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A novel application of photogrammetry to ground convergence monitoring in underground excavations

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ABSTRACT

Researchers from the National Institute for Occupational Safety and Health (NIOSH) Spokane Mining Research Division (SMRD) are evaluating the comparative performances of ground convergence monitoring methods currently utilized in underground mining. A portion of this research is exploring applications of photogrammetry for periodic visual assessment of slow-converging ground. This paper describes the photogrammetric systems evaluated, including their components and methodology. These systems include light-weight equipment easily carried by a single individual traversing rough terrain in underground mine environments. This study demonstrates how photogrammetric methods may complement or replace existing underground convergence monitoring techniques on the basis of time and personnel requirements, equipment cost and robustness, and overall data quality. This research supplements previous studies into photogrammetric and laser scanning methods, and enhances understanding of how digital technology may be utilized to maximize safety in underground excavations. NIOSH SMRD is committed to improving workforce health and safety through innovative research and applications of technology.

Keywords: photogrammetry, mining engineering, civil engineering, excavations, convergence monitoring, safety

1. INTRODUCTION

This study originated in an attempt to monitor bulk deformation of rock masses using photogrammetry. In practice, this involved close-range photogrammetry at normal orientations to the rock face and measurement of rock movement in the depth field[1]. Photographs of the sides and backs of tunnels were taken at roughly three-month intervals, then used in three-dimensional reconstructions to track general deformations over time. The success of this study led to investigations of other uses for photogrammetry in ground monitoring, including volumetric and linear support deformation monitoring and methods of corrosion monitoring[2,3]. During this work, a unique opportunity presented itself when photogrammetric measurements could be compared directly to precision measurements produced by vibrating wire crackmeters in a field environment[4]. The sub-millimeter accuracy of photogrammetric measurements in underground mining environments was verified through this study, and importantly, the possibility of reliable planimetric field measurements was confirmed. Reliable planimetric measurements, being perpendicular to camera orientation, would allow rock mass deformations of one portion of a tunnel to be observed from another portion. In scenarios where the area of interest is unsafe or unsupported, this means that measurements of the unsafe ground could be made from a safe location.

The remainder of this paper discusses optimized methods for conducting these types of photogrammetric measurements. The methods evolved over a five-year period of practical trial-and-error exercises in various mining and laboratory environments, culminating in the study forming the subject of this paper. The result is a reliable, cost-effective, and easy-to-use system for measuring ground convergence in underground excavations.

2. BACKGROUND AND DEVELOPMENT

2.1 Ground convergence in underground excavations

Ground convergence in underground excavations refers to the process by which artificial cavities within rock masses tend towards closure over time. Concentrations of stresses around these cavities combine with loss of confinement from within the cavity to "squeeze" the tunnel opening. This may happen quickly, such as during tunnel advancement and seismic

events, or more slowly in a phenomenon known as "creep"[5,6]. In both cases, the impact on underground civil and mining industry can be costly in terms of rehabilitation or catastrophic in terms of loss of life and entrapment of people. An effective method of monitoring closure rates would thus greatly benefit industry efforts to mitigate ground convergence.

In instances of dynamic ground convergence, a conceptual method of "ground reaction curve" (GRC) is used to clarify the relationship between ground support capacity and ground displacement[7,8,9,10,11]. Tunnel excavation is typically done using explosives, resulting in a sudden loss of rock mass (the excavated rock) accompanied by a dynamic release of energy (the detonation). The goal of GRC utilization is to determine what type of ground support and its installation timing that will minimize damage to the remaining rock mass and maximize support performance. This essentially means supporting the rock before it falls apart, but letting the rock de-stress enough to prevent destruction of the ground support. Successful balancing of ground de-stressing and ground support thus depends on accurate measurement of convergence rate and magnitude following each tunnel advancement.

