TECHNOLOGY FOR THE EARLY DETECTION AND WARNING OF IMPENDING UNDERGROUND MINE ROOF FALL

FINAL PROGRESS REPORT

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CONFIDENTIAL MATERIAL: Beginning of confidential material is marked on page 9.
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List of Terms and Abbreviations

AE	Acoustic Emission
ASIC	Application Specific Integrated Circuit
DEP	Department of Environmental Protection
HIT	An AE pressure wave detected by a sensor
MSHA	Mine Safety and Health Agency
NIOSH	National Institute of Occupational Health
RIB	Side-wall
RMSS	Roof Monitoring Safety System

ABSTRACT

This project addresses safety of miners in underground mines. Roof and rib falls are the primary cause of deaths and injuries in underground mines. An inexpensive module was developed that monitors continuously the state of integrity of these infrastructures. When a roof or rib structure weakens to a critical point beyond which it is certain to collapse unless intervention is exercised, the module sets off an alarm in time to alert the maintenance crew to take proactive action to prevent structure collapse. The crew provides temporary roof support followed by re-enforcement of the structure.

To implement the technology, modules are attached to existing roof and rib bolt plates or straps. Typically the sensors are set eight feet apart in a two-dimensional grid network across the roof and ribs. (In present ground support practice, roof bolts are routinely installed four or three feet apart in mine roofs as mine sections are being developed for mining.) Module attachment does not interfere in any way with coal production. When a structure has weakened to a critical level, the effected modules communicate an alarm through a wireless mesh network to the mining maintenance office displaying the weakened structure location on a video monitor in time for the maintenance crew to take proactive action to prevent roof or rib fall.

To develop the technology, Alertek had access to a University structure-testing laboratory. The technology was then tested successfully in active coalmines under induced roof collapse conditions. To implement the technology into a commercial, viable product, Alertek miniatured the needed electronics by developing an Application Specific Integrated Circuit (ASIC) 5 mm X 5 mm in size. The ASIC contains all the hardware and software that evaluates the signals coming from the infrastructure and determines the critical instant when an alarm is activated. The ASIC, battery, and micro-transceiver are assembled in an encapsulated container 1 inch in diameter and less than an inch long. Beta-sites inside active mines have been designated in order to further evaluate the performance of the devices before releasing them to the market.

From a financial viewpoint the new technology is also very attractive. Monetary savings resulting from the prevention of the production loss, and rebuilding and clean-up costs after a roof or rib fall by far exceed the investment in the sensing and alarm system.

SECTION 1

Significant (key) findings

The most significant finding of the project is that the new technology advanced in this project makes it possible to detect impending roof fall in underground mines sufficiently in advance to allow the maintenance crew to take proactive action to prevent roof fall. Consequently, the technology will help prevent deaths and injuries to miners in underground mines.

It was further proven that the needed electronics can be made rugged and reduced in size to make it practical for use inside active mines without interfering in any way with the coal production process.

The device was designed so that it can be readily mass-produced at a low cost making it economically attractive to mine owners.

Translation of Findings

The new technology can be applied directly to the work place in underground mines. Ground control in mines requires the routine installation of long (typically 8 feet long) roof bolts 4 feet, or 3 feet, apart forming a two-dimensional network in the roof and walls (ribs) of the work area. The bolts are tightened against bolt-plates or strips that are pressed against the roof or wall surface. The sensor/alarm modules developed in this project are attached magnetically to these plates and straps approximately eight feet apart. The modules form a mesh communication network that communicates an alarm to the maintenance office and displays the alarm location on a video screen,

Thus to implement the technology, the ground control group must add to its ground preparation procedure the attachment of the sensor/alarm modules. This can be done after the bolts have been installed or during bolt installation.

The price of the modules is low enough to make the use of the modules economically attractive. Roof and rib falls result in financial losses to the mine because of lost production and repair and clean-up costs. By preventing roof and rib fall, the financial savings exceed the cost of the modules. Hence, while the technology is designed to save lives and prevent injuries, it also lowers the mine operation cost.

Outcome/Impact

The implementation of the new technology will result in the elimination, or reduction, of deaths and injuries resulting from roof and rib falls in underground mines. Ground control present practice in underground mines includes the installation of roof and rib bolts to increase the structural integrity of the work place. To implement the new technology, an additional step, the installation of the sensor/alarm modules, must be added to this practice. This can be done without interfering with production.

