



AziSA: improving mining decisions with real-time data

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Synopsis

South African underground hard rock mines are typically managed using measurements made daily, weekly or even monthly of key parameters such as face advance, readiness to blast, blast success, temperature or dust levels. Health, safety and productivity can all be greatly improved if a real-time measurement system can inform decision making.

To enable this vision of widespread sensing, communication and decision support, CSIR has developed an open standard architecture for communication of sensor data, and a reference implementation using that standard. The standard, called AziSA, meaning 'to inform' in isiZulu, will allow any device that complies with it to join any network that supports it. The standard is designed for South African gold and platinum mines.

To be practical in a typical Bushveld platinum mine, a real-time sensor system needs to be robust, reliable and cheap:

- Sensors are equipped with power sources that will last as long as the sensor is required. In effect, sensors need to be disposable: cheap enough not to warrant repair if they break.
- Communication in the stope is wireless, to avoid the reliability problems associated with wire connections. For example, wires to sensors in the face area are unlikely to survive blasting.
- To get information out of the stope, the power line to the scraper winch is used as a communications link. Unlike a separate communications link, the power line will be repaired if damaged, because of its importance to production.
- Outside the stope, communications are transferred onto the mine communication infrastructure.

To succeed as a management system, the next key element is the use of software decision support tools that will analyse masses of real-time data to extract key parameters and trends for decision makers.

A range of sensors has been developed, including commercial sensors that have had wireless adapters added to make them AziSA compliant, and bespoke sensors that provide low cost sensing of typical mining parameters.

An important parameter in any sensor network is the location of the sensor. This has to be easy and cheap to establish, so a tool has been developed to locate sensors in the confines of a stope, using ultrasonic and radio techniques. Once sensors are installed and located, they associate their location to all data that they produce.

All the data from the system are captured at surface in a flexible database that can be queried by any application that requires data of any kind. It is simple to program alerts, and for actions to be associated with alerts. The use of wireless in stope also allows for communication from surface to the stope, or from stope to stope.

The first implementation of an AziSA compliant system is being installed as part of the Mine Health and Safety Council funded rockfall elimination project. The design is discussed, and a future application for a platinum mine is considered.

Introduction

Platinum mining in South Africa is typically undertaken on thin seams having low to moderate dip and huge lateral extent. The relatively poor grades dictate a high requirement for capital, but the extent of the orebodies provides a very long life of mine in which to recover that capital.

Historical mining practice has been dominated by hand operated drill and blast methods, although the industry is slowly moving towards mechanization. Hand operated drill and blast is cyclic, as mines must be vacated during blasting. The underground environment contains hazards to both health and safety, leading to accident levels that are higher than international norms. It can also lead to occupational health problems including noise induced hearing loss and heat stress.

The industry is also under pressure from various quarters:

- The demand for platinum is increasing, while supply levels remain constant, leading to increasing platinum prices. If supply cannot be increased, there is a risk that platinum may be substituted in its primary application, vehicle catalysts for diesel cars. If supply is increased, the price for platinum will fall. In either case, it is essential that platinum mining companies control costs
- The industry, local and globally, is suffering from an unprecedented skills shortage at all levels, from labourers through professionals to management. The availability of skills is now becoming a limiting factor in the development of new projects, and is also being felt as a damper to productivity on existing operations

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- The safety and health record of the South African mining industry, together with its environmental legacy, are slowly causing society to retract the social license to mine. This can be felt in the negative tone of media coverage of recent events such as the shaft accident at Elandsrand in October 2007¹¹, the silicosis compensation claim against Anglo American^{7,8}, and growing interest in pollution from tailings dams in the West Rand¹⁴. The social perspective of mining is leading directly to opposition to new operations, and indirectly to skills shortages.

Part of the solution lies in better management of narrow stope underground mining operations. If operations can be managed more effectively, costs can be controlled and health and safety can be improved, leading in the long term to the return of the social license to mine. The primary obstacle to better management at present is the absence of real-time objective information on which to base decisions.

