Predictive Network Modelling with Live Sensor Data

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ABSTRACT

Advanced fibre-optic based sensing systems are fast growing and replacing conventional sensors in many industries due to their reliable measurements, fast response, and intrinsically safe operations. The deployment of any sensor system however remains a potentially expense and disruptive activity and may be limited in areas with difficult or unsafe access, or without communication systems.

A predictive modelling tool that accepts live data and outputs both real and predictive estimations between sensors may have great application by limiting the number of sensors required, or covering areas unable to be monitored by sensors. A transient based simulation model incorporating real-time actual and simulated data can be merged to display predicted conditions through a mine or tunnelling system at any time. “Ventsim Visual” software is used as a graphical interface to demonstrate the effectiveness of this approach.

Keywords: Environmental Sensors, Computational Modelling, Mine Ventilation Simulation

1. INTRODUCTION

Mine atmosphere monitoring has been an important safety consideration. In the previous decade, high profile coal incidents in New Zealand, Turkey, and the USA resulted in the combined deaths of hundreds of miners, while reported deaths in China between 2001 and 2008 totalled over 8,000 fatalities from 1,027 reported accidents [1].

Brnich [2] chronicles a long history of mining disasters, and the impact they have had on modernising and improving safety and regulations at mines. More sophisticated sensors and better communication has played a large role in improving safety, and many of the restrictions of monitoring dangerous atmospheres is being resolved using new sensor technology, however the number and effective placement of the sensors remains both a budgetary and practical limitation in their wider use.

In most cases, coverage of every location of a large modern mine with sensors is not possible. In these cases, the combined use of real-time sensor information coupled with network analysis techniques to intelligently predict atmosphere in areas not covered by sensors promises to reduce cost and increase applicability of sensors in mines.

1.1. Early Detection Methods

It has long been recognised that poor atmospheric conditions in underground mines can result in poisoning of miners, gas explosions or fires [3]. In the 19th and early 20th centuries, miners would carry canaries into a mine to detect gases such as carbon monoxide, carbon dioxide and methane. In the presence of poor atmospheres, the normally songful canary would become quite and listless, a sign of abnormal atmosphere composition [4].

By the middle 20th century, new methods of gas detection were introduced using chemical reaction chemistry such as reactive paper or crystals that changed colour on exposure to certain gases. Methane or oxygen deficiencies could be detected by changes of flame colour behind a mesh screened device known as a safety lamp.

By the late 20th century to current day while chemical devices continue to be used for spot checks, most permanent or semi-permanent mounted devices had progressed to electro-chemical devices that could show readings through calibrated meters or electronic displays (Figure 1). In addition, the introduction of electronic communication methods such as solid cable, leaky feeder, coaxial cable, and fibre optic allowed the information to be instantly transmitted to a remote location for centralised monitoring, analysis and recording.

Figure 1: Drager X-am 5600 Electro Chemical Gas Detectors [5]

1.2. Modern Day Systems

Many mines today utilise an array of sensors to monitor everything from atmospheres and ventilation devices, to numerous other mining related conditions such as water, rock stability and equipment processes. In most cases, sensors are connected through centralised mine communication systems to transmit information back to a control room as shown in Figure 2.

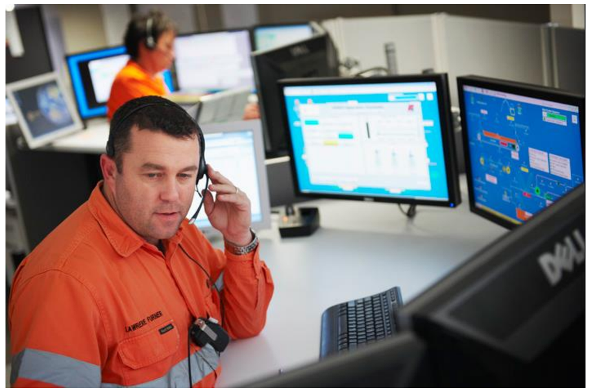

Figure 2: Mine Control Room (Courtesy Newcrest Mining, 2016)

In mines where atmosphere may not be deemed safe for electrical devices such as gassy coal mine, gas tube bundle systems are often used to suck small samples of atmosphere to a surface monitoring location [6]. The disadvantage of tube bundle systems is a time delay between collection and reporting of gas sample concentrations, however the introduction of fibre optic monitoring is promising to change this to intrinsically safe real-time monitoring capable of measuring contaminants such as methane from a long distance [7].