While the new technology was developed to increase safety in the workplace, it is also economically beneficial to the mine owner since the monetary savings associated with the prevention of a roof or rib fall exceed the cost of implementing the technology. Federal and State agency will have the option to regulate the use of the modules should it become necessary.

SECTION 2

Scientific Report

Background and Previous Work

Roof fall in underground mines remains a persistent problem demanding high costs in lives, injuries, and financial losses. Previous efforts to prevent roof fall through prediction of impending roof falls have failed. This project is taking an entirely different approach to early detection of impending roof fall by continuously monitoring directly the state of roof structure integrity and localizing critically weakened structures through clustering.

Roof bolts are routinely installed four or three feet apart to support roofs in underground mines. The bolts are anchored in the roof utilizing a settable resin around the bolt and the bolts are tightened to hold the various strata of the roof together. Less common is the use of an expandable mechanical anchor for anchorage. In either case, support is provided by the tensile load imparted to each bolt upon tightening the bolt head into tight abutment with the mine roof through a mounting plate, or strap, positioned between the mine roof and the bolt head.

Researchers studied and recommended methods and techniques to increase beam strength and improve roof support. Nevertheless, in time as mining continues, the strata may start to separate and develop a tensile load on the bolt. A layer of the strata may also shift horizontally exerting shear stress on the bolt. These forces can result in three different conditions causing roof collapse: (1) The bolt anchorage may fail causing the bolt to slide out of its position, (2) The bolt may fail and eventually break, and (3) The roof may “crack”, or “separate”, above the layers held in place by the bolts.

Patents based on bolt loading, tension, or strain measurements that claim to predict roof bolt failure have been issued in the U.S. and the UK. When a critical stress and corresponding strain are reached, the bolt enters the yield region after which it breaks. Thus it was believed that if the load (stress) or strain is measured, impending bolt breakage could be detected.

Experience in the field has shown that these methods are unreliable. They give false positive and false negative alarms. One reason is that no two bolts, even of the same model, are identical. Therefore “typical” or “average” values of stress or strain at which the material enters a critical level is meaningless when applied to any individual bolt. A second reason is that a bolt does not stretch uniformly along its length. While at one cross section a bolt may have entered the “yield” zone, at another cross section the bolt may not have entered the zone. It is more likely than not that the strain sensor is not attached just exactly at the one critical location where the breakage will occur.

Furthermore, this method does not address the anchorage resin and the surrounding strata that may weaken to a critical point before the bolt does.

A similar method, requiring the attachment of a load cell to the bolt, suffers many of the same weaknesses of the strain gauge method. In practice, not any one particular bolt enters the yield region at the “typical” or “average” critical stress value. Bolt failure resulting from shear stress is not considered at all in these measurements that use load cells or pressure sensitive discs. Yet shear loading contributes significantly to bolt failure in roof support in mines.

A different approach to predict roof fall addressed the measurement of roof sagging. This approach lead to the manufacture of a commercially available device referred to by its manufacturer as the “Telltale”.

Field tests have shown this method to be unreliable. To use the device, a borehole must be drilled into the roof to anchor the device. The instrument measures by how much the roof at a given location has sagged relative to a reference point. The reference point is the anchorage location of the instrument. In reality, the “reference” point is likely to drift as the roof structure weakens, resulting in false positive and false negative indications. The reliability is even lower because the technique assumes that a given amount of roof sagging indicates imminent roof fall. In reality the amount of roof sagging before a roof fails depends on the particular roof layer geometry, structure and material. In the US the use of the device is not recommended. Its use is mandated in the UK, the country in which it was invented.

Even if the device worked as claimed, it would require installing a large number of the devices (at a cost of over $150.00 each, not including installation costs) and keep moving and re-installing the devices as mining progressed. Each installation requires drilling a borehole for each device. The process would interfere with the mining process and would not be acceptable by the mining industry unless mandated.

The National Institute of Occupational Safety and Health (NIOSH) developed a Roof Monitoring Safety System (RMSS) that measures roof movement intended for use in wide-open roofs such as in room-and-pillar stone mines. NIOSH researchers say that their system turned out not to be suitable to predict roof fall.