Here we present a philosophy, a standard, and a reference implementation for a technology that can make widespread real-time sensing a reality in South African underground operations. We also show how the sensing can be used as an input to decision support systems, so that the operator is able to make better decisions without information overload.

Philosophy

In 1989, Ackoff described the concept of the data-information-knowledge-wisdom hierarchy¹, which underlies the architecture of the sensor-network discussed here. The hierarchy describes how measurements can become the basis for decisions (Figure 1).

- At the lowest level in the hierarchy are data. Ackoff and others^{1,2} define data as simply symbols, or what we call measurements. However, measurements have no value without some descriptive information as to when they were made and where they were made. A temperature reading of 29° C is meaningless. If it is the temperature today in Springbok, it becomes an item of data

- Information is formed by data in relationships. The data acquires meaning through its relationships with other data. For example, if other information is available for Springbok, such as wind speed and direction, and for other towns in the Northern Cape, the data are now becoming information
- Knowledge is the appropriate collection of information. It implies an application of data and information and is formed through the process of understanding patterns. Using information from all the towns in the western half of the country, and our knowledge that some weather patterns move from west to east, suggests that tomorrow will be warm in the eastern half of the country
- At the top of the hierarchy is wisdom. Wisdom is evaluated understanding. While the first three categories relate to the past, it is wisdom that deals with the future. From the knowledge that the weather will be fine in Johannesburg tomorrow, a wise person can make an informed decision about the future, such as whether to hold a braai or not.

In the context of a measurement system, data are raw measurements, stamped with time and date. Information is created by gathering data in a relational database, allowing connections to be identified. The process of generating knowledge out of information is still a frontier for computer science research because it is difficult for computer systems to reason about patterns. Finally, wisdom remains the domain of the human: even when knowledge can be deduced automatically from information and knowledge, decisions about the future are still made by humans.

In the context of decision support for mining, a similar hierarchy can be constructed. For example, ventilation is provided underground primarily to protect the health of workers, through providing a sound working environment, but also to protect the safety of workers by eliminating the build-up of explosive gases such as methane. To determine the state of the system, many sensors can be used. As illustrated in Figure 2, the data exist at the sensor level. This can be combined into systems, here for environment or

