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Development and Laboratory Trials of the Light-Based High-Resolution Target Movement Monitor for Monitoring Convergence at Underground Mines

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Abstract: This paper describes a development and laboratory evaluation of the light-based high-resolution target movement monitor which can be used to measure convergence at underground excavations with submillimeter accuracy. The monitor is based on unique measurement technology which was developed at the University of Missouri-Rolla. This system has the potential for high accuracy detection and monitoring of positional changes (as small as 0.1 mm with the current laboratory implementation) presented by many types of targets located in close proximity to or at far distances from the monitor. The sensitivity of the system to camera resolution and the error analysis as a function of the laser incident angle are described. The system utilizes custom computer processing, a high-resolution camera, and laser light to measure the distance to a target accurately in one dimension, but it can also be used for performing two-dimensional surface profiling or analyzing three-dimensional movement of the target. The ability of this optical system to measure ground movement with submillimeter accuracy will allow for monitoring ground convergence in areas of high traffic or which are inaccessible for the installation of traditional ground movement sensing devices.

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CE Database subject headings: Ground motion; Monitoring; Lasers; Mining.

Introduction

In 2005, the fall of a roof or back was the number one cause of all fatalities at underground coal mines in the United States (US) and resulted in nine deaths. Additionally, roof beam failures or sliding of rock wedges resulted in a majority of injuries occurring in underground U.S. mines (MSHA 2005). Ground failure in underground mines not only impacts the workers' safety, but also has a direct economic impact on the mining company through the loss of equipment or valuable mineral ore. To warn mining personnel of ground failure, many mines use some type of ground movement monitoring device (Chrzanowski 1990).

Ground movement monitors are not only used as warning devices. Underground mining results in continuous stress changes in the remaining rock, which immediately translates to deformation of the underground openings. Convergence monitoring of these openings, particularly when these openings are driven through rocks with a time-dependent behavior, provides essential information to assess the overall ground stability (Brady and Brown 2004). The data obtained from these monitors not only warn mine personnel about the potential hazards of rock failures, but also allow for a better understanding of rock failure mechanisms (Kovari and Amstad 1993; Kwon and Wilson 1999; Marshall et al. 2000). Based on the gathered data from ground movement monitors, personnel can calculate the mine-induced stresses around the excavations, make recommendations about the required rock support and the geometry of future excavations, and make decisions about the mining techniques which must be used to advance the underground development safely and most economically.

This paper describes the development of the light-based high-resolution target movement monitor (HRTMM) first described in (Gray et al. 2007). The approach uses computer processing of a ditial image of a projected laser spot. The laboratory experiments show the measurement accuracy for submillimeter positional changes. The effects of camera resolution and of laser incident angle are investigated. The system is described in the context of the mining applications.

Review of Currently Available Convergence Monitors

One of the most popular group of ground movement monitors used at underground mines is convergence monitors (Chrzanowski 1990). Convergence monitors measure relative displace-

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Table 1. Common Convergence Monitors Based on (United States Army Corps of Engineers 2002)

Convergence monitor	Range (m)	Accuracy
Tape extensometer	30	0.1 mm
Invar wire strain gauge	20	0.05 mm
Vibrating wire strain gauge	1	1 microstrain
Rod, tube, and torpedo extensometers	6	0.1 mm

ment between two points located on the opposing or neighboring walls of underground excavations.

Many different types of convergence monitoring devices are used in underground mines such as those in Table 1. However, most of these devices require installation of wire or measuring tape, which is attached to two or more reference points on the opposing sides of the excavation (Iannacchione et al. 2000). Since the installation requires physical stretching of the wire or tape, such devices cannot be installed in unstable mine openings, because the safety of the people installing these meters can be compromised; these devices also cannot be used in traffic areas, since they would obstruct traveling ways (Brady and Brown 2004). All of these devices are limited to monitoring spot deformations of excavation surfaces. Optical ground movement approaches can overcome the limitations of the currently available ground convergence monitors. However, the currently available on-the-market optical distance measuring technologies either do not have the required accuracy or are too expensive to be used as ground convergence monitors (Wolf and Ghilani 2006).

