EVALUATING TECHNIQUES FOR MONITORING ROCK FALLS AND SLOPE STABILITY

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ABSTRACT

While less than 1% of reported accidents are associated with slope stability problems, slope failures were responsible for about 15% of all U.S. surface mine fatalities between 1995 and 2001. Small rockfalls, which may involve hand-sized rocks weighing only a few kilograms, can cause fatal injuries to workers away from the protection of large machinery. Massive highwall failures containing a million cubic meters of material or more can be fatal even for heavy equipment operators. As part of an ongoing study at the Spokane Research Laboratory of the National Institute for Occupational Safety and Health, several remote-sensing technologies are being evaluated as tools to monitor slopes for hazards and to assess slope stability. Field tests of a hyperspectral imager were conducted to assess its value for improving geologic maps of potentially unstable alteration zones on mine slopes. An interferometric radar device capable of detecting very small displacements on slopes awaits final assembly and field testing. Computerized monitoring methods using images from digital and video cameras are being assessed for application to mine slope surveillance. These and other techniques will eventually provide new tools to augment current methods for monitoring ground control hazards in mines.

INTRODUCTION

The mission of the Spokane Research Laboratory, National Institute for Occupational Safety and Health, is mine safety and health research. A current project involves enhanced recognition of slope stability hazards at surface mines. Since 1995, 34 miners have died in slope failure accidents at surface mines in the United States. Shovel operators and drillers suffered the greatest numbers of fatalities. Fatal slope failures range from small, hand-sized rocks weighing only a few kilograms to massive highwall failures containing a million cubic meters or more of material. Small rockfalls generally cause fatal injuries to workers on foot who are away from the protection of large machinery. Large rockfalls are responsible for fatal injuries to virtually anyone who ventures under or on top of unstable slopes, including the operators of large equipment.

A principal objective of the project is to improve the means for detecting conditions in open-pit mines that could lead to catastrophic slope failure. Three types of remote sensing technology—hyperspectral imaging, interferometric radar, and photographic image analysis—are being developed as tools to help recognize potential hazards at mine sites. These technologies have been developed mainly for airborne or satellite instruments, but their spatial resolutions are not normally sufficient to be very useful in addressing local ground control problems in surface mines. Adaptation and simplification of these technologies for use with ground-based platforms could provide a cost-effective means to reduce injuries from the catastrophic failure of mine slopes.

HYPERSPECTRAL IMAGING

Every material on or off the Earth's surface reflects light in a characteristic pattern; the manner in which light of different wavelengths is reflected or absorbed from each material is known as its reflectance spectrum. By filtering reflected light to specific wavelengths (colors in the visible part of the spectrum), images can be created that enhance our ability to differentiate materials. Multispectral imaging makes use of a few broad wavelength bands in the electromagnetic spectrum, primarily visible and infrared. Hyperspectral imaging refers to obtaining reflectance spectra for the region being imaged over a large number of discrete, contiguous spectral bands. A contributing factor in many highwall failures is the presence and distribution of mechanically incompetent, clay-rich altered rock in pit walls. Most alteration minerals have characteristic absorption features that can be recognized with hyperspectral imaging and thus can be used to help identify these weakened, altered rocks. Hyperspectral imaging has been shown to provide objective information for mineral identification and to help in the inherently subjective process of geologic mapping.

Field instruments are commercially available that can analyze light reflected from a single point within a scene, but an imaging system can record spectral reflectance data for an entire scene, adding a spatial dimension to the data. High-resolution spectral imagery can assist in remotely compiling objective geologic maps of mine highwalls and other hazardous slopes (*1*). A ground-based spectral imager could provide—

- An alternative to high-cost, logistically complex airborne and satellite spectral imagery,
- More capability than nonimaging (point by point)

spectrometers currently being used to augment mapping, and
- Flexibility in timely acquisition of images at various scales and view angles.

The output of a hyperspectral imager is a stack of images over a spectral range, referred to as an image cube, where the image is in two spatial dimensions plus a third, or spectral, dimension identified by its wavelength (figure 1). A radiant energy value is recorded for each data point (pixel) in the image for every wavelength sampled so that a spectrum is collected for each pixel in the image.

Spectro-Polarimetric Imager

Field trials were conducted of a prototype ground-based spectral imager developed by Denes at Carnegie Mellon Research Institute (*2*). The instrument collects spectral images at visible and near-infrared wavelengths to generate a data cube that can be processed by standard hyperspectral techniques. An acousto-optical tunable filter (AOTF) produces a diffracted beam at the specified wavelength that is passed to a monochrome charge-coupled device (CCD) camera. An external host computer controls the filter and collects an image at each selected wavelength through a frame-grabber board (*3*). A liquid-crystal, variable-phase retarder provides optional polarimetric control for the imaging system.

