Single detector thermal raster scanning: Project IRIS

Jason V. Ha*[a], Sean Willie[b], Andrew Vanauken[b], Shea Meyer[b]
*[a]CREOL, The College of Optics and Photonics, University of Central Florida, 4304 Scorpius St, Orlando, FL, USA 32816-2700; [b]College of Engineering and Computer Science, University of Central Florida, 4328 Scorpius St, Orlando, FL, USA 32816-2362

ABSTRACT

Medium voltage electrical switchgear assemblies can develop localized thermal hotspots that may indicate deteriorating components which can be a useful indication of impending failure. Traditional thermal imaging systems in use for detecting these hotspots are often over complex and insufficient costed. This project presents the design and implementation of a low-cost raster-scanned thermal imaging system that uses a single thermopile detector and a two-axis scanning mirror to reconstruct thermal images of a target scene. The system was designed to image a 140 mm × 140 mm region at an approximate working distance of 500 mm while providing sufficient spatial sampling to detect hotspots on the order of 20 mm × 20 mm. The optical architecture consists of a scanning mirror, objective lens, long-wave infrared bandpass filter, and thermopile detector, while an ESP32 microcontroller coordinates mechanical scanning and data acquisition. Emphasis is placed here on the optical architecture, optomechanical design, detector integration, and the small signal processing considerations. Design decisions were guided by analyses of available signal strength, optical field of view, sampling requirements, optoelectronic integration, and manufacturability using computer-aided design. A prototype scanning assembly was fabricated using 3D printing and incorporates a stepper motor-driven pan-tilt mechanism to perform raster scanning. At the time of writing, full system integration and quantitative characterization are ongoing, and we discuss our methodologies to evaluate system performance. The presented design demonstrates the feasibility of a mechanically scanned, single-detector thermal imaging approach as a low-cost alternative for hotspot detection.

Keywords: Thermal, Raster, Optics, Imaging, Thermopile, LWIR, Student, Undergraduate

1. INTRODUCTION

Electrical power distribution equipment experiences thermal loading during operation, and abnormal temperature increases can indicate conditions such as loose connections, excessive resistance, insulation degradation, or component failure. Early detection of localized thermal anomalies enables preventative maintenance and reduces the likelihood of unexpected equipment failures and safety hazards. Infrared thermography is widely used for non-contact temperature monitoring in industrial inspection and predictive maintenance applications.[1,3] Commercial thermal imaging systems commonly rely on focal plane array (FPA) detectors that provide high spatial resolution and real-time imaging capability; however, the complexity and cost of detector arrays and associated electronics can limit their use in cost-sensitive applications.[4,5] For applications where high-speed imaging and high spatial resolution are not required, mechanically scanned thermal imaging systems provide a lower-cost alternative by replacing the detector array with a single infrared detector that sequentially samples the scene.[1,2]

This work presents the design and implementation of a proof-of-concept raster-scanned thermal imaging system for hotspot detection in medium-voltage electrical switchgear. The proposed system utilizes a single LWIR thermopile detector combined with a two-axis scanning mirror, optical collection system, and embedded control electronics to reconstruct thermal images through controlled mechanical motion. The primary objective of this work was to demonstrate the feasibility of a low-cost single-detector thermal imaging architecture using commercially available components and additive manufacturing techniques. The design focuses on the integration of optical, optomechanical, and low-noise electronic subsystems required to produce a functional thermal imaging prototype.

2. SYSTEM REQUIREMENTS

System requirements were established to define the intended functionality and performance targets of the thermal imaging prototype. The primary objective was to develop a low-cost, non-contact system capable of detecting and approximately localizing thermal hotspots within medium-voltage electrical switchgear. In addition to thermal image reconstruction, supplementary measurements were incorporated to provide additional context regarding system operation, including detector temperature monitoring, PCB temperature monitoring, and inertial measurements for future system diagnostics and compensation.