Development of the Light-Based High-Resolution Target Movement Monitor

Recent research at the University of Missouri-Rolla has led to the development of an optical system, which can remotely measure positional changes in targets located at any distance with the submillimeter accuracy required for measurements of ground convergence at underground mines (Gray 2006, Gray et al. 2007). This project to develop a ground convergence monitor had three main objectives:

- The range of the system must be at least 5 m;
- The sensitivity of the sensor must allow for resolution of at least 0.1 mm; and
- The cost of the monitor must be attractive for the mining industry.

Development of the light-based HRTMM is based on these objectives. A description and preliminary results of the developed system are presented herein.

Description of the Methodology

The HRTMM system uses the Tachometric method, or triangulation method, to measure distance changes between the monitor and the object. The tachometric method of distance measurement has been used in surveying for hundreds of years, and one of the techniques using this method is the distance measurement with the Subtense Bar (Kavanagh and Bird 2000). Other commercially available triangulation-based systems can measure laser spot positions on a linear photodiode array. However, these array-based systems have a limited accuracy due to spattering of the laser spot and are awkward due to the positioning and presence of the active array on the target surface. The HRTMM does not have these deficiencies.

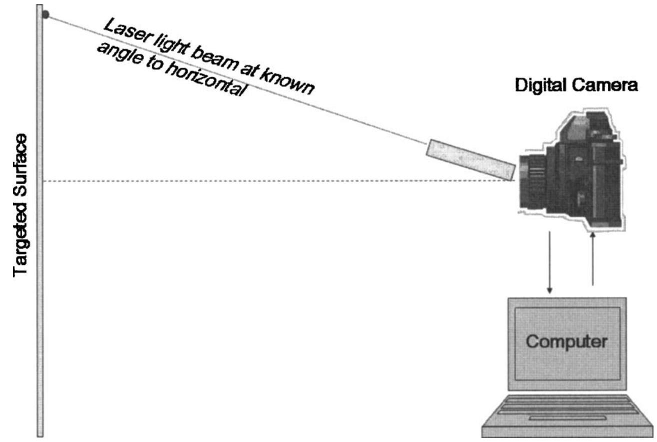

Fig. 1. Basic setup for the light-based HRTMM

In the HRTMM system, the two-dimensional position of a projected laser spot is recorded by a digital camera; the software processing finds the centroid of the laser spot, which is used as a reference point to very accurately determine the position of the laser spot. The software can measure the centroid position to subpixel accuracy and is currently set to measure the centroid position with a 0.001 pixel resolution.

The UMR system also allows for detection of multiple laser spots, which can be used for recording rotation of the monitored target plane, but it cannot detect the movement when the target moves in a perpendicular direction to the camera's optical axis. However, such movement of the target plane can be measured if the target is marked by a "reference point" such as a red dot made with a marker in a well illuminated environment or by a red LED light in a dark environment. The upgrade from single—to three-dimensional measurement capabilities of the UMR system requires only an increase in the number of lasers which can be purchased for \$10-\$50 each. The camera and software can process multiple spots.

Basic Laboratory Setup for HRTMM

The basic setup for the HRTMM system consists of one laser which is set at a fixed angle to the horizon, as shown in Fig. 1. The laser illuminates one small, bright spot on a target surface opposite the laser. The spot is then photographed by a digital camera located in a known location with respect to the laser. The digital photograph is processed with custom software to calculate the X-Y coordinates of the spot, expressed in the pixels. The $X=0$, and $Y=0$ coordinates refer to the position of the upper left corner of the captured image. Having calculated the X-Y coordinates of the light spot, the horizontal distance between the surface of the object and the camera can be calculated (Gray 2006, Gray et al. 2007). The code loads an image with a specific format, including but not limited to bitmap, jpeg, portable network graphic, etc.

