# I.R.I.S.

## INFRARED RELIABILITY INSPECTION SYSTEM

## FINAL PRESENTATION

Group 3: Sean Willie, Andrew VanAuken, Jason Ha, Shea Meyer

# MEET THE TEAM

Jason Ha

Photonic Science & Engineering

Andrew VanAuken

Electrical Engineering

Sean Willie

Electrical Engineering

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Computer Engineering

# PROBLEM & MOTIVATION

Andrew VanAuken
EE

- Electrical equipment such as switchgear and transformers can develop overheating that may lead to equipment failure, downtime, and arc-flash hazards.
- Current thermal inspections are typically performed manually using handheld infrared cameras and only provide periodic snapshots of equipment.
- While infrared inspection windows improve safety, most monitoring solutions do not provide continuous temperature trending.
- The goal of IRIS is to develop a low-cost, thermal monitoring system that continuously detects hotspots and tracks temperature trends through existing IR windows.

# GOALS & OBJECTIVES

Andrew VanAuken
EE

- Continuous thermal monitoring of electrical equipment
  - Monitor equipment through infrared inspection window.
- Early hotspot detection
  - Identify abnormal temperature rise.
- Improve safety
  - Reduce the need to open electrical enclosures.
- Remote monitoring and alerts
  - Provide temperature data and notifications through a web dashboard.

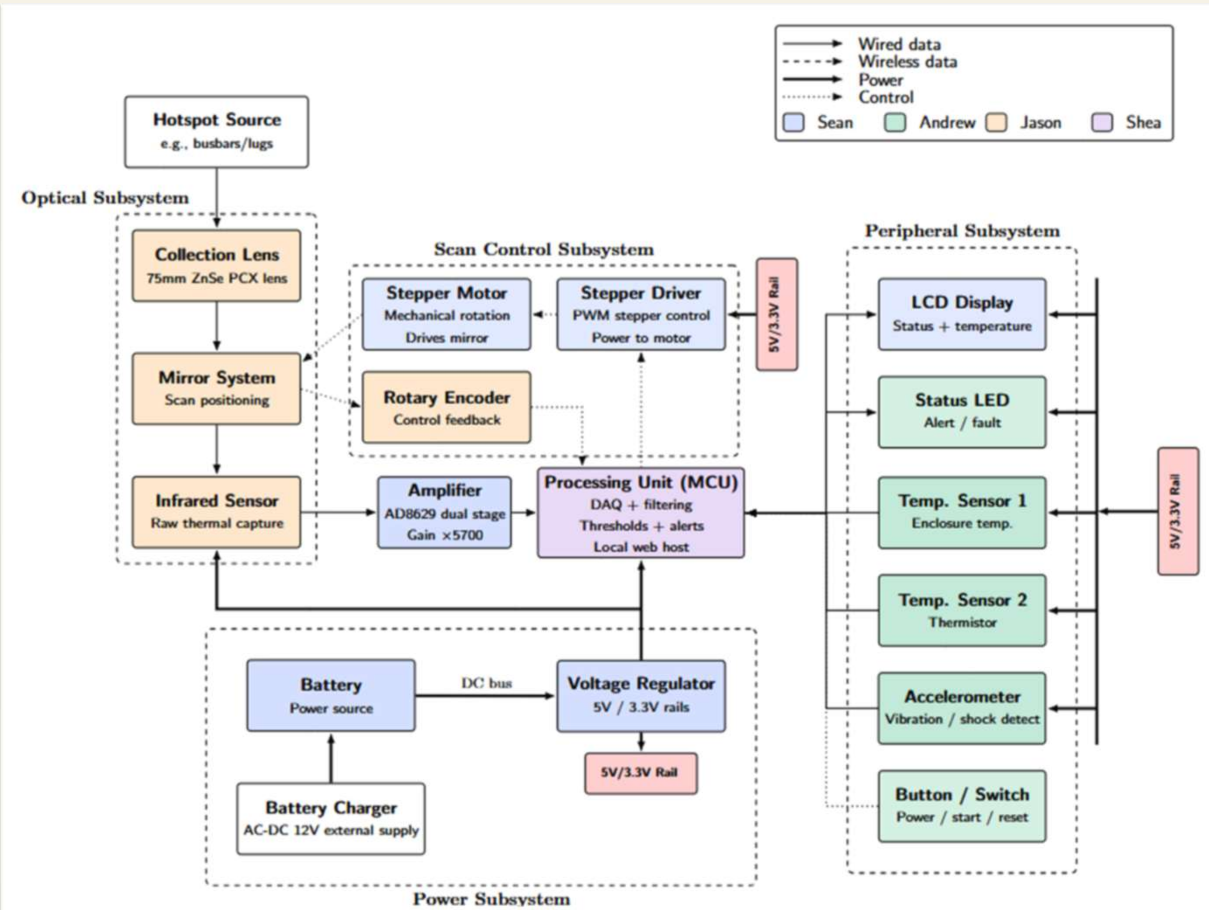
# ENGINEERING SPECIFICATIONS

| Parameter | Specification | Description |
|---|---|---|
| Imaging Temperature Range | 40-120°C | Operating temperature range detectable by the system |
| Temperature Accuracy | ±10°C | Maximum allowed measurement error |
| Field of View (FOV) | ≥ 15° × 15° | Angular coverage of the monitored scene |
| Frame Rate | ≥ 0.033 fps | Thermal image update frequency |
| Spatial Resolution | ≤ 20 mm | Minimum feature size that can be resolved |
| Stimulus-to-Alert-Response Time | ≤ 30 s | Time from anomaly detection to user alert |
| Hotspot Detection Accuracy | ≥ 90% | Correct identification of thermal anomalies |
| False Alarm Rate | ≤ 5% | Maximum allowable false hotspot detections |
| Data Update Rate | ≥ 1 frame/min | Dashboard refresh frequency |
| Dashboard Latency | ≤ 5 s | Delay between acquisition and display |
| Average Power Consumption | ≤ 35 W | Average system power draw over one hour |
| Battery Life | ≥ 4 hr | Continuous operating time on battery power |
| Signal-to-Noise Ratio (SNR) | ≥ 10 dB | Minimum acceptable signal quality |

Jason Ha
PSE

- Highlighted specifications are validated through testing
- Signal related specifications designed to account for small signal availability.

# HARDWARE BLOCK DIAGRAM




Sean Willie
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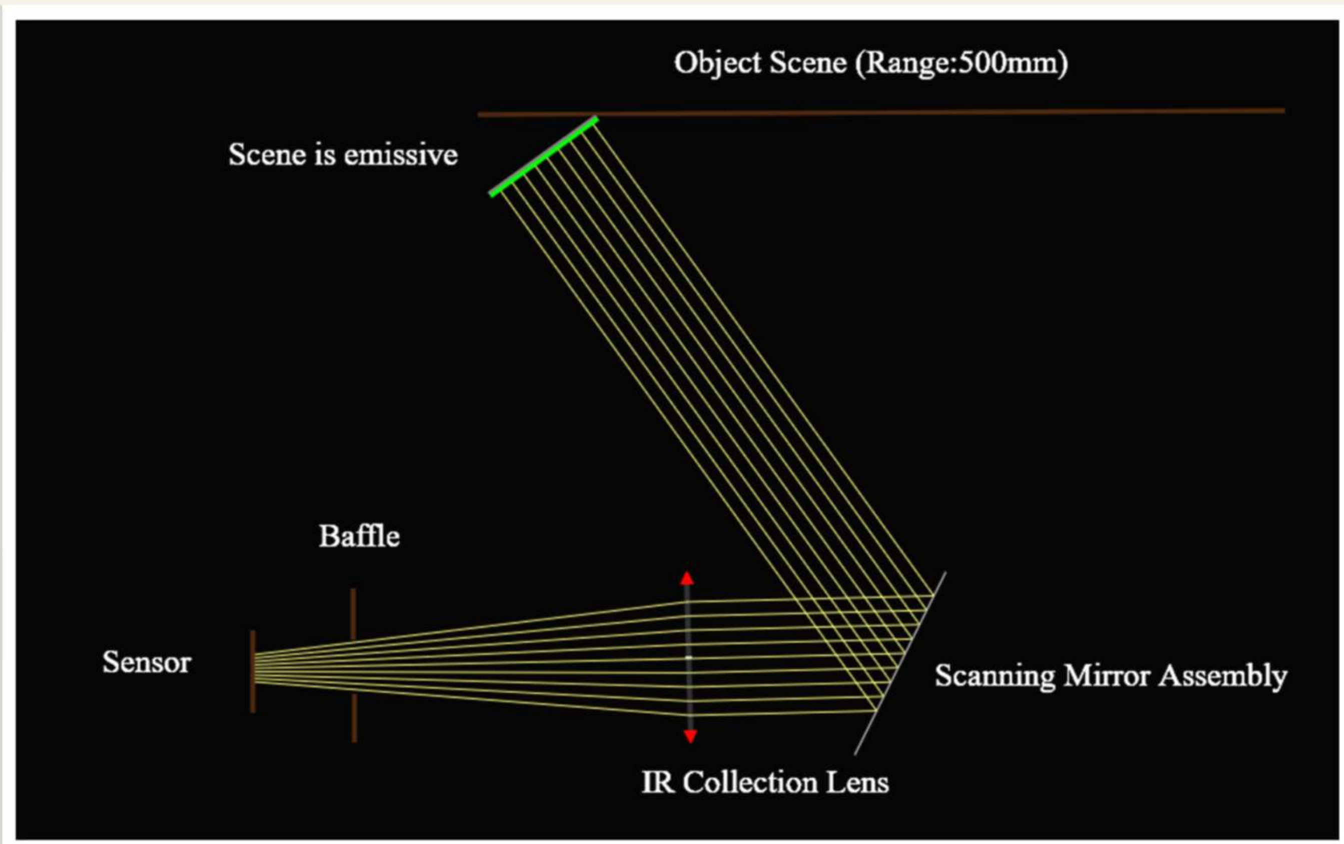
Key functions:

- Optics: Physical signal acquisition
- Amplification stage: Signal conditioning & processing
- Reliable mechanical scanning
- Supporting functions (power, displays, buttons)

# OPTICS SCANNING SCHEMATIC





Jason Ha
PSE


- The mirror assembly sweeps the instantaneous view of the sensor across the target scene.
- Sensor and the location of the IFOV is described well by the law of reflection.
- Thermal measurements are collected point-by-point for image reconstruction.