2.2 Monitoring ground convergence

Photogrammetry has already been successfully implemented for geometric and spatial analyses in underground openings in rock[12,13,14,15]. Photogrammetry has not, however, been demonstrated successfully in the aspect of the type of convergence monitoring useful for GRC development. To test this capability of photogrammetry, current industry methods were examined for replication. One method of monitoring convergence in underground excavations involves the installation of instruments directly into the rock mass. These instruments measure their own deformation as the rock mass deforms, thus providing an indirect measurement of overall tunnel convergence. A simpler method is the direct measurement of the distance between fixed points on either side of the tunnel. If the measured distance decreases, tunnel closure can be reasonably assumed. In either case, photogrammetric methods would involve the tracking of point positions relative to one another in space over time, though with the added benefits of no permanent instrument installations, nor any direct physical presence under unsupported ground.

3. TESTING METHODOLOGY

3.1 Equipment selection

Having established baseline underground civil and mining industry standards of convergence monitoring, the specific equipment for photogrammetric replication of industry methods could be defined and chosen. Most areas of tunnel advancements lack sufficient lighting for standard photographic methods. Early iterations of SMRD photogrammetric systems used basic camera flashes, which led to significant differential shadowing brightness effects. Night vision and infrared cameras were then considered, but were found inadequate due to insufficient ambient light, for the former, and insufficient temperature gradations, for the latter. This eventually led to the decision to use standard digital cameras combined with auxiliary lighting sources. The final selections for this study are shown in Tables 1 and 2, along with their qualities pertinent to the desired application: resolution, coverage, and cost for the cameras; and brightness, weight, and cost for lighting. Camera resolution and coverage, along with lighting brightness, are important factors in determining the allowable distance between the user and the area of interest. In cases where the area of interest is unsafe, greater values for each of these variables allows for more separation between the user and danger. Lighting weight is important for users travelling on foot, or through messy work areas, where physical burden must be minimal for safe and effective work.

Table 1. Cameras used in this study, along with their megapixel count, diagonal angle of view, and approximate off-the-shelf cost. Parenthetical terms will be used for shorthand references to the item throughout this paper.

Camera	Megapixels	Field of View	OTS Cost
Canon EOS 5D Mark III[16] (Canon DSLR)†	22.3	94.5º	$2,500
Canon PowerShot ELPH 360 HS[17] (Canon P&S)‡	20.2	71.5º	$250
Apple iPhone 6S[18] (iPhone)‡	12.0	73.0º	$500

† Field of view using a Canon EF 20mm f/2.8 USM lens[19] – also factored into OTS Cost.

‡ Using factory default lenses, no zoom.

Table 2. Lighting units used in this study, along with their lumen count, approximate weight, and approximate off-the-shelf cost. Parenthetical terms will be used for shorthand references to the item throughout this paper.

Lighting Unit	Lumens	Weight	OTS Cost
Pelican 9460 RALS[20] (Pelican)†	6,000	24.9 kg	$2,000
Milwaukee M18 Radius LED Site Light[21] (Milwaukee)†‡	4,400	5.5 kg	$450
Canon MR-14EX II Macro Ring Lite[22] (Ring Lite)†	variable	0.6 kg	$550

† Batteries included in Weight and OTS Cost

‡ Battery charger included in OTS Cost, but not in Weight

The Canon EOS 5D Mark III[16] (Canon DSLR) with a 20-mm lens was selected to represent the top-end amateur camera option. The Canon PowerShot ELPH 360 HS[17] (Canon P&S), on the other hand, was chosen to represent the standard point-and-shoot camera, already in common use by industry. The third option, an Apple iPhone 6S[18] (iPhone), was chosen to represent the potential future of industry photography, as smart phones are becoming increasingly common in data collection and site documentation. The Pelican 9460 RALS[20] (Pelican) lighting unit was chosen to represent the top-end commercial battery-powered work light, while the Milwaukee M18 Radius LED Site Light[21] (Milwaukee) represented a more affordable option. The Canon MR-14EX II Macro Ring Lite[22] (Ring Lite) was selected to represent a camera-mounted lighting option, as it is a flash alternative that produces no shadowing, though it could only be used with the Canon DSLR. It should be noted that these camera and lighting options were selected simply because they were already in possession of the researchers. Finally, Agisoft PhotoScan Pro[23] (PhotoScan), with a market cost of $3,500 per license, was used for photogrammetric processing and analysis for its balance of ease-of-use, quality, and affordability.

