UNIVERSITY OF THE WITWATERSRAND

A SPATIO-TEMPORAL MODELLING AND ANALYSIS OF DIGITAL SENSOR DATA FOR UNDERGROUND MINE HEALTH AND SAFETY

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Declaration

I, Calvin Oduor Opiti, declare that this research report is my own unaided work. It is being submitted to the Degree of Master of Science in Geographical Information Systems and Remote Sensing at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

Signature of Candidate

…………**12th**…day of…**October**……......20**17**………..in…**Johannesburg**….

Abstract

Health and safety of employees within their work environment is critical. In the mining industry and especially in underground mines, monitoring and management of health and safety of employees is particularly important

Most underground mines today are not fully mechanized, except for coal mines. The industry thus still relies on and employs human personnel. Monitoring and managing these mines and hence personnel health and safety as they undertake their trade is therefore a necessity. Implementation of technology, especially in digital sensor systems and real-time spatial analysis systems, provides a means by which health and safety risk factors can be monitored and information gathered to facilitate determination of prevailing risks or prediction of such risks. Technology therefore can be used to make better decisions and implement specialized emergency response to avert or reduce the extent of injuries, casualties and damages in an underground mine.

This research project looks into determination of prominent risk factors in an underground mine, determination of parameters for modeling of such risk factors and the implementation of ESRI’s ArcGIS platform for the retrieval and analysis of streaming sensor data about this parameter from an underground mine. A proof of concept (POC) system is developed that analyses streaming digital sensor data and determines the status of the underground mine environment. The results from this analysis are displayed in a dashboard application for a control room environment.

The results and achievements of this research project, especially from a dashboard system perspective, show the possibilities of an integrated GIS-based solution for real-time data processing and determination of the prevailing conditions in an underground mine. This solution also opens up a wide pool of possibilities through which systems integration and its benefits can be achieved, especially in underground mines and focusing on health and safety, as previously silo systems can be integrated at data levels, enabling data sharing, analysis, predictions and making of informed decisions.

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This project and the accompanying research report document was not without its ups and downs, but was successfully carried out and in time. For this achievement, I would like to acknowledge the following people and institutions for their assistance, leading to the success of this research:

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Acronyms

2D	Two Dimensions
3D	Three Dimensions
4D	Four Dimensions
CAD	Computer Aided Design
CM	Chamber of Mines
CSV	Comma separated values
DPM	Diesel Particulate Matter
ESRI	Environmental Systems Research Institute, Inc.
GDP	Gross Domestic Product
GIS	Geographical Information Systems
JPEG	Joint Photographic Experts Group
POC	Proof of Concept
R	The R project for Statistical Computing
RDBMS	Relational Database Management Systems
SCP	Secure Copy
SDE	Spatial Database Engine
WMI	Wits Mining Institute

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1. INTRODUCTION

1.1. Introduction

South Africa's mining industry has been and still is a major driving force behind the development and advancement of her economy. The industry has contributed to the shaping of the country politically, culturally and economically. The City of Johannesburg, for instance, was founded as a result of the discovery and mining of gold in the early 1880s. The city initially started as a tent-hut informal settlement within 5 years of the discoveries and later grew, within a decade, into a more formal city with well laid out semi-permanent entities and settlements (Nhlengetwa & Hein, 2015).

The mining industry in South Africa (SA) is significant, contributing approximately 8% to the National Gross Domestic Product (GDP). In 2015, the industry contributed R286 billion towards South African GDP (Chamber of Mines, 2017b). The country is mineral rich, producing 10% of the world's gold and has 40% of the world's known resources, with an estimated 36000 tonnes (t) of undeveloped resources, which amounts to about one third of the world's unmined gold (Department of Mineral Resources, South Africa, 2016). The industry is also a major employer in the country. It provides both direct and indirect livelihood to the employees, their families and the society at large. The SA mining industry directly employs about 457,698 miners and approximately 4.5 million dependants (Chamber of Mines, 2017a)

Underground mines in South Africa are not fully mechanised or automated, except for coal mines, thus still employing labour intensive methods of mining. Coal mines, though mechanised, employs approximately 77,226 miners. Gold and platinum mines on the hand have a larger employee base, with employee figures at 172,369 for platinum and 115,822 for gold (Chamber of Mines, 2017b). Thousands of human personnel are employed in both underground and surface mines, with high employee numbers in gold, coal, platinum, iron ores, diamonds and copper mines. With this high number of human personnel employed in the industry, their health and safety while undertaking their trade, especially labouring in underground mines, with all its dangers, is therefore a major concern.

Safety within the mines is of high importance to the mining industry (Hebblewhite, 2009). Accidents and health risks in mines, as discussed further at section 2.2 of Literature Review chapter, have significant consequences, including closure of mines, financial loses and in severe cases, death of mine personnel. Therefore an initiative to monitor and manage underground mines for such mine accidents, health and safety risks and factors leads to better progress in maintaining high levels of health and safety in an underground mine environment (Şalap *et al.*, 2009).

The advancements in the technological developments and their applications in the mining sector have greatly contributed to the reduction of incidences or accidents in the industry. This is with regards to the different aspects such as exploration, excavation, mineral processing and transportation (Malinowska & Hejmanowski, 2010; Lee & Park, 2013).

One technology that finds application in the mining industry is Geographical Information Systems (GIS) as an enterprise Information Communication and Technology (ICT) system and product. GIS finds application in the mining industry mainly for services involving exploration, evaluation of the ore resources, facility management, environmental impact assessment, modelling environmental conditions within mines, health and safety assessments, planning evacuation routes, planning reclamation activities, among others.

Implementation of sensors and monitoring systems facilitates improvement of health and safety in mines. These are used to monitor and report various safety and environmental conditions in surface and underground mines. The digital data from these systems can be analysed and used to predict and prevent disaster and hence save lives in an underground mine.

Technology is used in an underground mine for real-time monitoring and management of health, safety and environmental conditions through the implementation of sensor systems. In a mine environment these sensors and systems are often not integrated. This project, which is part of the larger Digital Mining project, herein referred to as DigiMine Project, by Wits Mining Institute (WMI), is aimed at implementing a GIS-based monitoring system that will facilitate the integration of separate sensors and mine monitoring systems in an underground mine. The DigiMine Project targets implementation of real-time risk assessment and management system, aimed at zero harm and maximum benefits. This is to be achieved through the implementation of an end-to-end monitoring system with an integrated GIS. In addition to this, real-time communication systems, processing of the sensor data for visualization and decision making will also be implemented and managed from a central point – the control room.