Software in the host computer sets the spectral range, spectral bandwidth, and polarization parameters for data collection. The controller can switch at 30 microseconds per spectral band over wavelengths of 450 to 1000 nm, normally at 10-nm intervals. In sweep mode, the AOTF sequences through the full spectral range of the instrument, collecting the maximum amount of information in a scene. In switching mode, the instrument alternates between a small number of parameter settings for quick collection of specific bands for the sampled scene. The switching mode can be programmed to obtain band ratio images in real time.

Data Collection and Preprocessing

A test site at a surface mine in California was selected because the diagnostic spectral features of its rare-earth mineral assemblage are in the spectral range of the present instrument. Twelve hyperspectral images were collected, including pit highwalls, outcrops, drill core from the ore zone, and hand samples. Example images are shown in figure 2. Additional images of hand specimens under artificial light were collected in the laboratory. These images were used as an aid in calibrating and evaluating the instrument. Thin sections were made of both ore and host rocks to assist in interpreting spectral images.

The mineral deposits occur as carbonatite veins associated with potassium-rich igneous rocks that intruded a block of Precambrian metamorphic rocks. The carbonatites, apparently of magmatic origin, consist mainly of calcite, dolomite, ankerite, and siderite. Bastnaesite, a fluorocarbonate of lanthanide series metals and the principal rare-earth-bearing mineral present, constitutes 5% to 15% of much of the ore body and locally exceeds 60% (*4*). Rare-earth elements of the lanthanide series (cerium, lanthanum, neodymium, europium, and others) produced at the mine have been used in petroleum- and pollution-control catalysts, specialty glasses and magnets, and television and computer monitor phosphors. Diagnostic spectral characteristics of the rare-earth assemblage correspond to published spectra of neodymium oxide, with at least eight distinctive absorption features between 450 and 1000 nm. Spectral reflectance data for the deposit were published by Rowan and others (*5*).

The data consist of 47 bands from 480 to 940 nm in 10-nm intervals each collected at four polarizations. Data preprocessing and most of the subsequent analysis was done using basic procedures from ENVI software (Research Systems, Inc., Boulder, CO).[1] For each scene, original raw data comprising 190 bitmap files were compiled into data cubes. Original data sets consisted of 640- by 480-pixel images. Each analyzed scene contained a white card and a black card that were used to correct for path radiance and to normalize the data to relative reflectance.

For this study, reflectance spectra of rare-earth ore from the same site were measured to evaluate the images. The spectra were collected with a full-range spectroradiometer (Analytical Spectral Devices, Inc.) at 1-nm resolution and resampled to 10-nm resolution. These profiles had very good agreement with published spectra and U.S. Geological Survey library profiles for neodymium oxide (*6*). The most diagnostic absorption features occur at approximately 740, 800, and 870 nm.

Data were compiled into image cubes, and basic analysis was done for each of the scenes. A sampling of single pixels from the resulting data cube showed numerous spectral profiles that are related to the expected rare-earth mineral assemblage. Spectra in figure 3 show a range of correlation with the spectra measured from bastnaesite ore with the spectroradiometer. Some of the profiles match nearly all the characteristic absorption features for the ore, and several show the asymmetry at the 790- to 800-nm feature. An artifact in the images is a set of near-vertical to diagonal light and dark stripes apparently resulting from radio frequency (RF) noise at the AOTF boundary.

Image Analysis

A first classification of the normalized images was based on two endmembers defined as regions of interest for the ore zone (lower portion) and host rocks (upper portion) within the image. The result was quite reasonable, leaving about 20% of the image unclassified. A cross-track illumination correction was applied to the original images to reduce the effect of RF striping and an apparent x-axis gradient in the original images. The corrected images yielded an improved classification, including larger areas of ore endmember correlation in the left side of the image (figure 4).

Several other classification methods and settings, including noise reduction transformations and predetermined matched filtering analyses, showed no particular improvement. A pure pixel analysis using endmember spectra from the image resulted in classification of only very small areas within the scene.

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[1] Mention of specific products and manufacturers does not imply endorsement by the National Institute for Occupational Safety and Health.