Real-time monitoring allows mines to make informed decisions based on actual conditions, rather than delayed measurements and assumed data. In some cases, this can predict impending dangerous conditions (such as a build-up in explosive gases or the initial stages of spontaneous combustion) which allow action plans to be in place to remediate the condition [8]. In other cases, the sensors can detect conditions that indicate a failure has already occurred (such as a fire) and trigger emergency response procedures and possibly evacuation plans.

1.3. Limitations of Real-time Sensors

Full mine coverage at every underground location in most cases is not practical. Apart from the cost implications, it may not even be possible due to area access limitations, installation design or restrictions in bandwidth for communication. Mines must therefore traditionally rely on interpreting information between sensors manually. Human interpretation from experienced and trained personnel offers a viable alternative if the network of airways is simple, however in the case of dozens or even hundreds of alternate pathways, this method becomes unreliable and prone to human error.

2. COMBINING SIMULATION METHODS WITH REAL-TIME SENSOR MONITORING

Studies have shown the use of ventilation models to present real-time sensor data is more effective than demonstrated the effectiveness of overlaying data onto mapped simulation picture [9] as well as showing the potential benefits of using simulation maps in the event of a mine emergency [10]. Yang [11] showed the benefit of using simulation to predict sources of fires and Griffin [8] demonstrated the benefits of using computer network simulation to optimise the location of the real-time sensors.

2.1. Use of Steady-State Simulation Methods

When combined with a network flow model, real-time sensors can be used to 'inject' a gas source at the sensor location. Steady-state simulation tools can be used to predict downstream conditions between sensors. The simplest methods utilise algorithms that calculate the proportionally weighted mixing of contaminant concentrations at junctions downstream from sensors [12]. Dispersion, layering and incomplete mixing of contaminates at junctions is ignored in a simplified model although can be modelled if more accuracy is required although computational time for real time simulation may be a limitation. For mine networks where distances between sensors may be large, the time delay from when a sensor may read the contaminant, to when the contaminant enters a downstream region becomes important to consider. The distribution of contaminants by instantaneous steady-state distribution becomes more difficult to reconcile with reality and provides a less accurate picture of gas distribution at a set time.

For example, if a high gas concentration passes a sensor, then steady-state simulation will show that the pathway downstream from this sensor to the next downstream sensor will be instantly engulfed in a similar gas composition. This however may take some time to occur and conditions in a large portion of the mine may remain uncontaminated for some time. Another problem is raised when the sensor may subsequently receive uncontaminated air during which time the downstream contaminated air is still travelling through the mine. Steady-state simulation will erase the existence of previous downstream gases, despite their presence still travelling through the network.

2.2. Use of Transient Simulation Methods

To resolve the problem of time based distribution, a transient or dynamic method of distribution must be used. Stewart [13] described a method of compartmentalising or discretising of model such that small parcels or cells of gas can travel dynamically with calculate velocities and mix through a mine. A similar method called Lagrangian mechanics is often used to describe dynamic systems using discrete parcels defined by a time allocation for size. As these cells pass over sensor location, they are charged with the sensor gas contamination readings.

In summary, information from a sensor can be inferred to travel downstream from the location at an average speed of the velocity of the airflow (actual speed can vary across the cross-sectional profile but for simplicity this is ignored). As the discrete parcels of air with sensor derived contamination pass through the network model, when new sensors are encountered downstream, updated information replaces the previous information in the parcels, and continue downstream to the next sensors. When the discrete parcel encounter a junction, the parcels are mixed based on a mass flow rate, and redistributed downstream. Using such a technique a complete downstream predictive model can be built from limited sensor data.

