24-049

Ground Control Monitoring: A Comprehensive Guide for Mine Operators on Instrumentation and Data Acquisition Currently Used by the National Institute for Occupational Safety and Health (NIOSH)

Todd Minoski
CDC NIOSH, Pittsburgh, PA

Mark Mazzella
CDC NIOSH, Pittsburgh, PA

Matthew McElhinney
CDC NIOSH, Pittsburgh, PA

Craig Compton
CDC NIOSH, Pittsburgh, PA

Morgan Sears
CDC NIOSH, Pittsburgh, PA

ABSTRACT

The National Institute for Occupational Safety and Health (NIOSH) is staffed with Engineers, Geologists, and Field Technicians conducting a variety of ground control research. The mission of the ground control teams within the Mine Systems Safety Branch (MSSB) is to eliminate ground failures leading to mineworker injuries and fatalities. Advancing the science behind ground control relies heavily on conducting mutually beneficial research at participating mines which is detailed in specific references throughout the paper.

The ground control teams have several types of field instruments at their disposal to measure the ground response in underground mines. These include borehole pressure cells (BPCs), vibrating wire stress meters (VWs), hollow inclusion cells (Hi-Cells), roof and rib extensometers, load cells, and convergence meters. These instruments are used to measure changes in pressure, strain, and displacement within the underground environment.

Instrumentation data is collected automatically using intrinsically safe or MSHA permissible dataloggers if required. Information is transmitted to the dataloggers using approved cable to distances of 200–1,000 ft. depending on the type of datalogger being used. Once mining is completed, the dataloggers are retrieved and brought to the surface, providing in-mine data to mine management and engineers for the conditions currently being encountered in a particular mine.

This data, in conjunction with geologic data and stress mapping, can be used to validate numerical models. The practical application of these models is extremely important for mine management and engineers, particularly when faced with more challenging mine environments. Insight gained from applying these models can be used to make better engineering-based judgments for areas that will be mined in the future. The impact of such applications can result in a reduction of ground-fall accidents and injuries as well as generally safer working conditions.

INTRODUCTION

The National Institute for Occupational Safety and Health (NIOSH) relies heavily on field instrumentation to carry out ground control research. The data collected and knowledge gained not only assists in the validation of models and insight on potential ground control hazards but can also be mutually beneficial to the participating mine. The ground behavior analyzed can provide the information to make better engineering-based judgments when planning future mining areas.

Through decades of instrumenting underground mines, NIOSH has adapted, designed, and innovated many aspects of ground-control monitoring. This paper

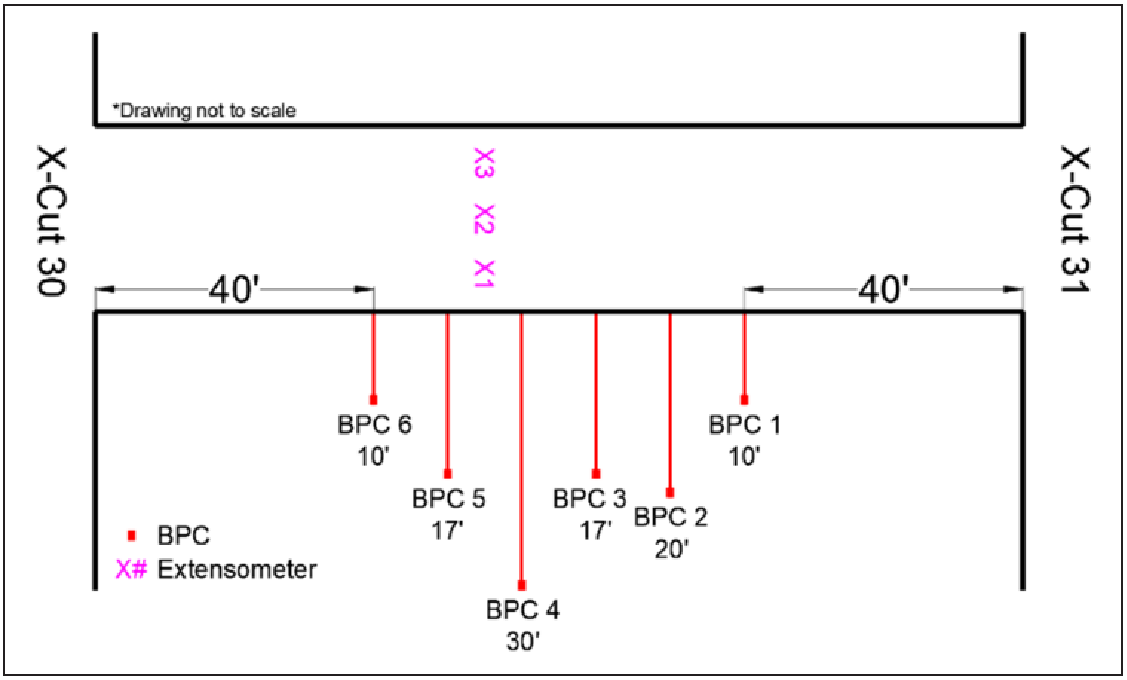

Figure 1. Example instrumentation layout in a mine entry utilizing multiple instrumentation types (after McElhinney et al., 2023)

provides a comprehensive consideration of ground monitoring instrumentation, installation best practices, and data collection methods for monitoring the ever-changing mine environment.

INSTRUMENTATION AND INSTALLATION

Ground monitoring instrumentation can be categorized into groups based on what the instrument measures. These measures include displacement, stress, and load. These three measurements typically cover the areas of interests when monitoring an underground mine. While not every instrument at NIOSH's disposal is installed at a specific field site, a combination of them can be strategically arranged to produce the most impactful outcome. (Figure 1).