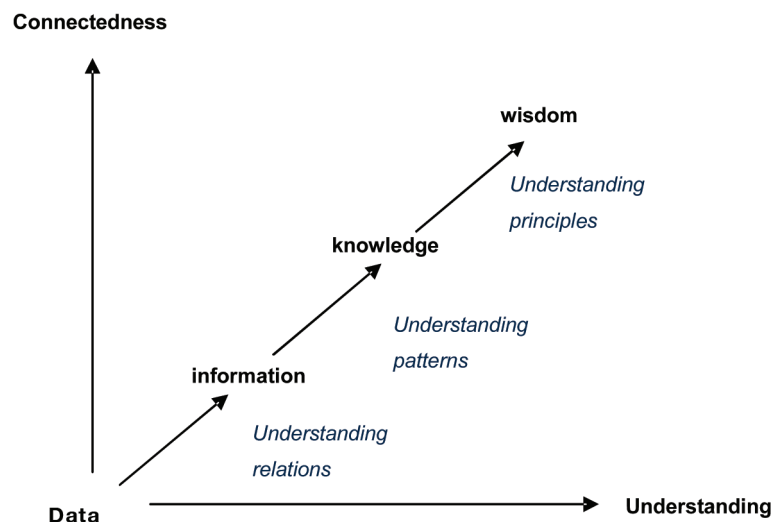


Figure 1 – The data-information-knowledge-wisdom hierarchy

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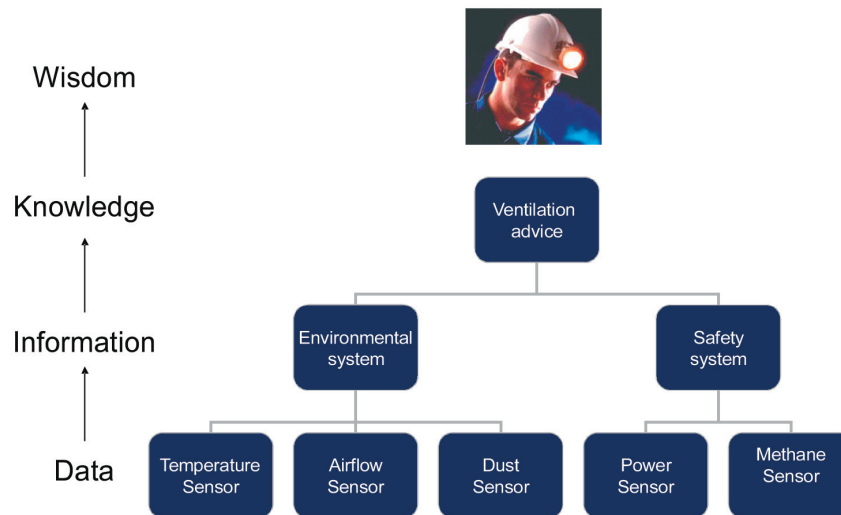


Figure 2—Environmental sensors as an example of how the AziSA hierarchy can be applied in mining applications

safety, at the level of information. At the knowledge level, advice can be given on the solutions to both environmental and safety problems. In both cases, the knowledge is encapsulated as ventilation advice. At the top level of the hierarchy the wisdom of the decision maker informs decisions on actions to take, as a result of knowledge provided by the system.

The AziSA standard

AziSA is a specification for an open measurement and control network architecture that can form the basis of systems that apply the data-information-knowledge-wisdom hierarchy in underground platinum and gold mines. AziSA itself is an open standard, which references other open standards, including IEEE 1451⁹, Zigbee¹⁶ and CORBA¹³.

Physical and logical architecture

The physical architecture of a typical deep-level platinum mine resembles an upside-down tree: it consists of a single shaft, branching underground into a network of haulages and cross-cuts, similar to the branches of a tree, with working places at the end of the haulages, analogous to the leaves on a tree.

The physical architecture suggests a logical architecture that forms the basis of the AziSA specification (Figure 3), discussed in more detail in¹⁵. At the root of the tree is the class 1, the network controller and data warehouse. There is a single class 1 in an AziSA network. The class 1 communicates with a number of class 2s. Typically, there will be a class 2 in each working place that has AziSA sensors installed. The sensors themselves communicate with class 2s, and with each other, and are further classified as class 3s and 4s.

The class hierarchy is defined by decision making power:

- Class 4 devices are capable only of making measurements, and of passing these back to the class 2s and the class 1
- Class 3 devices can take measurements, but can also

make decisions based on their own information. For example, a methane sensor could be a class 3 device: on measuring methane above a threshold, it could initiate a local alarm

- Class 2 devices aggregate data from all the class 3s and 4s in their wireless network. They can then use data from multiple sensors to make decisions, but they can use data from only their local wireless network, and not from sensors reporting to other class 2s. For example, if a methane sensor signals a high methane level, and an air flow meter signals a low airflow rate, the situation is more serious because the lack of airflow indicates that methane is not being cleared. The class 2 might then raise an alarm over a wider area than the alarm raised by a single class 3
- Class 1 devices have access to all the data in the

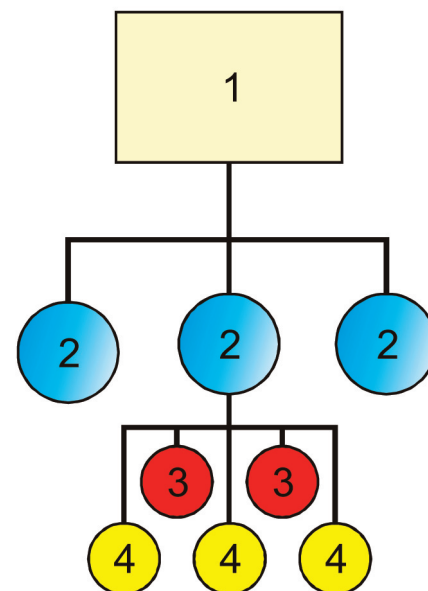


Figure 3—The AziSA logical architecture

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network. Their primary task is to collect and store data, but applications that access the data on the class 1 can then undertake analysis in order to provide diagnostic information. To continue with the example, if a class 2 has raised an alarm as a result of poor airflow and methane build-up, an analysis program using class 1 data might query data from nearby networks to determine if the ventilation has failed generally or just in that single area. It can then issue a warning with advice on corrective action.