1.2. WMI Digital Mining Project

The Mining Institute of the University of the Witwatersrand – Wits Mining Institute (WMI) – has embarked on a large project to automate the various underground mine operations. The project, called DigiMine Project, entails the use of technology to provide continuous monitoring and management of the various processes, functions and operations in an underground mine.

Health and safety is of paramount concern within an underground mine environment. This requirement to improve health and safety standards within the underground mines is one of the major driving forces to actualization of this project. Wits DigiMine Project is aimed at providing real-time risk assessment and management, targeting zero harm and maximum benefit. More information relating to WMI and DigiMine Project can be found at https://www.wits.ac.za/wmi/.

a) Current Situation

Continuous monitoring of the underground mine environment is one of the objectives of the DigiMine Project. To achieve this objective, the WMI has successfully conducted and implemented a project – a subset of the larger DigiMine Project – involving building of a mock underground mine, complete with an entrance, shaft, tunnel and a stope. Figures-1, 1-2 and 1-3 below shows Wits mock underground mine. The mine's surface corresponds to the roof of the Chamber of Mines and it includes a weather station and seismographer. The tunnel section of the mock mine is located on the lower ground floor of the Chamber of Mines (CM) building and is visible as an extension of the Chamber of Mines on the left of figure 1-1.

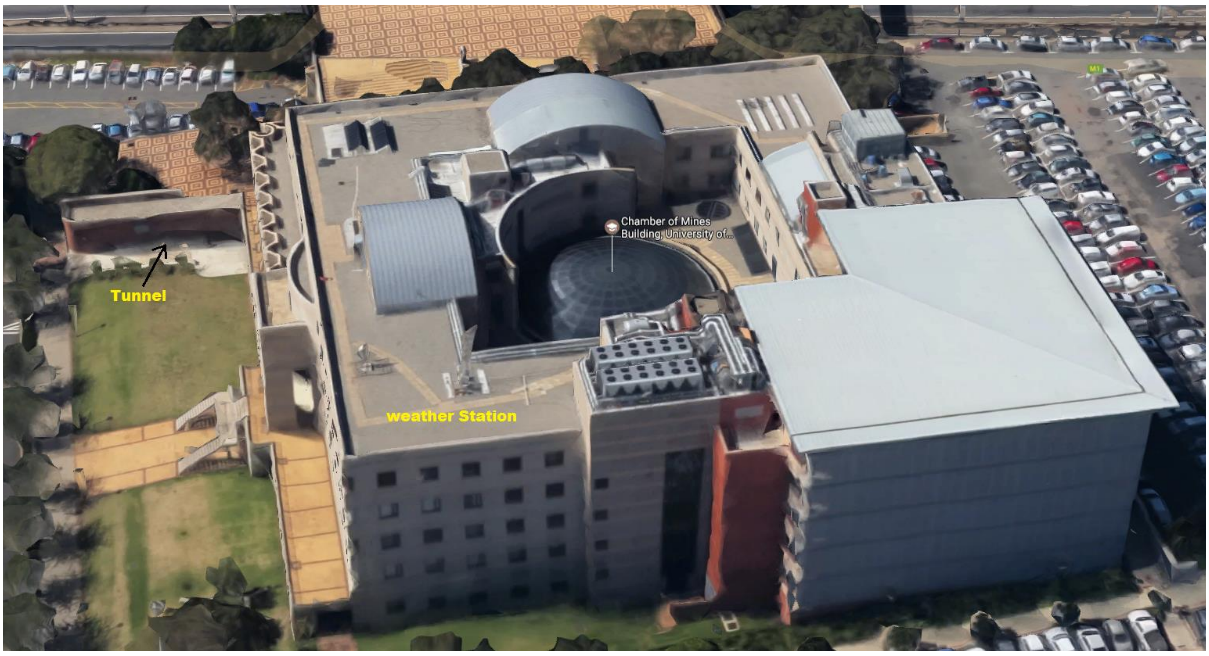


Figure 1- 1A 3D Google maps image of the Chamber of Mines building. A weather station is located on the roof (representing the surface of the mock underground mine) and a tunnel section at the lower ground section of the building (source: Author)

Figure 1- 2 An image of a weather station present at on the surface of the mock underground mine, showing instruments for measuring temperature, humidity, rain water levels and pH (source: Author)

Figure 1- 3 Images of the tunnel section of the mock underground mine (source: Author)

Monitoring systems and sensors have been installed within the underground mock mine at the Chamber of Mines building on the west campus of the University of the Witwatersrand. These systems include:

- Sensors which detect, measure and record different parameters in the mine e.g. toxic gases, humidity and temperature;
- Sensors for the detection of seismicity, rock movements and mine instability;
- Communication systems software to relay data and information between the mine and control room; and
- Camera systems for capture of graphic data within the mine, mostly for safety and security purposes.

These systems and sensors (a list of the different and already installed sensors is presented in table 3-1, have been supplied and implemented by different organisations in the software and systems development market. This is with respect to mine-industry software, offering different services and functionalities. These systems from different vendors include:

- Vibratech Systems & Software – for monitoring rock movements and seismicity
- Schauenburg Systems & Software – for gas detection within the mine
- Milestone Systems & Software – for camera systems and security management
- MineRP Systems & Software – an enterprise resource planning system for mines
- ESRI's ArcGIS Platform – for spatial data management and modelling

Presently, the different systems put in place are silo packages, offering a variety of separate functionalities that are not interoperable. These systems also come with their own personalized sensor systems, database and algorithms to retrieve and store recordings or observations from the underground mine environment. These readings are analysed and information obtained and interpreted to gain meaning and situation of the current situation in the mine. These systems operate as silos, therefore hindering the objective of providing a single and centralised monitoring and management environment of the underground mine. Although each silo is regarded as leading practice, these systems were not designed with their integrations with other systems in mind. The capability to integrate with other underground mine systems would allow for data and information sharing and analysis, which would prove valuable for operational and executive decision making and management from within the control room and other departments within the mine and/or industry.

b) Expectations

The success of the DigiMine Project in providing a centralised end-to-end solution is dependent on the integration of these systems and sensors. Integration will enable data sharing and analysis to facilitate the continuous monitoring and management objective. Inclusion of a data or machine learning component alongside the integrated system will add to the abilities in data processing, analysis and predictions from the sensor data.