This specific site, for example, is arranged to monitor roof displacements across the width of the entry. The anchor depths can correspond to either bolted horizons or specific stratigraphic horizons in the roof. The BPCs are installed into the pillar at varying depths. The specific depths, in this case, allow for both redundancy in measurement as well as providing a stress profile across the pillar.

Successful implementation of ground-control monitoring hinges largely on the meticulous installation of the instrumentation. Not all, but most of the instrumentation currently being used by NIOSH requires a borehole for installation. The borehole serves as the conduit between the physical environment and parameter being analyzed. Ensuring that interaction is reliable depends on the diameter, depth, orientation, and cleanliness of the borehole. The borehole is achieved by using a multitude of rock boring drill bits, auger steel, hex steel, and drilling equipment. A roof bolting machine is typically used to drill the vertical and horizontal holes required for installation although handheld hydraulic and pneumatic drills such as the TURMAG (MINOVA, 2019) have been used in the past and are available to accomplish similar results. The following will highlight the specific function, application, and installation procedures of each instrument currently being used by NIOSH researchers.

DISPLACEMENT INSTRUMENTATION

Understanding the dynamic nature of strata movement in the underground environment is very important for mine engineers and management tasked with designing support systems. Displacement instrumentation serves as a cornerstone in this endeavor, offering insights into the movements within the mine's roof and floor strata. The following instruments are currently used by NIOSH researchers when the measurement of strata displacement is desired. These instruments can be divided into three distinct categories, those that measure displacement in a single direction, those that measure convergence, and those that measure displacement velocity or acceleration (seismicity).

Roof-to-floor Extensometers

The roof-to-floor extensometer, used to measure convergence, utilizes a cable-actuated position sensor (string potentiometer) to measure movement (See Figure 2). This instrument is typically installed in a mine opening where standing support is present (See Figure 3). Its purpose is to accurately measure the convergence between the roof and floor of the mine during active mining or long-term entry stability studies such as those involving bleeder entries (Klemetti et al., 2018)

Figure 2. Example of a string potentiometer

Figure 3. Complete extensometer installed on a can-type support in conjunction with a standing support load cell

Installation of the roof-to-floor extensometer is usually accomplished by mounting a cable-actuated position sensor to a standing support (See Figure 3). Although in some circumstances, with the use of strong magnets, the extensometer can be mounted between a roof bolt plate and an anchor point on the mine floor or on metal CAN type standing supports. The installation procedure of the roof-to-floor extensometer at specific field sites is as follows:

- Locate a standing support for installation.
- Find a location on the standing support that is plumb, so the potentiometer's string can be run roof to floor without any obstructions.
- Position the instrument at the top of the standing support with the string and eyelet pointing down.
- Secure the instrument to the top of the standing support using nails/screws through the mounting bracket attached.
- Find a location near the bottom of the standing support to drive a nail or screw into for the corresponding anchor point.
- Carefully pull the string out until it stops and then let it retract a few inches. DO NOT pull hard or it will damage the instrument. DO NOT let go and allow the string to snap back into the instrument as it can cause damage.
- Roughly determine the extra length of wire that will be needed to connect it to the corresponding anchor point at the bottom of the support.
- Thread the wire through the eyelet on the instrument making a loop and securing it with a metal wire crimp.
- Carefully pull the wire extension down towards the bottom anchor point until it stops.
- Let the wire retract a few inches and make a loop using a metal crimp at that location of the bottom anchor point.
- Hook the wire over the corresponding anchor point
- Installation is complete and an initial zero reading should be recorded.

Multipoint Roof Extensometers

The multipoint roof extensometer in current use by NIOSH is a product of our own innovation (see Figure 4). Crafted and assembled in-house by skilled technicians, this extensometer offers the flexibility to be adjusted and modified as needed according to specific requirements. The enclosure contains slide potentiometers with a range of 100 mm that attach to varying anchor depths in the mine roof. The predetermined anchor locations allow for the monitoring

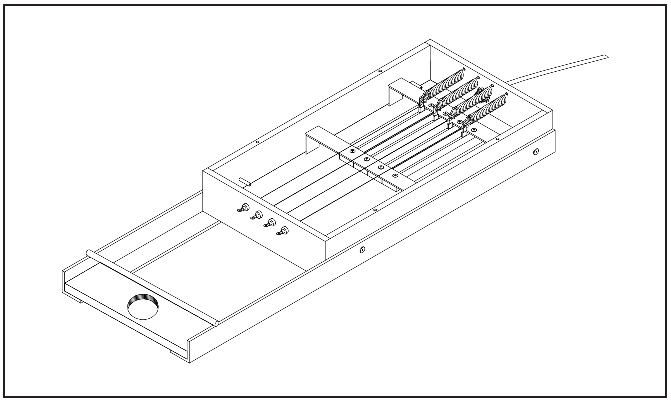

Figure 4. Rendering of the NIOSH custom multipoint roof extensometer utilizing four anchor points