3.2 Test design

A mock mine served as the environment for this study, the known dimensions of which could serve as test measurements for photogrammetric comparison. This test environment resembled the heading of an actual shotcrete-lined tunnel and could be put in near-blackout lighting conditions. A diagram of the testing space is shown in Figure 1.
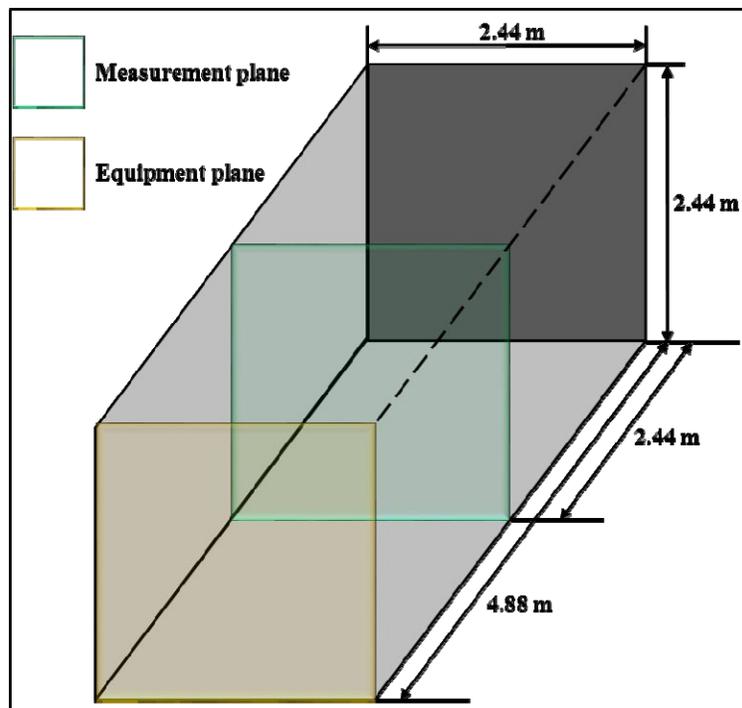

Figure 1. Diagram of tunnel heading (farthest plane), measurement (middle plane) and equipment (nearest plane) locations used in the study of optimal photogrammetric convergence monitoring equipment in a mock square tunnel environment.

The space is bookended by a tunnel heading plane (rear) and equipment setup plane (fore). Equidistant from each of these planes was the area of interest (middle), where markers and scale bars were placed for control and measurement comparison. The area of interest, or measurement plane, was located one tunnel diameter away from the tunnel heading, as the rock mass here is of greatest interest to GRC development. In a real tunneling environment, the area between the measurement plane and tunnel heading would also be unsupported, making it unsafe to enter. The equipment plane was therefore placed at two tunnel diameters away from the heading, which would provide users suitable protection from the unsupported rock mass.