This research, as part of the overall Digital Mining Project, provides a foundation through which the integration of the systems will be carried out and functional capabilities that come about as a result of systems integration be determined. This is especially with regards to integration with an enterprise GIS and provision of a centralised repository for the sensor data and provision of a real-time visualization platform in the form of a dashboard.

1.3. Statement of Problem

The economy of South Africa has been shaped and advanced by mining activities. Despite the harsh and dangerous underground mine environments, employee figures in South African mining industry is still high.

Many miners have become casualties and even lost their lives while mining underground. This is due to exposure to high levels of toxic gases, lower levels of oxygen, contaminated water, rock debris falling on them, mine fires, drowning, and collapse of mines as a result of the underlying weight and seismic activities (Mahdevari *et al.*, 2014). South Africa has also had her share of mining disasters, which includes CoalBrook Mine disaster of 1960 where 435 miners died due to disintegration and collapse of pillars supporting tunnel roofs; Kinkross Mine disaster of 1986 where a fire broke out leading to 177 miners choking to death from toxic fumes from burning plastics and polyurethane; coal dust explosion at Middelbult colliery in 1993; a major land subsidence at Lily Mine in Barberton, Mpumalanga on the 5th of February 2016 with 3 of 79 miners were never recovered; and as well, Marikana Platinum mine disaster where 34 miners lost their lives when police opened fire on protesting miners (Leger, 1991; Elbra, 2013; Oosthuizen, 2003; Skiti *et al.*, 2016; Phala, 2016).

The health and safety of miners is of major concern and the effort to reduce the fatalities and accidents is important. The focus of underground mine safety is to strengthen monitoring and early warning systems of human carelessness and disasters such as fires, gas, pressure, dust and floods. Injuries that results from the machinery used by the personnel while underground needs close monitoring too, with an aim of zero harm to the underground mine workers.

Underground mining conditions, parameters and machinery can be monitored and managed to eliminate or reduce the effects and harm to the miners. Technology has advanced, paving way for implementation of digital monitoring and analysis systems, for improving health and safety. These systems can be used to predict dangers prevalent underground, make decisions that automate countermeasures to avert danger, locate mine personnel and provide guidance to safer regions (Li *et al.*, 2008; Maity *et al.*, 2012).

The problem that exists in the mining industry as relates to ensuring health and safety of miners, is that a variety of technological systems have been implemented, and most often from different vendors. These systems operate as independent units and collect valuable information that, when shared and analysed together, would provide valuable insight, especially with regards to health and safety and smart operations in the mine. Additionally, the data obtained from the sensor implementations in an underground mine are not analysed in real-time. This means that the information obtained from such data is often out dated, which could result into serious harm and many casualties due to late response in taking action.

Systems and sensor integration and the real-time analysis of the shared or fused data are therefore the driving factors towards the prediction and ensuring of safety conditions within underground mines.

1.4. Research Questions

To undertake this research study, looking into the application of technology and especially integrated GIS for the monitoring of underground mines and real-time decision making for improved health and safety, the following research questions were posed:

1. What are the most common scenarios in an underground mine that pose health and safety risks to the miners?
2. What are the best methods and parameters to model such scenarios provide countermeasures, real-time decisions and automated response using GIS?
3. Do the ESRI GIS solutions and GeoEvent Management Systems allow for modelling of such scenarios, real-time decision making and safety response?

1.5. Aim

The main aim of this research is demonstrating and evaluating the functional capabilities of an Integrated Enterprise GIS, specifically ESRI's ArcGIS platform and GeoEvent Management Systems, in the modelling and real-time monitoring, analysis and management of digital sensor data. This project looks into determining and evaluating the capabilities of ESRI software and its extended possibilities when integrated with legacy mining solutions, with a special focus in sensor data analysis for improved health and safety in an underground mine.

ESRI's ArcGIS platform is used in this research, based on Wits Mining Institute's research interests and through a donation of the ArcGIS software stack and sponsorship of the research by ESRI South Africa. This research, as tasked to the author by WMI, uses ESRI software and platform for an integrated GIS-based underground mine monitoring solution. Other research exercises conducted by fellow colleagues at WMI, within the DigiMine project umbrella, will look into using other software platforms for an integrated solution to mine health and safety risk scenarios that have been established in this work.

1.6. Objectives

To achieve the above stated aim, the following are the objectives of this research:

1. To identify the most frequent scenarios that pose danger to the health and safety of miners in an underground mine and determine the causes of such risk factors for a better understanding, leading to development of solutions to improve health and safety in underground mines.
2. To investigate and determine the appropriate and best integration technology and methodology, to integrate VibraTech and ArcGIS applications, for improved efficiency and responsiveness of the mine monitoring systems.
3. To use application development and integration methodologies in the development of a real-time monitoring and management prototype system, with a dashboard system for control room operations, based on ESRI's ArcGIS platform.
4. To determine functional capabilities of an integrated GIS-based monitoring system in underground mines beyond control room operations, including data analysis and predictions, from an integrated solution on ArcGIS platform

2. LITERATURE REVIEW

2.1. Introduction

Mining is the process by which people and machinery are used to extract economic materials and natural resources such as gold, diamonds, limestone and sand, to name a few, from the earth. These operations have been carried out across the globe since pre-historic times, for instance, "*Lion Cave"* in Swaziland with radiocarbon dating at 43,000 years, was mined by the Palaeolithic humans for hematite to make red pigment ochre (Mkpuma *et al.*, 2015).

Presently, there are a number of different machinery and technological advancements that are used in mining (Leeuw & Mtegha, 2016). These have contributed to the automation of a variety of tasks and processes involved, from exploration to extraction. Despite deployment of advanced and automated machinery for mineral extraction, especially in coal mining, the mining industry still relies on human labour and therefore employs a large number of miners, alongside these machinery for carrying out different operations within underground mines. This therefore exposes the thousands of human personnel working underground to a variety of health and safety issues, which are prominent in underground mines.