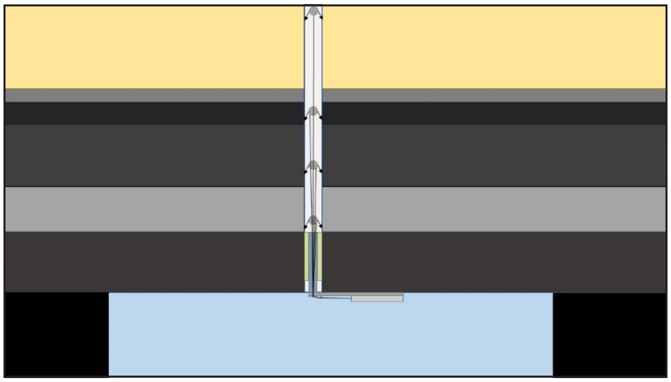

Figure 5. Cross-section view of an installed 4-point roof extensometer depicting anchor horizons in the roof

of roof separation and movement between the varying strata (see Figure 5). The typical multipoint roof extensometer consists of four anchor points, although six-point and eight-point versions have been implemented in the past. Historically, anchor locations have been selected based on anchorage horizons of the primary and secondary support (Klemetti et al., 2017). The best practices and installation procedures are as follows:

- Find a flat section of roof free of dips or protruding rocks to ensure a secure attachment of the extensometer enclosure.
- Using the roof bolting machine, drill a 1-3/8" hole to the deepest anchor depth.
- Once the hole is drilled, install the corresponding anchors at the predetermined depths with an insertion rod, starting with the deepest anchor first.
- After all the anchors are installed, the anchor wires must be fed through the 1-¼" mounting pipe.
- The mounting pipe will then be coated in PLEXUS MA300 (ITW Performance Polymers, 2022) or similar epoxy and pushed up into the hole, securing the extensometer box to the roof. Wooden wedges can be used to help secure the pipe inside the hole until the epoxy is cured (see Figure 6).
- Attach the labeled anchor wire to its corresponding eyelet on the roof extensometer box using a metal wire crimp. Pull the eyelet about ¼" out and secure the metal crimp, removing any slack in line and creating adequate line tension.
- Once all anchor points are connected, initial zero readings should be recorded.

Figure 6. Installation of a multipoint roof extensometer depicting the insertion of mounting pipe into the borehole and securing with wedges

Multipoint Borehole Extensometers (MPBX)

The multipoint borehole extensometer (MPBX) is a geotechnical instrument designed to monitor changes in the distance between downhole anchors, each set at a specified depth in the borehole with a measurement head at the mouth of the hole. Typically installed into the pillar or rib, the MPBX applications in mines include but are not limited to being used:

- to study the deformation of the roof and rib of a mine during an excavation (Rashed et al., 2021),
- to examine the effectiveness of roof and rib support systems,
- to determine the potential for roof and rib instabilities.

NIOSH researchers are currently using the MPBX produced by Mine Design Technologies, Inc. (MDT) (Mine Design Technologies, 2018). Therefore, the following installation procedures are applicable for the MDT, Inc. brand of MPBX. Figure 7 shows the key components of the MPBX produced by MDT. The installation procedure used

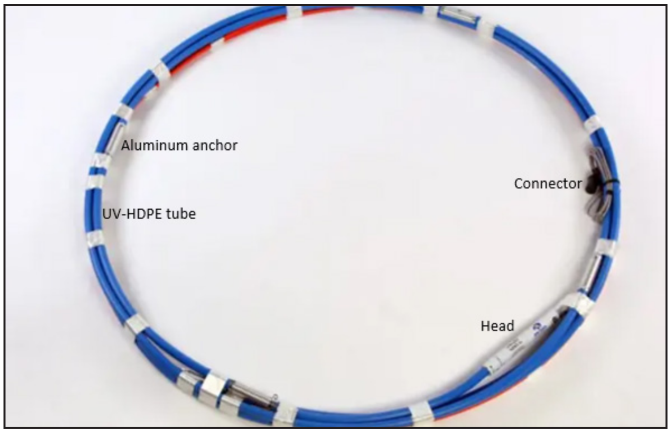

Figure 7. MDT Inc.'s MPBX unit with labels showing the location of key components

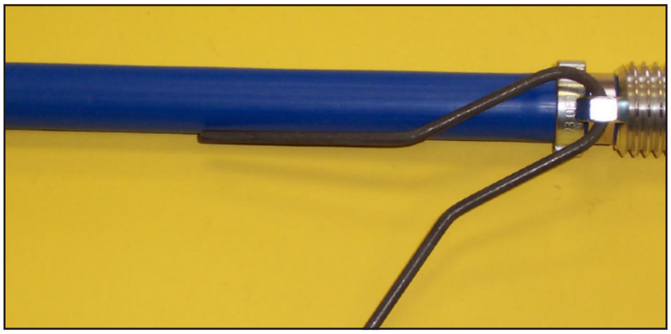

Figure 8. Safety spring hanger installed in the deepest anchor

by NIOSH researchers for the MPBX produced by MDT, Inc. are summarized in the following:

- Drill borehole of 2" diameter with borehole sloping slightly downward with a length long enough to accommodate the MPBX with the instrument head recessed in the hole.
- Ensure the borehole is free of debris prior to installing the MPBX.
- The MPBX ships coiled. Cut required tape to uncoil MPBX and roll it out along the floor of the entry.
- Before inserting the MPBX in the borehole, ensure that the safety spring hanger is in place (See Figure 8).
- Slide the MPBX into the borehole until the MPBX head is about 2" inside the collar of the hole.
- The MPBX head can be held in place using wooden wedges while the sacrificial grout tube is inserted 3–4' into the hole along with a breather tube.
- The collar is packed with rags to keep grout from escaping and ensuring a fully grouted hole.
- Mix grout at a 0.42 to 0.46 water-to-cement ratio to ensure proper encasement.
- Continue pumping until you can see the grout coming out of the breather tube from the collar of the borehole.
- Shut the grout pump off, cut the breather tube, kink it over to keep suction in the borehole. Then proceed to cut and kink the sacrificial grout tube.