To scale the photographs for photogrammetric measurements, relative scaling options were chosen to lessen demands on the user and industry. Relative scaling has the benefit of being self-containing, meaning no additional sources of global control, like GIS or traditional surveying, are required for measurement analysis. Scaling and control was provided by 1-m scale bars manufactured and calibrated by Cultural Heritage Imaging[24] (CHI). These scale bars are lightweight, durable, and accurate to 0.1 mm, and by placing them in the measurement plane, accurate scaling and control is provided to all other measurements calculated in the same plane. In Figure 2, placements of the CHI scale bars can be seen from the perspective of the equipment plane.
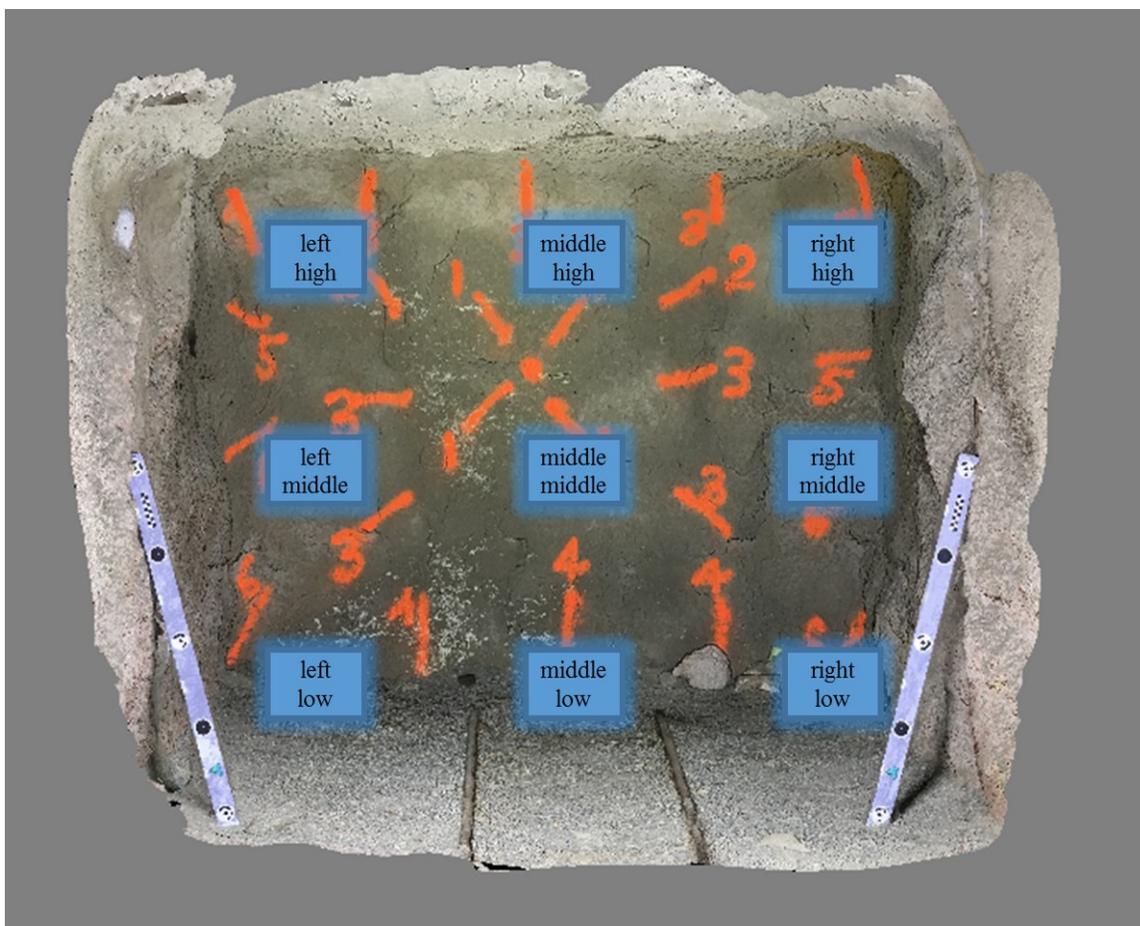

Figure 2. Example of photogrammetry using fixed orientation and variable position methods for camera placement in data collection for tunnel convergence monitoring. Box labels refer to camera location relative to tunnel center (left, middle, right) and elevation relative to tunnel floor (high, middle, low). Also shown are CHI scale bars, leaning against the right and left walls.