Several constraints were considered during system development, including the operating environment, spectral requirements, cost, and manufacturability. The intended application within electrical enclosures established a target working distance of approximately 500 mm. Since thermal radiation from objects near typical operating temperatures is primarily emitted within the long-wave infrared (LWIR) region, the optical system was designed for operation within the 8–14 µm wavelength range.[1,2] Additionally, the use of commercially available components and additive manufacturing methods constrained the mechanical design and influenced component selection.

Quantitative specifications were established using preliminary optical analysis to define achievable targets for the prototype. Estimates of field of view, spatial sampling, detector characteristics, and scanning requirements were used to establish design benchmarks for the imaging system. These specifications provided evaluation criteria for the optical, mechanical, and electronic subsystems developed throughout the project.

Table 1. Engineering Specifications Table

Parameter	Specification	Description
Imaging Temperature Range	40–120 °C	Detectable operating temperature range
Temperature Accuracy	±10 °C	Maximum allowable measurement error
Field of View (FOV)	≥15° × 15°	Angular coverage of monitored scene
Frame Rate	≥0.033 fps	Thermal image update frequency
Spatial Resolution	≤20 mm	Minimum resolvable feature size
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 detections
Data Update Rate	≥1 frame/min	Dashboard refresh frequency
Dashboard Latency	≤5 s	Acquisition-to-display delay
Average Power Consumption	≤35 W	Average system power draw
Battery Life	≥4 hr	Continuous operating duration
Signal-to-Noise Ratio (SNR)	≥10 dB	Minimum acceptable signal quality

3. SYSTEM DESIGN

The system was developed as an integration of three primary subsystems: the optical assembly, optomechanical scanning mechanism, and low-noise signal acquisition electronics. Each subsystem was designed to satisfy the requirements established during the preliminary design phase while maintaining a low-cost and manufacturable architecture. Particular consideration was given to optical alignment, mechanical reliability, and preservation of the low-level thermal signal produced by the thermopile detector. The final architecture combines a mechanically scanned LWIR optical system with custom electronics and embedded control. The following sections describe the feasibility analysis, component selection, and subsystem designs used to develop the thermal imaging prototype.

3.1 Optoelectronic Feasibility Analysis and Component Selection

Prior to detailed system design, an optoelectronic feasibility analysis was performed to evaluate whether a single-detector thermal imaging approach could meet the intended application requirements. Preliminary calculations were used to estimate optical throughput, detector sampling requirements, field of view, signal levels, and amplification requirements. This analysis guided component selection and established practical limits for the optical and electronic subsystems. Radiometric analysis was performed to estimate the infrared power incident on the detector based on contributions from the target scene, optical collection system, and detector characteristics.[1,2] The following equation was used to determine the radiometric contributions to the power at the detector.

Equation 1. Radiometric Contributions at the Detector

$$P_{\text{det}} = L_{\text{target}} A_{\text{lens}} \Omega_{\text{target}} \tau_{\text{opt}} + \sum_i L_i A_{\text{lens}} \Omega_i \tau_i \quad (1)$$

The use of a single LWIR thermopile detector was selected as a lower-cost alternative to focal plane array sensors while maintaining the ability to reconstruct thermal images through mechanical scanning. Detector selection was based on spectral response, field of view, active area size, sensitivity, and compatibility with the intended imaging geometry. The objective lens and LWIR bandpass filter were selected to provide sufficient scene coverage while operating within the 8–14 μm wavelength range. Because the thermopile output produces a low-level analog signal, signal conditioning components were evaluated based on noise performance, offset voltage, bias current, and thermal stability/drift. These considerations led to the selection of the AD8629 precision operational amplifier for signal amplification. Additional components, including the ESP32 controller and stepper motors, were selected based on cost, availability, and compatibility with the required scanning and acquisition functions.