Transitioning from understanding displacement to the inherent stresses within the rock, it is crucial to recognize the interconnectedness of these metrics. Rock stress instrumentation attempts to measure the forces and pressures exerted within the mine's geological formations. Just as displacement instruments measure the movement, rock stress instrumentation measures the internal pressures that lead to these displacements.

Geophones

In mining applications, geophones are typically the seismic sensor of choice due to their affordability, wide bandwidth, and dependability (Institute of Mine Seismology, n.d.). The Institute of Mine Seismology (IMS) Model 3G14 14Hz geophone (see Figure 9) is model currently used by NIOSH researchers to measure mining induced seismicity in deep longwall coal mines (Van Dyke et al., 2018).

The Tri-Axial Seismic Sensor is typically installed down hole from the surface through means of a preexisting coal bed methane (CBM) well (See Figure 10). After the gas

Figure 9. IMS Model 3G14 geophone (after Institute of Mine Seismology, 2013)

has been extracted, the well is plugged up to the sensor installation depth at roughly 1000ft. A fabricated lowering assembly is recommended when installing the sensor as it assists in vertical orientation within the casing and provides an attachment point for a steel winch cable. This method also allows for a safe and controlled decent, while providing support to the sensors data cable. Typical installation procedures are as follows:

- Prepare/Fabricate a lowering assembly.
- Insert the sensor body into the assembly and tighten the set screws to secure it.
- Attach 1/8" stainless steel cable to lowering assembly.
- Insure adequate winch cable for installation depth.
- If data cable needs extended, create watertight splice as needed.
- Attach marking tags in 100ft increments to the data cable.
- Install sensor into well casing and lower using a power winch.
- Attached data cable to stainless steel cable with cable ties at the 100ft marking tags.
- Lower until sensor reaches desired depth.
- Secure stainless-steel cable at the surface to support the hanging assembly.
- Fill the well casing with grout to encapsulate the sensor.
- Data cable is attached to a seismograph and continuously monitored.

Historically, NIOSH researchers have used other geophone and accelerometer offerings such as those from ESG Solutions (ESG Solution, n.d.) and others. There are several commercially available sensors on the market, some of which may be better suited to other applications such as microseismics, in mine installation, etc.

ROCK STRESS INSTRUMENTATION

Vibrating Wire Biaxial Stressmeters

Vibrating wire biaxial stressmeters measure the change in strain in the surrounding rockmass. Due to its biaxial orientation, this allows the change in principle stresses to be calculated simultaneously. Currently, NIOSH uses the GEOKON Model 4350 Biaxial Stressmeter (see Figure 11) is designed to measure changes in stress in hard rocks, rocksalt, potash, concrete, ice, and other elastic and viscoelastic materials (GEOKON, 2023).

The sensor is commonly positioned in proximity to active mining zones or regions anticipated to experience stress fluctuations, aiming to quantify the stress changes within the surrounding mine strata. This information can be used on its own to infer the state of stress redistribution or in conjunction with other methods, such as numerical modeling, to validate or provide additional context (Slaker et al., 2020; Zahl et al., 2002).

Figure 10. Photo depicting the initial installation of an IMS Model 3G14 geophone into a gas well

Figure 11. GEOKON Model 4350 Biaxial Stressmeter (after GEOKON, 2023)

The sensor is designed as a thick-walled steel cylinder, which is grouted in a borehole or embedded in the material to be studied. Utilizing either three or six vibrating wire strain gauges, radial deformations of the cylinder are captured. Through the application of derived theoretical equations, the corresponding stress variations are calculated. The

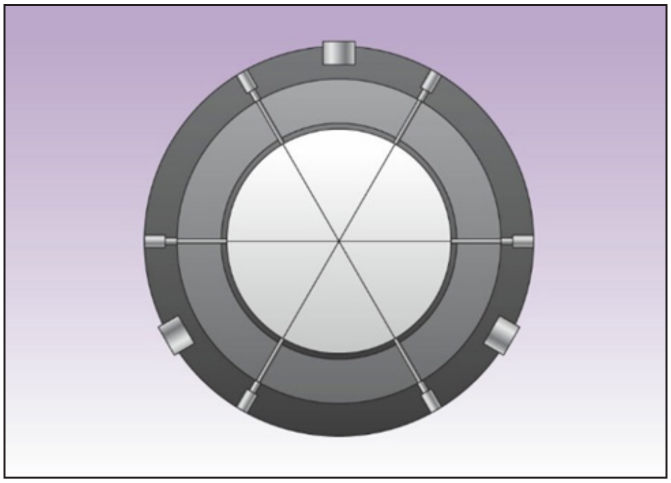

Figure 12. Cross-section rendering of the GEOKON Model 4350 Biaxial Stressmeter depicting the location and orientation of strain gauges within the instrument

Figure 13. Hollow Inclusion (HI) Cell depicting the cell itself, plunger, wooden dowel, and a pre-selected length of cable

measurements, taken at 60° intervals in the plane orthogonal to the borehole, facilitate the analysis of changes in the biaxial stress field surrounding the sensor (see Figure 12).

Refer to the VW 4350 Manual for additional description, specifications, procedures, and theory of operation (GEOKON, 2019). The following installation procedures primarily relate to practices and experience at NIOSH.