Health and safety within underground mines is a major concern in the industry. These issues, in as much as they are in most cases inevitable, technology enables for their real time monitoring and management.

This chapter and the sections below, therefore cover documented health and safety risk factors for underground mines and case studies and solutions employed to mitigate on such risks, especially with regards to real-time analysis and integrations with GIS applications.

2.2. Underground Mines: Health & Safety Risks and Causal Factors

There are many methods to the activity of mining, which can be broadly categorized into surface and underground mining. Though not from an environmental and social impact perspective, surface mining is regarded as the most advantageous method, as it offers a cheaper means of extraction of the minerals and ores. It is therefore a rather economical method to mining. Surface mines are also characterized by less exposure to toxic fumes, therefore providing a safer means of mineral extraction. Recovery and rehabilitation of surface mines is also possible (Sahu *et al.*, 2015), only it is generally more difficult compared to underground mines.

On the other hand, underground mining is considered more environmentally acceptable. This is attributed to the method having a smaller footprint on the terrain as compared to open pits. One major advantage of an underground mine over surface mine is that less waste material per unit production is extracted. Waste rock is removed to gain access to the precious ores (Jain *et al.*, 2016).

All these methods of mining have an effect on the environment. Mining activities contribute to the destruction of the environment. Subsidence of the overlying terrain over underground mines, considered the most serious geological hazard, affects slopes, damages engineering structures, settlement areas, natural lakes and river flows and even allows for infiltration of contaminants in to groundwater (Altun *et al.*, 2010). Harmful gases and chemicals also get released in underground mines, contributing to the contamination of water (Othmani *et al.*, 2015).

Other than the effects to the environment, continuous excavation and mineral extraction activities carried out in mines have dire effects to human beings, especially workers on these mines and to those residing within the vicinity of these mines. Mine workers are often exposed to a variety of toxic and harmful materials or agents, such as coal dusts, silica dusts, diesel particulate matter (DPM) and noise among others. Traumatic injuries are easily and quickly recognized with their causes readily identifiable. On the other hand, occupational diseases are slow, and the mine workers can be exposed to such toxic and harmful environments over a long period of time (Scott & Grayson, 2016).

Critical hazards that are specifically linked to underground mines include fires, floods, collapse of walls and overlying structures or rock falls, presence of contaminants in the atmosphere, dust and gas explosions. Any one of these hazards could lead to the other or come about as a result of the other. For instance fires could result into gas explosions inside the mine which in turn contributes to the presence of contaminants within the mine environment (Dolozme, 2016).

Mining today is at industrial scale, and involves the blasting, crushing and dumping of wastes in large acres of land. Mountains can be blasted to rubble and dug deeper looking for precious minerals. This leaves large open pits that can be too deep, even at depths below the water table, thereby resulting in artificial lakes. Continuation of mining activities results into wastes and toxic chemical being damped into these lakes, hence leading to their contamination. These lakes therefore sit as toxic attractions to wildlife and migratory birds. Human beings also get affected when they consume the waters from such lakes.

Contributing factors leading to the collapse of mines includes induced seismicity (Leake *et al.*, 2017; Parghi & Alam, 2017), rock mass subsidence, use of explosives, fracturing of support pillars (Wei *et al.*, 2009) and gas/dust explosions while underground. Most mines are also often located in seismically active regions. Such conditions particularly expose the workers to serious risks that could come about due to tremors, earthquakes which cause instability and hence collapsing of the mines and falling of large rocks, injuring or killing the personnel underground.

The space available in underground mines is limited and confined; therefore it is difficult to manage contaminants such as dust particles, aerosols, diesel fumes, particulate matter and toxic gases. These dust particles and contaminants in the air could lead to *pneumoconiosis*. A severe form of this disease is silicosis which is due to abundance of silica. In coal mining, dusts particles in the air results into “coal worker’s pneumoconiosis” or “anthracnosis”, a disease which rarely shows any symptoms or signs but is very severe (Cho & Lee, 1978). Presence of asbestos in the air results into a variation known as asbestosis, which in some situations can develop into a malignant condition. Dust particles and contaminants present in an underground mine environment could also lead to poisoning when inhaled or absorbed into the human body. This could lead to damage of the central nervous system, resulting in parkinsonian-like syndrome. Uranium poisoning is also known to occur among uranium ore miners and the disease is characterized by renal damages. The table below provides a summary of the mine health and safety risks, as identified by Cho and Lee (1978).

Table 2- 1 Summary of the major health hazards in mines (Cho & Lee, 1978)

Agents	**Hazards**	**Conditions**
Physical		
High temperature and humidity	Heatstroke; heat cramp; heat exhaustion; lassitude; irritability; collapse; anxiety; lowered morale	Deep underground work
Cold	frostbite; trench foot; aggravated Raynaud's disease	Ground work in winter; high-altitude mines
Sudden variation in temperature	Respiratory diseases; aggravated rheumatism	Moving from hot working areas to cold surface conditions
Change of atmospheric pressure	Bends (joint pain); chokes (chest pain); air embolism; neuralgia; toothache; paranassi sinusitis	Work in deep underground or high altitude mines
Poor lighting	Nystagmus (now rare); loss of visual acuity; giddiness	Face work
Noise	Occupational deafness	Rock drilling; blasting
Vibration	Raynaud's syndrome	Rock drilling
Ionizing radiation	Radiation hazards	working with radioactive ore
Limited working space	Beat disease (cellulitis and bursitis of joints); displacement and dislocation of joints	Work in narrow seems and in contorted positions
Accident	various	Dangerous work both in and out of the pit
Chemical		
Dust	Pneumoconiosis (silicosis, coal miner's lung, siderosis); induced and aggravated respiratory diseases; poisoning by lead, arsenic, mercury, manganese.	Working with mineral dust both in and out of the pit
Poisonous gases; Oxygen deficiency	Gas poisoning (CO, CO_2, NO_x, SO_2, Methane); anoxia (dyspnea, dizziness)	Blasting; Inadequate ventilation
Mine Water	Occupational dermatosis	Underwater work in the pit
Biological		
Infections from parasites and fungi	Ankylostomiasis; sporotrichosis; tinea pedis and /or capitis; leptospirosis (Weil's diseases)	Working in a high-humid or poorly ventilated pit, which are conducive for growth of fungi and parasites

Proper ventilation is important in reducing the harm that might come about from such contaminants. Ventilation introduces fresh and cool air to these working environments and as well removing stale, contaminated air. In underground mines, proper ventilation ensures that hazardous substances are diluted and removed, there is control of the environment from overheating and that plenty of oxygen is available for the mine workers and for engine combustion (Norman & Caldwell, 2011).