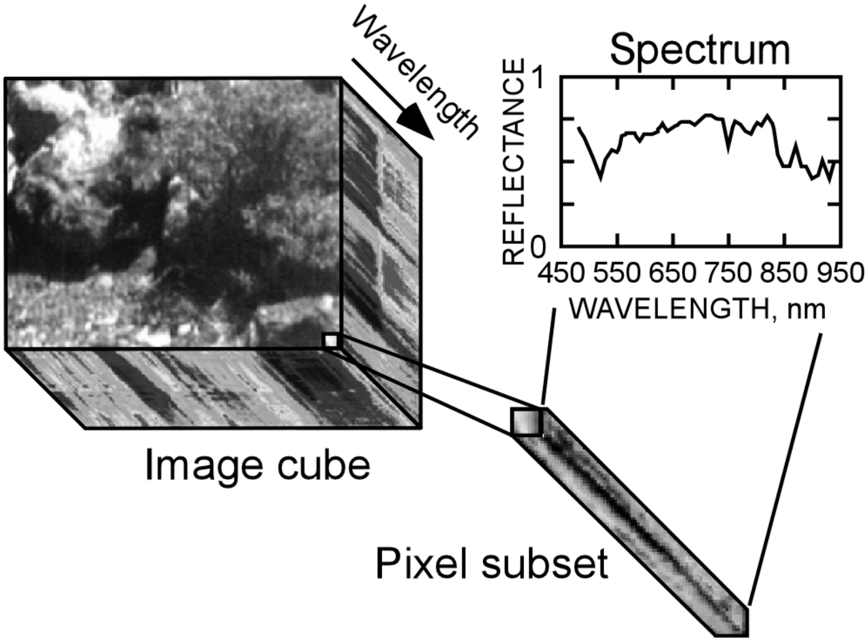

Figure 1.—Hyperspectral image cube showing relation to spectra; top image is a false-color composite of rocks and vegetation.

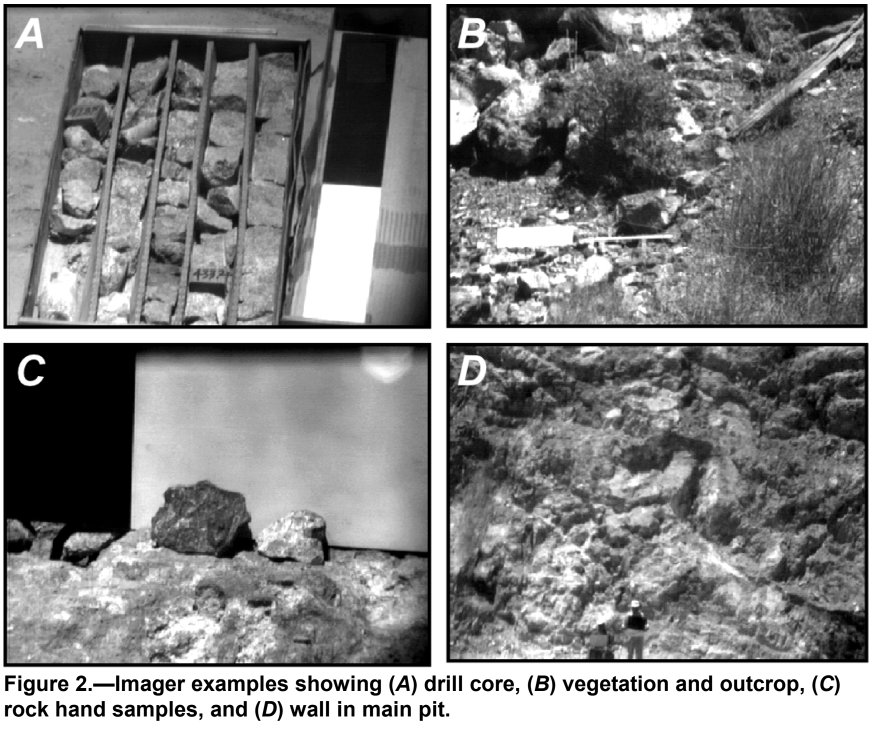

Figure 2.—Imager examples showing (*A*) drill core, (*B*) vegetation and outcrop, (*C*) rock hand samples, and (*D*) wall in main pit.

