan</td></tr>
<tr><td>Wiring and Cable Management</td><td>Dylan</td></tr>
<tr><td>Optical Design/Integration</td><td rowspan="2">Dylan</td><td></td></tr>
<tr><td>Spectrum Comparison Software</td><td>Jayden</td></tr>
<tr><td>Computer Vision</td><td rowspan="2">Jayden</td><td></td></tr>
<tr><td>ROS Integration</td><td>Sayed</td></tr>
<tr><td>Robot Arm Design</td><td rowspan="3">Tristan</td><td></td></tr>
<tr><td>Optical Housing Design</td><td>Dylan</td></tr>
<tr><td>Electrical enclosure Design</td><td>Sayed</td></tr>
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