- Drill a 2.5" diameter borehole, typically horizontal or subhorizontal into pillar at the required depth.
- Ensuring the hole is clean and free of debris is cruital for setting orientation in place.
- Downward sloping hole provides ease of grouting and ensure full encapsulation of the sensor.
- Grout can be pumped in or poured depending on the slope.
- High-strength and fine-grained expansive grout is recommended.
- Attach a thin steel wire to the anchor release hook on the sensor.
- Partially fill the hole with grout, then orient the sensor where gauge 1 is vertical and proceed to push the sensor to the back of the hole maintaining orientation marked on insertion rods.
- Once the sensor is at the back of the hole, pull the anchor release cable while keeping the sensor orientied correctly. This will lock the orientation as the insertion rods are removed and the grout sets up.
- In some instances, the hole is too large for the orientation anchor to set, and this can be overcome by swiftly pulling back on insertion rods, freeing them from the oriented sensor.
- Allow up to 28 days of curing time for reliable instrument measurements.

Hollow Inclusion (HI) Cell

The Hollow Inclusion (HI) Cell (see Figure 13), an innovation by the Commonwealth Scientific and Industrial Research Organization (CSIRO), was designed for the task of measuring three-dimensional stress in rock and concrete substrates (Duncan-Fama and Pender, 1980). Over the years, its efficacy has been demonstrated in assessing stress and strain dynamics within concrete tunnels and various infrastructural elements.

The highly sensitive strain gauges are bonded to the rock in a novel mechanical process using temperature-specific glue packs, allowing the gauges to become attached to the rock in a reasonable amount of time. The sensor can be left in-situ for long-term stress change measurement (Gearhart et al., 2017) or can be over-cored to see the strain change to determine a stress profile of that section of rock (Earth Sciences, 2020).

The HI Cell requires several on-site preparation steps before it is suitable for installation. The following will address those steps along with the installation procedures.

- A 2-½" nominal diameter hole is drilled into the roof at the specified angle and to the specified depth.
- The hole can be drilled either wet or dry depending on the bits being used.
- At the end of the 2-½» diameter hole, a finishing bit is used to drill a 1-½» diameter hole of an appropriate length for the HI Cell to be installed into.

- If the hole was not drilled wet, hollow insertion rods are used to clean the hole with water, and the hole is dried prior to installation.
- To prepare the HI Cell, the pieces of the instrument are gathered, the exterior surface of the HI Cell is sanded to increase the bond strength of the cell and the epoxy, the two-part epoxy is mixed, and the hollow interior of the cell is filled with the epoxy.
- Once the cell is filled with epoxy, the pusher tube is inserted part way into the cell as shown in Figure 11, and small, easily deformable metal pins are inserted into the body to keep the pusher in place.
- The wooden dowel is affixed to the end of the pusher tube and the HI Cell is ready for insertion.
- The same setting rods used to clean the hole are now used for the insertion of the HI Cell.
- The HI Cell is gently pushed to the back of the hole and once resistance is met, a final strong push is used to break the metal pins, force the pusher into the hollow body, and squeeze the two-part epoxy out of the hollow body filling the annulus of the borehole.
- At this point, insertion is complete. The insertion rods are tied off to roof bolts and left in place overnight for the epoxy to set.
- The following day, the insertion rods are removed, and the HI Cell is connected to the datalogger.

Borehole Pressure Cells

The Borehole Pressure Cell (BPC) is designed to detect changes in rock stress and is intended for placement within a borehole through grouting. The BPC (Panek and Stock, 1964) is crafted from two steel plates, seamlessly welded along their edges. These sheets are shaped into a unique "dog bone" design, similar to a borehole flatjack. The void between the sheets is then filled with hydraulic fluid to the desired setting pressure. Stainless steel tubing then links the BPC to a pressure gauge and/or pressure transducer located outside the borehole (see Figure 14).

Typically, BPCs are prepped and pre-cast for installation such that they arrive at the field site as shown at the top of Figure 14 (Miller and Sporcic, 1964)—that is, complete with stainless-steel, high-pressure tubing, pressure sensing assembly, and pressure transducer. If desired, the BPC can also be post-grouted following installation. Installation of the BPC at the specified field site is as follows:

- A 2-¼" nominal diameter hole is drilled into the rib horizontally to the specified depth.
- The hole is cleaned by the continued rotation of the auger steel in the hole.

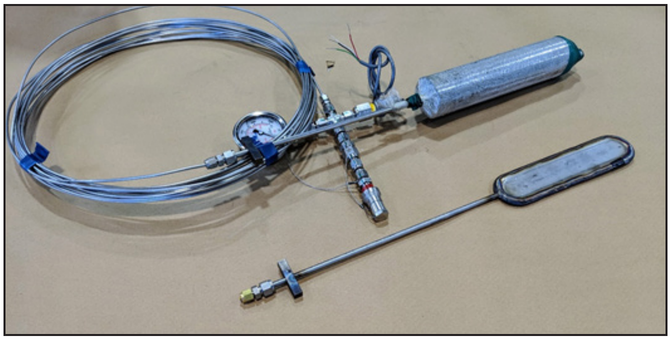

Figure 14. Example of an uncast BPC (bottom) and a pre-cast BPC pressure sensing assembly ready for field installation (top)

- Secondary cleaning of the hole is completed using chimney sweep brushes or cleanout tool if necessary.
- The BPC is then inserted into the hole perpendicular to the desired stress orientation using insertion rods with a BPC specific adapter.
- After insertion, if the BPC is pre-grouted, the BPC is then pressurized to the desired setting pressure (typically 1.1 times the overburden depth in psi).
- If the BPC is post-grouted, grout is poured in the hole and left to set based on the manufacturer's recommendations. Upon setting, the BPC is then pressurized to the final setting pressure.
- Once the setting pressure is achieved, excess tubing is coiled and hung appropriately off a rib or roof bolt plate or spad nail.

Moving beyond the measurement of the inherent stresses within the rock itself, it is also important to understand the support loading characteristics as well. Support load instrumentation attempts to measure the forces on ground support structures such as roof bolts and standing support in the mine.