Scope of the AziSA specification

The AziSA specification describes the hierarchy discussed above; a set of messages that must be understood by all compliant devices; and a data storage format that allows for generalized storage of data, even from sensors that have not yet been invented. To comply with the standard, this basic set of characteristics has to be implemented. A key part of the specification are that sensors need to be able to describe themselves. Sensor metadata are implemented through the IEEE 1451 transducer electronic data sheet or TEDS specification⁹.

Further, AziSA contains profiles. These are standard ways of implementing specific features in an AziSA compliant network. At present, two profiles exist: AziSA Zigbee and AziSA TCP/IP.

AziSA networks do not have to use the profiles, unless they use the specific technologies. For example, the standard does not require that a sensor network be wireless, or that it be Zigbee if it is wireless. However, if the sensor network is a Zigbee network, the standard requires the Zigbee protocols to also be compliant with the AziSA Zigbee profile.

AziSA Zigbee profile

A sensor and communications network for widespread sensing in underground mines has to fulfil a number of requirements:

- It has to be cheap. Sensors need to be low cost to be widely deployed
- Sensors have to be maintenance free. In many cases, the working places where sensors might be deployed rapidly become back areas where no access is available
- Deployment has to be quick and painless. At present, a major cost in any sensor deployment is the cost of wiring in the sensor.

The first requirement for the sensor network is that the sensors themselves need to be wireless. The wireless network is further constrained by the requirement for low maintenance: battery life should be sufficient for the entire life of attached sensors.

For low cost, and low power, Zigbee was chosen as the wireless sensor network backbone. Zigbee is an emerging standard for very low power, low data rate, wireless mesh networking⁶. It is expected to become as ubiquitous as Bluetooth for applications such as energy management and home automation, and components to implement Zigbee communications links are targeted at a quarter of the price of Bluetooth components.

In a typical AziSA network, all communication between class 2s, 3s and 4s would be via AziSA Zigbee.

AziSA TCP/IP profile

In the AziSA standard, the communications links between the various class 2s and the class 1 are not specified. The simplest hardware and transport layer to implement in practice is probably Ethernet, TCP/IP. If TCP/IP is used as the transport medium, the AziSA TCP/IP profile defines the method of communicating between the class 2 and the class 1.

The profile is implemented using CORBA: the Common Object Request Broker Architecture is a standard defined by the OMG (Object Management Group) that defines how software components written in different programming languages can access other components over the network¹². It forms the basis of a distributed programming model in which programs written in, say, C++ and Java can communicate with each other remotely. In our case the class 2 aggregator nodes are embedded Linux devices programmed in C++, and the class 1 server node is a Windows computer running Java; the class 1 and class 2 can share each other's object model, so that accessing the class 2 becomes as simple as the class 1 making a remote method call.

CORBA handles the details of how the actual data are transmitted between these computers, and thus establishes the standard so that these different platforms can interoperate. It allows the system designer to work at a higher level, without having to worry about the mechanics of data transfer and with confidence that any compliant CORBA implementation can be used. Software can then be written with the appropriate language and tools for the given platform, knowing that all components share a common protocol.

The shared object model is specified by a description language known as IDL, which defines classes and the relationship between them. This IDL can then be compiled into either Java or C++. The AziSA CORBA profile provides an object model that encapsulates the interaction of the server and its aggregators.

Implementation

The AziSA project, as undertaken by CSIR, delivers a standard and a reference implementation. The implementation is not the standard: other implementations using very different technologies can comply with the standard. However, the reference implementation is described here as an example of a physical AziSA system that has been constructed and is operational.