Also shown in Figure 2 is the photographic method used to collect images. This method uses fixed camera orientations, relative to the measurement plane, combined with varying camera positions within the equipment plane. In practice, this means pointing the camera straight towards the end of the tunnel for every picture, while changing its elevation and lateral position to obtain the multiple perspectives needed for photogrammetric reconstruction. The blue boxes in Figure 2 represent camera locations, with their corresponding location relative to tunnel center (left, middle, right) and elevation relative to tunnel floor (high, middle, low). To maintain uniform spacing between camera positions within the equipment plane, the selected lighting unit was placed in the center of the tunnel. The "middle" photographs were taken while standing over the light, with the flanking positions each being halfway between the light and each wall. A method for consistency in camera elevation is shown in Figure 3, which employs the user's body as the point of reference. In larger excavations, a monopod could be used to gain more variance in elevation, along with additional lateral positions (i.e., "far left" and "middle left"). In this particular study, only nine photographs were required for sufficient data capture. The total time required to place the scale bars, lights, and take all nine pictures was less than 10 minutes.

Figure 3. Method for maintaining consistent camera elevations when using fixed orientation and variable position methods in data collection for tunnel convergence monitoring. Box labels correspond with camera elevations described in Figure 2.

4. DISCUSSION OF RESULTS

The viability of photogrammetry in applications of tunnel convergence monitoring was tested by comparing its measurements to those of arbitrarily selected, point-to-point distances of known value. This is shown in Figure 4, where one wall-to-wall distance (d1) and one ceiling-to-floor distance (d2) were defined for repeated comparative

measurements. For additional testing, and to account for manual measurement error in cross-tunnel measurements, one of the two CHI scale bars (d3) was also used to verify photogrammetric measurements. Photogrammetrically measured distances were compared to these three known distances through multiple iterations using various combinations of cameras and lighting units.
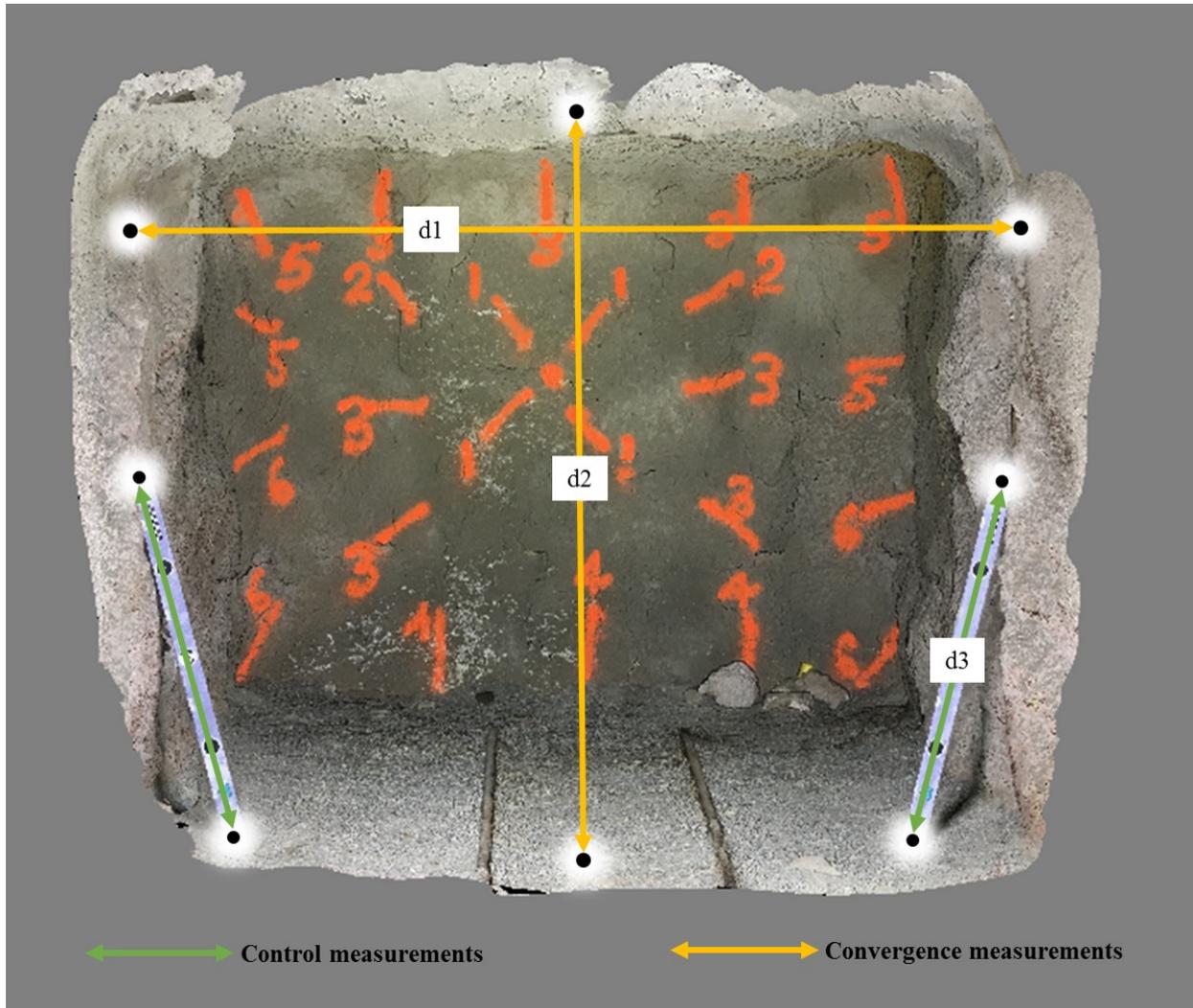