For a simulation system, provided the simulation computational calculations are sufficiently fast, the transient simulation is constrained by real-time to ensure contamination spread speed matches reality. To model gas mixtures downstream from a junction, a simple mass flow mixed formula assuming perfect mixing at the junction can be assumed.

$$Gm = \frac{\sum (G_{1..n} \times Q_{1..n})}{\sum Q_{1..n}} \qquad (1)$$

Where *Gm* is the downstream mixed airflow gas concentration, $Q_{1..n}$ is the flows in to the junction from connecting airways (m^3/s) and $G_{1..n}$ is the concentrations of gas at the junctions connected to the outgoing airways. For even more accurate simulation, diffusion techniques can be used to spread gas between cells with a diffusion coefficient [14]

2.3. Visual Display – Steady-State

A steady-state downstream prediction simulation is performed starting at actual sensor locations, with pathway concentrations sourced from sensor information. Downstream information is propagated, mixed homogenously at junctions, and passed into all airways departing downstream junctions until the ventilation exhaust exits are reached. Where recirculation exists or junctions continue to be changed from upstream information, the process iterates until a steady-state solution is reached. The steady-state simulation ignores the time-based effects of gas sensor changes and would only be an accurate depiction if the gas sensor values did not change significantly over time. A typical view of a steady-state distribution is shown in Figure 3. The view shows the limitations of steady state simulation of sensors as gas levels remain consistent between sensors until the next sensor update, and peaks and variations in previous sensor values are erased by the new sensor values.

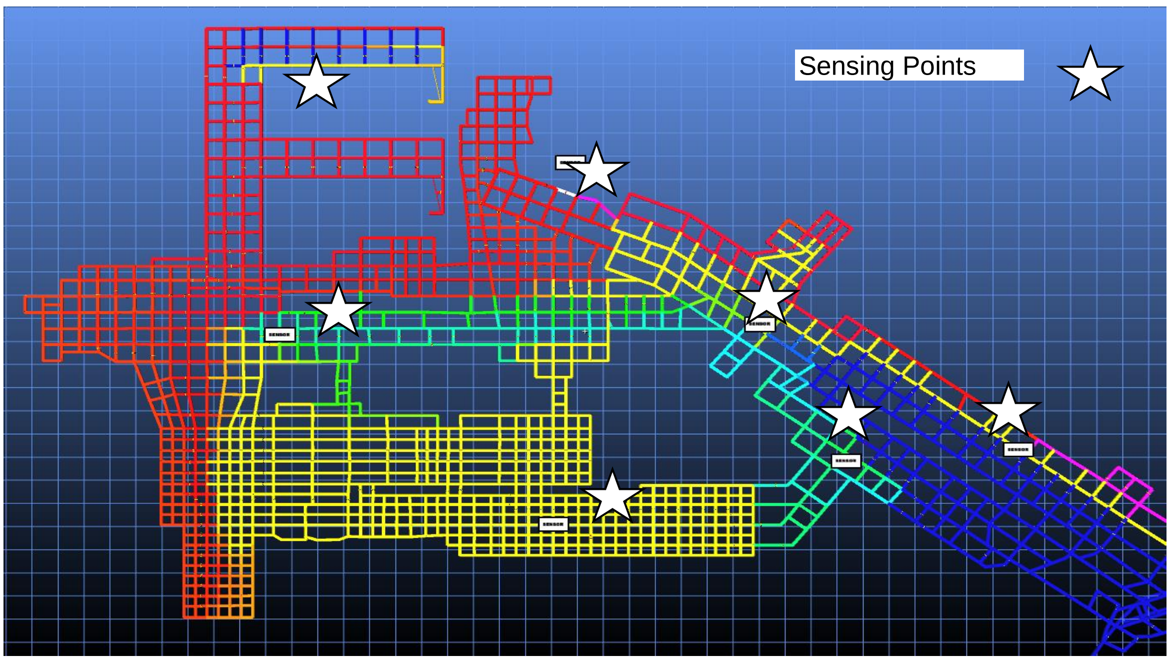

Figure 3: Steady State simulated contaminants downstream from sensors (gas concentrations shown in different colours)

2.4. Visual Display – Transient State

A transient process can be initially populated with real time steady state simulation values. Although the downstream steady-state information may not be initially entirely correct because of the lack of time-based spread of contaminants, the subsequent transient process will gradually correct the model over time, as actual air velocities and gas movements fill the model with real-time data.