3.2 Optical Architecture and Detector Integration

The optical system was designed around a single LWIR thermopile detector and a mechanically scanned field of view. Unlike focal plane array systems that capture spatial information simultaneously, this architecture reconstructs a thermal image by sequentially sampling regions of the scene through controlled mirror motion. Single-detector infrared imaging provides a lower-complexity alternative by reducing detector requirements while maintaining thermal measurement capability.[1,2] The optical path consists of the target scene, two-axis scanning mirror, objective lens, LWIR bandpass filter, and thermopile detector. The scanning mirror directs infrared radiation from different regions of the scene toward the objective lens, which focuses the collected radiation onto the detector active area. Optical design considerations included detector characteristics, field of view, spatial sampling, and radiometric signal collection, while mechanical integration was considered alongside optical design to maintain alignment and maximize detector signal.[3,7,8]

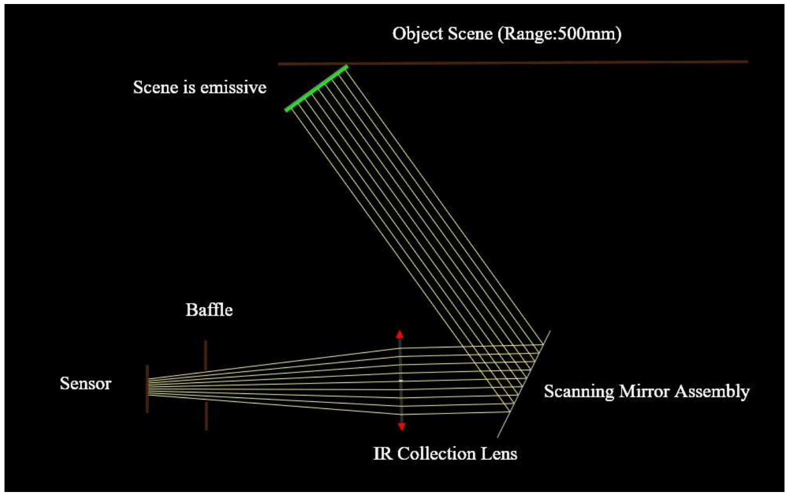

Figure 1. Geometric Optical Signal Path

3.3 Optomechanical Scanning System

The scanning mechanism provides two-dimensional raster motion using a pan-tilt mirror assembly. The horizontal axis consists of a base rotation stage driven directly by a 28BYJ-48 stepper motor, while the vertical axis rotates the mirror through a mechanical transmission. This configuration provides independent control of horizontal and vertical scanning within a compact architecture. The vertical axis uses a herringbone gear transmission consisting of an input gear, idler gear, and output gear. All 3 gears are identical resulting in no net gear reduction, as the stepper motor is already internally reduced. This choice preserves the inherent angular resolution while avoid torque or speed reductions. During testing, limitations due to gear flexibility, backlash, and variable center distance were observed which resulted in our current gear design rather than more simple spur gears. Increasing gear thickness from 3 mm to 10 mm improved stiffness and reduced mechanical deformation without requiring a change in architecture.

The mirror rotation axis was designed to minimize the offset between the mechanical axis and reflective surface. Although the ideal axis would pass directly through the mirror surface, practical constraints from mirror thickness and mounting hardware prevent perfect alignment. Minimizing this offset reduces beam translation and optical path variation during scanning. The scanner was operated using half-step motor control to improve positioning resolution. Testing showed that step timing strongly influenced mechanical stability, with shorter delays producing resonance and increased vibration. A step delay of approximately 10 ms provided reliable operation, while future improvements may include acceleration profiles and reduced backlash through improved transmission designs.

3.4 Optical Alignment and Stray Radiation Control

Maintaining optical alignment was critical due to the small active area of the thermopile detector and the sensitivity of infrared measurements to unwanted radiation. A modular mechanical structure was developed to support alignment between the objective lens, filter, and detector while allowing adjustment during prototyping. A translation mechanism along the vertical axis was incorporated to account for accumulated manufacturing tolerances and optimize detector positioning. In addition, a lens tube and internal baffle structure were implemented to reduce stray radiation reaching the detector from off-axis sources and internal reflections. These features improve measurement reliability while maintaining a compact and manufacturable optical assembly.