Figure 4. Diagram of measurements used to evaluate accuracy of equipment for photogrammetric monitoring of tunnel convergence. Black circles with white halos mark measurement points, green lines denote scale bar control measurements, and yellow lines denote tunnel width and height measurements.

The goal of this exercise was to determine what combination of photogrammetry equipment performed most similarly to current, manual methods of monitoring ground convergence. The results of this exercise are shown in Table 3 in terms of the average relative difference of photogrammetric measurements from real distances. In general, cm-level accuracy is sufficient for most mining applications, but in the case of GRC development, accuracies closer to mm-level are preferred. The iPhone/Pelican pairing came closest in this regard. In all practicality, both Canon P&S pairings performed adequately, along with the Canon DSLR/Milwaukee and iPhone/Milwaukee pairings. Based on these results of this study, several photogrammetric options appear to be suitable for ground convergence monitoring.

Table 3. The accuracy of each type of camera/lighting unit combination tested in this study, defined in terms of the relative differences of their measurements from each of the three known measurements, averaged across multiple iterations.

Camera	Lighting Unit	Accuracy (average relative difference)
Canon DSLR	Pelican Milwaukee Ring Lite	8.7 mm 3.3 mm 13.6 mm
Canon P&S	Pelican Milwaukee	2.9 mm 2.2 mm
iPhone	Pelican Milwaukee	1.1 mm 4.4 mm