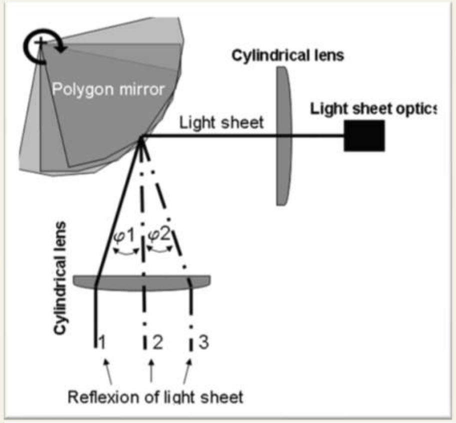
# IMAGING ARCHITECTURE SELECTION


| Architecture | Advantages | Disadvantages |
|---|---|---|
| Line Scanning | Simplifies detector requirements | Requires controlled motion along two axes and larger mechanical assembly |
| Polygon Mirror Scanning | High-speed, precise scanning | IR-compatible components difficult to source and expensive |
| Raster Scanning | Cost-effective, highly controllable, compact design | Slower acquisition and sensitive to backlash |

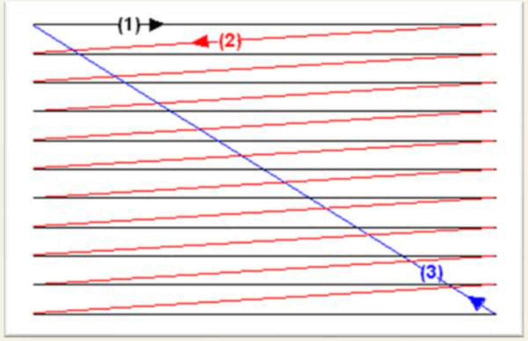
**Reasons:**
- Does not require motion of the target scene.
- Supports cost-efficient system implementation.
- Compact optical architecture.
- Compatible with the FOV requirements.

Raster scanning was chosen because it offers the best balance of cost, controllability, and implementation complexity while satisfying the project's imaging requirements.


Line Scanning




Polygon Mirror Scanning




Raster Scanning

# INFRARED LENS/MIRROR SELECTION

| Parameter | Ge PCX 12.7 mm | Ge PCX 25 mm | ZnSe PCX |
|---|---|---|---|
| Material | Germanium | Germanium | Zinc Selenide |
| EFFL | 50.8 mm | 35 mm | 75 mm |
| Spectral Range | 2–14 µm | 2–14 µm | 0.6–18 µm |
| Approx. F/# | f/4 | f/1.4 | f/2 |
| Price | $270 | $655 | $312 |

**Reasons:**
- Both provide transmission in our target LWIR range.
- The selected lens sets our IFOV, and at 75mm creates a small IFOV for fully resolved imaging.
- Both are cost effective options in their performance class.

The ZnSe lens sacrifices some optical transmission, but is priced effectively, and readily available, unlike the similarly priced germanium lens.

| Parameter | Thorlabs PF10-03-M02 | Thorlabs PF10-03-M01 | Thorlabs ME1-G01 |
|---|---|---|---|
| Material | Mid-IR Enhanced Gold | Standard Protected Gold | Protected Aluminum |
| Diameter | 25.4 mm (1 inch) | 25.4 mm (1 inch) | 25.4 mm (1 inch) |
| Spectral range | 8–14 µm | 0.8 – 20 µm | 2 – 20 µm |
| Approx. reflectivity | ~95% in LWIR | ~96% in LWIR | ~95% in LWIR |
| Price | $76.01 | $70 | $36.67 |

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PSE

# THERMAL SENSOR SELECTION

| Parameter | HMS J21 Thermopile with 8-14 um filter | Thorlabs TD2X Unmounted Thermal Power Detector | Amphenol Thermometrics ZTP-135SR |
|---|---|---|---|
| Sensitivity | 44 V/W | >0.1 V/W typ | 62 V/W |
| Output referred noise | 35 nV/ sqrt(hz) | 35 nV/ sqrt(hz) | 32 nV/ sqrt(hz) |
| Active area size | 1.2 mm^2 | 4.0 mm^2 | 0.49 mm^2 |
| Time constant | 10 ms | ~ 1.5 s (rise time) | 25 ms |
| Field of view | 120 degrees | 120 degrees | 85 degrees |

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Reasons:
- High sensitivity
- Does not include internal optics, it's effective field of view will be determined by our implementation
- Low Output Referred Noise density
- Fast time constant

- Important: Filter has some absorbance, and re-emittance will happen.

# SIGNAL AMPLIFIER SELECTION

Jason Ha
PSE

| Parameter | AD8629 | INA333 | AD8421 |
|---|---|---|---|
| Amplifier technology | Zero-drift chopper | Instrumentation amp | Three op-amp instrumentation amp |
| 0.1-10 Hz Noise | 0.5 µV p-p typ | 1 µV p-p typ | 1.5 µV p-p typ |
| Voltage drift | 0.002 µV/°C typ | 0.1 µV/°C typ | 0.2 µV/°C max |
| Voltage offset | 1 µV typ | 25 µV typ | 25 µV typ |
| Input bias current | 100 pA max | 200 pA typ | 500 pA max |

- Temperature drift was a large concern; AD8629 had performance orders of magnitude better.
- High performance in low-frequency noise
- Highly relevant reference circuits available- assists with analog design

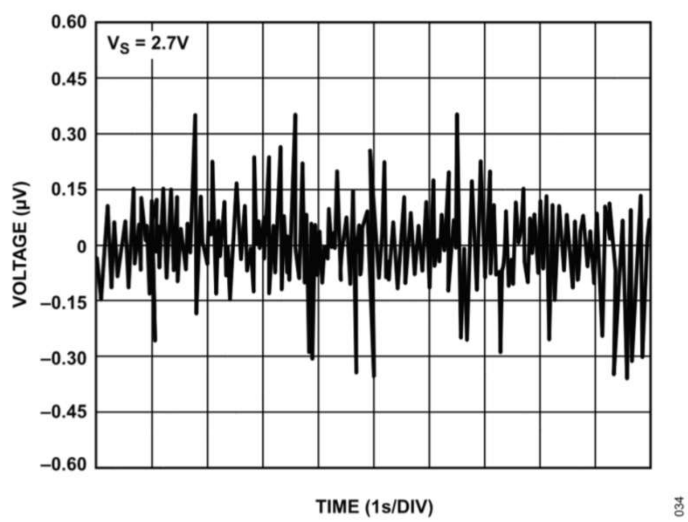


*Figure 36. 0.1 Hz to 10 Hz Noise*

AD8629 Input Referred Noise

# PROCESSING UNIT SELECTION

| Parameter | MSP430 | Raspberry Pi | ESP32-S3-WROOM-1 |
|---|---|---|---|
| Clock Speed | ~16-25 MHz | ~1.5 GHz | 240 MHz |
| Flash Memory | KB range | MicroSD storage | 4 MB |
| SRAM / RAM | KB range | 1-8 GB | 512 KB |
| Wi-Fi | No | Yes | Yes |
| Power Consumption | Very Low | High | Low-moderate |

Andrew VanAuken
EE

Reasons:

- Integrated Wi-Fi connectivity.
- Supports required peripherals and interfaces.
- Sufficient processing capability.
- Low cost and power consumption.

The ESP32-S3 provides significantly greater connectivity and processing capability than traditional microcontrollers while maintaining lower power consumption and cost.

# MOTION CONTROL SELECTION

Andrew VanAuken
EE

| Parameter | 28BYJ-48 | 17HE08-1004S | SF2421-10B11 |
|---|---|---|---|
| Operating Voltage | 5 V | 8–35 V | 24 V |
| Step Angle | 5.625°/64 (0.088° effective) | 1.8° | 1.8° |
| Steps/Rev | 2048 | 200 | 200 |
| Holding Torque | 34.3 mN·m | 170 mN·m | 290 mN·m |
| Rated Current | ~160 mA | 1 A/phase | 1 A/phase |

**Reasons:**

- Compatible with the 5 V power rail.
- High positional resolution for raster scanning.
- Sufficient torque for mirror actuation.

While larger bipolar steppers provide higher torque, the 28BYJ-48 offers the best balance of resolution, power compatibility, simplicity, and cost for the IRIS raster scanning system.