Yet another research direction was based on studies of micro-seismic emission. The studies deployed tens of geophones over roof areas close to a square mile. The geophones, or acoustic microphones were positioned hundreds or thousands feet apart across the mine roof ground and “listened” to pressure waves. The method used triangulation techniques to predict where the roof was approaching collapse. The geophones upper frequency limit was 4.5 Hz in some studies and 14 Hz in others. High frequencies on the order of hundreds or thousands of kilohertz cannot be detected over large areas because the strata severely attenuate high frequency pressure or sound waves. The goals of these studies were to understand roof behavior in order to help design mines as well as to devise roof fall prediction alarm systems. Such alarm systems would require the installation of geophones in boreholes in mines and move them into new boreholes as mining advanced. Measurements from each geophone would have to be read and entered into computations. According to the investigators, to determine whether a roof fall was imminent, and its location, it would be necessary to combine four computed parameters and *apply human interpretation*. To date these seismographic studies are unable to predict roof fall. Hindrances are the low frequency limitation and the non-homogeneous overburden properties that make knowledge of pressure wave propagation speeds in specific directions for all intent and purpose impossible.

Even if the approach were technically sound, it would have been unacceptable to the mining industry for daily use. It would interfere with, and slow down, the mining process. It would require drilling extra boreholes and keep moving monitoring equipment around as mining progressed.

Specific Aims of the Present Project

The primary aim of this project was to develop a technology for the early detection of impending roof and rib fall in underground mines in time for the maintenance crew to take proactive action to prevent roof and rib fall. The technology was to be based on direct measurement of the state of health of the monitored structure rather than to depend on "average" or "typical" data that do not really apply to any specific case. If designed properly, this approach would guaranty no false alarms and no missed alarms.

A second aim was to arrive at a way to make the technology suitable for mass production to manufacture inexpensive sensing and alarm devices that will make the technology practical and attractive to the mining industry.

Finally, to be acceptable by the mining industry, it was important that the technology not interfere in any way with coal production.

BEGINNING OF CONFIDENTIAL MATERIAL

Methodology

The approach was to take advantage of natural processes that occur in infrastructures resulting from structure deterioration and instability. Such a deterioration can ultimately result in structure collapse unless preventive intervening action is taken. As structural changes take place, the effected structure lowers its stored energy through the release of pressure waves known as acoustic emission (AE). This phenomenon is associated with the particular location in the structure where the pressure waves originate.

The challenge was to recognize AE signals and distinguish them from other sounds, use the signals so instability localization can be done by clustering rather than by triangulation. Then it was necessary to recognize a pattern that indicates impending roof fall rather than temporary instability.

To monitor directly the level of roof and rib structure deterioration, we have taken an entirely different approach from those taken by earlier investigators. The significance of this new approach is that, unlike for previous approaches, impending roof fall detection does not depend on typical or a statistical "average" value for reference. No individual structure is a statistical "average"; it has its own specific structure. Therefore, detection methods depending on an "average" value as reference are inherently flawed. They are prone to false alarms and to missed alarms. The new method is "self-referenced". That is, it monitors and records in memory the behavior under normal conditions of each monitored structure and evaluates the structure at any future instant in terms of its own recorded reference behavior. A second important innovation of the new method is, that unlike previous methods, it does not use triangulation to determine an impending roof fall location. Instead, it locates the troubled location by clustering. Triangulation techniques depend on the knowledge of the speed of pressure wave propagation in the roof material. Since the roof strata are composed of several different materials in layers, the propagation speed depends on the location and direction, structures and boundary interfaces. In a mine this information is not known and cannot be entered into the triangulation computations. Instead, typical or average values are being used which are meaningless in any particular situation. In the new method, each sensor monitors roof weakening within a distance of only five to ten feet from its location. Normally, when a roof structure weakens around a given bolt, neighboring bolts assume the additional burden and no collapse is indicated. But when two or three or more neighboring monitors indicate critical values of roof weakening, the cluster of indicators calls for action to prevent roof fall at the cluster location. This technology is being made economically feasible through the introduction of a proprietary ASIC (Application Specific Integrated Circuit) that results in a cost of a few dollars per sensor/alarm module.

The new method uses Acoustic Emission (AE) to monitor infrastructure weakening. When matter is under strain, structural changes occur. The changes occur in a way that lowers the stored energy in the matter. The changes can be associated with atomic re-locations, micro-cracks, macro-cracks, or expanding damage and breakage. The acoustic energy release is by acoustic emission. The acoustic energy wave propagates in all directions through the object to the surface. When the structural changes reach a critical level leading to collapse, unless intervening action is taken, the acoustic emission release pattern changes dramatically. Our detection method places an AE sensor on the object surface (bolt plate or strap, in the mine roof and ribs case). The method detects the AE waves and with the use of an embedded software program, recognizes the dramatic pattern change and activates an alarm. The alarm state is transmitted through a wireless mesh network to the maintenance office where the critical structure location is displayed on a video monitor. The maintenance crew then takes proactive action to prevent structure collapse.

