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Development of a Prototype Thermal Imaging Rockfall Detection System

Julia Potter, Benjamin Meyer, Brad Ross, James McNabb, John Keefner, and Chad Williams
University of Arizona Geotechnical Center of Excellence, Tucson, Arizona, US
Leonard D. Brown
University of Arizona Mel & Enid Zuckerman College of Public Health, Tucson, Arizona, US
Bobby Prescott
ASARCO, Sahuarita, Arizona, US
Albert Cabrejo
GroundProbe, Tucson, Arizona, US

ABSTRACT: Rockfalls pose a critical risk to the mining industry. In collaboration with NIOSH and industry partners, the Geotechnical Center of Excellence (GCE) has previously shown that thermal video can effectively observe rockfall events. Currently, work is underway to automate the detection, tracking, and alarming of these events. To facilitate this work, a prototype thermal imaging system that uses an early version of the detection algorithm has been developed. Designed to withstand extreme environments, the system can be easily transported with a light vehicle and installed in under 20 minutes. It includes a high-resolution security-type thermal camera, a tripod, a processing unit in a weatherproof case, and a backup battery to mitigate temporary power loss. While initially developed for detecting rockfall in open pit mines, the system can be customized for specific use cases. The presentation will provide an overview of the prototype's deployments and associated research to date, document lessons learned, and outline plans for future prototype development.

1. INTRODUCTION

Rockfalls and slope failures represent a critical and escalating risk to the mining industry, posing threats to both personnel and infrastructure. Despite great progress in monitoring solutions targeting movement at rates of inches per year to inches per day, there are limited methods to detect rapid movement due to rockfall in real time (Sharon and Eberhardt, 2020). Currently, rockfall mitigation is largely limited to ‘manual’ methods such as trigger lines and human spotters. While important progress has been made to analyze rockfall sources and deposition zones with unmanned aerial vehicle (UAV) and light detection and ranging (LiDAR) systems, this requires significant post-processing time (Walton, et. al, 2023; Graber and Santi, 2023; Wang, et.al, 2021). Two Doppler radar systems are in commercial development for rockfall detection, but neither has been widely adopted in the US mining industry, and there remains a notable absence of widely adopted tools in this domain (Viviani, et. al, 2020).

The research efforts of the Geotechnical Center of Excellence (GCE) seek to address this gap through two projects funded by National Institute for Occupational Safety and Health (NIOSH), the Application Testing Project (Phase 1) and the ongoing Automated Rockfall Recognition Project (Phase 2). Phase 1 of this work demonstrated the feasibility of utilizing thermal video cameras for rockfall detection. Through the development of a Mobile Monitoring Platform (MMP) equipped with four thermal cameras, the GCE collected extensive data from a variety of mine sites, laying the groundwork for the development of an automated detection algorithm (Wellman et al., 2022). Project Phase 2 builds upon this work through refinement and implementation of an automated rockfall recognition system using thermal video cameras in open-pit mines, thereby significantly enhancing safety in geotechnical risk management practices. To facilitate the deployment and scalability of the proposed system, a prototype tactical monitoring system was developed in collaboration with GroundProbe. This paper documents the design, deployment, and testing of the prototype system..

2. PROTOTYPE THERMAL IMAGING SYSTEM

Developed in collaboration with GroundProbe, the prototype thermal imaging system is a mobile, short-term rockfall detection solution designed for algorithm testing and on-site data collection. The system was manufactured by GroundProbe at their facility in Tucson, Arizona. The GCE outlined the necessary system requirements and provided feedback throughout the design process.

2.1. Technical Specifications

Featuring a 32° field of view, resolution of 640 × 480, and a maximum framerate of 30 frames per second, the FLIR FC-632-ID camera serves as the system's imaging component. This is a security-grade thermal camera with a relatively accessible price point (around $8,000 as of this writing) as well as the ability to output high bitrate (low compression) video. The camera's uncooled vanadium oxide microbolometer provides consistent performance with less need for maintenance than more expensive cooled thermal detectors. The camera has an operating temperature range of –50° C to 70° C (–58° F to 158° F). The system was designed such that other thermal cameras can be utilized with an appropriate mount. This flexibility allows for customization based on specific project requirements or advancements in thermal imaging technology.