# TEMPERATURE SENSOR SELECTION

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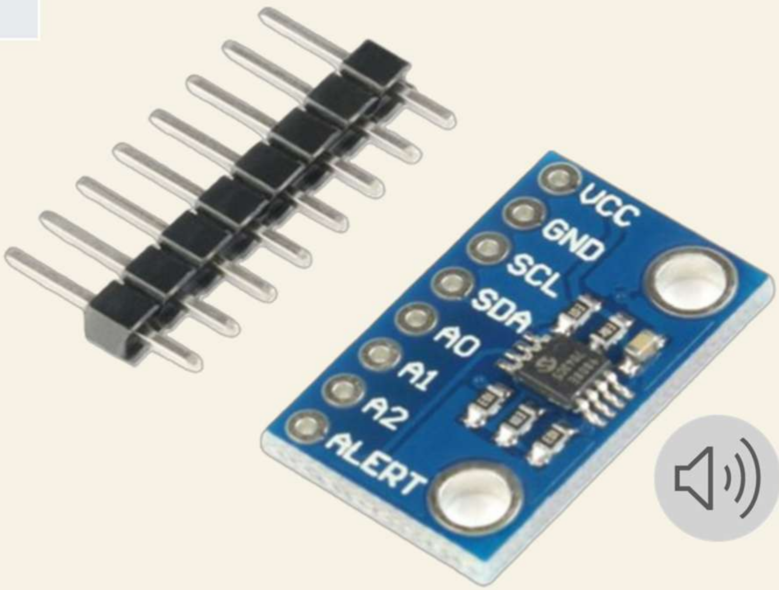
EE

| Parameter | DS18B20 | MCP9808 | TMP102 |
|---|---|---|---|
| Interface | 1-Wire | I²C | I²C |
| Accuracy | ±0.5°C | ±0.25°C | ±0.5°C |
| Operating Voltage | 3.0–5.5 V | 2.7–5.5 V | 1.4–3.5 V |
| Cost | $3–6 | $4–6 | $8–12 |

Reasons:

- Highest measurement accuracy.
- I²C communication.
- Compatible with ESP32 platform.
- Low power consumption.

The MCP9808 provides improved accuracy and simple integration at a slightly higher cost than basic temperature sensing solutions.



# POWER SYSTEM SELECTION

| Parameter | Ni-Cd | Ni-MH | Li-Ion |
|---|---|---|---|
| Nominal Cell Voltage | 1.25 V | 1.25 V | 3.6 V |
| Gravimetric Energy Density | ~50 Wh/kg | ~90 Wh/kg | ~210 Wh/kg |
| Self-Discharge / Month | 15–20% | 20–30% | 5–10% |
| Cycle Life | >1,000 | ~500 | ~500–1,000 |

**Reasons:**
- High energy density minimizes battery size and weight.
- Low self-discharge supports intermittent deployment.
- Supports the 4-hour runtime requirement.

Li-Ion provides the best balance of runtime, size, and weight while requiring battery protection and charging circuitry.

| Component | Selected | Reason |
|---|---|---|
| Battery Pack | Talentcell PB006B3 | 12.6–9.0 V DC output, DC5521 connector, included charger |
| 5 V Regulator | LM2596 Buck | 3 A output rating; supports motor/display rail |
| 3.3 V Regulator | AMS1117-3.3 | Low-noise rail for ESP32 and sensors |

Sean Willie
EE

# COMMUNICATION TECHNOLOGY SELECTION

Shea Meyer
CpE

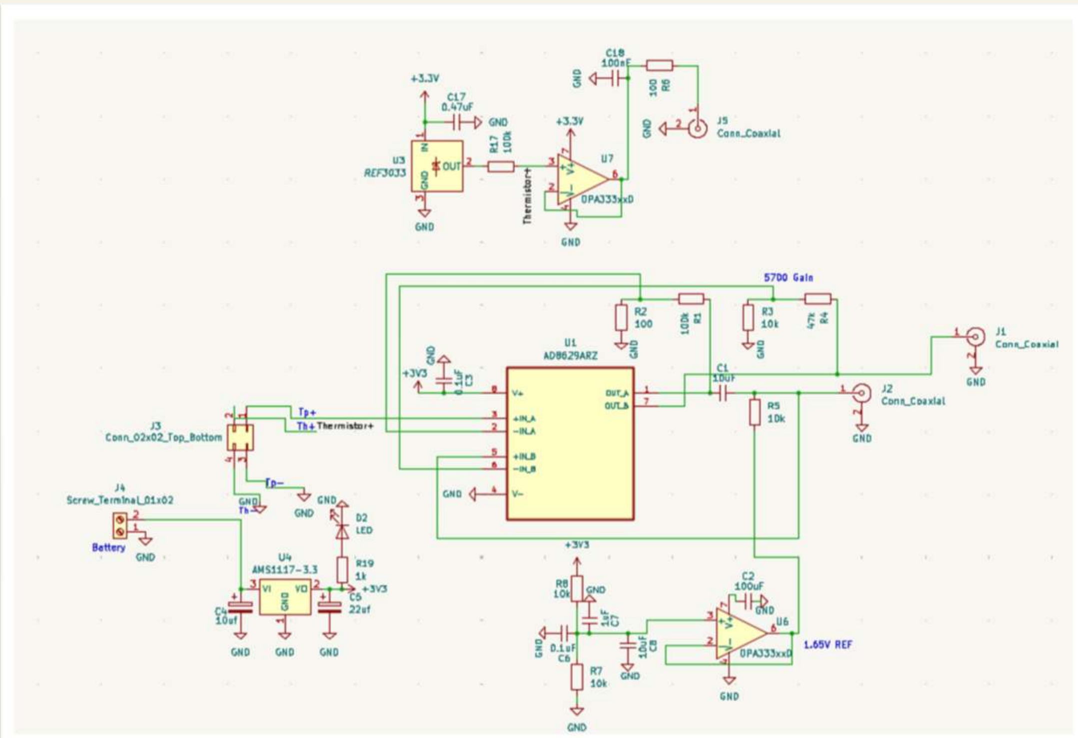
| Feature | Wi-Fi | Bluetooth LE | Zigbee | LoRa |
|---|---|---|---|---|
| Typical Data Rate | 54+ Mbps | Up to 2 Mbps | Up to 250 kbps | 0.3–50 kbps |
| Operating Range | ~45 m indoors | ~10–100 m | ~10–100 m | Up to 15 km |
| Power Consumption | High | Very Low | Low | Very Low |
| Native IP Support | Yes | No | No | No |
| ESP32-S3 Native Support | Yes | Yes | No | No |

**Reasons:**

- Direct IP support for web dashboard communication.
- Built into the ESP32-S3, so no external module is required.
- Better fit for local monitoring than long-range, low-data-rate options.

Wi-Fi consumes more power, but it provides the direct web connectivity needed for IRIS.

# THERMOPILE PREAMPLIFIER SCHEMATIC




- Our dedicated preamplifier board has separate power delivery (AMS1117) to reduce noise from the switching 5V regulator.
- AD8629 is used for the thermopile, while OPA333 is used for separate thermistor input amplification
- The gain (50000) brings us to a high enough level (0.5V-2.5V) for the ADC to read the thermopile
- The output is sent through coaxial cables to reduce interference from outside devices.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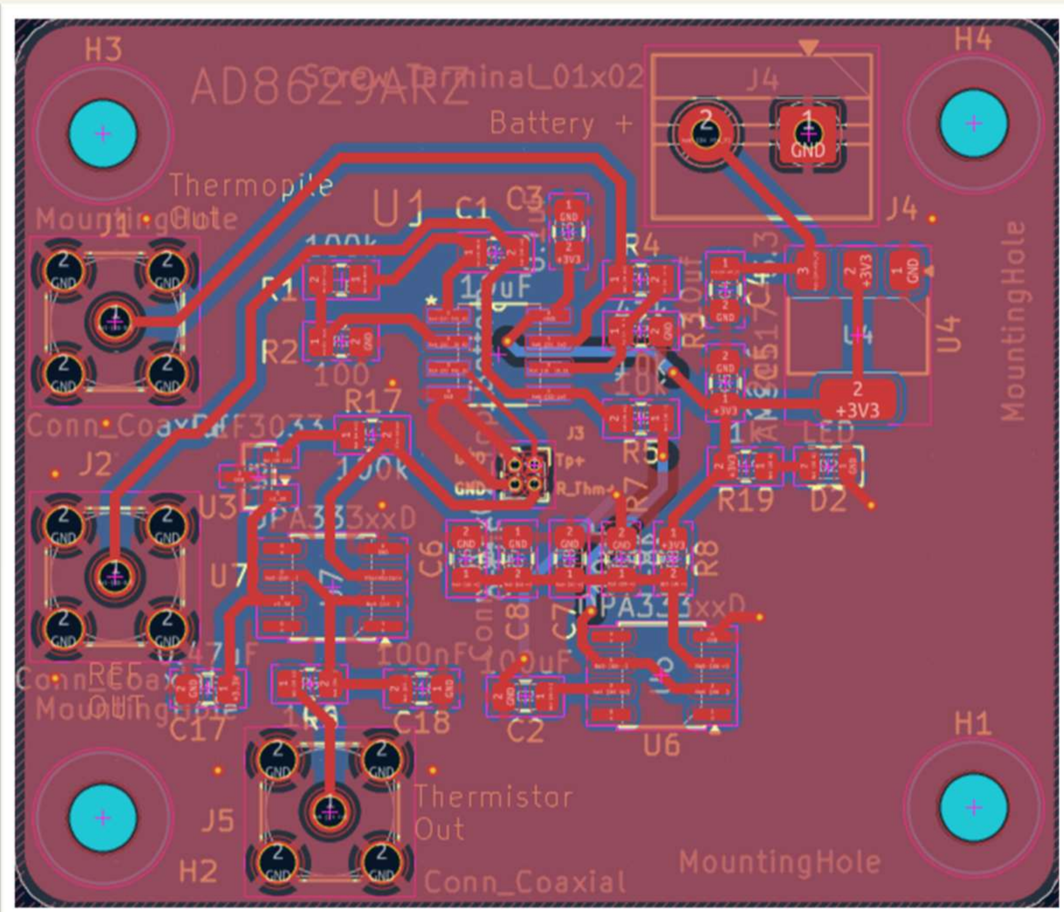
# THERMOPILE PREAMPLIFIER PCB DESIGN