SUPPORT LOAD INSTRUMENTATION

Roof and Rib Bolt Load Cell

Load cells installed on roof and rib bolts allow the load applied to the ungrounted length of the bolt to be measured. The GEOKON Model 3000 Load Cell (See Figure 15) utilizes strain gauges in Wheatstone bridge configuration to measure load forces and is currently used by NIOSH researchers. The steel body construction with a pass-through feature allows for installation on a variety of cable bolts, mechanical bolts, rib bolts or other anchored bolt mechanisms. The long-term and active mining load forces applied to roof and rib bolts are typically monitored using such load cells (Gearhart et al., 2017). NIOSH currently uses GEOKON Model 3000 (GEOKON, 2020) load cells

Figure 15. Example of a GEOKON Model 3000 load cell (after GEOKON, 2020)

in 50KIP and 100KIP capacity with a 1” passthrough. The installation procedures for a roof bolt load cell are as follows:

- Pre-drill a hole to the required depth and size to specification of the bolt being installed/monitored.
- Assemble onto bolt in the order of:
  – 1” thick washer
  – GEOKON Load Cell
  – 1” thick washer
  – Roof bolt plate.
- Using the bolting machine, push assembly into the hole.
- For mechanical anchor bolts, spin carefully, then tighten to specification.
- For resin bolts, allow an inch or so of space between the load-cell assembly and the roof line. (This will allow the bolt to be spun freely as resin is mixed without damaging the load cell). Spin the bolt the desired amount, then apply force to set (see Figure 16).

Standing Support Load Cell

The standing support load cell offers insight on real-world loading conditions being applied to standing support during long-term and active mining studies. This combined with a roof-to-floor extensometer (see Figure 3) can measure how well a support is performing as well as the overall entry stability (Klemetti et al., 2018). The construction of the standing support load cell consists of two seam-welded sheets of steel in the shape of a circle or square with varying dimensions to accommodate the standing support being used. There are welded bungs providing a fill port and a pressure transducer port. The bladder is typically preformed between two platens using pressurized water to a thickness of one inch, then calibrated under varying loads and tested for leaks prior to installation in the field. The installation procedure for standing support load cells are as follows:

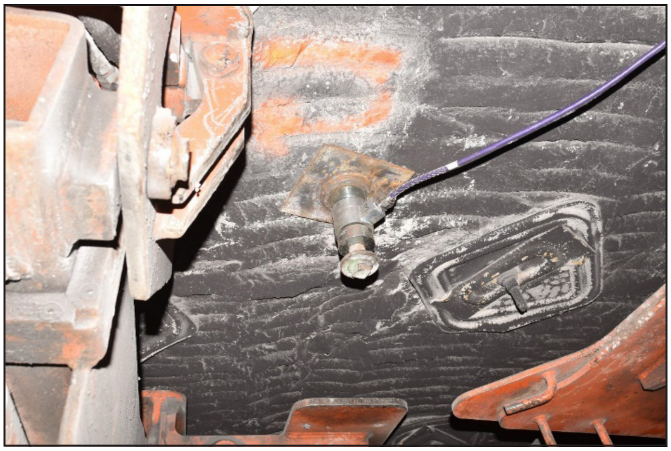

Figure 16. Completed installation of load cell on a cable bolt using the NIOSH installation procedure

- Installation of the standing support load cell requires a solid contact point to the bladder faces.
- This is achieved by using a stacked configuration of crib blocks and plywood on the top and bottom of the bladder.
- If installing underneath the standing support (i.e., pumpable supports), orient the pressure transducer up, provide a solid and level base using crib blocks on the mine floor, followed by a ¾” plywood, the load cell bladder, ¾” plywood, and another layer of crib blocks.
- If installing on top of the standing support (i.e., cans/posts/cribs), orient the pressure transducer down, provide a solid and level base using crib blocks on top of the support, followed by ¾” plywood, the load cell bladder, another sheet of ¾” plywood, and another row of crib blocks. Use wedges as needed to tightly secure against the mine roof.
- Connect the data cable and take initial readings.

The preceding sections have provided a comprehensive overview of the ground-control instrumentation used by NIOSH researchers at NIOSH. While many of the instrumentation devices on the market have some sort of manual readout, an appropriate data acquisition system is generally preferred. Data acquisition systems reduce labor, potential exposure, and collect more accurate data than manual readings alone. The following section discusses the data acquisition systems currently in use by NIOSH.

DATA ACQUISITION

Data collection represents the final phase of a field monitoring site. Following the installation of the required instrumentation, the routing of the data cables takes place, eventually converging at a central outby location. At this location, the data acquisition system resides and continuously monitors the site until the study ends or mining operations make access no longer possible. At this point, the entirety of the field instrumentation will be sacrificed, leaving only the data acquisition system to be recovered. The data can then be processed and analyzed to further understand ground movement and interaction. Currently, NIOSH uses two data acquisition systems, the Miniature Data Acquisition System (MIDAS) and the Campbell Scientific 21XQM Micrologger (Jones, 2012; Campbell Scientific, Inc., 1995).

The MIDAS system is a composite of various equipment elements that together form a high-accuracy analog-to-digital data recording system. This system is compatible with a wide range of resistive instruments. With its intrinsic safety and MSHA permissibility, the datalogger is especially suited for usage in the return-air courses of coal mines (see Figure 17). It can monitor up to 8 individual channels simultaneously or a combination of 4 individual and 4 differential channels when paired with the M4IAGPAR5 four-channel instrumentation amplifier board.