Transient modelling spreads the gas through the model at simulated air velocity speeds. If a gas mixture encounters a further sensor downstream, this sensor is assumed to have the most accurate information, and the values of the gas sensor override the transient values to produce a revised downstream gas concentration.

Differences between actual sensor values and upstream simulated values are likely to occur because of the introduction of new gas sources into an airway between the sensors, faulty sensors, or perhaps because of errors in the modelled flow and assumptions. Larger and lengthier discrepancies can be flagged as an unknown variable that may require further investigation for the source of the difference.

Nonetheless, the predicted gas values between sensors provides a best guess value of actual levels given the available information and importantly retain variations and spikes in the gas levels passing over the sensors within the model, even after the sensor information has changed. The result is a global model of both actual, simulated and historical gas values as shown in Figure 4.where variations in gas levels from previous readings can be clearly seen travelling through the model. Combined in a rich three dimensional graphic interface, this conveys more information than traditional sensor value readouts or historical trend graphs could alone.

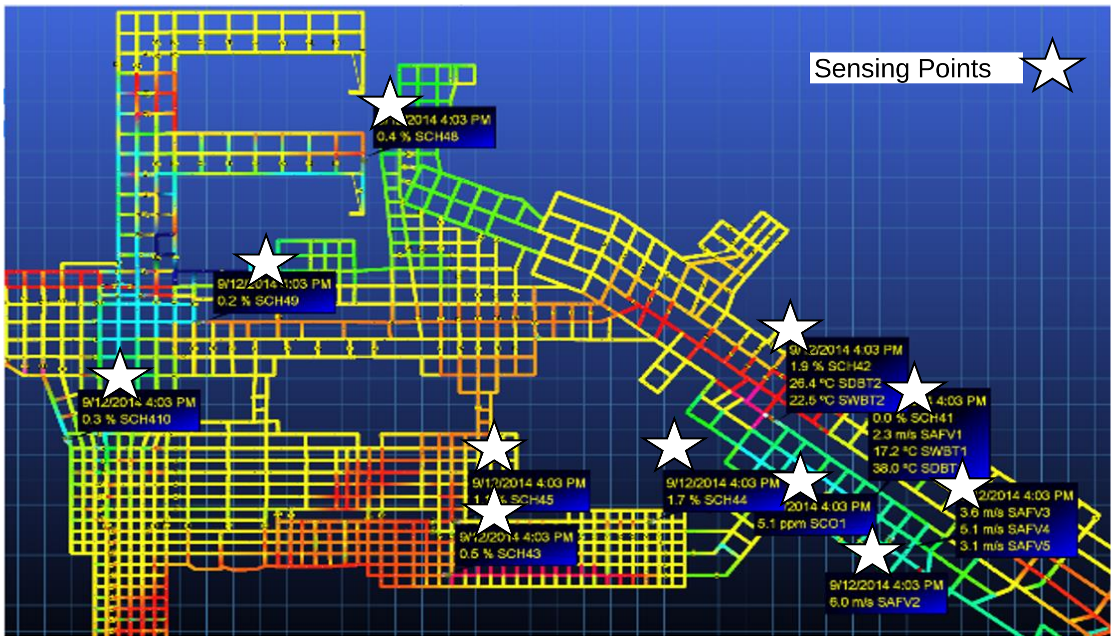

Figure 4: Transient Simulation of Downstream Sensors Gases (gas concentrations shown in different colours)

3. CONCLUSION

Predictive simulation of sensor information, particularly when combined with transient simulation methods can provide a mine wide indication of ventilation conditions, even in areas between or without sensors. While caution must be taken due to the predictive and potentially inaccurate nature of this type of estimation, it nonetheless forms a useful analysis tool to visually show likely atmospheric data for working area which would otherwise have no information.

When compared to tranditional methods of display, such as static schematic layouts with current sensor value labels, and trend graphs for historical sensor values, the transient simulation method demonstrates a far more intergrated and realistic view of the mine atmosphere in all places. The technique could potentially be used in any control room as an addition or even replacement for traditional static display methods, and may find uses in mine emergency control situations, fires or gas exceedence incidents, where hostile atmospheres between sensors could be tracked through a mine in real-time.

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