3.5 Low-Noise Signal Acquisition Electronics

The thermopile detector produces a low-level analog signal, requiring careful signal conditioning to maintain measurement accuracy. The electronics design focused on minimizing noise, thermal drift, and electromagnetic interference while amplifying the detector output for data acquisition. Early on in our research, we came to the conclusion that minimization of noise sources was tantamount to the success of the project. As noted before, the central electronic component, the AD8629 precision operational amplifier, was selected due primarily due to its low input offset voltage and low noise performance, along with exceptionally low thermal drift. PCB layout considerations included minimizing sensitive signal paths, reducing coupling between analog and digital circuitry, and improving grounding practices. During the implementation process, a Faraday shielding structure was designed around the amplification circuitry to reduce electromagnetic interference and improve signal stability. Temperature monitoring utilising the thermistor and and near the PCB was also included to provide additional environmental information for future calibration and compensation of temperature-dependent effects.

4. PROTOTYPE IMPLEMENTATION

The prototype was developed through an iterative subsystem validation approach, where the optical, mechanical, and electronic components were independently evaluated before full system integration. Initial testing was performed on an optical breadboard using a visible laser source to verify the optical path, component placement, and alignment procedure. As the system requirements became defined through testing, custom mechanical structures were developed and refined to support integration of the optical and electronic subsystems.

4.1 Mechanical Scanning Validation

The mechanical scanning system was the first subsystem independently validated. Testing focused on verifying the pan-tilt architecture, stepper motor control, and ability to perform controlled raster motion. Initial evaluations identified mechanical backlash, material flexibility, and tolerance difficulties as primary factors affecting motion reliability. Motor timing and mechanical design adjustments were implemented to improve scanning stability, resulting in a functional two-axis scanning platform suitable for integration with the optical system.

4.2 Electronics Integration and Signal Optimization

Following mechanical validation, the electronics subsystem was assembled and integrated with the thermopile detector and embedded controller. Initial testing focused on verifying signal acquisition and amplifier operation. Due to the low-level thermopile output, early measurements exhibited sensitivity to electrical interference and environmental noise. Additional shielding and circuit modifications were implemented to improve signal stability, resulting in a functional amplification stage suitable for integration with the complete imaging system.

4.3 System Integration

After validating the primary subsystems, the optical, mechanical, and electronic components were combined into a unified thermal imaging prototype. A modular enclosure approach was used to maintain accessibility during alignment and testing while allowing continued refinement of internal components. Final enclosure integration and system-level characterization will be completed following validation of the remaining optical and thermal performance metrics.

5. EXPERIMENTAL METHODS

Experimental methods were developed to evaluate the thermal imaging system under controlled and repeatable conditions. Since the intended application involves detecting localized thermal anomalies, a representative test scene was created to generate controlled hotspots within the operating range defined during the design phase. The characterization approach focused on establishing a calibrated thermal source and providing a repeatable method for evaluating the response of the imaging system.

5.1 Thermal Test Scene Design and Temperature Control

A controlled thermal test scene was developed to simulate localized hotspots within the target imaging environment. The test target consisted of a polyimide heating strip mounted on a thermally stable background, providing a compact heat source representative of the approximate 20 mm hotspot size targeted by the system. The narrow geometry of the heating element allowed us to evaluate our system's ability to detect hotspots at our required spatial extent. The heating element was controlled using a MOSFET driver circuit operated by a pulse-width modulation (PWM) signal generated from the ESP32 microcontroller. Adjusting the PWM duty cycle allowed the applied heating power to be controlled electronically, enabling repeatable generation of different temperature conditions. Using an external handheld digital infrared thermometer as a reference, PWM values were experimentally determined for a number of different testing temperatures. This setup provided a method for producing controlled thermal targets for calibration and future evaluation of spatial and temperature measurement performance.