Sensors

A number of sensors have been developed, and other sensors have been connected to AziSA radio modules to allow them to be included as AziSA sensors. As an open standard, it is expected that new sensors from different vendors will become available with time. The CSIR is not developing many novel sensors, but is working to integrate available sensors into the AziSA architecture:

- A novel closure meter sensor has been implemented already. It uses low power design to operate for weeks on a single battery, and has relatively low cost
- A basic environmental sensor has been implemented. It can measure temperature, and with external sensors can also measure humidity and airflow rate

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- It is planned to match a commercially available methane sensor with an AziSA radio to allow for real-time methane sensing
- A simple tilt sensor is being developed for rock monitoring applications
- Also for rock monitoring applications, an existing crack counter is being integrated with a Zigbee radio.

Zigbee is a relatively low data rate connection system. In addition, transmitting over a radio link consumes power, so the network spends most of its time asleep to minimize power consumption. These characteristics imply that video is not possible within a low power Zigbee network. However, a still camera would be a very useful sensor for returning pictures from workplaces. If the power budget can afford the required lighting, a still camera sensor will be developed.

Two mobile sensors are being developed or integrated into the AziSA standard:

- Research sponsored by the Mine Health and Safety Council showed that loose rock that might fall could be identified because it is slightly cooler than rock that is firmly attached to the surrounding rock mass¹⁰. The cooler rocks can be identified using a thermal infrared camera
- The CSIR has developed an electronic sounding tool that attempts to mimic the performance of an experienced miner in determining whether rock is attached firmly to the hangingwall. It cannot outperform the most experienced human miners, but does keep its performance level through a shift, and is not affected by illness or failing hearing.

Both of these two tools provide immediate information as to whether parts of the hangingwall may be loose or dangerous. By integrating a location sensor and communication to an AziSA system, the results from the sensors can be tied to specific locations and stored for analysis, allowing trends to be identified and risks to be assessed in advance of the first inspection of the day.

Location

It is intended that the system will support mobile sensors. As all data have to be tagged with location, a system of locating mobile sensors has been developed⁴. The system uses ultrasonic beacons each of which simultaneously transmits an ultrasonic pulse and an electromagnetic pulse. The electromagnetic pulse acts as the synchronization signal to measure the time-of-flight of the ultrasonic pulse. All the roaming sensors in the area can then determine the time of flight and hence distance to each beacon. With three or more beacons the mobile sensors can then trilaterate their positions. In surface conditions, location is remarkably accurate, down to centimetres under ideal conditions. While performance is expected to degrade underground, locations are only required with 250 mm—500 mm accuracy for many sensing purposes underground.

The prototype hardware is illustrated in Figure 4. The prototype hardware contains both ultrasonic transmitters and receivers, so can function as a beacon or as a roaming device. In practice, beacons will be deployed at known positions in the area where location is required, typically at, or close to, survey pegs. When fixed sensors are installed, their location can be determined and programmed into them using a separate handheld receiver unit. Mobile sensors, such as those attached to people, will contain ultrasonic receivers and

will automatically record position as the sensor moves.

Wireless network

The wireless network is being implemented using the AziSA Zigbee profile. The Zigbee development has been undertaken using an Ember Zigbee chipset, due to the ready availability of development tools. Zigbee devices from any manufacturer can be used within the network, but Zigbee is relatively immature, so some teething problems are bound to occur.

With time, it is expected that a very high degree of compliance with the basic Zigbee specification will be achieved by a number of radio transceiver manufacturers. Once basic Zigbee compliance has been achieved, adding the AziSA profile is relatively simple. A simple sensor board is illustrated in Figure 5. The board itself is green, with the Zigbee radio mounted on it in red. For scale, the whole circuit is about the size of a PP3 9V battery.

The aggregator, or class 2

In the CSIR implementation, the aggregator obtains power from the power supplied to the stope, usually for the scraper winch. It communicates with the class 1 along the power cable using a power line carrier modem, discussed below. Local communication with the wireless sensor network in the working place uses a Zigbee radio. The class 2 itself is implemented using a small computer called a Gumstix that runs a version of Linux⁵. The Gumstix is approximately 80 mm × 20 mm in size, and uses low power components. The use of a fully fledged operating system on the Gumstix allows for easy and rapid development of applications, and for remote access and debugging if required.