Data extraction is streamlined and user-friendly, facilitated by wireless transfers when near the MIDAS Reader interface, where the data is saved onto a micro-SD card. In many field locations, several MIDAS devices are employed to meet the demands of the instrumentation plan. With its extended battery life (up to one year), the MIDAS datalogger is a preferred choice for prolonged surveillance locations. While there are restrictions on cable lengths, 200 ft. from the monitoring location is typically adequate for most sites. Details on constraints, circuit diagrams, software instructions, and signal amplification computations are available in the instruction manual (Golder Associates, 2013).

The Campbell datalogger is a single unit with an integrated power supply, keyboard, and display and is also MSHA-approved for monitoring in the return airway of coal mines (see Figure 18). It offers 8 differential and 16 single-ended channels, 4 excitation outputs, 2 analog outputs, 6 control ports, and 4 pulse counters. With an added multiplexer, it supports up to 16 differential and 32 single-ended readings. The 21XQM micrologger can conduct 36 measurements using three-wire strain gauges for Hollow Inclusion Cells and supports cables up to 1,000 ft. Data is stored in the SM716QM module and accessed via Campbell Scientific's PC interface (Campbell Scientific, Inc., 1995).

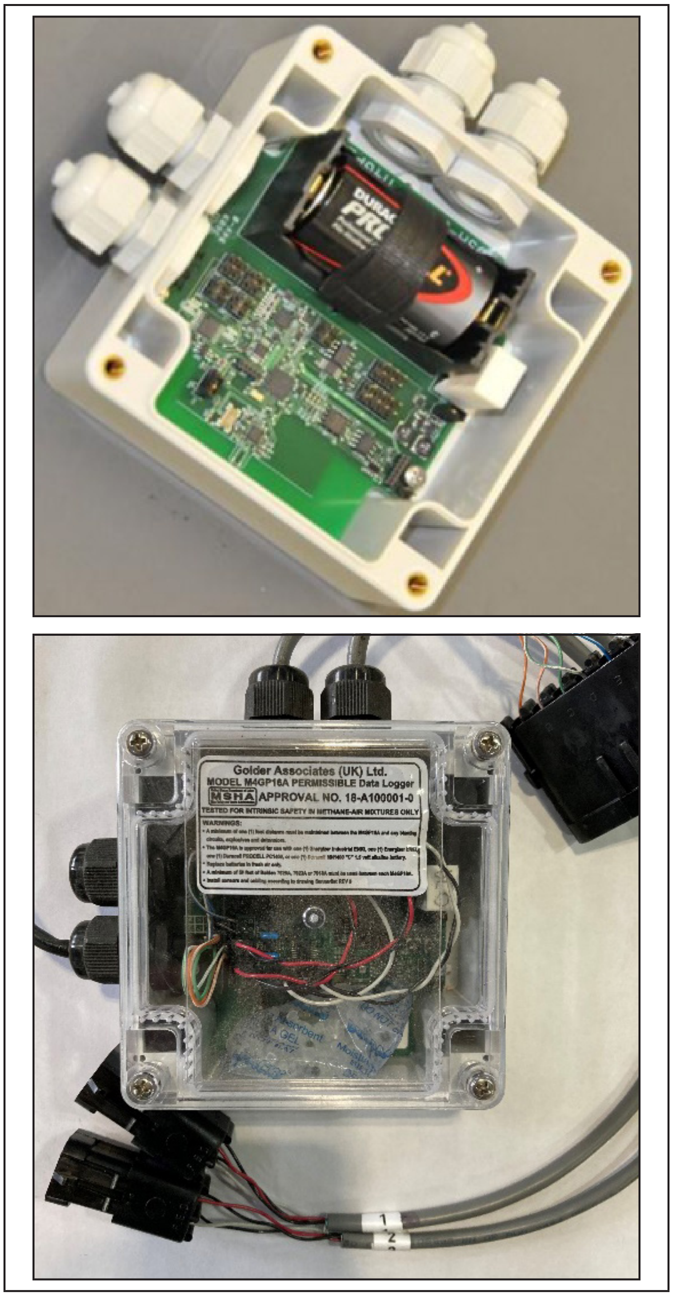

Figure 17. MIDAS showing internal components (top) and wired with weather pack connectors (bottom)

LIMITATIONS

This paper has provided a comprehensive overview of ground-control monitoring by NIOSH researchers using

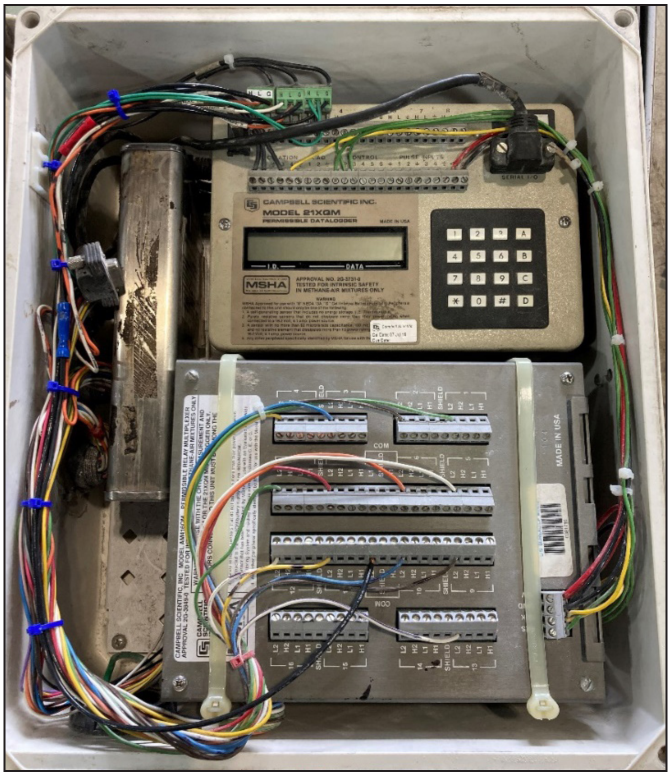

Figure 18. Campbell Scientific's 21XQM model is currently configured for monitoring Hollow Inclusion (HI) Cells