5.2 Temperature Calibration Methodology

Temperature calibration was performed to establish a relationship between the measured thermal response and the actual temperature of the test scene. A three-point calibration procedure was selected based on the intended operating range of the system rather than evenly spaced temperature intervals. The calibration points consisted of 40°C, representing the lower limit of the desired measurement range; 120°C, representing the upper design limit; and 90°C, representing a critical temperature threshold selected as a representative condition requiring further inspection. A quadratic fit was generated using these three calibration points to approximate the nonlinear response of the thermal measurement system across the operating range. The resulting calibration curve provides a temperature estimation model that prioritizes accuracy at application-relevant temperatures while accounting for the nonlinear behavior of the thermopile detector and associated signal conditioning electronics. Later in the project, additional calibration points would be added as needed to improve the temperature accuracy in different temperature ranges.

6. RESULTS

System performance was evaluated by comparing the prototype behavior against the quantitative requirements established during the design phase. Three key performance specifications were selected at the outset of the project for experimental validation based on their importance to the intended application and the overall functionality of the thermal imaging system. Each specification was evaluated through repeated measurements and numerous trials to assess both performance and consistency of the prototype.

Assisting in this characterization was our web dashboard, where we could view reconstructed images of the object such as seen in figure 2. Note that the grey pixels represent missing data.

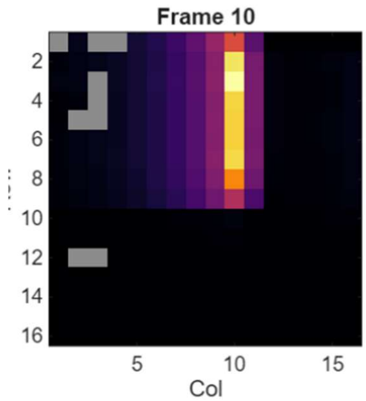

Figure 2. Geometric Optical Signal Path

Table 2. Summary of Tests

Performance Metric	Experimental Result	Requirement	Result
Frame Rate	0.040 ± 0.001 FPS	≥0.033 FPS	Pass
Stimulus-to-Alert Response Time	0.0054 ± 0.009 s	≤30 s	Pass
Temperature Accuracy (50 °C)	5.76 °C max error	±10 °C	Pass
Temperature Accuracy (90 °C)	9.97 °C max error	±10 °C	Pass
Temperature Accuracy (110 °C)	5.82 °C max error	±10 °C	Pass

Additionally, since the temperature of 90°C represents a critical threshold for determining whether or not a hotspot is present, additional analysis was done to determine the extent of edge spread in the result image as well as the statistical temperature deviance we can expect.