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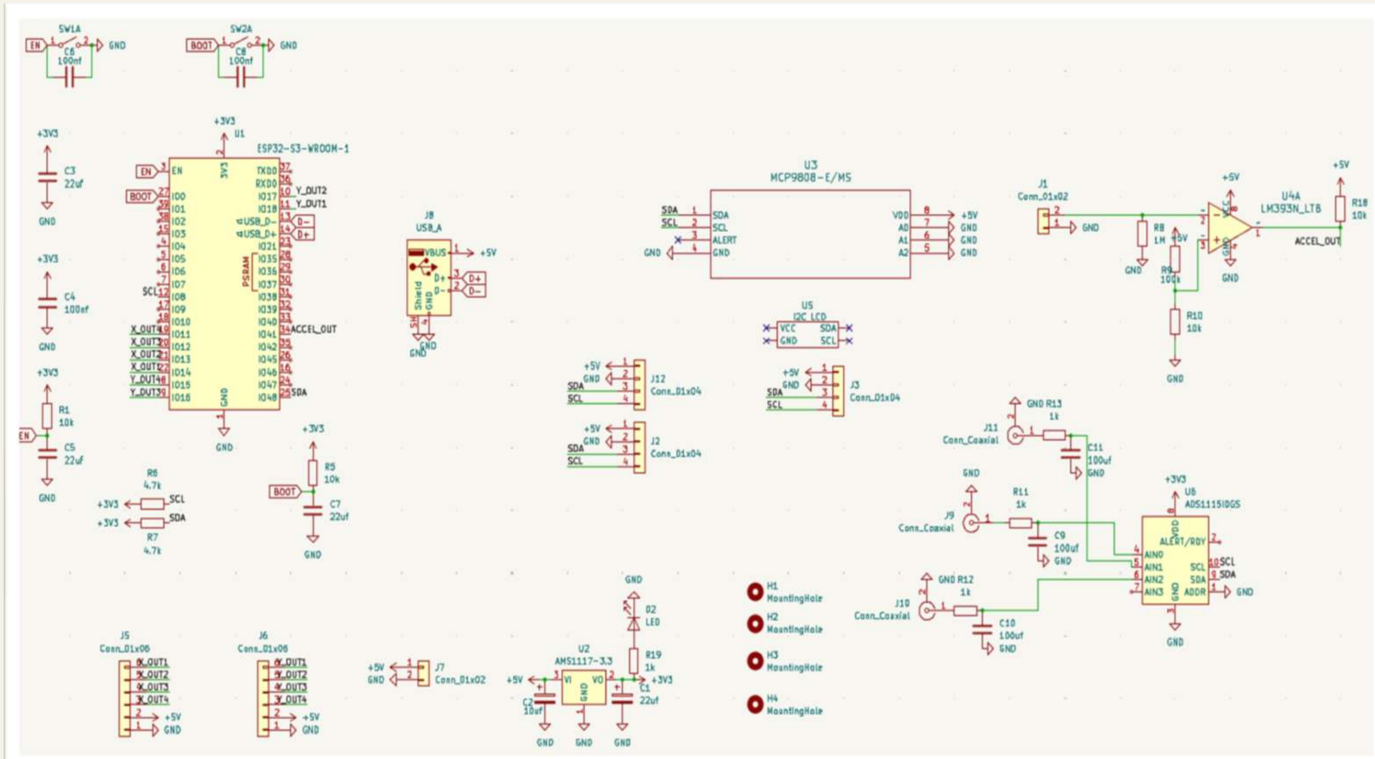
- The PCB design for the preamplifier meets the constraints of size and profile, fitting inside the lens tube.
- Input signal traces from the thermopile were kept as short as possible, to reduce electromagnetic interference.
- Thermopile input is put in the center, to mount the sensor center for the lens.

# MCU & PERIPHERAL SCHEMATIC





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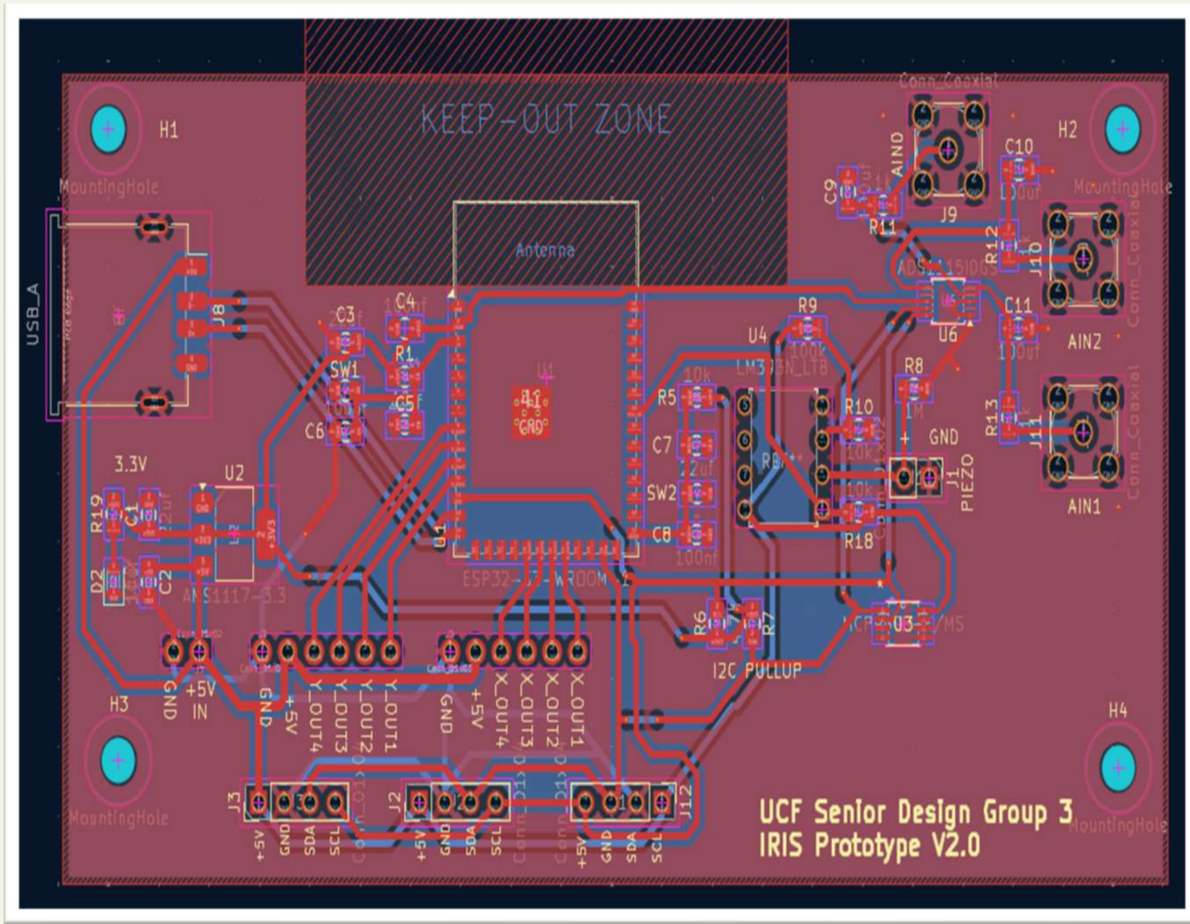
- The main MCU board contains the ESP32, MCP9808 temperature sensor, ADS1115 ADC, LM393 comparator, AMS1117 regulator, as well as connections for the drivers and external display.
- The MCU processes the infrared image and controls the scanning system.

