Underground Engineering

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Over 800 feet underground, surrounded by roughhewn walls under such tremendous pressure that leaning on them could cause them to violently explode, tests are run on a device which might someday be integral to rescuing miners trapped by cave-ins. The device, under development by a group of VMI cadets and professors, relies on seismic waves to transmit distress signals using the earth itself as a conduit. Essentially a modified speaker mounted on a spider-like frame, the VMIne is affixed to the roof of a mine tunnel and can produce vibrations that travel through the intervening rock which can be acquired by receivers many hundreds of feet above (Figure 1).

Figure 1: This is an early incarnation of the VMIne device. This generation of the device was tested in the limestone caves at the Natural Bridge Caverns, and its success led to further development and testing in commercial mines in Tennessee, West Virginia, and Pennsylvania.

Though mining fatalities are not nearly as common as they used to be, due largely to the efforts of the Mine Safety and Health Administration (MSHA), they still occur far too frequently, especially for the families affected by mining disasters. In 2012, there were 36 confirmed mining fatalities, and in 2013 there were 42. Though mines in the United States have been made considerably safer than they were twenty years ago, hazards are still ominously present in those dark tunnels in the earth. Heavy machinery make constant trips down narrow tunnels as miners engage in a flurry of activity in a hostile environment. The ubiquity of powerful digging machines and the constant threat of a natural disaster charge the atmosphere with nervous excitement, and every day workers in mines have to deal with the fear of being trapped in a deadly cave-in, despite the likelihood of such an occurrence being statistically rare.

To be trapped in a mine collapse is arguably one of the most terrifying experiences for a human being. In an instant, a miner's world can be shattered quite literally by a cave-in. One moment he is in a well-lit passageway supplied with a steady stream of clean air, the next he is plunged into absolute darkness. His air supply becomes slowly contaminated with carbon monoxide and methane, poisoning the lost and confused miner. Wired communication with his fellow miners and the surface are severed by thousands of tons of rock, and he is left helpless and invisible in the heart of the earth. The current safety system in place to guide miners beset by a cave-in consists of wires along the mine ceiling with fist-sized conic protrusions which allow a trapped and essentially blind miner to feel his way to the nearest safe house. These federally-mandated areas are stocked with food and supplies and supplied with plastic sheeting to deter methane from seeping in. If a miner can make it to a safe house he can survive up to two weeks on the emergency supplies of water, food, and oxygen. Beyond that span of time, a miner's chance of surviving dwindles as food and water run out and the air slowly becomes toxic. A well-paced borehole from the surface can provide trapped miners with fresh air, food, and water for months as was done in the Chilean mine disaster of 2010[1], however mines are often vast and in most cases of collapse rescuers do not know where to drill.

A perfect example of how ineffective communication methods doomed a group of miners trapped by a mine collapse is the mining disaster in Sago, West Virginia in January of 2006. In the early morning hours on January 2^{nd}, as the mine was reopened following the New Year's Holiday, thirteen miners in the first shift were trapped by an explosion between them and the surface entrance. The miners were approximately four kilometers from the entrance of the mine, and about 85 m below the surface. Two boreholes were drilled from the surface into areas where officials believed the trapped miners were located, but these turned up nothing. Professional mining operations are massive, sprawling complexes, and locating the correct position of miners with 15 cm boreholes is incredibly difficult, bordering on impossible, without a very good sense of the general area where they might be. Borehole drilling also requires specialized equipment and time, so rescuers cannot simply drill everywhere in the hopes of finding the trapped miners. In the case of the Sago disaster, the thirteen miners simply ran out of time. The tunnel they were trapped in rapidly filled with toxic levels of carbon monoxide, and twelve of the thirteen died in the dark depths of the mine simply because rescuers didn't know where to drill.

Not too far from the tragic mines in Sago, on an open field in Lexington, Virginia, cadets at the Virginia Military Institute test a device which could be instrumental in solving the communication issues which plague miners around the globe (Figure 2). Their efforts have resulted in the VMIne, a modified speaker which develops not acoustic but seismic waves, and allows signals to be sent through many hundreds of meters of rock and be received by a surface-mounted geophone which can pick out the specific transmitted frequencies amid a turbulent sea of background noise (Figure 3).