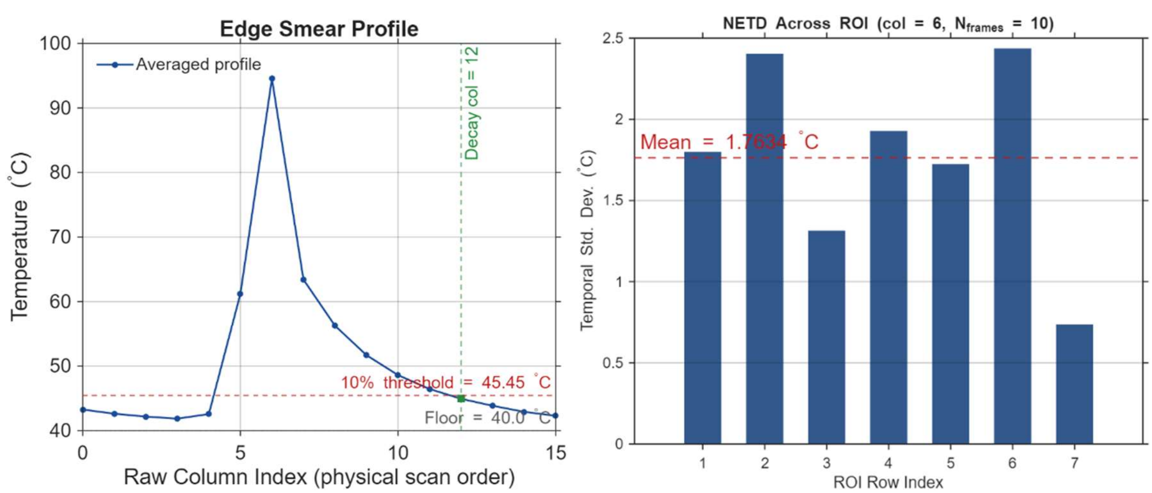

Figure 3. Geometric Optical Signal Path

7. DISCUSSION

The experimental results demonstrate the performance of the implemented single-detector thermal imaging architecture. Evaluation of the three primary performance metrics showed that the prototype achieved the intended design specifications for frame rate, hotspot detection, and temperature measurement accuracy. These results validate that the design decisions made in Project IRIS are sufficient for meeting our design needs while being implementable in a reduced timeline. Following refinement of the signal acquisition by increasing gain alongside multiple point system calibration, the prototype successfully achieved the target temperature accuracy across the evaluated operating range. Characterization at 50°C, 90°C, and 110°C demonstrated measurement accuracy within the specified design requirements, including reliable detection at the lower limit of the intended operating range and at the critical hotspot threshold temperature. These results confirm the effectiveness of the final amplifier configuration, calibration procedure, and overall optoelectronic design. Additionally, examining the information collected across several frames at the same temperature, analysis supports that effects such as edge spread or temperature equivalent noise are acceptable in operating conditions supporting the reliability of our system.

8. CONCLUSION

This work presented the design, implementation, and characterization of a low-cost raster-scanned thermal imaging system using a single LWIR thermopile detector and a two-axis scanning mirror for hotspot detection in medium-voltage electrical switchgear. The system integrates custom optical, mechanical, and electronic subsystems to provide a lower-cost alternative to focal plane array-based thermal imaging approaches. The prototype demonstrated the feasibility of combining mechanical raster scanning, LWIR optical collection, and low-noise signal conditioning into a compact thermal imaging platform. Key design challenges, including mechanical positioning, optical alignment, and microvolt-level signal acquisition, were addressed through iterative design and testing. Experimental characterization demonstrated that the prototype met its primary design objectives, including frame rate, hotspot detection capability, and temperature accuracy across the intended operating range. These results validate the proposed single-detector imaging architecture as a practical proof of concept and demonstrate the effectiveness of the integrated optomechanical and optoelectronic design. The developed system establishes a foundation for future improvements in imaging speed, spatial resolution, and mechanical packaging while demonstrating the potential of low-cost single-detector thermal imaging for industrial monitoring applications.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. Paul Leisher, Dr. Chong Yung Chan, Dr. Lei Wei, and Dr. Arthur Weeks for their guidance and support throughout the development of this project. We also thank the project reviewers, particularly Dr. Robert Grimmig, Dr. Piotr Kulik, and Dr. Qichen Yang, for their valuable feedback and recommendations that helped improve the design and implementation of the system.

REFERENCES

[1] X. P. V. Maldague, Theory and Practice of Infrared Technology for Nondestructive Testing, Wiley-Interscience, New York, NY (2001).
[2] M. Vollmer and K.-P. Möllmann, Infrared Thermal Imaging: Fundamentals, Research and Applications, 2nd ed., Wiley-VCH, Weinheim, Germany (2018).
[3] R. Usamentiaga, P. Venegas, J. Guerediaga, L. Vega, J. Molleda, and F. G. Bulnes, "Infrared thermography for temperature measurement and non-destructive testing," Sensors 14(7), 12305–12348 (2014).
[4] A. Rogalski, "Infrared detectors: an overview," Infrared Physics & Technology 43(3–5), 187–210 (2002).
[5] A. Rogalski, "Infrared detectors: status and trends," Progress in Quantum Electronics 27(2–3), 59–210 (2003).
[6] R. D. Hudson, Infrared System Engineering, Wiley-Interscience, New York, NY (1969).
[7] J. E. Greivenkamp, Field Guide to Geometrical Optics, SPIE Press, Bellingham, WA (2004).
[8] J. W. Goodman, Introduction to Fourier Optics, 3rd ed., Roberts & Company Publishers, Greenwood Village, CO (2005).