The class 2 continuously logs data collected in its network to solid state flash disks, and communicates that data to the class 1 when a communication link is available.

Communications underground

In the reference implementation, the class 2 communicates

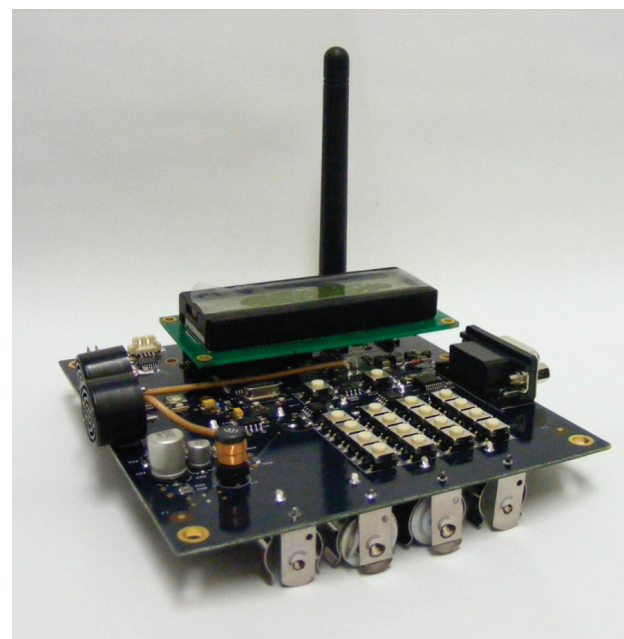


Figure 4—The ultrasonic time-of-flight location tool

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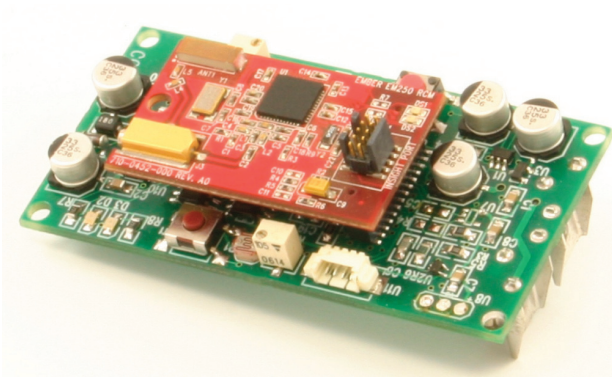


Figure 5—A sensor board with a Zigbee radio attached

directly to a power line carrier (PLC) modem. Another PLC modem is placed at the opposite end of the power line, where the signal can be transferred to the mine-wide communication network. In some mines additional hardware will be required to convey the PLC signals across transformers, while other mines have Ethernet available at the transformer that supplies the working place. In either case, TCP/IP is the transport medium.

The Class 1, or database

The class 1, on surface, collects data from across the network. It also controls the network, and can issue alarms back into the network, for transmission to people in the working places. Hardware wise, the class 1 is a standard server class machine, designed for high reliability. The major features of the class 1 are:

- Information about each sensor is stored, including its ID, its position and what it measures. This makes discovery possible: a client of the class 1 can determine whether sensors exist to provide particular types of data
- Data from the sensor are stored, always tagged with ID and time. If the sensor is mobile, the data are also tagged with its location; otherwise the location can be determined from the location of the sensor
- The class 1 can accept requests from external clients to register monitors. If a monitor is registered for a particular sensor or class of sensors, any new data acquired by the sensor will be distributed to that monitor as it arrives
- The database is designed to be readily queried
- The database design allows for unknown new sensor types to be included in the database automatically. A new type of sensor can be installed underground in a wireless sensor network, and the class 1 will start to acquire and store data from that sensor without prior programming to support the sensor.