The spot processing begins by identifying the light spots on the target background. A conversion from a color image to a black-and-white image is performed, and the laser spot is defined through the thresholding. (A pixel is changed to black if the pixel value is below the threshold value, or changed to white if the

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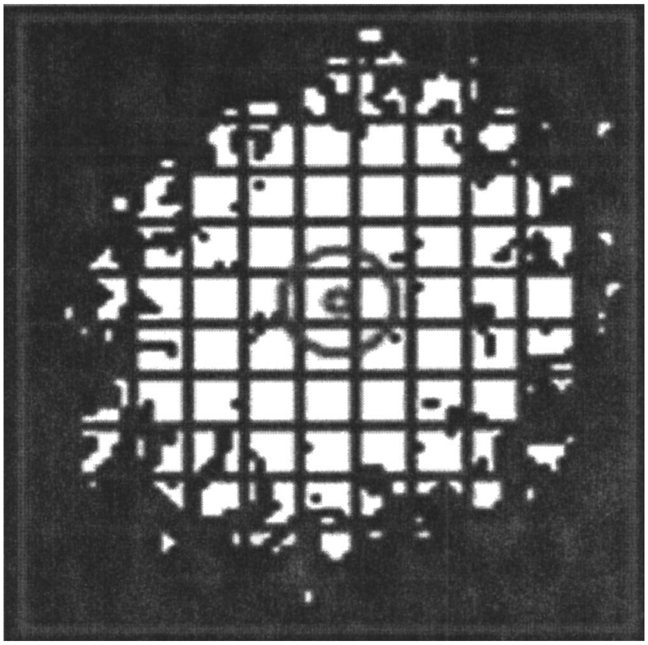

Fig. 2. Thresholded image of a laser spot showing centroid and window functioning

pixel value is above the threshold value.) Next, the laser spot is identified by an algorithm that clusters white pixels associated with a given spot and eliminates the noise pixels. The program keeps track of the relative *X* and *Y* positions of each white pixel, which are used to compute the centroid of each cluster, using the following equation:

$$X\,\text{Centroid Coordinate} = \frac{\sum X\,\text{Coordinates}}{\text{Area}} \tag{1}$$

The same formula applies for determining the *Y* centroids by summing the *Y* coordinates of the pixels in a cluster and again dividing by the area. Both the location of the centroids and the area of the white pixels are referenced by the software, and then used to calculate the distance between the monitor and the target.

The software is able to detect an arbitrary number of laser/light dots in the image as long as the processing time and power are unlimited and the dots do not overlap. A more complete description of the software is given in (Gray 2006) and (Gray et al. 2007).

Fig. 2 below shows a sample image which was taken using three lasers, thus, producing three laser dots (only one of which is shown in the figure). The black boxes represent the window function searching the image. The circle represents the location of the detected centroid. This method has the potential to yield high levels of accuracy in terms of its ability to detect distance changes between the monitor and the target.

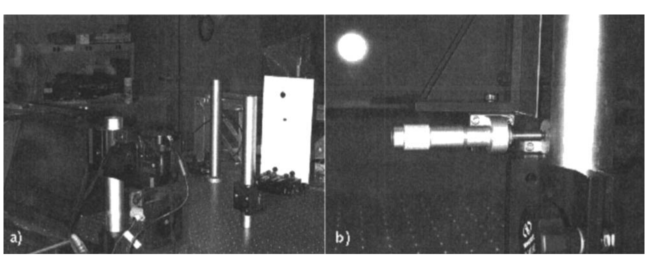

Fig. 3. Setup of the optical-based distance measuring device using single laser beam (a); micrometer used to move the white board target (b)

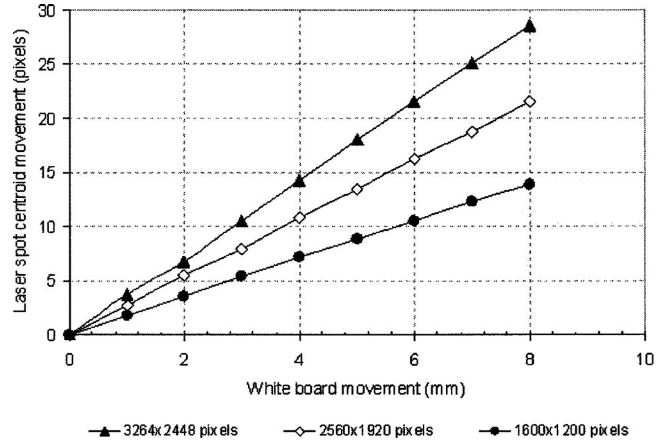

Fig. 4. Laser light centroid movement versus actual movement of white board target located 2 m from the monitor. Movement recorded using 3 camera resolution settings.