The computing component of the prototype system is a Dell Latitude 5424 Rugged Laptop, which was selected for its robust construction and reliability. Equipped with an Intel i7-8650U processor, 16 GB of RAM, and 1TB NVMe Storage, it offers adequate performance for data collection and storage.

An internal 256 Wh rechargeable LiPO4 battery allows for prolonged operations in areas lacking reliable line power. The system can be deployed for approximately five hours in tactical monitoring situations on battery power. Power-over-Ethernet (PoE) connectivity streamlines the integration of imaging and computing components.

The prototype system has two tripod options:

1. Tripod 1: A heavy-duty fixed-height metal tripod designed for long-term deployments in rugged environments.
2. Tripod 2: A lightweight and adjustable surveyor's tripod that can be easily adjusted to meet the needs and characteristics of a worksite for short-term, tactical deployments.

Figure 1 shows the prototype system, while deployed with Tripod 2 at a mine in northern Nevada. Figure 2 shows a closer look the processing, battery, and PoE components of the system.

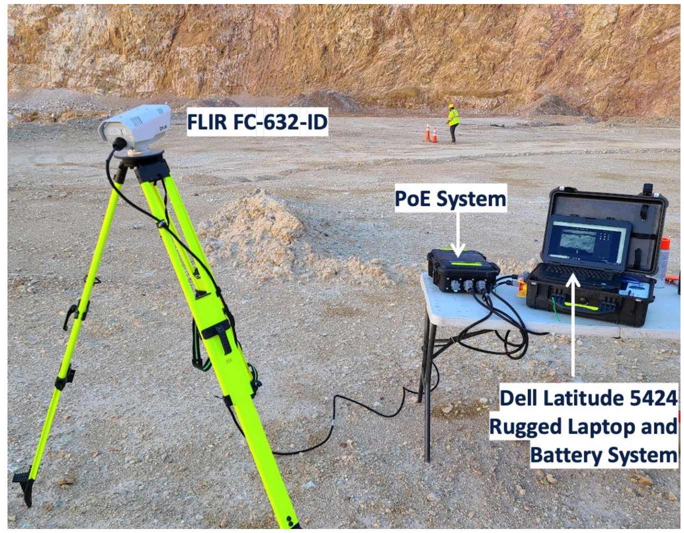

Fig. 1. Prototype tactical monitoring system deployed at a mine in Nevada.

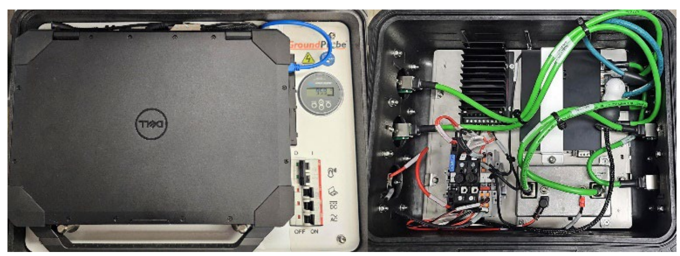

Fig. 2. The prototype system processing unit (left) and PoE injection system (right).

2.2. Design Considerations for Extreme Environments

The prototype system was engineered to withstand the rugged conditions prevalent in mining environments, while ensuring operational efficiency and adaptability. All system components are enclosed with robust weatherproof storage boxes, engineered to endure extreme environmental conditions. These enclosures provide protection against heavy precipitation, snow, temperatures from –30 degrees to 130 degrees Fahrenheit, and wind speeds exceeding 80 miles per hour.

The FLIR FC-632-ID camera is rated IP66 and IP67 (dust-tight and capable of withstanding powerful water jets or submersion in 1 meter of water for periods of 30 minutes). The processing unit, battery components, and power system are housed in Pelican cases with all internal components secured in place. Additionally, all connecting cables between the components (not including the alternating current power cable for line charging) feature rugged, weatherproof sheathing, cable glands between cable and connector, and rubber gaskets used as pressure seals for the connectors. The AC power connector from the processing unit case uses a gasketed insert to prevent water and dust intrusion when not in use.

2.3. System Installation, Transport, and Portability

Setup of the system's physical and software components can be completed in approximately five minutes when using default settings. However, software setup time varies by the amount of tailoring (e.g., region masking, fall angle definition) necessary for the site conditions.

The prototype system was designed to be lightweight enough that it could be transported to an observation site and installed by a single person. This can be achieved when deployed with Tripod 2. Deployment with the more rugged Tripod 1 requires transport with a light vehicle. The weight of each system component and of the resulting total system with different tripod configurations are approximated in Table 1.