Terrestrial heat increases with depth (Cho & Lee, 1978), with the geothermal gradient for South Africa being at 1°C per 100m. This means that in underground mines, coupled with heat generated from diesel engines and body head from workers, temperatures can get really high. High temperatures can result in i) *heat strokes* – symptomized by high fever, cessation of sweating and leads to sudden loss of consciousness ; ii) *heat exhaustion* – resulting from rapid pulsing and heavy sweating due to overheating; and iii) *heat cramps* – painful spasms of the involuntary muscles of the abdomen, caused by depletion of salt (Cho & Lee, 1978). Such disorders can be remedied through an efficient ventilation system, reduction of humidity and in some cases refrigeration.

There are measures that are being put in place, by the industry players and stakeholders including governments, to reduce and possibly eliminate underground mine accidents and provide a safe and healthy working environment for the underground mine workers. Laws have been enacted by governments and pegged on ensuring the mining industry provides a conducive and favourable working environment for the human personnel. In South Africa, for instance, health and safety in the mining industry is governed by Act 29 of the 1996 – Mine Health and Safety Act. The base premise of the Act is:

- Ensuring owner responsibility by creating codes of practice, training, identification of hazard and their investigation for improved health and safety;
- safeguard employee rights to not be forced to work in a hazardous environment;
- Creation of the Inspectorate of Mining Health and Safety; and
- Establishment of a three-party Mine Health and Safety Council

The enforcement of the Act is aimed at uplifting all health and safety standards in South Africa’s mining industry and as well, at promoting the adaptation of work to man and each man to his work environment.

The enactment of laws can only go as far as providing a legal basis and guidelines to curbing risky incidents and how to manage disasters and accidents in the mining industry. To further reduce the occurrence of underground mine accidents and fatalities, implementation of functional technological systems and applications is a necessity and major requirement.

Advancements in technology, computing and web services have opened floodgates to development and implementation of applications and solutions. Such solutions and applications are quite necessary for underground mines and can be purposed at the elimination or reduction of accidents and hazardous situations. Monitoring and management of underground mine environments through the application of technology can thus contribute to reduction of the extent of damages, injuries, loss of lives or livelihoods and even operational costs of running the mining facility (Kumar, 2015).

2.3. Purposeful Systems Development and Testing

Advancements in technology, computing and web-based systems have resulted in the development of solutions that not only contribute to a more productive and cost-effective operationalizing of underground mining activities, but also contributing to increased confidence in a secure, safe and healthy working environments for the underground mine personnel.

The design and development of such systems or applications is aimed at specified and predetermined functionalities in an industry. This takes into consideration a number of criteria and processes that are undertaken in the design and development of said systems and machinery to be developed for various uses. Horberry (2012) defines a four stage process that is applied in the development of the technologies for the sake of health and safety. These are:

- Phase 1 – the identification of the technological needs, user requirements and cost risk analysis
- Phase 2 – the design, procurement and deployment process of the technologies, especially from a user-centric perspective
- Phase 3 – the iterative evaluation and verification of the processes
- Phase 4 – the dissemination of the outcomes from the above three phases being looked into

Based on the above phases, two take backs are evident and can be picked up, especially with relation to design and development of functional systems or applications/solutions, that is, i) consideration of the needs and requirements of the eventual users of the solution and ii) adherence to the system development life cycles leading to an important step of solution testing before their implementation. One major flaw in the design and development of application solutions, especially in the mining industry, is neglecting to consider user-centric perspectives, especially in relation to various categories such as personnel, equipment and physical or social environments; and the different stages on an incident – pre-event, event and post event (Haddon, 1972). These technological needs and user-centric perspectives contribute to the developed and implemented system or machinery being accepted and adopted, which directly results in efficiency and productivity within the workplace. And in the case of safety and health of the personnel, the implemented system will achieve its intended purpose of making the workplace safe, healthy and secure.

System development methodologies, defined as standard processes used by an institutions in carrying out necessary steps in analysis, design, implementation and maintenance of information systems (Hoffer *et al.*, 2013), are often aimed at a purpose to enhance the productivity within the organization and its employees (Benzzine, 2002). System development is therefore an incremental process whereby the whole system is divided into small and easily manageable builds in a module. Each module passes through the requirements, design and testing phases before a release of the module is implemented, as indicated in figure 2-1 below.

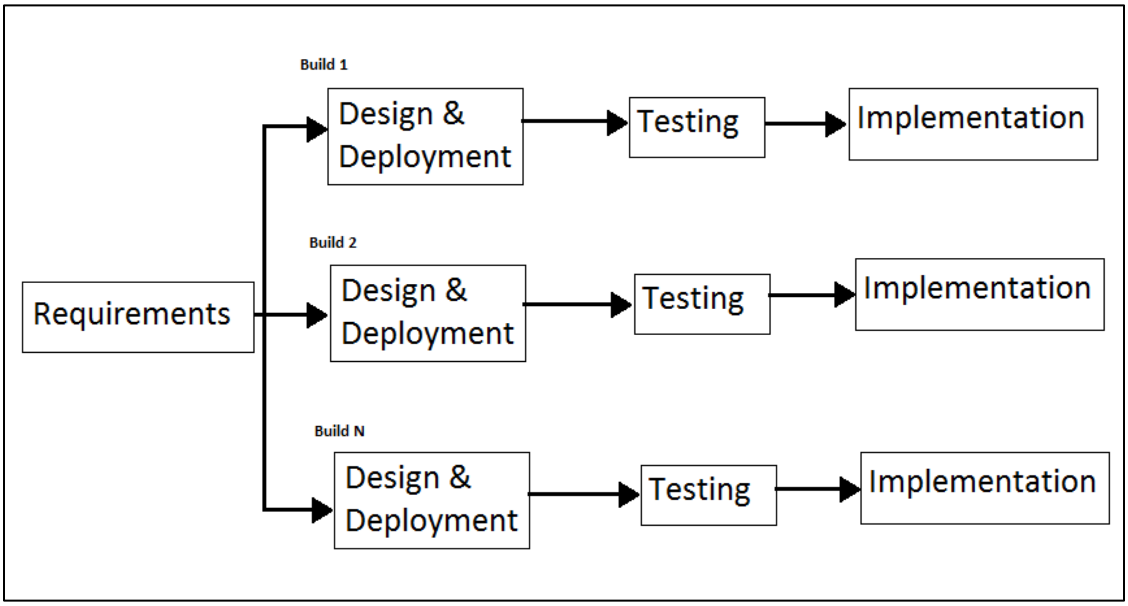


Figure 2- 1 A diagram of an incremental life cycle model in system development (ISTQB Exam Certification, 2017)