displacement and stress-measuring instrumentation. Specific products mentioned in this paper are in use by NIOSH, but this is not intended to provide an all-inclusive list of instrumentation and data acquisition systems on the market. There are multiple variations of these products, particularly in the area of displacement measurement, available to the consumer. These include various extensometers often referred to as telltales, miner's helpers, or guardian angels. Additionally, there are many other devices capable of measuring strain, pressure, and deformation of boreholes at consumers' disposal.

Other limitations to implementing a ground-control monitoring program include accessibility to MSHA-approved/permissible dataloggers, availability of certain instrumentation, and NIOSH's interpretation and adaptation of installation procedures. The most challenging constraint to overcome pertains to MSHA-approved data monitoring systems.

Currently, there are no currently available permissible monitoring systems like the Campbell and MIDAS systems discussed previously. Nonpermissible monitoring systems can currently be purchased for use in nongassy mines. Because of this, there is gap in underground coal instrumentation needs related to a commercially available permissible datalogger that meets MSHA requirements. To bridge this gap, periodic readings can be taken with the use of handheld readout devices provided by instrument manufacturers.

The availability of instrumentation poses a challenge, particularly for the in-house production of the multipoint roof extensometer. Similarly, the standing support load cell has availability constraints, as the steel bladders are currently contracted for manufacturing in accordance with NIOSH specifications. The components of both items are available commercially for operators willing to do some light fabrication or have custom orders made. Additionally, multiple alternatives for roof extensometers are available on the market but will require modification to the installation procedures based on the manufacturer's recommendations.

Some of the installation procedures provided in this guideline have been modestly adjusted from manufacturer specifications to accommodate the limitations of the mine environment and equipment capabilities. These guidelines represent NIOSH's best practices, aiming to minimize impact to mine production yet maintain data reliability and quality.

CONCLUSION

In conclusion, this paper presented the available ground-control instrumentation and data acquisition used by NIOSH researchers. Mine operators and engineers who intend to start or enhance a ground-control monitoring program can use this information as a reference guide to better understand what instrumentation is available, what it is capable of measuring, and how NIOSH researchers utilize this data to further the NIOSH mission of reducing groundfall-related injuries and fatalities. Through highlighting the application and installation procedures of each instrument, data monitoring, and possible limitations, this guideline equips mine operators with the necessary resources to conduct their own comprehensive studies.

DISCLAIMER

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH.

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24-050

Hierarchical Training Pipeline for Event-Based Robotic Perception Models for Autonomous Roof Bolting

Rik Banerjee
M3 Robotics Lab, Colorado School of Mines
Golden CO, USA

Akram Marseet
M3 Robotics Lab, Colorado School of Mines
Golden CO, USA

Andrew J. Petruska
M3 Robotics Lab, Colorado School of Mines
Golden CO, USA

ABSTRACT

Event cameras are used for their performance in high dynamic-range lighting conditions which are canonical to active mining environments. Direct labeling of event-based image data to train a model to perform semantic segmentation using traditional methods is slow and error-prone. This study proposes a framework to use roughly hand-labeled color images from a mine as an input to an intermediary probabilistic algorithm called alphamatting to generate a ground-truth data set. These high-fidelity labels can be used to train a semantic segmentation model to differentiate the support strap from the roof. This model can then be leveraged to segment an event-based scene to enable autonomous roof bolting. This pipeline has been shown to achieve an accuracy of 88% with a false positive rate of 3%.

INTRODUCTION

Roof bolting is commonly regarded as one of the riskiest occupations in the United States [1]–[4]. This arises from several factors: the operator faces the danger of sustaining injuries from the bolting machine [5], and there exists a risk of becoming a victim of a roof collapse [6]. Furthermore, a significant portion of accidents occurs when operators with less than one year of drilling experience are engaged in bolting. Enhancing miner safety and productivity could be achieved by relieving operators of the need to be underground to identify roof drilling areas, position, and operate the drill. The low-light conditions in underground mines have been studied to have a measurable adverse effect on the health of the miners [7]. A robotic solution can be used to automate this process.

As can be seen in Figure 1, automating this process faces a two-fold challenge. Firstly, the autonomous system needs to classify the visual scene into *Rock* and *Not Rock*. This can be achieved by a process called semantic segmentation [8]. Secondly, a three-dimensional (3D) representation of the surface needs to be computed by using either stereovision or a depth sensor. This paper will present an architecture to solve the issue of semantically recognizing rock in an underground mine during active drilling operations. This means that the system needs to withstand vibrational loads, dust clouds, and challenging lighting conditions [7]. These elements pose challenges for implementing ready-made computer vision products to address these issues. Additionally, this work will introduce the use of neuromorphic sensors called event cameras, to perform the semantic segmentation task [9].

These cameras provide numerous benefits compared to traditional ones, including low latency, high temporal resolution, and an exceptionally high dynamic range [10]. These features enable effective information capture in a dynamic mining setting, resisting issues such as motion blur from vibrating sensor platforms, shadows from single-point source lighting, and interference from dust clouds. However, due to the novelty of this sensor, there is a lack of

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This work is supported by National Institute for Occupational Safety & Health | NIOSH/Project 75D30121C12206.