Table 1. Approximate weight of system components

Component	Approximate Weight (kg)
Processing unit	17
Power-over-Ethernet System	4
Camera and Case	4
Cables	<1
Tripod 1	20
Tripod 2	7
Prototype System with Tripod 1	45
Prototype System with Tripod 2	33

Long-distance transport of the unit requires ground shipping using hazardous materials labeling due to the size of the battery, which exceeds FAA guidelines for lithium batteries on domestic flights.

3. AUTOMATION OF ROCKFALL DETECTION, TRACKING, AND ALARMING

An automated method of detecting and alarming for rockfall and other fall hazards has been developed as part of project Phase 2. The automated tracking system utilizes long-wave infrared (LWIR or "thermal") video to monitor rockfall at all stages of the diurnal cycle, through dust and light-to-moderate precipitation.

The automated detection approach is driven by the characteristics of the prototype system hardware and by our subject matter (falling rock). The Dell Rugged Latitude laptop includes an Intel I7-8650U processor and lacks NVIDIA graphics. Operating with these hardware constraints drovedevelopment of a CPU-based algorithm that does not leverage CUDA-based parallelism. The processor limitations have necessitated prioritization of computational efficiency, resulting in an algorithm that does not require a high-end CPU or graphics card to run in real time.

Rockfall can include large and easily visible singular rocks, slides of aggregate material, or falling objects that are only evident on thermal video from the scouring left by their impact with the rock face. Due to the irregular structure of slope surfaces in open pit mines and similar environments, rockfall can drastically change direction and shape from frame to frame as falling objects are deflected or dislodge other material.

Based on these characteristics, the algorithm utilizes predictive filtering and motion heuristics, in which multiple objects are tracked. The alarming component is triggered by the way in which objects move rather than on matches with predetermined shapes. The resulting software is not machine-learning based and does not require retraining to accommodate new data or rely on recognizable corners for maintaining the identity of an object from one frame to another.

3.1. Purpose of the Thermal Imaging System

Commercially-available uncooled thermal cameras are low resolution and record at slower frame rates when compared to modern visual-light cameras. Despite these drawbacks, thermal cameras are capable of operation day or night and in conditions of light to moderate precipitation that would render visual-light cameras ineffective. As rocks fall out of face or impact slopes, there is a thermal difference between the freshly-exposed or scoured area and the surrounding rock face, as well as between the falling rock and the surrounding face. These differences are detectable through thermal imaging, and can provide greater contrast than may be seen with a visible-light video of rocks falling past similarly-colored material. Phase 1 of our project proved that thermal cameras can reveal rockfall throughout the diurnal cycle and in extreme ambient temperatures (ranging from –25°F to 122°F).

3.2. Algorithmic Process

A software algorithm has been implemented to detect and characterize object motion and then to issue alarms where appropriate. Figure 3 presents a human-initiated rockfall. Figure 4 illustrates important algorithmic steps and results. The algorithm consists of the following steps:

- **(i)** Background Generation: To minimize detections due to pixel flicker in thermal video, we generate a background image from the average of the previous 50 frames. This is used to minimize false motion detections from slight brightness flickering of pixels (common in this style of thermal camera).
- **(ii)** Blob Detection: These motion detections are grouped into areas or regions of motion by combining nearby pixels. This consolidates close movement detections, allowing the system to more efficiently characterize motion than would otherwise be possible.

(iii) Location Prediction: Expected locations for all previously identified moving objects are estimated using predictive Kalman filters (Kalman, 1960) These filters consider previously-known locations of the object plus current velocity to judge likely location.