Figure 2: Cadet Will Flathers sets up a fourth-generation version of the VMIne on the parade field at the Virginia Military Institute. It many design iterations before the team developed a prototype that worked at depths of typical mines.

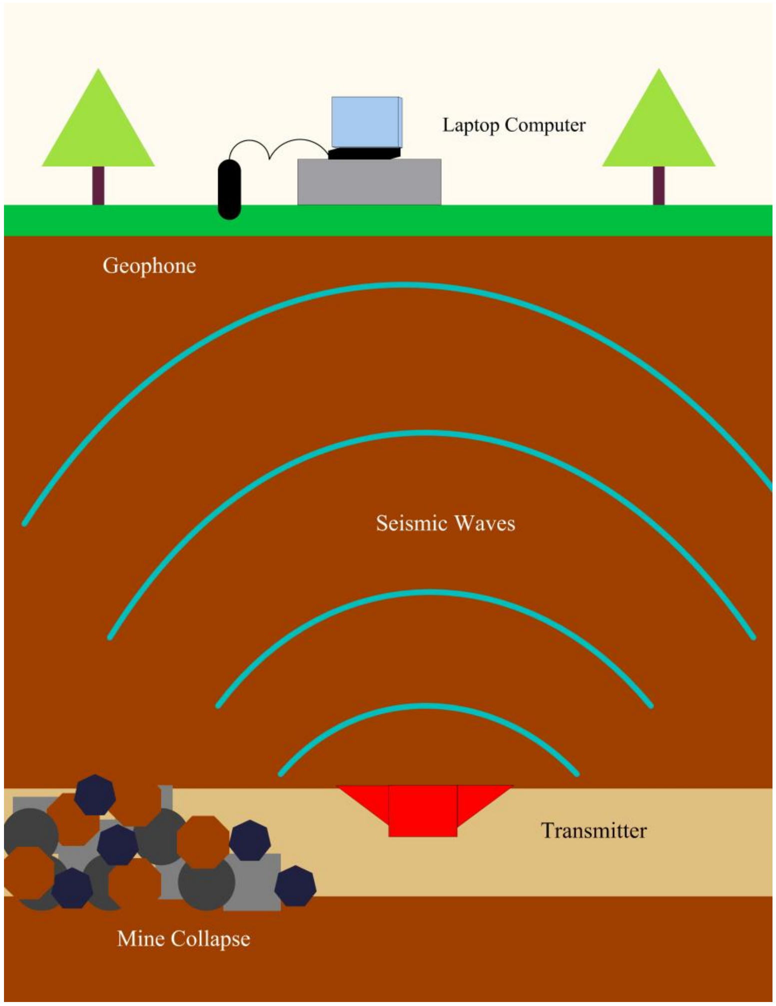

Figure 3: This schematic demonstrates how the VMIne is used. The transmitter, attached to the roof of a mine passageway, sends out seismic waves when activated. These waves travel through the rock and dirt and are picked up by a receiver topside. The frequency content of the signal is analyzed by a laptop computer, and the received signals are matched to pre-surveyed locations of safe houses in the mine.

The VMIne works using seismic signaling. Unlike radio waves and other common methods of communication that become less effective as more material is placed between the transmitter and receiver, the denser the intervening medium the better low-frequency pressure waves travel. This allows the signal transmitted by the device to travel from mine caves deep underground to the surface relatively intact, and in good cases principally degrading not from absorption but simply by spreading out with the characteristic $1/r^2$ drop in signal strength. Yet this drop is substantial, and when the seismic transmitter is placed 300 m down like a deep east coast coal mine (Figure 4), the signal received from the topside geophone is about 1 part per 100,000 parts confounding noise. A leaf landing on the ground 3 m from the geophone creates a greater seismic disturbance than the signal. To address this problem, each seismic transmitter uses a precisely-calibrated frequency keyed to that particular transmitter's safe haven location. In the event of a collapse, the topside geophone's information is analyzed in real-time using Fourier Transforms. In the first few seconds the short time window creates large sidelobes in the analyzed signal, blurring the transmitter's power under omnipresent background noise. After perhaps 15 seconds the resolution becomes fine enough to resolve the single frequency-locked beacon rising up out of the noise floor (see Figure 5), and the frequency location identifies the particular safe house and therefore its pre-surveyed location. Multiple seismic distress calls give rise to multiple peaks and each can be separately identified.