Laboratory Evaluation of the Effects of Camera Resolution

An experiment was performed using a basic setup with a single laser and an eight Megapixel camera. A triangulation technique was used, where a single laser beam was shone on a white surface at a 63.4 degree angle to the target surface normal, and the board was positioned 2 m from the digital camera [Fig. 3(a)]. Then the board was moved away from the camera in 1 mm increments using a manual micrometer [Fig. 3(b)].

Each of the positions of the white board was photographed using 8, 5, and 2 Megapixel resolution camera settings. The results of this experiment are presented in Fig. 4, and they illustrate almost perfect linearity between the target movement and centroid movement of laser spots. The results also showed no visible decrease in the quality of the data when the laser light spot was photographed with the lower camera resolution settings. This finding is very important, since it illustrates that the HRTMM system can use inexpensive low-resolution cameras without compromising the data quality.

The linearity of the results was verified by calculating the correlation coefficient, *r*, which had an average value of 0.9999 and coefficient of determination, R^2, with an average value of 0.9998 for this test (Table 2). The correlation coefficient is a number between −1 and 1 that shows the degree to which two variables are linearly related. A perfect linear relationship with positive

Table 2. Results of Linearity Verification for Data Illustrated in Fig. 4

Resolution (pixels)	Distance (m)	Laser angle to target normal (degrees)	Coefficient of determination	Correlation coefficient
3,264 × 2,448	2	63.4	0.9997	0.9998
2,560 × 1,920	2	63.4	0.9998	0.9999
1,600 × 1,200	2	63.4	0.9998	0.9999
		Average	0.9998	0.9999

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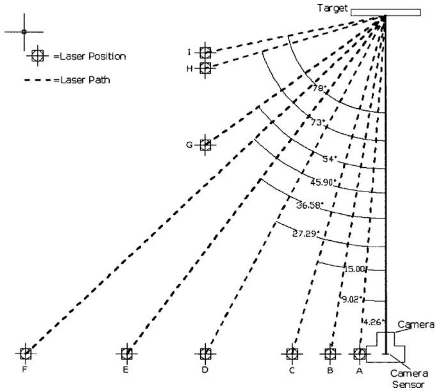

Position ID	Incident Angle	r value
A	4.26	0.994
B	9.02	0.997
C	15.00	0.999
D	27.29	1.000
E	36.58	1.000
F	45.90	1.000
G	53.50	1.000
H	73.25	0.998
I	78.00	0.993

Position ID	Incident Angle	R^2 value
A	4.26	0.988
B	9.02	0.994
C	15.00	0.998
D	27.29	1.000
E	36.58	1.000
F	45.90	1.000
G	53.50	1.000
H	73.25	0.995
I	78.00	0.987

Fig. 5. Laser incident angle positions relative to camera and target and their associated angles and errors

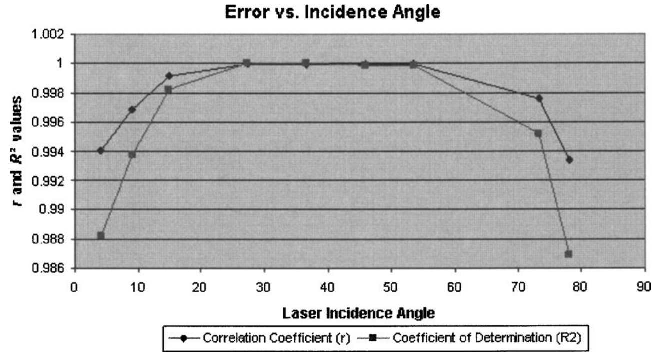

Fig. 6. Relative error due to the change in laser incidence angle

slope will give a coefficient of 1. A perfect linear relationship with a negative slope will give a coefficient of −1, and a correlation coefficient of 0 means that there is no linear relationship between the variables. The coefficient of determination measures the proportion of variability in a sample of paired data. It is a number between zero and one. A value close to one suggests a good model (Johnson and Bhattacharyya 1992).