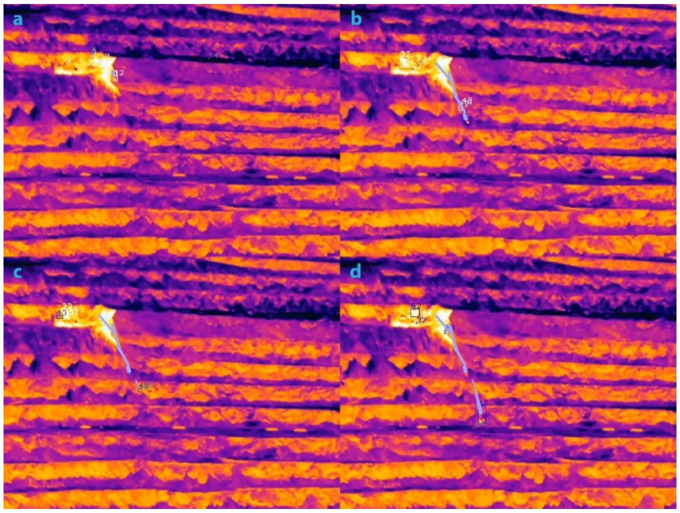

Fig 3. Example of algorithm tracking results on a human-initiated rockfall. a) frame taken 1 second after initial detection of rockfall b) frame taken 6 seconds afte initial detection of rockfall c) frame taken 8 seconds after initiation of rockfall d) frame taken 12 seconds after initiation of rockfall.

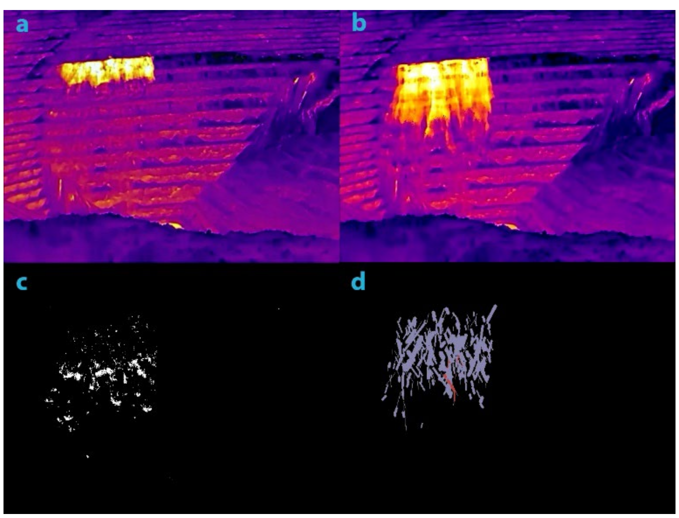

Fig 4. Example of algorithm performance on rockfall caused by a planned blast at an open pit mine. a) frame taken 7 seconds after blast event b) frame taken 15 seconds after event c) subtracted background showing instantaneous differences / motion in current frame vs previous 50 frames d) tracked fall detections from start of video clip to current frame.

(iv) Track Assignment: Observed current-frame motion is compared with all previously identified moving objects using a Hungarian/Munkres filter with thresholding (Munkres 1957). Motion near the predicted location of tracked objects is used to extend movement paths. Motion outside of those matches causes the creation of new track assignments. Any other identified objects are flagged as "unseen" until motion is visible along an object's expected path.

(v) Motion Characterization: The paths of all identified moving objects are evaluated against the characteristics of a "fall hazard". For this study, characteristics used to define fall hazard include direction and speed of movement (velocity).

(vi) Alarming: Alarms are triggered when tracked objects meet the motion characterization criteria. Alarm options currently include screen representation of motion path, audio alert, and console/JSON output.

Notably, the rapidly changing shape of rockfall events based on the interaction between moving or fragmenting rock and underlying slope structure makes the subject material very difficult to characterize or track based on similar corners or edges as is done in most artificial intelligence (AI) methods of object recognition and tracking. This reinforces the need for a solution based on how an object moves rather than the specific characteristics (size, shape) of a moving object.

3.3. *Tailoring results to sites*

A preliminary user interface (GUI) was developed to enable tailoring of the algorithm to site specific requirements. Key parameters for background segmentation and motion characterization are defined by the user based on deployment site characteristics. These include video stabilization options, controls for minimum and maximum speeds for a fall detection, how long a tracked object can be stationary or unseen before being retired from consideration, maximum distance that a motion could be considered as part of an existing fall, and which angles of motion should be considered a fall hazard.

The GUI also includes a masking option to exclude areas of noninterest from consideration and methods for defining expected fall angles based on the orientation of the pit walls in the camera frame (Fig. 4).