There are a variety of software development processes and methodologies, such as the widely used and common Agile Development Model. Agile methods involve the development of small incremental releases through rapid cycles. Each release undergoes thorough testing to ensure software quality is maintained. Agile development is aimed at breaking down activities into smaller and less effort extensive activities involved in development of the application (Yang *et al.*, 2016).

In terms of software and application testing, there are different levels to carrying out this process, depending on the model of application development employed. These levels, as discussed by Repasi (2009), include and are characterized as:

1. *Unit Level Testing (ULT)* – This level involves the isolation of specific units within the system from other components and tests carried out with regards to its specifications
2. *Integration Level Testing (ILT)* – This level of testing is mainly focused on determining and verifying the inter-working between the different units and finalized components of the application. This testing is done with reference to the technical design specifications for the components and the system at large
3. *System Level Testing (SLT)* – This is a testing phase that involves testing of all the components within the system/application. Tests are conducted against the functional and non-functional requirements as per the descriptions in the functional design of the system. Here tests are carried out as per the developers' and system integrators perspectives.
4. *Acceptance Level Testing (ALT)* – This is the same as system level tests only from the perspective of the stakeholders – users and customers. This level of testing is mainly to validate the system as opposed to verification as in System Level Testing.

Testing of applications does not only cater for the 'traditional' applications but also involves web based applications. In this context web applications are considered a distributed system with client-server architecture, which as expounded on by Di Lucca and Fasolino (2006), includes the following characteristics:

- A large user base, distributed around the world and can access the system concurrently
- Heterogeneous environments of execution with different hardware, network connectivity, servers and browsers
- The ability to generate components at run time depending on user input and server status

The goals for undertaking web application testing include:

- Determining web application behavior especially when a large number of users access the application concurrently
- Behaviour of the application when accessed through different web browsers, especially as relates to content rendering
- Testing the security and ability of the application to be protected from malicious and unauthorized access

Today, there are a variety of technologies and systems that have been developed for the measurement, recording and monitoring of these underground mining factors and parameters. These include, but not limited to:

- Sensor systems – that are very sensitive to measurement of minute changes in temperatures, seismicity, changes in air quality and toxic gases.
- Communication systems – that relay the sensor observations to the control room systems. These also provide two-way communication of information to/from the miners, which is important in promoting safety within the underground mines.
- Data analysis systems – these are systems powerful enough and specifically programmed to interpret and make sense of the data recorded from the underground mines, with minimal input from the users, i.e. through data mining and machine learning (Han *et al.*, 2012; Zaki & Meira Jr., 2014)
- Camera systems – for the capture and recording of graphical imagery and video of the events that occur in the underground mine. Mostly used for surveillance and security purposes in underground mines
- Database systems – stores all the data and measurements from the underground mine environment and related to the mining personnel, especially their health information and location within the underground mines.

2.4. Real-Time 4D GIS Monitoring and Management Systems

a) Real-Time Monitoring Systems with Sensors

Real-time systems are defined as any kind of a system which not only processes data based on an input but does so within a defined time period (Peters, 2008). Development and implementation of such systems are vital for a monitoring and management system, and especially with regards to health and safety.

Health and safety in underground mines requires continuous and real-time measurements and monitoring of environmental factors within the mine, locations of static and mobile machinery and their interaction with human personnel while in the mine. Such information finds use in providing warnings, forecasting of eminent dangers and thereby reducing or preventing injuries and fatalities on the mine workers.

Various monitoring and management systems have been developed and implemented to improve health and safety, not only in underground mines, but also in caves and tourist sites. A system has been implemented for real-time monitoring of environmental parameters in a tourist cave, ‘El Saplao’ Cave in the North of Spain (Novas *et al.*, 2017). The system monitors indoors and outdoors temperatures, relative humidity, wind speeds, atmospheric pressure and even the presence and count of visitors in the caves. It also maintains the caves such that visitors get access only when the system reports the microclimate to be conducive and sustainable.

Anglo American, owning and operating coal, platinum and gold mines in South Africa developed and implemented a monitoring system, AerView (Roberts, 2007) with sensor systems measuring parameters such as CO, CH_4, temperature and airflow velocity within the underground mines. The system is effective in fire and methane gas detection, through the use of a Becon^{TM} smoke sensor equipped with fire discriminating algorithm.

Technology used in the development of these systems includes the use of sensor system at remote locations inside the caves and underground mines, fitted with specific purpose microcontrollers with embedded programs for data pre-processing, that is, data filtering, scaling and proper formatting (Novas *et al.*, 2017).

The systems also include a central monitoring station with server implementations, running windows or Linux operating systems and relational database management systems (RDBMS) installed, such as Microsoft Access, MySQL and SQL server RDBMS. These servers function to interrogate the independent sensor stations for data, through a daemon service (Novas *et al.*, 2017), record the data on interactive databases, provides real-time data on an interactive webserver and allows for querying for historical data on the databases.