# MCU & PERIPHERAL PCB DESIGN

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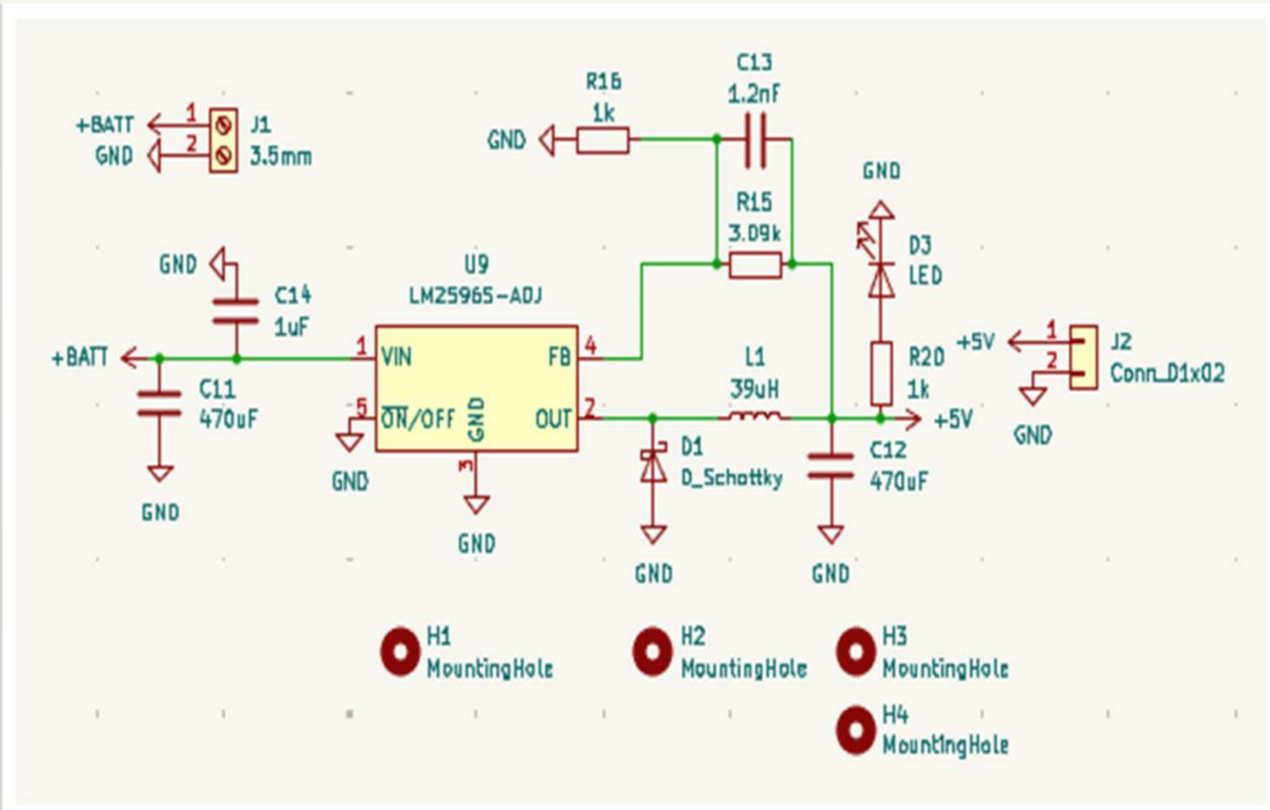
- The MCU PCB is designed to reduce the noise transfer to the analog inputs.
- Digital connections are kept on the left and bottom side, while analog connections are on the top right corner.
- Analog connections are as close to the ADC as possible to avoid interference from I2C lines.
- Stepper drivers are given larger traces to power the motors.

# 5V REGULATOR SCHEMATIC

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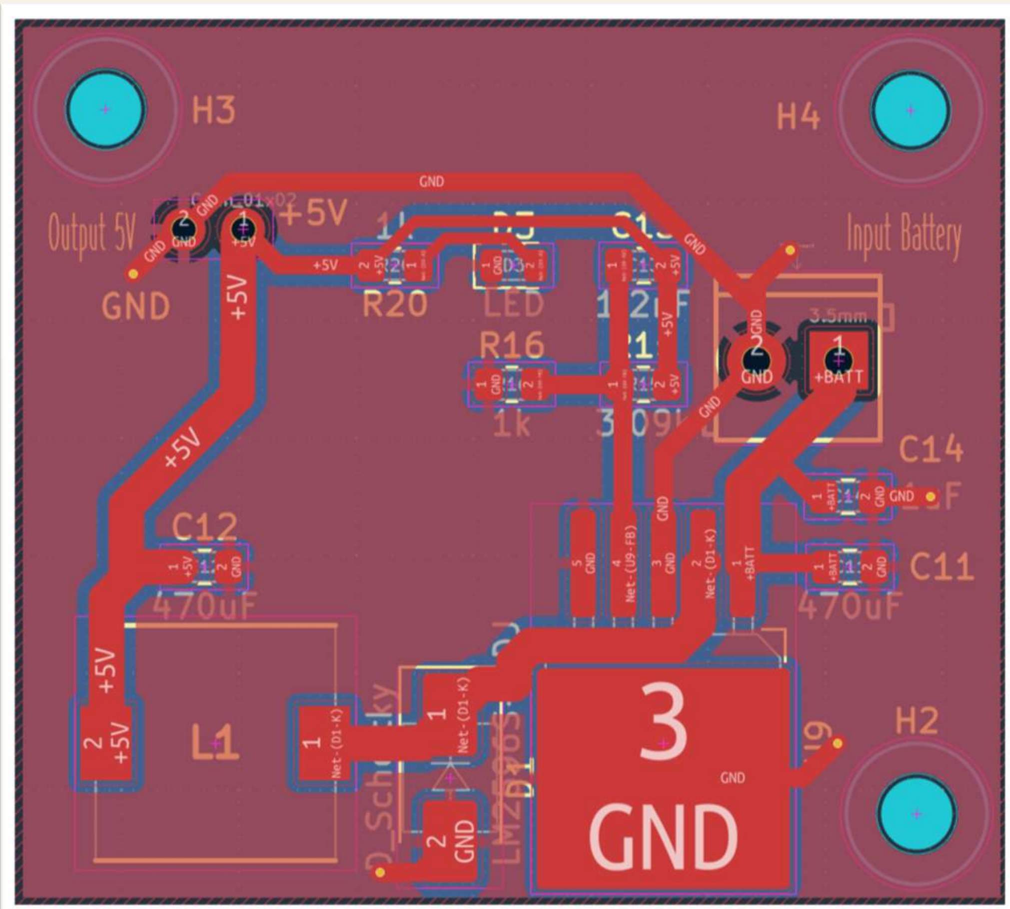
- The 5V regulator takes the battery input and ensures it is kept in a safe range for the MCU and components.
- Design choices were made based on the datasheet from TI and outside references.
- The regulator is kept on a separate board to give modularity in case of failure.

# 5V REGULATOR PCB DESIGN

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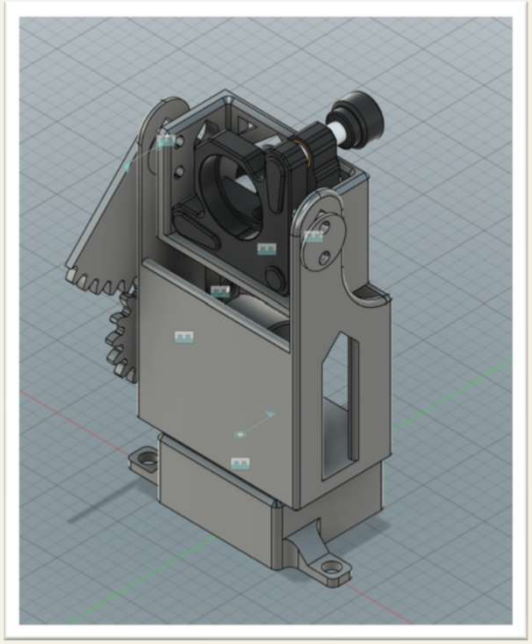
- The 5V regulator PCB is designed to ensure stable power delivery for the entire system.
- Power traces were made thick to avoid overheating.
- An output LED was added for troubleshooting and ensuring output.

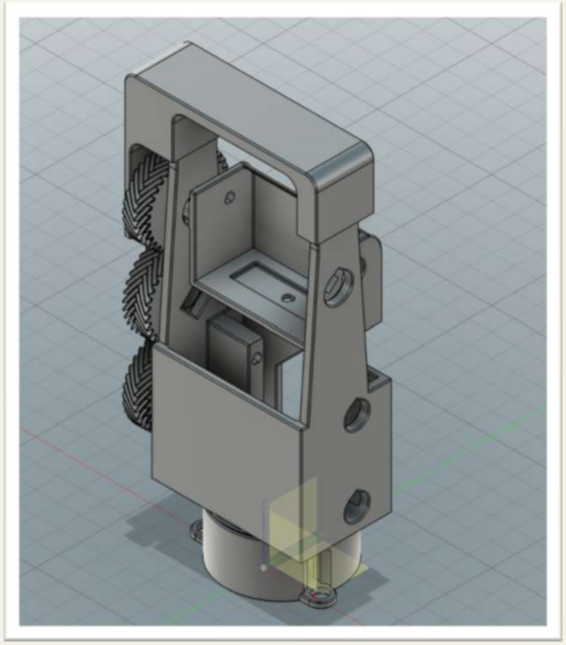
# OPTO-MECH DESIGN: MIRROR SCANNER

Jason Ha
PSE

Key Functions:
- Reliability scanning
- Appropriate accuracy
- Compatible with external hardware (such as encoders, motors, optics mounts)