4. PROTOTYPE DEPLOYMENT AND TESTING

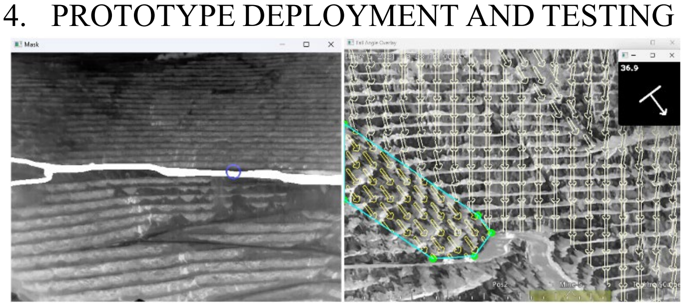

Fig. 5. Interface options for site characterization, including an example of the masking feature applied to an active haul road (left) and an example of user-defined expected angle of rockfall for deployment sites without three-dimensional topographic data (right).

Development of the prototype system was completed in July 2023. Since that time, the system has been deployed to several mine sites in Arizona and Nevada.

4.1. Testing Phase 1 – Recording, Archiving, and Remote Access Capabilities

Initial deployments consisted of several tests at UArizona's San Xavier student mining laboratory (SX Mine) in August 2023, and at a mine in Nevada in September 2023 (Nevada Mine). During the Testing Phase 1 tests at the SX Mine, the system successfully recorded and archived thermal video.

Several issues were encountered during two days of testing at the Nevada Mine. The system was able to record and archive video during the first day of testing, however, remote connection was not successful, and it was discovered that tracking of live rockfall was experiencing a significant lag. After troubleshooting on the first day, the system was deployed to archive video without simultaneous tracking. On the second day of testing, the power components experienced an unexplained failure which ended data collection earlier than anticipated. The system was transported to GroundProbe's Tucson facility for troubleshooting, where the issue was identified and addressed. However, concerns regarding the reliability of the power system persisted due to intermittent outages during subsequent deployments.

Future deployments were limited to mines within driving distance of UArizona to allow for more efficient troubleshooting.

4.2. Testing Phase 2 – Initial Algorithm Implementation

A second phase of testing performed between the GCE's offices on the UArizona campus and at the SX Mine commenced in October 2023. This phase focused on assessing the system's ability to perform real-time detection. While the prototype successfully detected movement in real-time, limitations of the laptop computer's processing power were observed. The system was not able to concurrently facilitate real-time detection while also archiving recorded video for subsequent analysis.

4.3. Testing Phase 3 – Algorithm Implementation

The issues observed during Testing Phase 2 provided valuable insights that lead to improved algorithm efficiency. Each stage of the algorithm was evaluated to determine causes of delay and potential processing improvements as follows:

- Roughly 15% of the algorithm's processing time was consumed by an optical flow calculation used only in the video stabilization operation on the camera input. Phases 1 and 2 of testing revealed no significant detection benefits resulting from the stabilization process, so the video stabilization step was removed.
- Archiving the original thermal video without the algorithm outputs accounts for roughly another third (32%) of processing time. Archiving original video will be optional in a production version of the system, but is vital during development as it allows the original video to be re-processed using the latest software improvements.
- The detection software was redesigned to take advantage of multiple CPU cores, reducing bottlenecks in video processing.
- Another 18% of processing time is spent waiting for user interaction (checking for user keystrokes, etc.). No opportunities for efficiency improvements were identified for this necessary step.

Further testing with the resulting improved software solution was completed between January and March 2024. This testing involved real-time processing on video from three minutes up to 11 hours. All field tests showed successful real-time motion processing with simultaneous archiving of video, indicating successful resolution of the lag issue discovered in Testing Phase 2. Future work will include further prolonged testing of the algorithm.

5. RESEARCH FINDINGS AND FUTURE WORK

The work documented herein has resulted in a prototype rockfall monitoring solution, including an automated detection algorithm, preliminary software, and data acquisition system. The technology readiness level for the prototype system is currently TRL6 (prototype demonstration in relevant environment). The physical prototype and algorithm have been successfully field tested in a non-active mining environment, generating positive rockfall detections. Upcoming advancements will include final development and adaptation of the rockfall detection algorithm and software and improved iterations to the data acquisition system to facilitate reliable, short-term monitoring of safety-critical areas.