Figure 4: Profs. Squire and Sullivan set up the 12th generation of the VMIne in a commercial mine in Tennessee under the watchful eyes of a federal MSHA safety representative. The tests demonstrated that the VMIne could communicate in the deepest typical east coast mines, and shortly after the team licensed the device to a major mine safety equipment manufacturer.

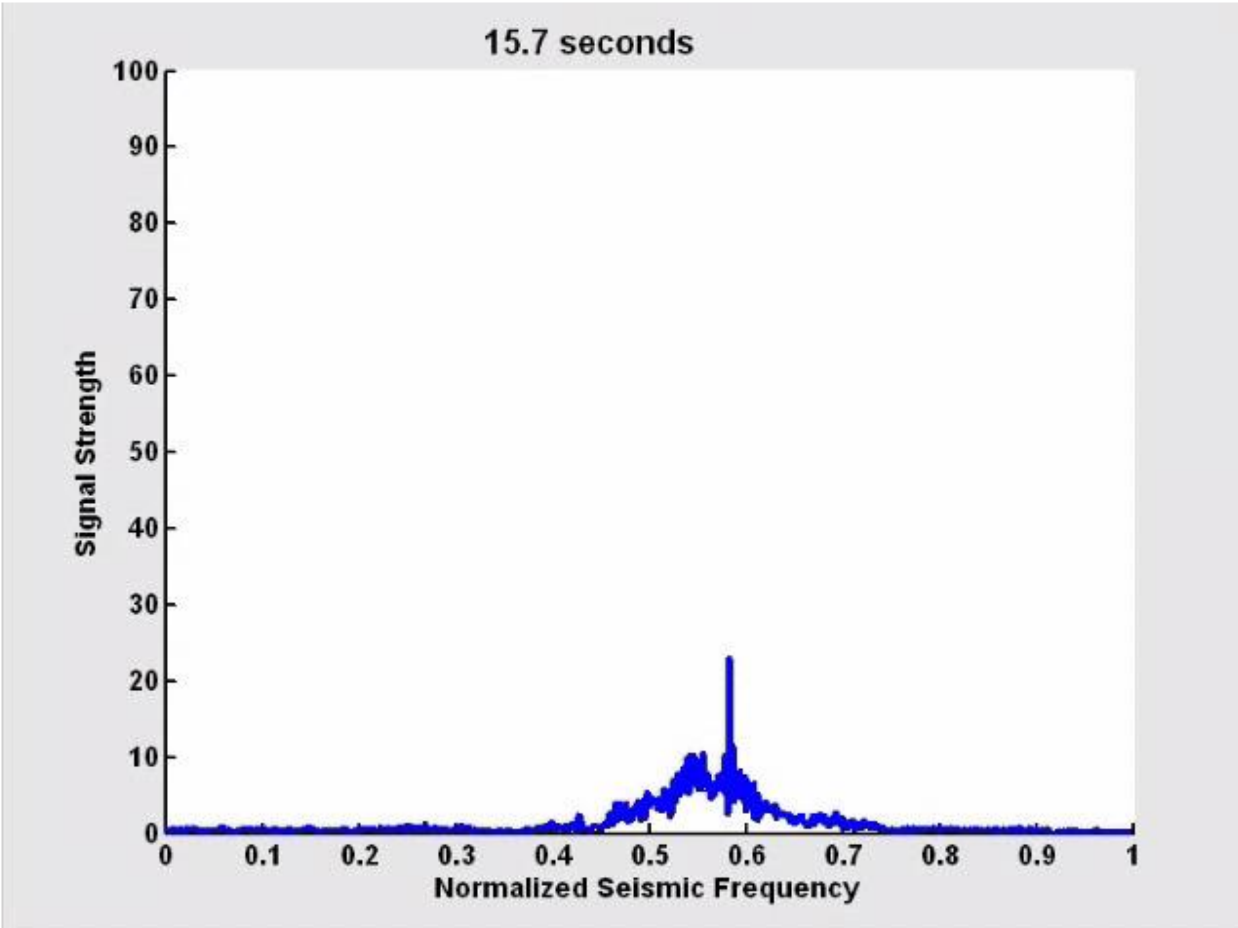

Figure 5: The laptop attached to the VMIne receiver shows a single transmitter’s signal emerging from the background noise floor after about 15 seconds of reception. It will rise linearly higher with further acquisition time. Rescuers reading the screen can associate a particular transmitter with the received frequency, which pinpoints mine collapse survivors in a pre-surveyed safe house location, enabling air boring or rescue operations to commence.