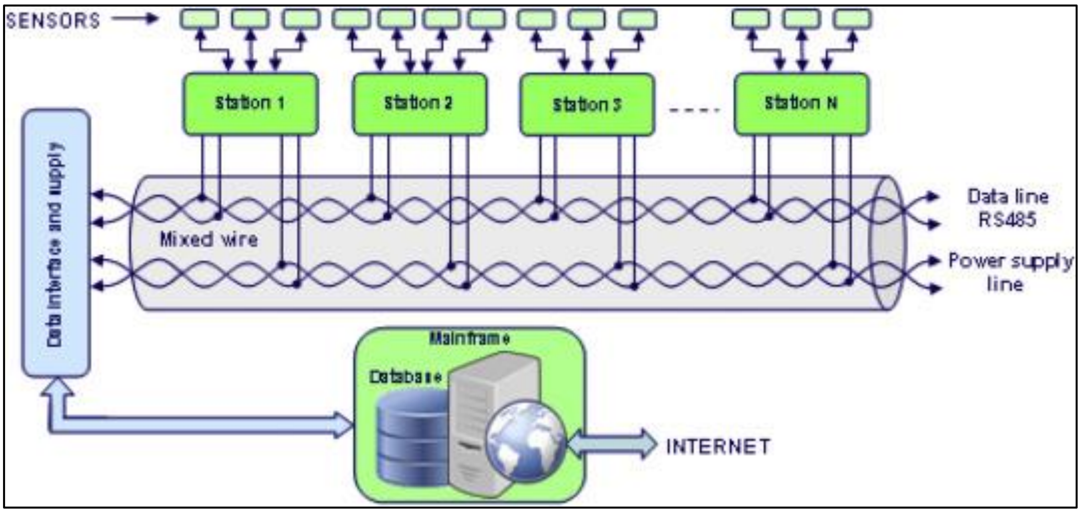


Figure 2- 2 Structure of the station systems (Novas et al., 2017)

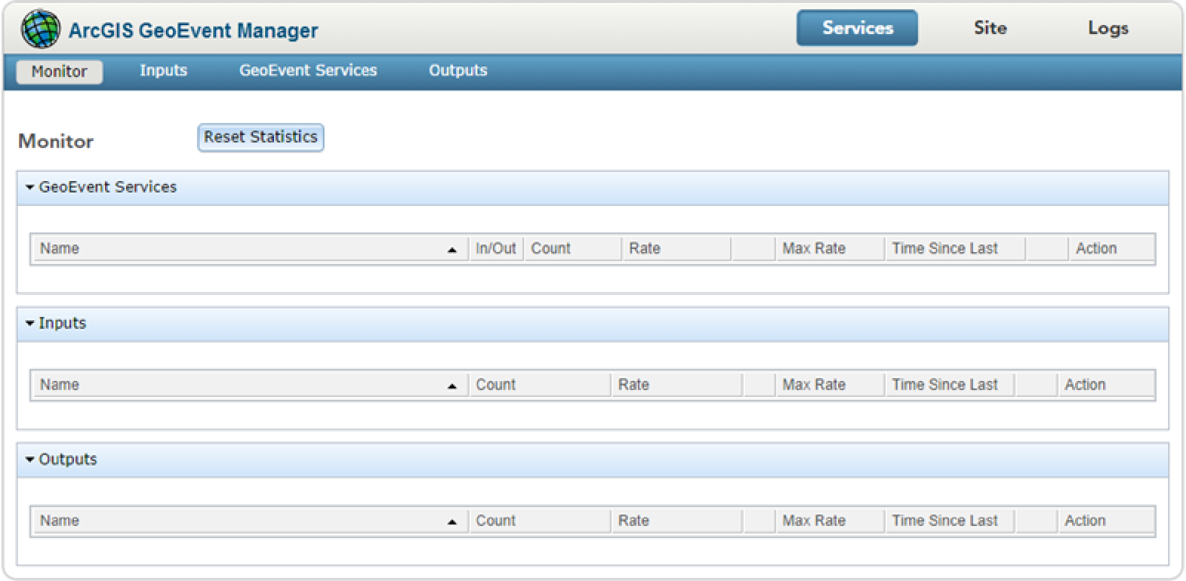
Relaying of recorded data from the sensor systems to the central/control stations is achieved through a variety of technologies. This is either through the use of wired or wireless communication networks, such as Transmission Control Protocol/Internet protocol (TCP/IP), General Packet Radio Service (GPRS) (Roberts, 2007), short messaging services (SMS) through Global System for Mobile Communications (GSM) (Zhang *et al.*, 2011).

b) GIS-based Real-Time Monitoring & Management Systems

A GIS is an integrated system with components including hardware, software, geographical/spatial data and human resources or users. This system mainly functions in collecting, storing, updating, analysing and displaying/visualizing of the spatial data in the form of a map. Integration of GIS to real-time monitoring and management systems provides additional advantage in its functionality in spatial analysis and location based services. Real-time GIS enables continuous updating of maps and databases, personnel and equipment tracking and sending out of alerts to key personnel when dangerous events are predicted or happen, and thereby enabling faster decision making and response (ESRI, 2016a).

GeoEvent for Server, an ArcGIS for Server extension developed by ESRI enables real-time data processing where users can connect to streaming data from sensors, perform analysis and derive information from the data (LaMar, 2014). The extension enables organisations to filter and process the event data, any type of streaming data, in real-time (Liezelesri, 2016).

The real-time data processing workflow with the extension is managed through the ArcGIS GeoEvent Manager, which provides an interface for creation and configuration of data inputs & outputs, design and publishing of GeoEvent Services and GeoEvent Definitions that function to interpret incoming GeoEvents (ESRI, 2016c). GeoEvent Definitions define the schema of the data expected for the event data being received and allow the processor to interpret the events.