<u>Re*search and development stages*</u>

We made feasibility studies prior to phase I funding to determine the validity of our new concept for early detection of impending roof fall by applying the technology in a laboratory setting to tests of conditions that lead to underground roof fall. Roof falls in mines occur because of structural deterioration of roof bolts, and/or deterioration of the anchorage resin that holds the bolts in place, and/or the deterioration of the strata surrounding the bolts. The tests have shown that our technology detects all three conditions in time for a maintenance crew to take proactive action to prevent roof fall.

Next, in Phase I, we designed monitoring and recording equipment suitable for testing inside underground coalmines. We received Mine Safety and Health Agency (MSHA) and Pennsylvania Department of Environmental Protection (DEP) certifications to use the equipment in coalmines. We performed tests in a long-wall mine and concluded that the sensor responded as required.

In phase II we performed additional tests to fine-tune our new technology. We directed our focus to miniaturize our hardware with embedded software to make it suitable for routine application in coal mines and to make it commercially feasible, convenient and useful.

The original sensor was housed in a separate package and the signal conditioning and processing electronics was assembled into a 4 inch X 3 inch X 1 inch enclosure. Figure 1, on the next page, shows the sensor and electronic package mounted on the roof of an underground coalmine next to the cutting face of a long-wall.

Fig. 1 Sensor and Signal Processing Electronics Package

The sensor, shown on the left side, is attached to a metal bolt strap on the roof. It is protected with white epoxy. The electronics (center) is connected with a cable to the sensor and it is strapped to the roof. To the right is an optic fiber carrying the output of the electronic package to the monitoring equipment in a fresh-air area 1,000 feet away. The monitoring equipment is shown in Figure 2 below.

Fig.2. Custom Data Acquisition and Replay Equipment

The warning signal signature, obtained four hours before the roof fell, is shown in Figure 3 below.

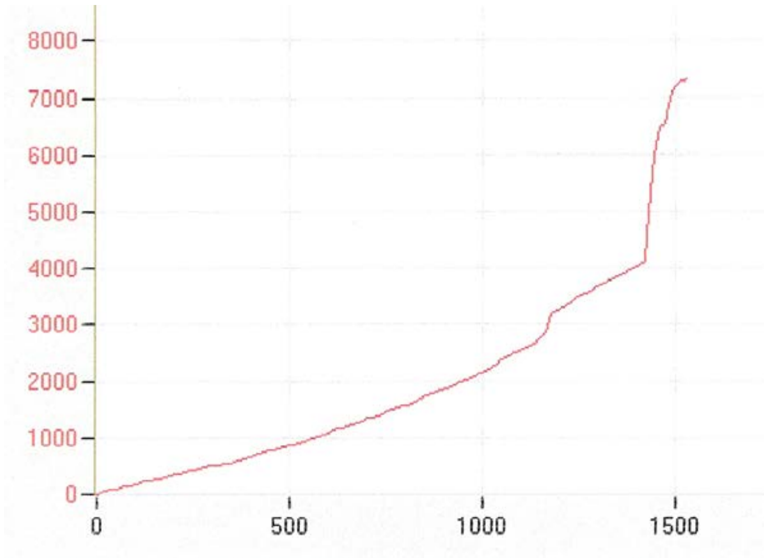

Fig. 3 Recorded Signature of the Alert/Alarm Signal

The recording begins as the roof enters the alert state after the signal increased above the normal background noise. The alarm is given shortly before the 1500 mark before the recording ends.

To commercialize the technology, it was necessary to miniaturize the electronics to make it easy to use and inexpensive. The electronics was converted to a customized Application Specific Integrated Circuit (ASIC) of dimensions 5 mm X 5 mm (3/16 inch X 3/16 inch). All the needed amplification and signal processing capability as well as the analysis and decision making software are contained in this chip. The alarm will be sent through a wireless communication network to the maintenance office. The ASIC together with a transceiver, battery, activation switch, and mounting magnet are housed in a 1 inch diameter module, less than an inch long. The components, together with a quarter coin for size comparison, are shown in Figure 4 on the next page.

The chip in the center of the figure is the ASIC. The second chip is the transceiver. The magnet is on the right, the battery is on the left, and the sensor is between the battery and the coin (included for size comparison).