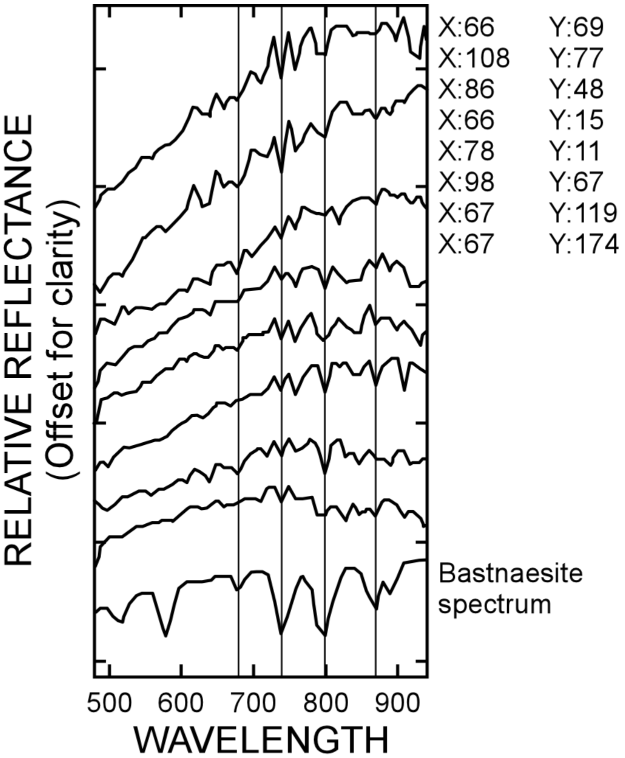

Figure 3.—Sampling of spectra from main pit west wall that correlate with bastnaesite.

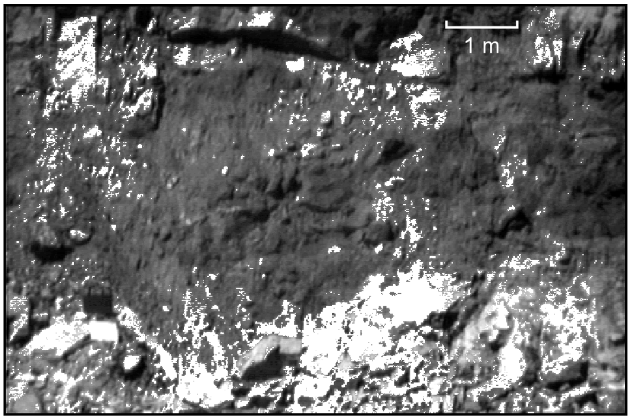

Figure 4.—Classification of pit wall image using spectra derived from image and cross-track illumination correction; white areas are classified as ore.

Basic analysis was also done on hyperspectral images collected under artificial illumination in the laboratory. The results show that the method can be used to characterize scenes at different scales where pixel dimension is controlled by magnification and distance to the object. The images in figure 5 show mineral samples from a distance of about 3 m. An averaged spectrum from the elliptical "region of interest" highlighted on the small specimen of nearly pure bastnaesite on the left of each image was used to classify the scene using the matched filtering routine. Bastnaesite in both the mineral specimen and the mixed ore sample on the right are highlighted.

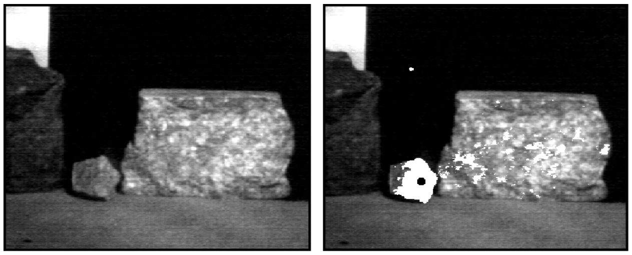

Figure 5.—Classification of rock sample in the laboratory; spectra from a region of bastnaesite mineral specimen (black spot) were used to classify scene. Bastnaesite is shown as white areas in both mineral specimen and mixed ore sample.

The field tests clearly illustrated the capabilities of the method for collecting hyperspectral images and discriminating materials, validating the concept of remotely characterizing the mineral composition of mine slopes. However, the spectral range of the instrument tested limits its application in identifying geologic materials. In addition, the signal-to-noise ratio in the data limited detailed classification of the images. Ground truthing and feature extraction based on image-derived spectra were essential for reliable mapping of geologic samples and scenes.

A spectral imager in the 1.0 to 2.5 micrometer part of the infrared spectrum, where spectral features for clays and other minerals are more distinctive, would be more useful for mapping clay-altered rocks. Such an imager would assist in creating objective geologic maps of mine highwalls and other hazardous slopes from a safe position as well as help define faults, shear zones, and fracture systems in mine slopes and characterize drill core, rock chips, and hand samples in the field and in the laboratory. Thermal infrared imaging offers some promise of helping to distinguish geologic structures in mine walls. Differential cooling that results from water saturation levels and flows in wall rocks could be mapped to reveal geologic faults, contacts, and altered zones. Research will be conducted in this area with ground-based instruments.

INTERFEROMETRIC RADAR

The Spokane Research Laboratory has supported development of a ground-based radar at Brigham Young University (BYU). The technology stems from research efforts by Long at BYU to build a relatively low-cost interferometric synthetic aperture radar (InSAR) that can be deployed in light aircraft and operated at low altitudes. Project funding facilitated field tests of a ground-based version of the radar system to detect and measure displacement on mine slopes. Displacement measurements will be used to track mass movement of failing slopes in surface mines and possibly to warn of imminent catastrophic collapse.