4.1 Subjective matters

There are several subjective factors to take into consideration when selecting from the above camera/lighting combinations. In this study, the more expensive equipment options did not necessarily provide significant advantages over the cheaper options. For example, the cheapest and lightest combination, the Canon P&S/Milwaukee pairing, performed better than all other combinations, except the iPhone/Pelican pair. Alternatively, while the Ring Lite reduces equipment burden by attaching directly to the camera, it suffers from irritating lighting anomalies that can require multiple image capture attempts. In spite of eliminating shadowing issues, the Ring Lite flash has a tendency to cause the camera to focus randomly on different parts of the scene. As illustrated by Figure 5, static lighting allows the user much more control over camera focus, which leads to higher quality reconstructions and easier measurement point location during analysis.
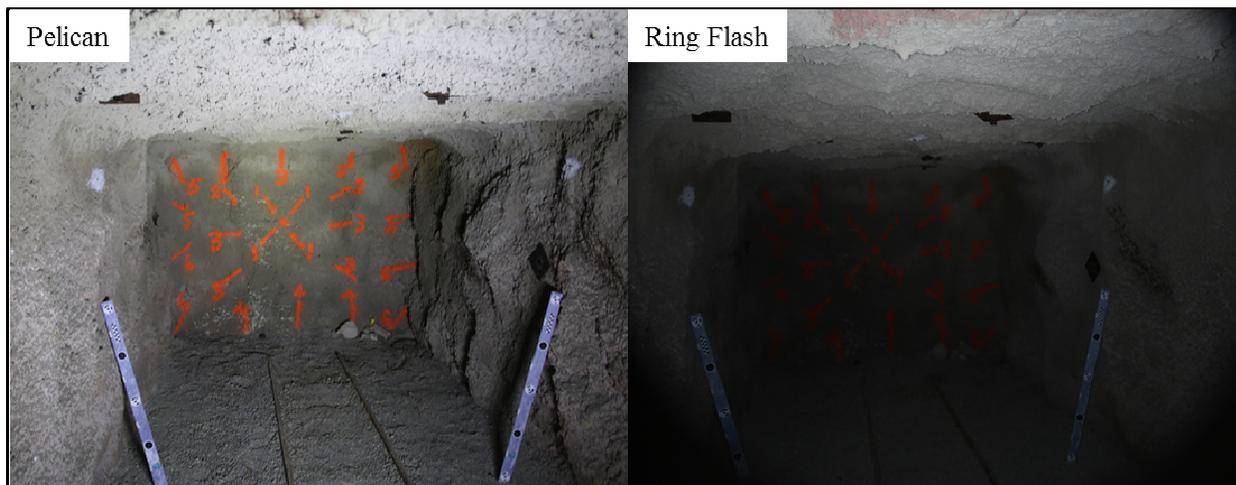

Figure 5. Example of differential brightness among photos from the same orientation and position. The left photo represents the best case scenario, while the right photo represents the worst. Uniform brightness allows for higher quality reconstructions and easier measurement point location. The iPhone again performed best in this aspect.

Ease of user experience during both image capture and data processing were also considered in this study. For example, all three cameras were left in factory default settings, accounting for the likely scenario where the user does not have time to fine-tune their camera. As such, this placed the Canon DSLR at a disadvantage, as illustrated by Figure 6. In this figure, the top left photo is a closeup of a CHI scale bar measuring point. The white dot in the center is the exact point used for scale bar calibration, thus making identification of this point during processing critical to measurement success. The other three photos in Figure 6 were cropped from actual test pictures used in this study. The scale bar's white dot is most visible in the iPhone picture, while it is hardly distinguishable in the Canon DSLR photograph. The Canon DSLR's