Converting information to knowledge and wisdom

In the AziSA architecture, the final step of mining the data stored on the class 1 is left to clients of the class 1. How this is done is not specified by the standard. Once the AziSA infrastructure is designed and in place, adding additional sensors, or additional communications methods or additional

networks is expected to be relatively easy. However, the challenge of using the data will remain. Each application of a sensor network is likely to require substantial investment in design to capture the processes currently undertaken by people to synthesize data into knowledge. What AziSA does do, is free the designer from concerns over the hardware required to get the data.

Case studies

A rock belt monitoring system

The first application of AziSA principles and components of an AziSA system was to a system for monitoring ore and waste belts on a gold mine. On this particular mine, gold ore is associated with uranium, and therefore with modest levels of radioactivity, whereas waste is not radioactive. Geiger counters are mounted above each belt, monitoring the rock that comes past on its way to the plant or to the waste tip. The Geiger counters can determine if the wrong rock is on the belt.

The mine also has a system of radio frequency tags that are scattered in the stope faces before blasting. After blasting, they join the recently blasted rock as it travels through the mine transport system. As the tags pass the Geiger counters, their identification can be determined, pinpointing the location on the mine where ore or waste is coming from.

In the system the Geiger counter is connected to a simulated class 4 running on class 2 hardware, and communicating through software to the class 2 program running on the same hardware. The link from the class 2 to the class 1 is hardwired Ethernet TCP/IP and runs on the mine's control network. The communication protocol used is AziSA TCP/IP, and the database on the class 1 complies with AziSA specifications. A web server also running on the class 1 makes information from the system available to clients on the mine, who can observe the radioactivity history of each belt at any time.

The system does not provide the highest levels of the D-I-K-W hierarchy, but does show how sensing can improve mine management: problems in ore waste allocation can be quickly identified, traced to source and corrected.

A rockfall early warning system

The Mine Health and Safety Council gazetted a project in 2006 to research and develop a system to provide mines with an early warning of rockfalls. The CSIR was awarded the project, and is using AziSA as the infrastructure to undertake the monitoring³.

In this application, the parameters to be monitored are still to be determined. There is no known unequivocal precursor to a rockfall, so a major component of the work is to monitor a number of potential precursors on a large number of mines, in the hope of statistically linking a particular precursor to a rockfall under specific circumstances. As the project has developed, it has migrated from detecting precursors to quantifying the risk of a rockfall in a particular working place.

An AziSA compliant sensor network is being deployed at a gold mine. Zigbee closure meters have been installed, together with a class 2, PLC communications and a class 1. At the time of writing, the system was being commissioned.

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In the short term, closure is the primary parameter that will be monitored. Other parameters of interest are microseismic activity in the panel (not to be confused with mine-wide seismic activity), the thermal signature of loose rocks in the hangingwall, and the state of rock as determined by barring. In the case of barring, the miner doing the barring can become a mobile sensor, with his location determined by ultrasonic transducers. The location of good and bad hangingwall conditions can therefore be mapped, and continuity can be determined from day to day. In the future, geotechnical information determined from drilling rate can be added to the network.

In this application, alarms may be generated at all levels of the hierarchy:

- A class 3 device can raise a local alarm, for example a closure meter can determine from rapid closure that a rockfall is imminent
- A class 2 device can raise an alarm in a panel, for example if a number of microseismic sensors simultaneously start to indicate failure occurring at several locations in the panel
- A class 1 device can take data from several locations on the mine and pass that to a client system, which could issue a warning based on a combination of local closure, regional closure, regional seismicity and current mining layouts. In this case, the warning is likely to be of increased risk, rather than imminent failure.

The future in platinum mines

The AziSA infrastructure can make it possible to measure and manage aspects of a mine that are currently impossible to deal with in real time. The list of potential applications is long, but can include:

- Asset tracking
- In-stope text communication
- Energy use monitoring and control
- Drill utilization monitoring
- Emergency communications using PLC along power lines instead of dedicated telephone lines
- Environmental management
- Scheduling optimization for locos and trackless machine.