Synthetic aperture radar (SAR) uses electronic techniques to create a very long virtual antenna by processing pulsed signals from a real antenna as it moves past a target area. Because the width of the radar beam is inversely proportional to the length of the transmitting antenna, this long virtual antenna allows high-resolution imagery. SAR systems in airborne or earth orbit platforms have

Figure 6.—InSAR image of urban Logan, UT, area.

been used to generate high-quality digital elevation maps of the earth's surface. InSAR techniques compare images collected at different times but at nearly the same viewing angle to map displacements in the time-lapse SAR images. The technique has been used to map ground displacement, at resolutions measured in millimeters caused by natural hazards such as earthquakes, volcanic activity, and landslides (*7-8)*, and subsidence caused by the extraction of ground water, oil and gas, or minerals (*9-11*). These pioneering studies have generated enormous interest in the earth science community because they point to an entirely new way to study the surface of the earth. SAR data from the Earth Resource Satellite-1 (ERS-1) have recently been used to measure ice stream velocity in Antarctica, co-seismic displacement associated with the Landers and other earthquakes in California, and volcanic deformation on Mt. Etna that may be preparatory to a major eruption. This is the first time that the velocity or displacement fields associated with these phenomena have been captured with virtually complete spatial coverage.

The compact InSAR developed at BYU's Center for Remote Sensing is intended to make imaging radar inexpensive enough for small-scale mapping projects (figure 6). The system was funded in part by a NASA grant (*12*) and has been used recently in collaboration with the U.S. Geological Survey to periodically collect images of a landslide area in Colorado.

Prism-based survey networks, extensometers, and other standard instruments sample movement only at discrete points on a slope. These instruments are effective in very accurately recording both the direction and magnitude of displacements, but sample points need to be strategically placed where motion will occur. Displacements between sample points may be underestimated or missed altogether. One answer to this undersampling problem when covering large areas is a new generation of scanning laser instruments that can generate three-dimensional models of mine slopes without reflector prisms. Laser scanners have been used successfully in large surface mines, but their range and accuracy can be impaired by differences in the reflectivity of the rock, the angle of the rock face, weather, or dust. Manufacturers of prismless range finders generally claim a range of 500 m or less. Radar can cover large surface areas for true two-dimensional monitoring. In addition, radar is able to function day and night in almost any weather condition, and atmospheric dust or haze have little effect. Radar's active transmit/receive mode of operation provides an advantage over passive optical methods that depend on solar or other illumination.

A slope monitoring radar capable of detecting hazards needs a much shorter repeat time and better ground resolution than airborne and satellite systems can provide. Ground-based interferometric radar systems have been designed to monitor displacement of unstable slopes: a two-dimensional scanning system was proposed to monitor slopes above highwall coal mine operations in Australia (*13*); a ground-based system has been integrated with other devices in a landslide monitoring network in France and has been used for temporary monitoring of active volcanoes (*14*).

Natural Hazards Radar System

BYU's Center for Remote Sensing developed a stationary ground-based natural hazards radar system capable of detecting and measuring slope movements. Assistance by NIOSH led to a variation of the system for use in monitoring mine slopes (*15*). Although radar technology has been widely used for the last 50 years, only in the last 10 years have advancing computer capabilities provided the low-cost processing power needed for interferometric computation. The widespread adoption of modern wireless communications devices has resulted in practical integrated circuits for microwave frequencies that can be used in task-specific radar applications. The BYU instrument evolved from one designed for the Canadian National Railroad to test the application of interferometric radar to the detection of rock falls and washouts along rail corridors (*16*).

The system consists of a radar transmitter, two receivers, three antennas, and a computer controller (figure 7). The transmitter produces a 10-GHz pulse with a 300-MHz linear-frequency-modulation (LFM) waveform. In an LFM or "chirp" waveform, frequency is increased linearly over the duration of the pulse. The frequency difference between the transmitted pulse and the returning echo captured at the receiving antennas is proportional to the distance traveled to the target. These difference frequencies can be divided into range cells with a resolution of 2 to 3 m at a range of 300 to 400 m. Interferometry is employed to refine this distance measurement by using two identical receive antennas a short distance apart. By comparing the phase difference in the received signal at each antenna, precision of the measurement in each range cell is narrowed to a fraction of the signal wavelength (about 3 cm at 10 GHz). With a 7° beam-width transmitting antenna, the system has a 12-m footprint at a range of 100 m.