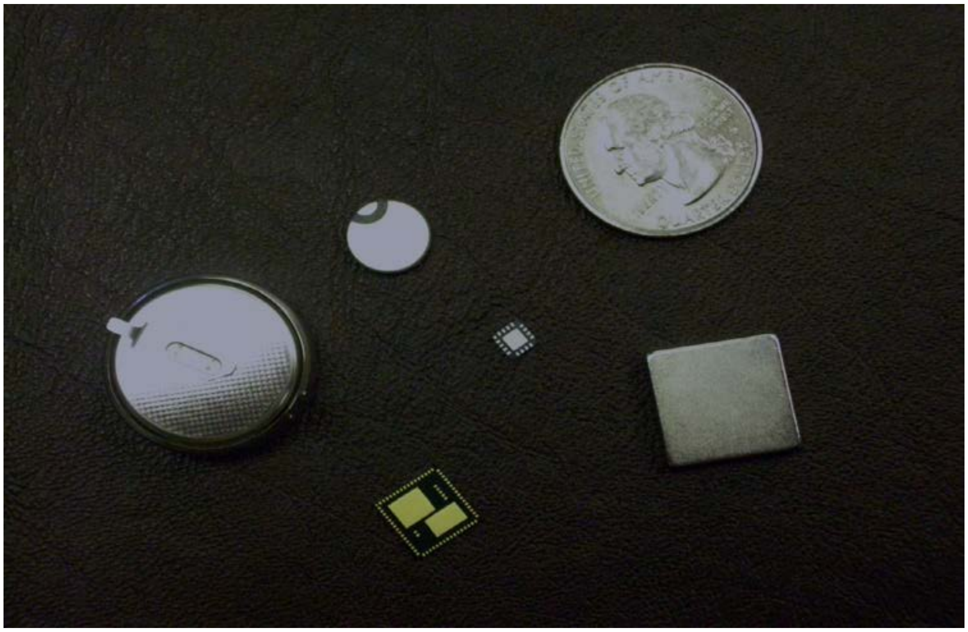

Fig. 4 Module Components

(The quarter coin is shown for size comparison)

Figure 5 below shows the Sensor/Alarm module housing.

Fig. 5 Sensor/Alarm Module Housing

Figure 6 below shows the module assembly structure.

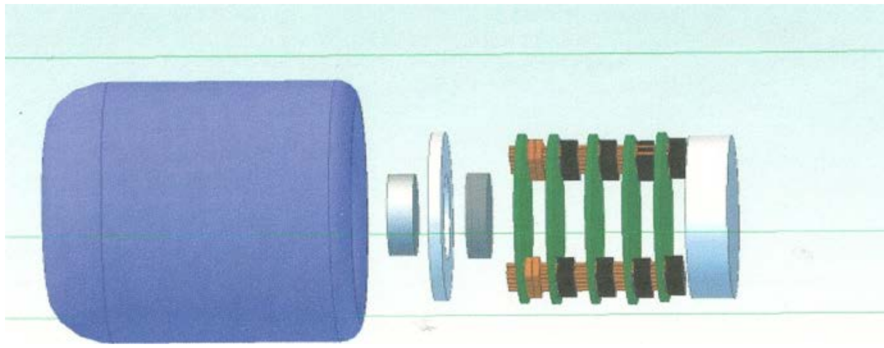

Fig. 6 Module Assembly

The sensor accepts the signals generated by the structure. The ASIC analyzes the contents and determines several stages in the structure's state of integrity. It determines the noise level under normal excavation conditions. It determines an alert condition when there is increased activity in the structure. It determines when the activity is temporary and a new equilibrium has been reached and it sets an alarm when the structure enters a critical condition when structure collapse is imminent unless external intervention to support the structure is exercised. The transceiver sends the alarm signal to the maintenance office video display screen.

We have selected several beta-sites in active underground mines. The sensor/alarm units will be installed as soon as MSHA approval is secured. We are in discussions with a number of organizations for support in commercializing the product and entering the market.

END OF CONFIDENTIAL MATERIAL

Results and Discussion

The aims of this project were met. A technology that predicts impending roof and rib fall was developed and tested. In planned roof fall test near the face of long-walls the alarm was given about four hours before the roof fell. Through roof fall studies related to unplanned, accidental roof falls it is expected that the alarm will be given one to two days before roof fall. In such situations the structure's gradual deterioration takes place over weeks and months.

Conclusions

A module, one inch in diameter and three quarters of an inch long, using the new technology has been built and tested. The product will be market-ready as soon as it receives MSHA certification and undergoes beta-site verification. Discussions with a number of established organizations are underway for mass-production and large-scale marketing and distribution.