settings could eventually be adjusted to produce superior images, but it is not reasonable to expect industry users to devote the required time when cheaper and simpler options provide similar results.
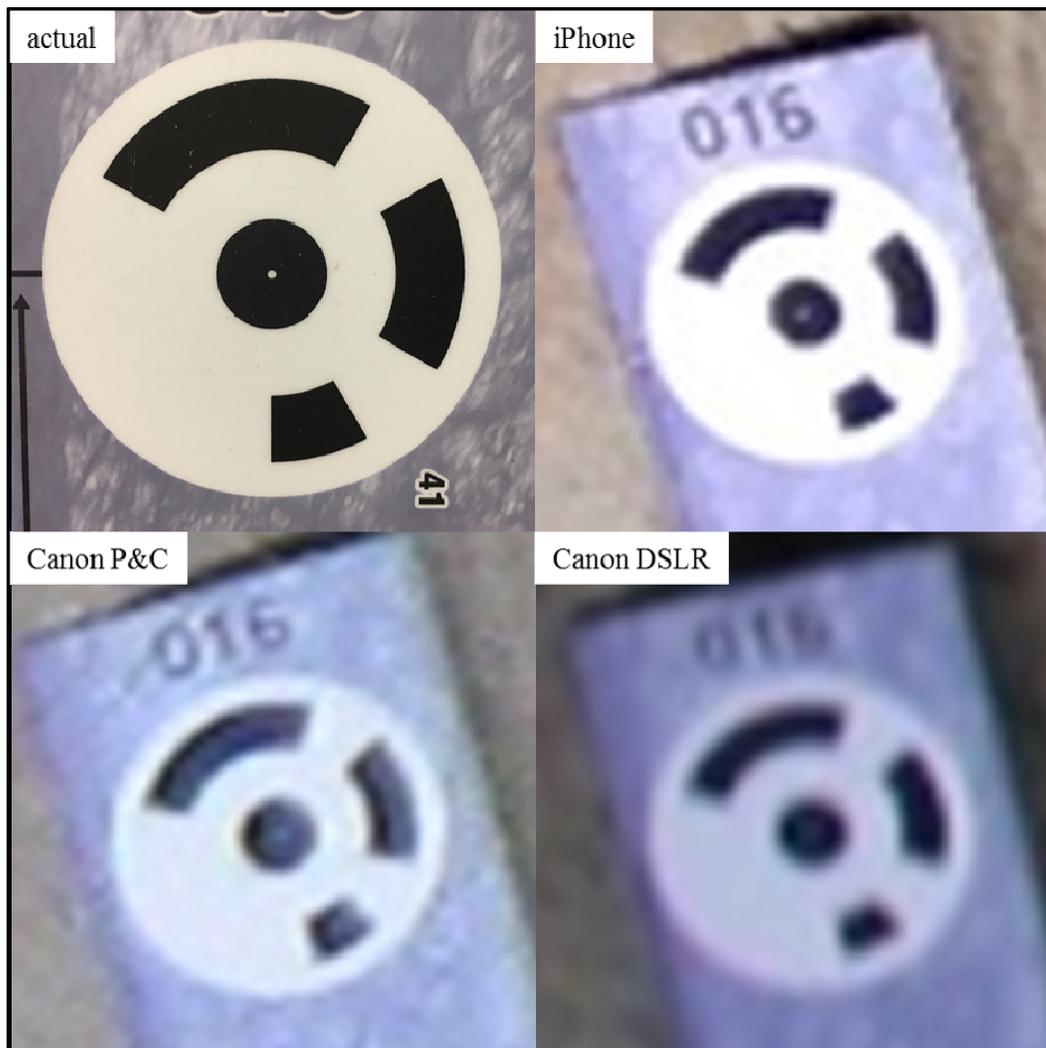

Figure 6. Illustration of differing color contrasts using various cameras at factory default settings. The "actual" photo was taken at 0.1 m, with the other three representing test photos from 4.88 m. Greater contrast allows for easier and more precise identification of measurement points. The iPhone performed best in this aspect.

5. CONCLUSIONS

In conclusion, this study sought to determine whether photogrammetric methods could be used to monitor ground convergence in underground excavations. Existing methods were considered and used to determine photogrammetric system requirements and components. Once these systems were defined, each one was put through an identical laboratory test, in which known dimensions of a mock underground tunnel served as benchmarks of system success. Based on their accuracy relative to known distances, several of these photogrammetric systems were deemed effective alternatives to current industry standards. An evaluation of system cost, weight, and ease of use in relation to performance served as the final filter.

The next steps will include expanding and refining the dataset in continued laboratory testing, as well as field experimentation. A greater range of test environments is needed, along with comparative data, to mature this method of ground convergence monitoring. Efforts are also needed in making full use of photogrammetric datasets, which can provide thousands of measurements points in the same time it takes for manual measurements to produce only two. It is hoped that these continued efforts will lead to a better understanding of how ground responds to mining and civil excavations, which in turn would improve the worker safety throughout the underground civil and mining industries.

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DISCLAIMER

The findings and conclusions in this paper are those of the author(s) and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH). Mention of any company or product does not constitute endorsement by NIOSH.

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