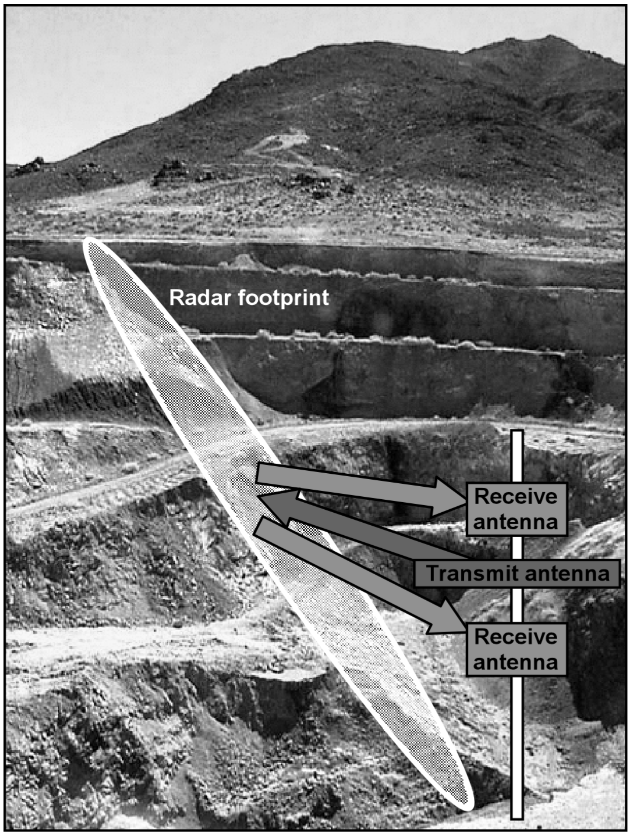

Figure 7.—Stationary array, displacement detection radar

Field Tests

Initial tests of a prototype interferometric instrument showed that the technology is workable at relatively low cost. One technical obstacle was to generate a sufficiently stable and linear LFM signal. A new instrument will include a fully coherent oscillator and an improved chirp transmitter to maximize long-term stability. In a second approach, the airborne SAR system was modified to function as a fixed differential phase monitor for experiments in detecting mine slope displacements. Outdoor tests are being conducted with this instrument, and slope monitoring experiments at a suitable mine site are planned for spring of 2002.

PHOTOGRAPHIC IMAGE ANALYSIS

Digital camera and computer technologies provide tools to derive far more information from images than was possible just a few years ago. Small differences between pairs of images can be readily detected, changes can be quantified in pixel counts or area percentages, and images are time stamped for easy sequencing and animation. These capabilities can be used to enhance mine slope monitoring. McVey and others (*17*) used a 35-mm camera and carefully positioned reflectors to measure deformation over time in an underground mine. Processed film was used to measure deflections to a resolution of 0.5 mm, but the use of reflectors adds substantial complexity to the installation process and limits analysis to sites with reflectors. Corthésy and others (*18*) described a differencing technique using before and after digital images to detect rock displacements in an underground mine. The results were similar to those described here except that the use of artificial illumination in the underground environment may simplify noise filtering.

Photographic change detection can be used in a time lapse mode to record such things as bench loading, fracture development, creep and mass movements, and fallen rock sources. A real-time slope monitoring system using low-cost video cameras can be used to generate rock fall warnings where workers could be at risk.

Photographic Change Detection

High-resolution digital images collected at regular intervals or before and after events can be sequenced and compared to determine total displacement and rates of change. The human eye is highly adapted to detect movement, allowing change between images to be readily seen simply by flipping from one to the other. Sequences of images can be viewed as animations that depict scene changes from beginning to end. Computer analysis can begin with one of several relatively inexpensive image-processing software packages (e.g., Adobe Photoshop, JASC Paintshop) that provide layering or mathematical operators for image manipulation. In a subtraction or differencing operation between two nearly identical images, intensity values for corresponding pixels from each image are subtracted, resulting in a low value (dark) if the pixels are the same in the two images. For any pixels that have different intensity values between the two images, i.e., if there is a change, the result will be bright.

A change-detection experiment demonstrated one method of using photographic techniques to identify and characterize rock falls on mine slopes. A rock fall event was set up by positioning rocks at the top of a highwall. As the rock fall was triggered, a sequence of images was collected using a digital camera in time-lapse mode. The first image in figure 8 shows the rocks at the top of the highwall, the second image shows the rocks falling, and the third shows the difference image with a threshold adjusted to enhance changes. Movement of vegetation in the wind caused the noise at the top of the difference image.