5.1. Lessons Learned

Early versions of the rockfall detection algorithm were developed on significantly faster computers than the prototype tactical system's laptop and were tested using archived video rather than live rockfall events. The lag between real-time events and detection results in Testing Phase 2 highlighted the need for an algorithmic solution that was developed to perform well on slower hardware. Some initial assumptions of necessary features (such as automatic motion stabilization to counteract camera shake) were found to be non-critical during testing. While setup and tailoring of the system can be done in less than 20 minutes, ease of portability could be improved. The separate computer, PoE system, camera, and tripod are difficult for a single operator to carry. Currently, the unit requires ground shipping as a "hazardous good" due to battery size, limiting the ability to quickly deploy to a location beyond driving distance.

5.2. Further Development and Adaptation of Software

The prototype software establishes a groundwork for development of a commercially viable software system for detecting, tracking, and alarming for rockfall. Further developments will focus on gathering feedback from industry focus groups, incorporating research findings regarding complementary technologies and additional geotechnical applications, and design of a front-end interface for deployment across various operating systems to align with diverse user hardware preferences. The tracking algorithm will undergo continuous updates to enhance software efficiencies and remain aligned with advancements in hardware processing capabilities. The determination of appropriate site-specific algorithm parameters (vectors for motion heuristics and sensitivity thresholds appropriate for separating true movement from background noise) will be improved. Where digital elevation models are available, the expected angle of rockfall will be automatically calculated based on three-dimensional topographic data and georeferencing of each pixel in the video with a 3D coordinate will be performed, resulting in more accurate tracking and alarming of rockfall events.

Previous work has documented the exponential increase in frequency of rockfall before a major slope failure event (Schafer et al., 2023). Future work will include expansion of the prototype's alarming capabilities to include frequency-based alarm triggering, alerting operators to an increase in rockfall events which could represent larger slope instabilities. Other previous work in the field has documented the use of thermal imaging to identify rock bridges (and thus potential points of future failure) on El Capitan in Yosemite National Park. (Guerin et al., 2019). Future work on this project could leverage and expand on Guerin et al.'s work to identify areas of potential failure in a mining environment.

5.3. Further Development of the Data Acquisition System

The prototype data acquisition system provided valuable insights that will inform future system builds. A primary component of planned future work includes the development of a tactical solution like the existing prototype, with enhancements made based on experience gained during project Phase 2, with the ultimate goal of producing a product capable of short-term monitoring of safety-critical areas when rapid data generation and alarming is needed (e.g., personnel working in high rockfall risk areas).

Considerations and anticipated future work needed to meet this goal are summarized below.

- Future prototype development will incorporate alternate computing infrastructure options to better meet the demands of simultaneous data processing and storage.
- Future work will explore alternate, reliable power system design which meets all applicable requirements for domestic air travel in the US.
- The cameras tested with the Version 0 prototype use a PoE interface that requires a local ethernet network with a power-injection solution. This prototype currently has separate housing cases for the PoE network, processing/battery unit, and camera. The inter-case cabling and tripod must be carried separately from these three cases. While the entire system can be carried by a single person, a more consolidated solution would increase ease of deployment. Future prototype development will explore more compact solutions such as an all-in-one wheeled weatherproof case containing system components.

6. CONCLUSION

The collaborative efforts between the GCE, NIOSH, and industry partners have resulted in the successful development and testing of a prototype tactical monitoring system using thermal imaging for rockfall detection in mining environments. This represents a significant step forward in addressing the critical risk posed by rockfall to the mining industry.

The GCE has demonstrated the viability of using commercial off-the-shelf thermal cameras and moderate computing hardware to automatically detect and alert for rockfall in open pit mining environments. Cost-efficient options for real-time rockfall detection and monitoring are a critical need in the mining industry, and the prototype developed for this project represents one avenue to meeting that need.

Field testing of the prototype system has yielded valuable insights, leading to improvements in both hardware and software components. Early deployments of the prototype system resulted in a greater understanding of the ideal physical characteristics of an improved thermal rockfall detection device as well as a more efficient software solution for rockfall detection and tracking. The difficulties encountered in the deployment and testing process led to advancements in performance and efficiency for algorithmic fall hazard identification and tracking. The resulting integrated hardware/software system represents a first step towards a new situational awareness and personnel safety monitoring technology, and will continue to be improved through future research, testing, and prototyping.

Overall, the prototype thermal imaging system represents a significant advancement in geotechnical risk management practices, promoting increased safety and efficiency in mining operations. Future work will focus on optimizing the data acquisition system for short-term monitoring of safety critical areas, while exploring the applicability of this technology for long-term, strategic monitoring use cases.

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