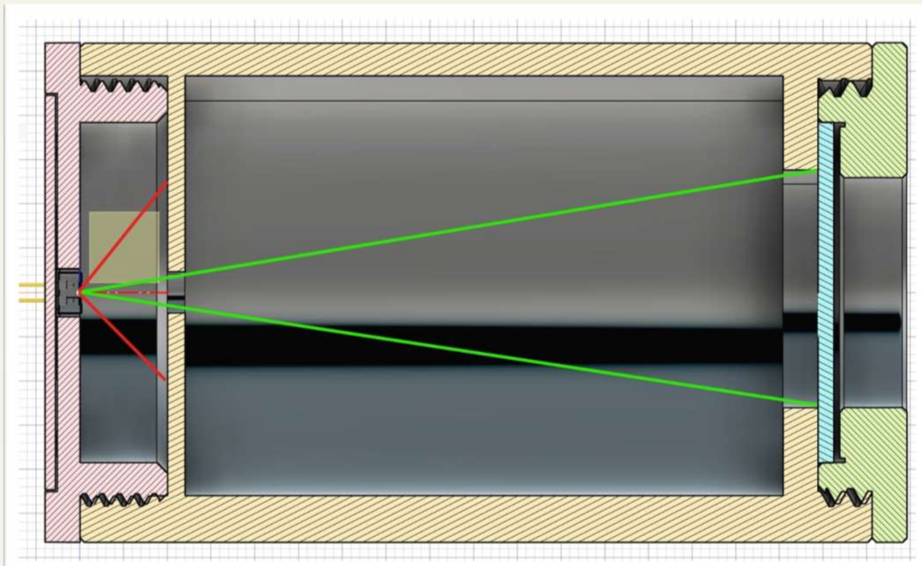


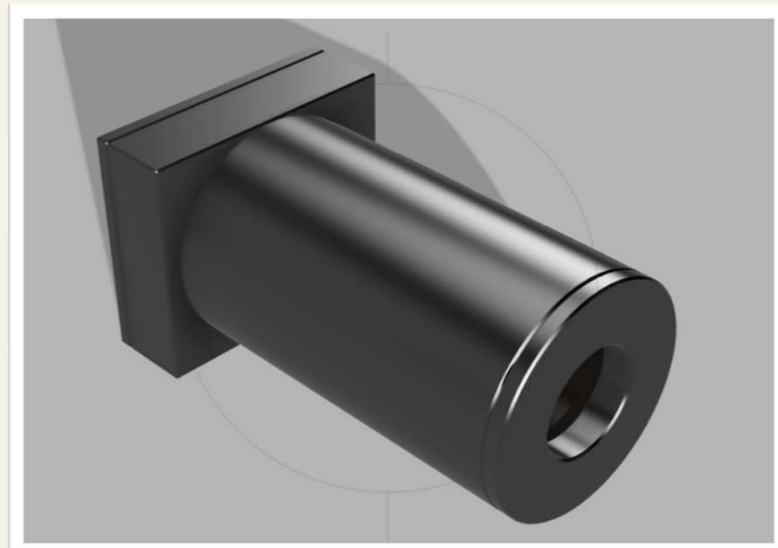
Gimbal v1.2
- Established basic functions
- Characterization revealed flaws in design/implementation
- Confirmed engineering assumptions



Gimbal v2.2
- Herringbone Gears decrease effective backlash/torque transmission loss
- Metal bearings decrease resistance and improve reliability
- Geometry results in more rigidly defined structure

# OPTO-MECHANIC DESIGN: LENS TUBE + BAFFLE





Jason Ha
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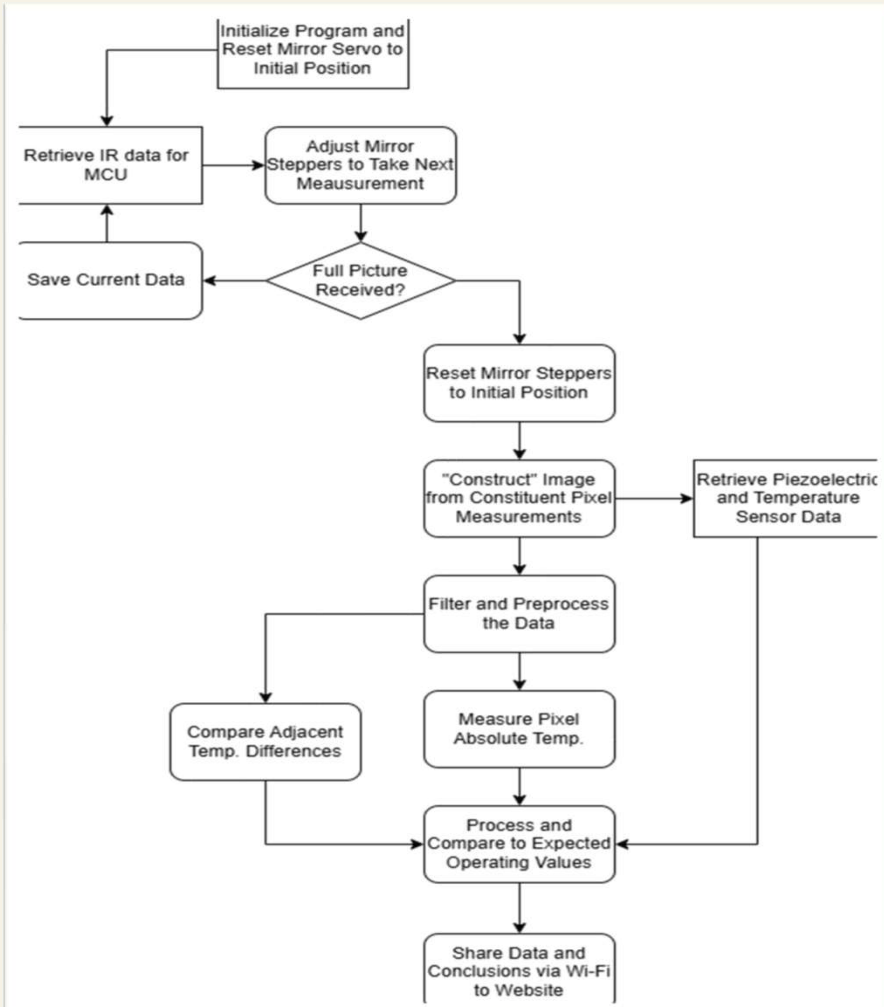
- Threaded insert design allows for fine adjustment to place sensor at position of best signal.
- The high friction of the plastic threads removes concern for misalignment.
- The integrated optical baffle reduces background and stray radiation while also lowering re-emittance.

# ESP32 SOFTWARE ARCHITECTURE




Shea Meyer
CpE

- Coordinates sensing, raster scanning, and peripheral control.
- Organizes firmware using concurrent FreeRTOS tasks.
- Process thermal measurements and hotspot detection.

# LANGUAGE SELECTION

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CpE

Reasons:

- Familiar and reliable.
- Low overhead.
- Strong ESP32 support.
- Works well with FreeRTOS.

| Feature | C | C++ | MicroPython |
|---|---|---|---|
| Library Availability | High | Highest | Moderate |
| Familiarity | High | Low | Moderate |
| Ease of Use | Moderate | Low | High |
| Suitability | High | Moderate | Moderate |

# FRAMEWORK SELECTION

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| Feature | Arduino | ESP-IDF |
|---|---|---|
| Ease of Use | High | Moderate |
| ESP32 Support | Good | Excellent |
| RT Support | Limited | Strong |
| Low-Level Control | Limited | High |
| Familiarity | Moderate | High |

Reasons:
- Official ESP32 framework.
- Better real-time support.
- Greater hardware control.

# REAL TIME TASK OVERVIEW

| Tasks | Purpose |
| --- | --- |
| stepper_task | Manage raster scanning |
| encoder_task | Measures from rotary encoder |
| POST_task | Receive all data and post to backend server |
| temperature_task | Sending ambient temperature data |
| vibration_task | Sending piezoelectric data |

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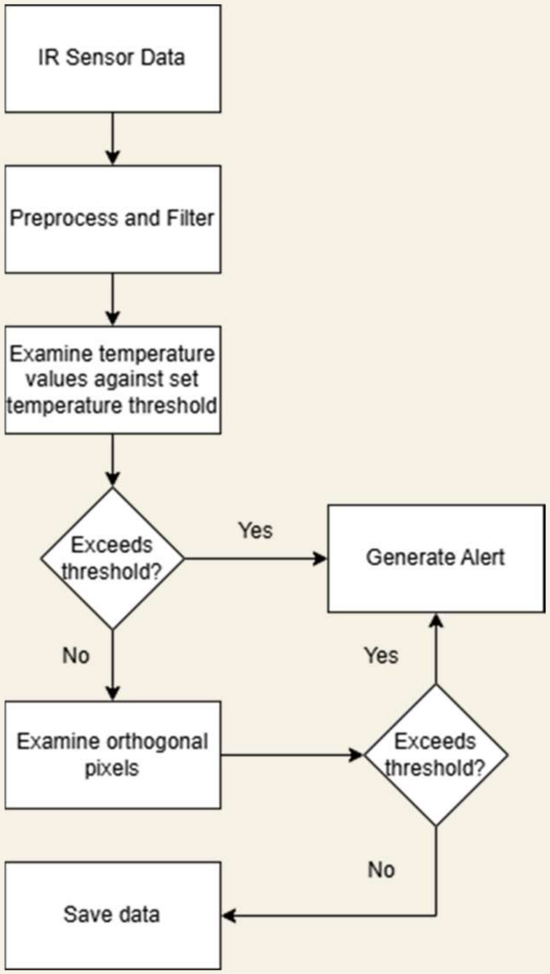
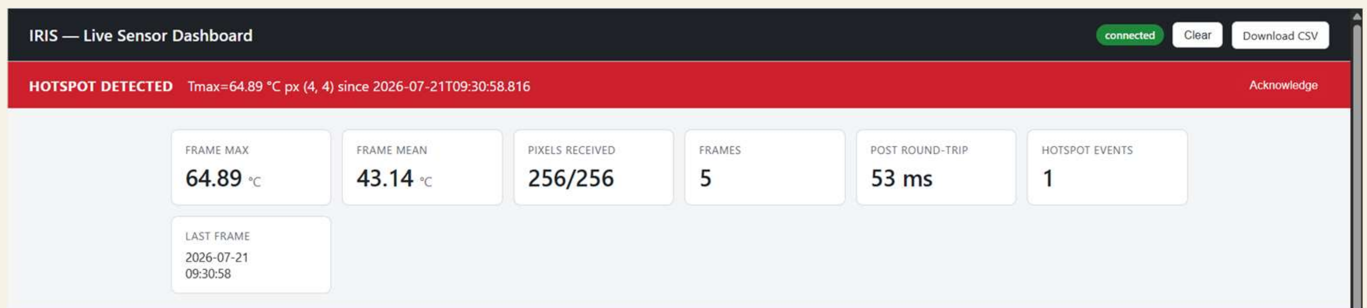
**Features:**

- Execution of sensing, motion, and communication tasks.
- Modular task separation simplifies development and debugging.
- Continuous system operation during raster scanning.