The digital camera used to collect these images will capture an image in standard time-lapse mode at intervals as short as 1 min. This repeat time is too slow to record details of rock falls. Capture rates as fast as 2 sec/frame are possible, but built-in processing time for each image before another can be collected may result in events being missed. This method is best suited to long-term monitoring where images might be collected once a day or less often.

Photographic change detection requires that image sequences be nearly exact in position and view in order to reveal changes. The most reliable technique is to secure the camera in position and move it only after all images have been collected. However, software is available that can process images that were collected from slightly different camera positions (*19-21)*. The process involves spatially adjusting one image to match scale, rotation, and parallax differences of a second image. Fiducial or ground control points in the two images are inserted to control the registration process (figure 9). The adjusted image can then be compared visually or with a commercial photo editor.

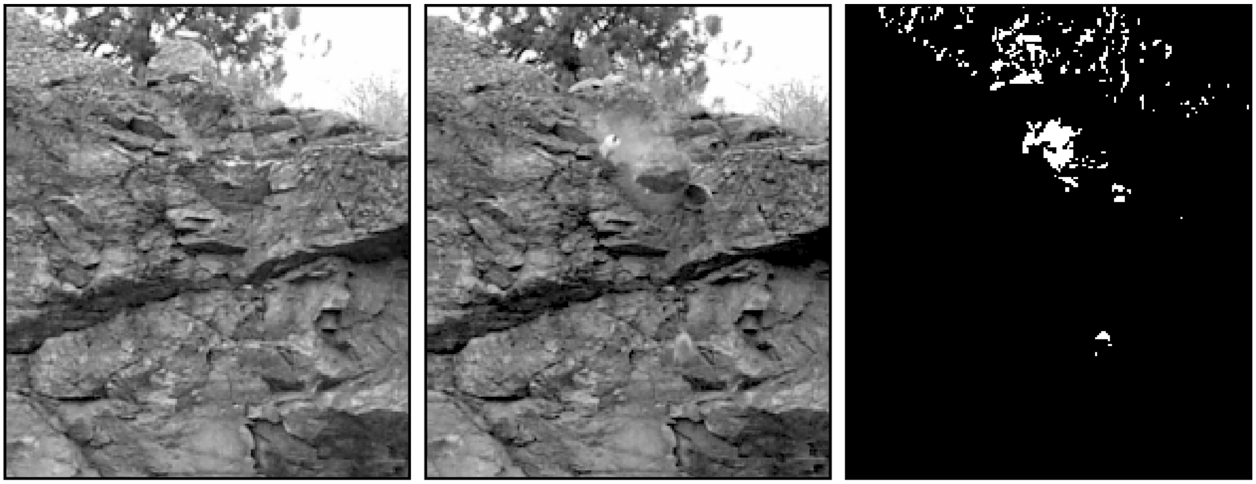

Figure 8.—In a rockfall experiment, rocks positioned at the top of a highwall are shown in the left image, the rocks falling are shown in the middle image, and the difference image with a threshold adjusted to enhance changes is shown on the right.

It is clear that the digital camera will work quite well for time-lapse monitoring of slopes, but video cameras will likely be a better choice for warning of slope movements in hazard zones.

Real-Time Monitoring

Real-time monitoring of a mine slope to avoid injuries from falling rocks requires a very fast response time, so that a worker at risk is given enough time to get out of the way or find cover. Surveillance devices are available that can monitor a specified area and detect motion in a video image. These devices were developed in the security industry and are designed to signal an alarm when motion is detected and record images of the scene as long as motion is taking place. This technology is being tested for application to mine slope monitoring.

A basic surveillance system built around hardware and software from Strategic Vista, Inc., Markam, ON, was tested in the laboratory and in limited field trials. The system includes a color 1/3-inch (0.85-mm) CCD video camera with 480 lines of resolution, automatic iris, and a power zoom lens. The camera is connected by means of an external frame grabber to the USB port on a laptop computer. The computer, with a Windows 98 operating system, runs programs that display real-time and recorded video images.