An emerging application is in personal environmental monitoring. The exposure of miners to occupational health hazards such as noise or diesel particulate matter can be measured using personal dosimeters. To take prompt management action to control sources of exposure, it is necessary to link personal exposure to the source of exposure in near real time. If personal dosimeters are part of an AziSA network, as mobile sensors, and transmit their data back in near real time, it then becomes possible see anomalous events, for example a sudden increase in dust exposure, and take management intervention, for example to increase ventilation to the affected area. The benefit of linking to personal dosimetry is that control of physical stressors is concentrated in the areas of the mine where the most people are present, limiting costs and increasing effectiveness of control measures.

Conclusion

AziSA is a set of standards and a reference implementation, an architecture for a sensing and communication infrastructure, and for a set of tools. AziSA is not an application: many applications will run using underlying AziSA architecture. However, AziSA can be used to define an infrastructure for data acquisition and control, which can be shared by a large number of applications.

At present, a prototype full implementation of AziSA is being installed on a gold mine, to be followed before April 2009 by installations on several other mines, including platinum mines.

As the implementation matures, it is hoped that manufacturers of mining instrumentation will start to make their equipment AziSA compliant, to the benefit of the industry as whole.

The concept has proved itself in its ability to provide management information to control waste tipping at a gold mine. Many other applications await.

References

1. ACKOFF, R.L. From Data to Wisdom, *Journal of Applied Systems Analysis*, vol. 16, 1989. pp. 3–9.
2. BELLINGER, G., CASTRO, D., and MILLS, M. Data, Information, Knowledge and Wisdom, www.systems-thinking.com/dikw/dikw.html, retrieved 3/07/2008, 2007.
3. BRINK, V.-Z. and ROBERTS, M.K.C. Early Warning and/or Continuous Risk Assessment of Rockfalls in Deep South African Mines, *4th International Seminar on Deep and High Stress Mining*, Perth, Australia, 7–9 November 2007.
4. FERREIRA, G. An implementation of ultrasonic time-of-flight based localization, *2nd International Conference on Wireless Communication in Under-ground and Confined Areas*, Val-d'Or, Quebec, 25–27 August, 2008.
5. GUMSTIX, Dream, design and deliver, <http://gumstix.com/about.html>, retrieved 22/7/2008.
6. KINNEY, P. ZigBee Technology: Wireless Control that Simply Works, *IEEE Communications Design Conference*, October 2003.
7. MOMBORG, E. Anglo being sued for R20m, *Sunday Independent*, 30 September, 2007, http://www.iol.co.za/index.php?art_id=vn20070930090754591C491908, retrieved 3/07/2008.
8. MORRIS, R. Silicosis prevalence among gold miners continues to soar, study finds, *Business Report*, February 17 2008, <http://www.busrep.co.za/index.php?fArticleId=4256504>, retrieved 3/07/2008.
9. NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY, IEEE 1451 Home Page, <http://ieee1451.nist.gov/>, retrieved 23/7/2008.
10. OLDROYD, D.C. A feasibility study of thermal imaging equipment to identify potential rockfalls, SIM 040202, Department of Mineral and Energy Affairs, South Africa, 2006.
11. OLIVIER, M. Harmony's Elandsrand mine to close for up to 6 weeks after accident, www.miningweekly.com/article.php?id=118363, retrieved 3/07/2008.
12. OMG GROUP, CORBA Basics, <http://www.omg.org/gettingstarted/corbafaq.htm>, retrieved 24/07/2008.
13. OMG GROUP, CORBA/e Draft Adopted Specification, <http://www.omg.org/cgi-bin/apps/doc?ptc/06-05-01.pdf>, retrieved 23/7/2008.
14. SUPER DUMP, *Special Assignment*, SABC, 18 June, 2008, <http://www.sabcnews.com/specialassignment/features/1806/script.html>, retrieved 3/07/2008.
15. STEWART, R. DONOVAN, S.J. HAARHOFF, J., and VOGT, D. AziSA: an architecture for underground measurement and control networks, *2nd International Conference on Wireless Communication in Underground and Confined Areas*, Val-d'Or, Quebec, 25–27 August, 2008.
16. ZIGBEE ALLIANCE, Download Zigbee Technical Documents, http://www.zigbee.org/en/spec_download/zigbee_downloads.asp, registration required, retrieved 23/7/2008. ♦