# HOTSPOT DETECTION ALGORITHM




- Filters and evaluates thermal measurements.
- Applies threshold-based hotspot detection.
- Generates alerts for abnormal conditions.

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# WEB BACKEND SELECTION

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| Feature | Python | Go | Node.js |
|---|---|---|---|
| Performance | Moderate | High | High |
| Real-Time Support | Moderate | High | High |
| Familiarity | High | Low | Low |
| Full-Stack Capability | No | No | Yes |

Reasons:

- Real-time data streaming.
- Unified frontend/backend language.
- Easy integration.

# WEB DASHBOARD SELECTION

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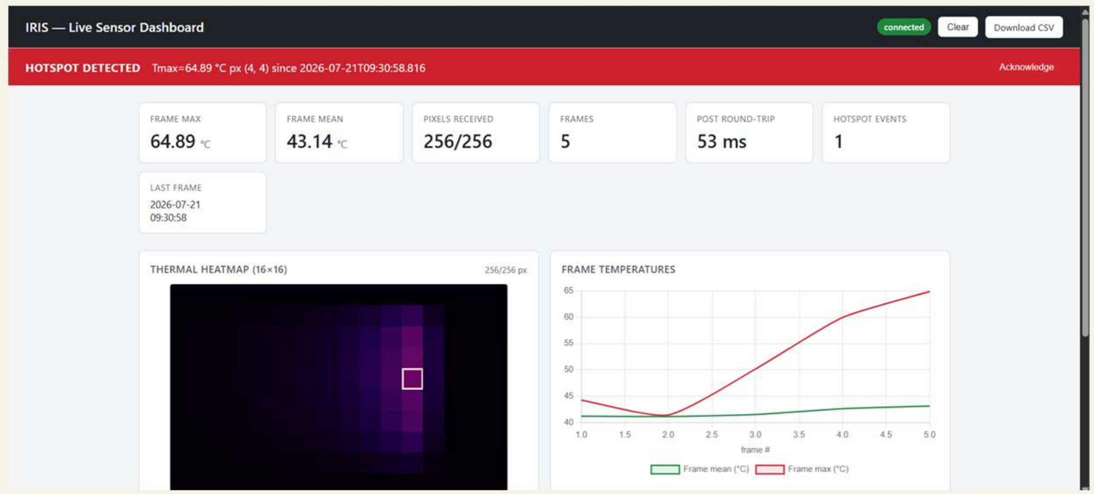
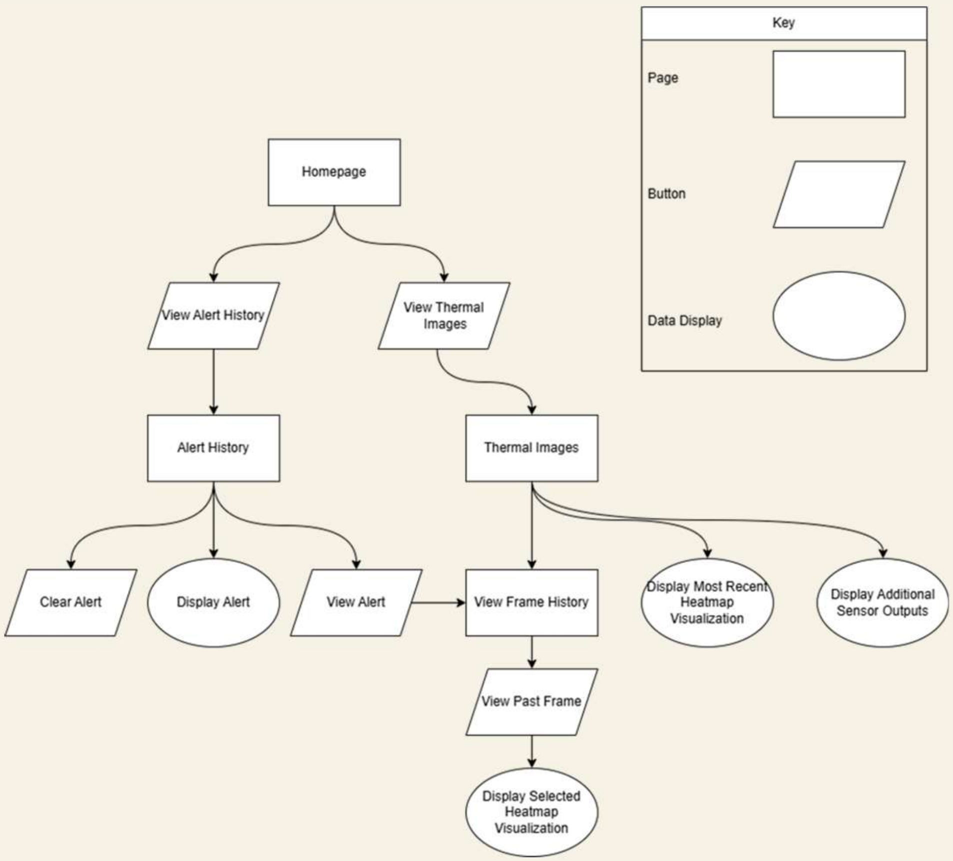
| Feature | HTML/JS | React | Vue |
|---|---|---|---|
| Learning Curve | Low | High | Moderate |
| Component Reuse | Low | High | High |
| Real-Time Updates | Manual | Built-In | Built-In |
| Visualization Libraries | Limited | Extensive | Moderate |




**Reasons:**

- Component-based architecture.
- Strong visualization support.
- Ideal for thermal heatmaps.

# WEB UI FLOW

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- View live thermal images and sensor data.
- Review alert history and hotspot events.
- Access scan data history and previous heatmaps.

# WEB HOSTING AND COMMUNICATION

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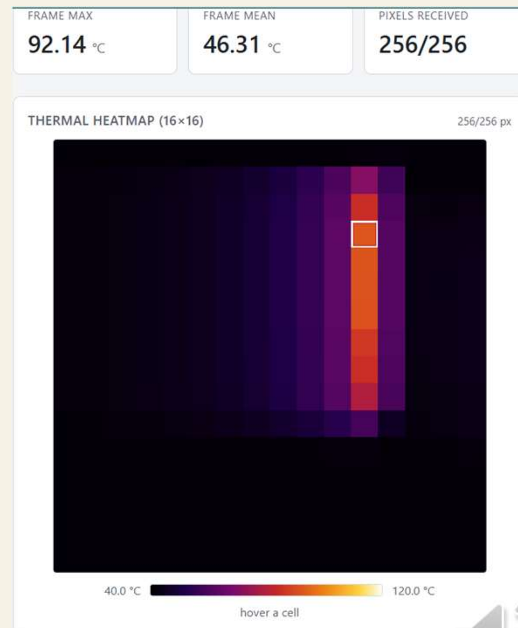
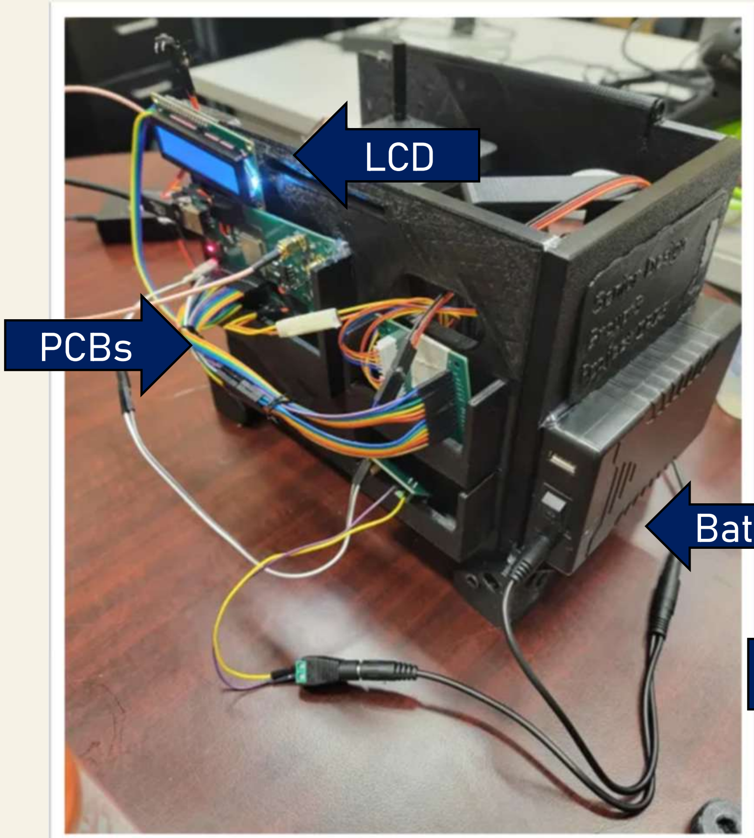
| Layer | Selected Technology | Role |
|---|---|---|
| Backend Runtime | Node.js | HTTP server, real-time event handling |
| Backend Framework | Express | Routing, middleware, API endpoints |
| Real-Time Communication | Socket.IO | Streaming thermal grids and alerts to browser |
| Visualization | React + Canvas/SVG Library | Thermal heatmap rendering |
| Data Storage | SQLite | Scan history and alert persistence |
| ESP32 Backend Protocol | HTTP POST (JSON) over Wi-Fi | Periodic scan upload from ESP32 |