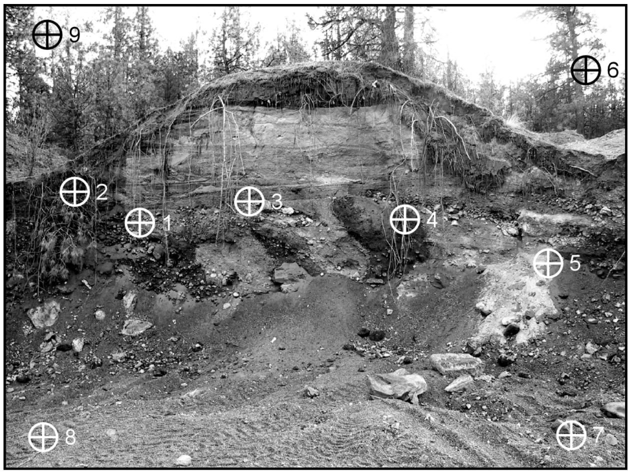

Figure 9.—Fiducial points used for spatial registration of image pairs

The system can be set to record video frames and sound an audio alarm when motion is detected. Detection is accomplished by algorithms that monitor the intensity value of each pixel in the scene. When sufficient change is detected, video frames containing the motion are recorded to the computer hard drive and the alarm is activated. Sensitivity of the trigger is adjustable from 0% to 100% of the view area. Captured images are 320 by 240 pixels. A region can be selected within the field of view where motion will trigger the record and alarm functions; this allows motion to occur in other parts of the view without triggering unwanted alarms. This system can also be configured to view the scene remotely through an Internet connection and to dial a designated telephone number.

Laboratory tests showed that motion is readily detected and recorded. During a continuous test over a 40-hour period, more than 100 individual events triggered the system, capturing a total of 15.6 min of video at about four frames/sec. Individual events ranged from less than 1 sec to more than 3 min in duration. The resulting files totaled 26.7 Mb of hard drive memory. Other tests showed that very slow motion within the detection area would not trigger the alarm and that when detected motion stopped, the alarm would cease even though elements within the scene had changed from the original image.

Field tests in a local gravel pit showed that rock fall events could be captured by the system (figure 10). The system was set up to monitor highwalls between10 and 17 m high at ranges of 30 to 80 m. Rocks at least 15 cm were dropped from the top of the slopes to generate minor rock falls. The dropped rocks and rock falls were sufficient to trigger the detection system, sounding an audio alarm and recording images of the rock fall. In one 13-min interval of continuous monitoring, seven motion events were detected, including each of three induced rock falls. The rock fall events

Figure 10.—Spokane Rock Products pit and video change-detection camera

lasted from 3.1 to 4.0 sec. Event times and durations are shown in figure 11.

In addition to warning workers in the vicinity of hazardous rock slopes, recorded video images will allow safety investigators to reconstruct a rock fall and help identify areas of unstable ground. One big advantage of motion-triggered video monitoring is that only short intervals of recorded images need to be reviewed in the process. One problem with the current setup is that the laptop's LCD screen is difficult to use in bright outdoor light. The cameras need to be suitable for use in bright to dim lighting conditions and in adverse weather.

CONCLUSIONS

A portable ground-based hyperspectral imager in the 1- to 2.5-micrometer range could provide objective information to assist in the inherently subjective process of geologic identification and mapping. It would be a higher-resolution alternative to expensive airborne and satellite imagery. Such an instrument would have more capability than the nonimaging (point by point) spectrometers currently used to augment mapping. However, a practical field instrument is not available. Optical components in the required wavelengths are costly, and development awaits adequate funding.

Ground-based interferometric radar has the potential of measuring displacements over large areas of mine highwalls at unprecedented resolution. The technology has been deployed at some locations. Development will continue, and practical systems are likely to be expensive but available in the near future.

Digital and video cameras have already proven valuable for recording mine slope conditions. Computer tools using time-lapse and motion sensing methods can provide means to document slope failures and warn workers of rock falls. Basic development work will look to streamline the framing, capturing, and processing of digital images.

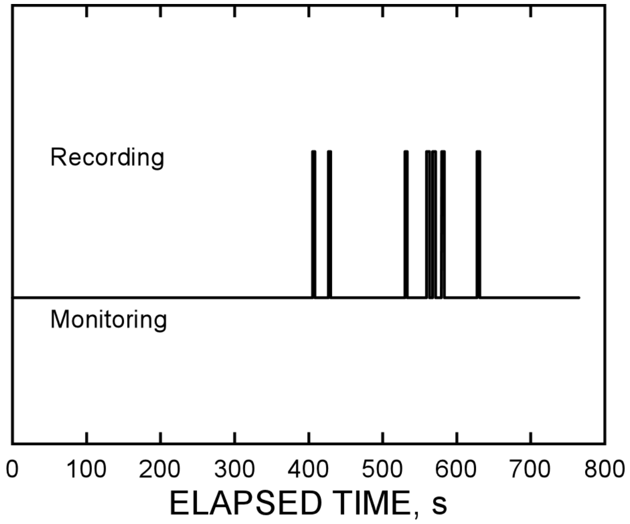

Figure 11.—During this 13-min interval, about 25 sec of video was recorded for seven motion events that included three rock falls, each lasting less than 4 sec.

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