HRTMM Response to Laser Incident Angle

The incident angle of the laser upon the target is known to significantly affect the resolution of this monitor. Prior work has shown that the resolution of the monitor increases as the laser incident angle becomes larger (less normal to the target) (Gray et al. 2007). However, at larger incident angles the spot is significantly changed. Previous work lacked a full error analysis of this variable to determine the optimum range of angles.

In order to determine the monitor error associated with the incident angle of the laser, an evaluation was carried out. In this test, the camera was placed perpendicular to and 1,008 mm from the target surface. The laser was placed on the same horizontal plane as the target and the camera, and all three components were mounted on a Newport optical vibration-isolation table with breadboard. The position of the incident laser was adjusted to have a wide range of incident angles ranging from 4.25°–78° (Fig. 5). Low-angle measurements were made by measuring the distance from the center of the camera sensor to the laser diode and calculating the angle. High-angle measurements (angles $>46°$) were measured by reading the dial on a rotational stage with a resolution of 1°. The laser was mounted on this rotational stage. The change in laser positions between the high and low angle measurements was necessitated by the insufficient width of the optical table and can be seen in Fig. 5.

For each individual incident angle, the target was cycled through 8.00 mm of total movement using a micrometer stage. Centroid movement data were collected once every 1.00 mm allowing for nine data points from each cycle. The cycle was repeated 10 times for each incident angle. The data were downloaded to a computer and processed by the HRTMM software.

Regression analysis was completed on the data and the r and R^2 values were determined for each incidence angle. It was found that the quality of the data is excellent in the midrange of incident angles and decreases on both the high and low ends (Fig. 6). The decreases on either end of the angle range can be explained. It is important to note that across the entire range of angles, the errors introduced due to the laser speckle and target texture are the same.

On the low end of the range, increases in distance to the target result in very insignificant movements of the centroid due to the shallow incident angle. In this instance, the amount of error due to laser speckle and target texture is very large relative to the actual change in centroid position, causing lower r and R^2 values to be seen. It is unlikely that lasers positioned at these low incident angles would provide useful results from the monitor as the monitor resolution is also lower.

On the high end of the angle range, the incident laser light strikes the target at such a high incident angle that the spot is attenuated and distorted significantly. The overall area of the laser spot, as sensed by the monitor, is increased. Consequently, the average intensity of the laser light over this larger area is reduced and the spot is highly elliptical. The processing is less effective for these extreme incident angles than for lower angles. To keep the error below about 0.5%, the laser incident angles should be between approximately 25 and 55 degrees.

Conclusion

The development and laboratory evaluation of the HRTMM system are described. The experiments showed that the system can detect the submillimeter movement of the whiteboard target even with low-resolution cameras. The best performance with regard to laser incidence angle was between 25 and 55 degrees. The system accuracy should allow for monitoring of the ground movement in underground excavations with high traffic or which are inaccessible for installation of traditional ground movement devices, as well as in areas where conventional convergence monitors are used. The presented test results are very promising, however, it should be pointed out that these experiments were conducted under ideal laboratory conditions, and the system evaluation was based on a limited number of experiments.

To implement this monitor as a widespread technology, further evaluation is necessary both in the laboratory and in the field. Evaluation and development of new procedures and methods for taking and recording measurements are also necessary in order to fully understand and utilize this monitor's capabilities. The authors of this paper plan to conduct further laboratory tests, which will evaluate the capabilities of the monitor in conditions simulating the environment at underground mines, testing in particular the effects of dust and humidity on the accuracy of the system. The instrument is currently scheduled to be field tested at the

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UMR experimental mine and at underground lead mines located in Southern Missouri, which are owned by the Doe Run Company.

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