The transmitter itself is a 40 cm bass speaker modified to exert force into the ground. Unlike a normal speaker, which makes sound by vibrating a voice cone which in turn moves the surrounding air, the modified speaker’s voice cone is immobilized against the surface of the rock by a mandrel, and thus it is the 15 kg speaker frame that moves. This causes a pressure wave to be transferred into the earth with very little power lost to acoustic sound.

The first prototype to test the seismic wave concept was developed by Will Flathers, a junior at the Virginia Military Institute and advisors Dr. Jim Squire and Dr. Jay Sullivan shortly following the Sago mine disaster. The first prototype was tested on a nearby field, and failed. The second one did as well. The third worked – but then the researchers realized they were measuring acoustic, not seismic, coupling, and that design too was panned. It was not until the fourth generation that they achieved purely seismic signaling to 15 m.

Summer quickly flew by, and research and development was carried over into the academic year. Life at the Virginia Military Institute differs in many regards from that at most other colleges. The campus of VMI is relatively small compared to other universities, and to test the device cadets sometimes had to share the parade field with various other groups on campus. On one such occasion, the local Army ROTC department decided to use the experiment as the target for their training scenarios, and the testing area was subsequently "invaded" and "secured" by cadets in Army training. Despite the various distractions of the school year, the VMIne system was soon optimized to the point that it was ready for more challenging tests than across parade fields. The first real test site was in the limestone caves at the Natural Bridge Caverns, located only a short distance from VMI. Testing was a struggle in the caverns. The team could not affix the transmitter to the ceiling around colonies of bats, as the caverns are located in a national park and the bats are federally-protected species; many ideal sites were nixed because of this. The best site remaining provided its own set of challenges. The floor was sloped, making stabilizing the transmitter difficult. One of the professors working with the team was nearly injured when one of the 3 m legs attached to the 35 kg transmitter snapped as he was supporting it high on a ladder, causing the device to rotate precariously around one of the remaining legs before it was immobilized by a student who found a nearby broom handle.

The device was patented, naming the undergraduate who worked on it and his advisors, and further improved. By the 12th generation it was licensed to a major international global supplier of mine safety equipment, and is now on the 14th generation and ready to be manufactured in quantity. Its first commercial sale is waiting only on examination from the federal Mine Safety and Health Administration (MSHA), which must approve every high current electrical device used in mines to ensure it cannot cause an explosion in a high-methane atmosphere. This approval process is detailed and is expected to take roughly two years before working miners see the first units. Someday, miners trapped by a cave-in may be relying on this device to allow rescue teams to quickly locate them and drill a borehole to sustain them until a rescue operation can be mounted. Soothed by the deep bass hum of the transmitter, a trapped miner can patiently wait, safe in the knowledge that help will arrive shortly.

About the Authors:

Joseph LaMagna is currently a sophomore at the Virginia Military Institute's Electrical and Computer Engineering Department. While not laboring over Laplace Transforms and opamp circuits, he can often be found playing the bagpipes in the VMI Pipe Band, or electric guitar in the VMI Jazz Ensemble. Upon graduation he hopes to commission as an officer in the U.S. Army and fly helicopters.

James Squire is a professor at VMI James Squire is a Professor of Electrical Engineering at the Virginia Military Institute. Dr. Squire received a B.S. from the United States Military Academy and his Ph.D. from the Massachusetts Institute of Technology. He was awarded a Bronze Star in the Army during Desert Storm and was selected as Virginia's Rising Star professor in 2004. He maintains an active consulting practice in design of electronic props for movie and television production.

Read More About It:

1. Barrioneuvo A., Romero S., "Trapped 68 Days, First Chilean Miners Taste Freedom." *New York Times*, October 12, 2012.

2. Squire J.C., Sullivan G.A., Baker E.W., and Flathers G.W. "Proof-of-concept Testing of a Deep Seismic Communication Device." *Society for Mining, Metallurgy, and Exploration*, Vol. 326, pp. 97-100, 2009.