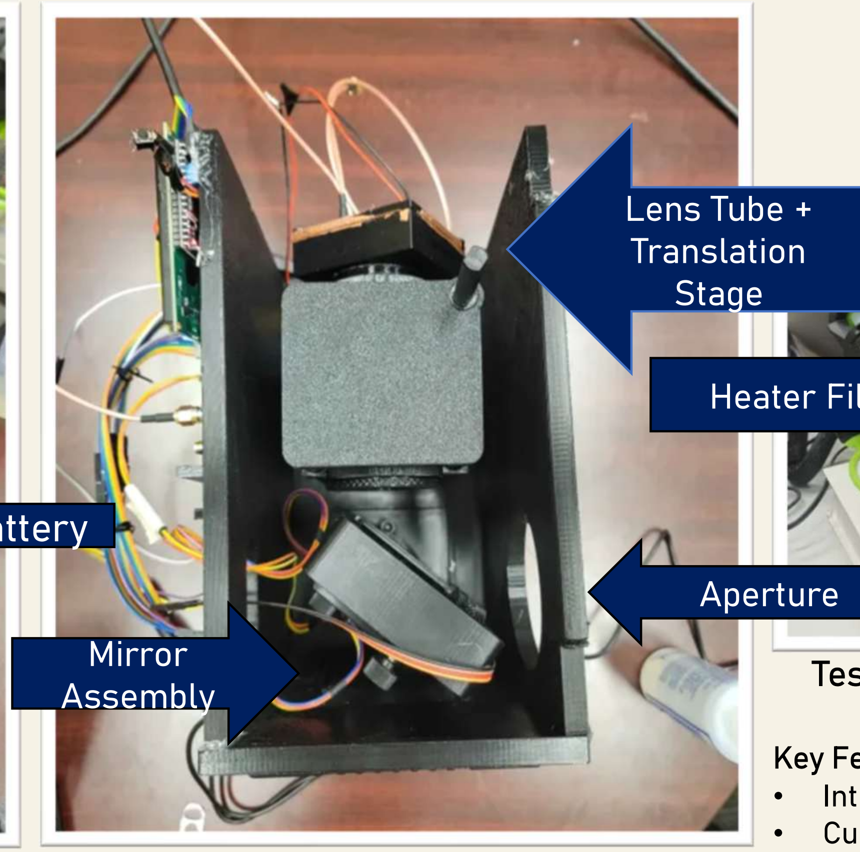

- Displays live thermal images and system status.
- Provides hotspot alerts and event history.
- Supports review of previous thermal scans and sensor data.
- Locally hosted on ESP32 for browser-based access.

# COMPLETE IRIS PROTOTYPE

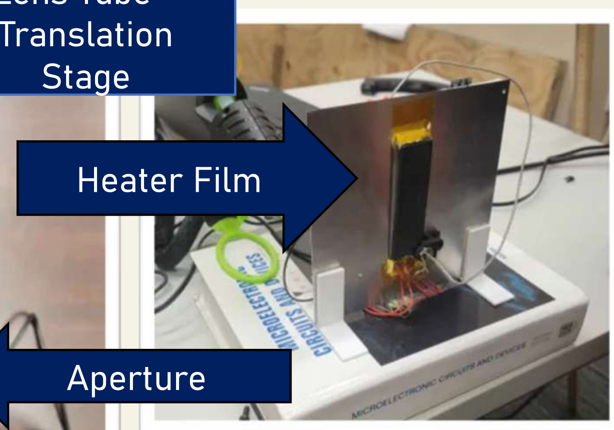
Jason Ha
PSE




Final Prototype




Internal Layout




Test Target/ Heat Source

Key Features

- Integrated subsystems
- Custom PCBs and ESP32
- LCD display
- Portable battery-powered operation
- Wireless dashboard connectivity

# SYSTEM OPERATION

Andrew VanAuken
EE

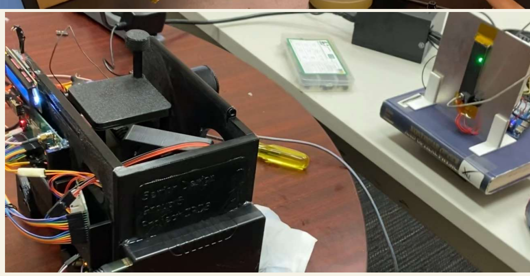
Thermal Image → Dashboard Screenshot → Alert Notification

Operational Workflow

- Thermal image reconstructed from raster scan
- Dashboard updated with thermal data
- Hotspot alerts generated when thresholds are exceeded

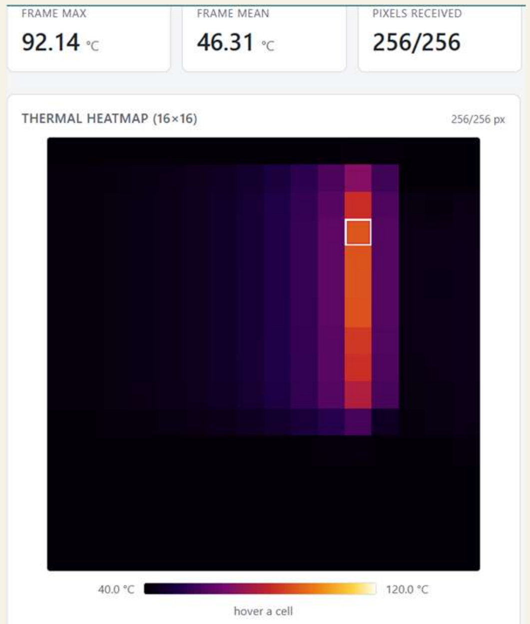
# SYSTEM VALIDATION

## Sub-system Validation

- Ensures mechanical and sensing are work separately
- Verify mechanical scanning before using lens assembly

## Imaging Validation




- Verified integration produces sensible image
- Calibration across specified imaging range

## Communication Validation


- LCD display operation
- Dashboard updates
- Wi-Fi communication

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# PERFORMANCE RESULTS

| Requirement | Target | Measured | Status |
|---|---|---|---|
| Temperature Accuracy | ±10°C | Max Error: 9.97°C | Pass |
| Frame Rate | ≥0.033 fps | 0.040 fps | Pass |
| Alert Response | ≤30 s | 0.054 s | Pass |

Andrew VanAuken
EE

# CHALLENGES & SOLUTIONS

| Challenge | Solution |
| --- | --- |
| Weak thermopile signal | Increasing gain, decreasing speed, sampling more |
| Mechanical backlash, slop | Gear design, inclusion of metal interfaces and hardware |
| Optical alignment | 2 axis adjustable optics, calibration |
| EMI susceptibility | PCB layout optimization, physical shielding (faraday cage) |
| Temperature drift | Removing capacitance between amplifier stages |
| Reading lower temperature range values | Increased amplifier gain from 20,000 to 150,000 |

Jason Ha
PSE

# BUDGET

| Subsystem | Components | Cost |
|---|---|---|
| Optical System | $CaF_2$ Lens, Gold Mirror | $413.02 |
| Thermal Sensing | HMS J21 Thermopile sensor | $29.20 |
| Motion Control | Stepper Motors, Drivers | $11.90 |
| Processing & Sensors | ESP32, MCP9808, Accelerometer | $41.98 |
| Power System | Li-Ion Batteries, Regulators | $11.98 |
| Mechanical Components | Filament, other hardware | $12.99 |
| PCB Fabrication | Main, Amplifier, Encoder, Stepper, Regulator PCBs + Stencils | $104.85 |
| Total | | $625.92 |

Andrew VanAuken
EE

# WORK DISTRIBUTION

| Team Member | Major | Primary Responsibilities | Secondary Responsibilities |
|---|---|---|---|
| Shea Meyer | Computer Engineering | • Microcontroller Integration<br>• Sensor Data Processing<br>• IoT & Web Functionality | • Servo & Mirror Coordination |
| Jason Ha | Photonic Science & Engineering | • Optical System Design<br>• Optomechanical Design & Alignment | • Image Processing & Display<br>• Optical/Imaging System Calibration<br>• Optoelectronic Design |
| Sean Willie | Electrical Engineering | • PCB Design | • Power Supply Design<br>• Enclosure Design |
| Andrew VanAuken | Electrical Engineering | • Protection Circuitry | • Display & UI<br>• Auxiliary Temperature & Vibration Sensors |

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