GeoEvent Services

Name	In/Out	Count	Rate		Max Rate	Time Since Last		Action

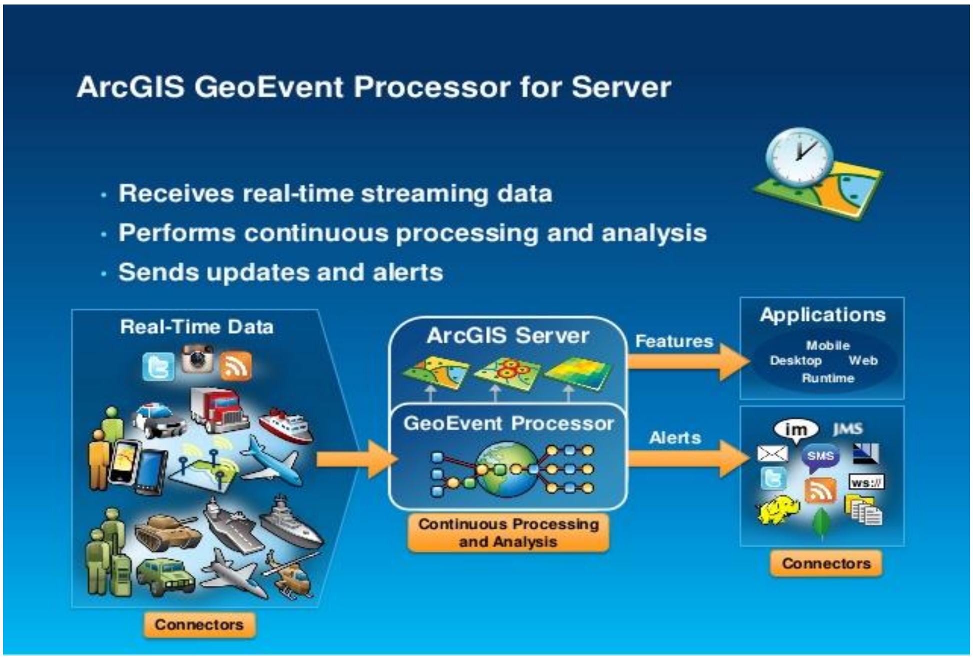
Inputs

Name	Count	Rate		Max Rate	Time Since Last		Action

Outputs

Name	Count	Rate		Max Rate	Time Since Last		Action

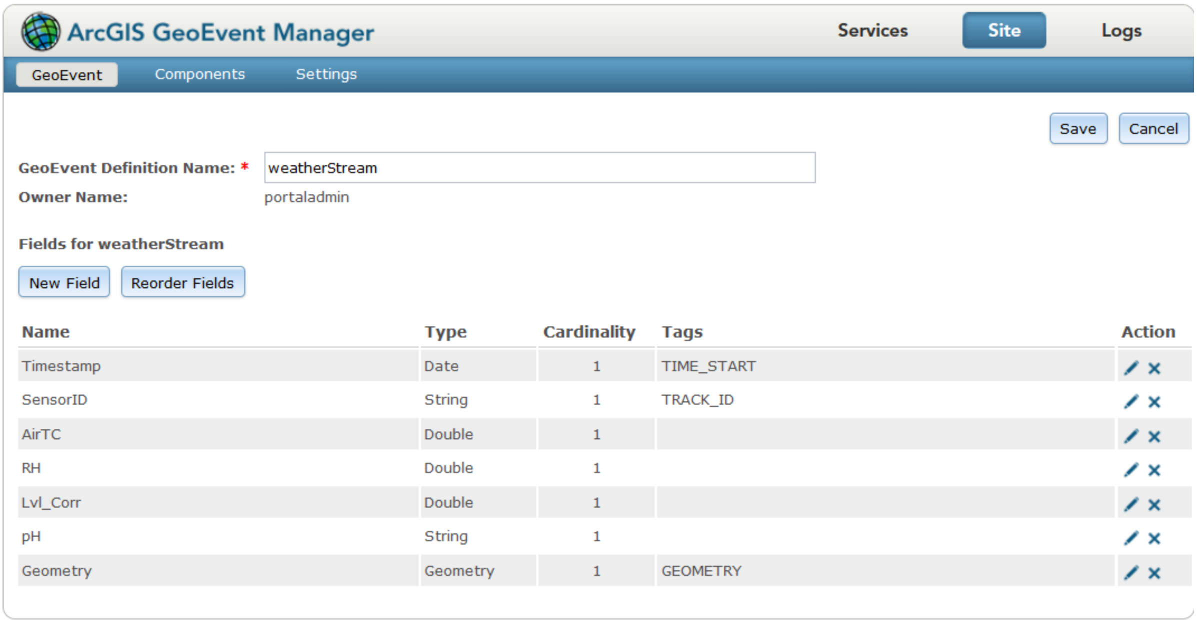
Figure 2- 3 A GeoEvent Manager web platform from which configuration of data inputs, outputs and geoevent processing services in carried out and monitored (ESRI, 2017)



ArcGIS GeoEvent Processor for Server

- Receives real-time streaming data
- Performs continuous processing and analysis
- Sends updates and alerts

Figure 2- 4 A process workflow for GeoEvent applications/systems showing the source of real-time geo-data and the processes involved in their analysis, leading to information retrieval, decision making and sending out of alerts (LaMar, 2014)



GeoEvent Definition Name: * weatherStream
Owner Name: portaladmin

Fields for weatherStream

Name	Type	Cardinality	Tags	Action
Timestamp	Date	1	TIME_START	✎ ✕
SensorID	String	1	TRACK_ID	✎ ✕
AirTC	Double	1		✎ ✕
RH	Double	1		✎ ✕
Lvl_Corr	Double	1		✎ ✕
pH	String	1		✎ ✕
Geometry	Geometry	1	GEOMETRY	✎ ✕

Figure 2- 5 GeoEvent Definition file showing field names and properties of the streaming data Intelligent Response and Rescue System (source: Author)

The basic purpose of a real-time monitoring and management system is its ability to predict future events from the real-time and continuous analysis and interpretation of incoming data. This prediction enables the decision makers to prepare for, respond and provide rescue in cases when an alert is sent, or a dangerous event occurs in an underground mine.

In addition to the real-time monitoring and management system that collects and analyses sensor data about environmental parameters in an underground mine, an intelligent response and rescue system is also necessary for the unfortunate situation where the health and safety of underground mine workers in threatened or under risk. An intelligent response and rescue system therefore basically consists of:

- A database system – which contains information about the underground plans, facilities, the underground environment, positions and status of the workers
- A monitoring center/station – a secure space or control room with a server system that acquires information, either from the databases and/or sensor networks and present real-time information to rescuers or decision makers and send feedback or commands back to personnel carrying mobile sensors or communication gadgets
- Fixed underground sensor networks – for data collection and transfer between surface and underground regions and for positions functionalities
- Mobile devices – which facilitates communication of information to underground personnel, as well as for tracking purposes.

Figure 2-6 below shows a summarised graphical view of a typical intelligent response and rescue system with its components and their functions, both underground and on surface levels.

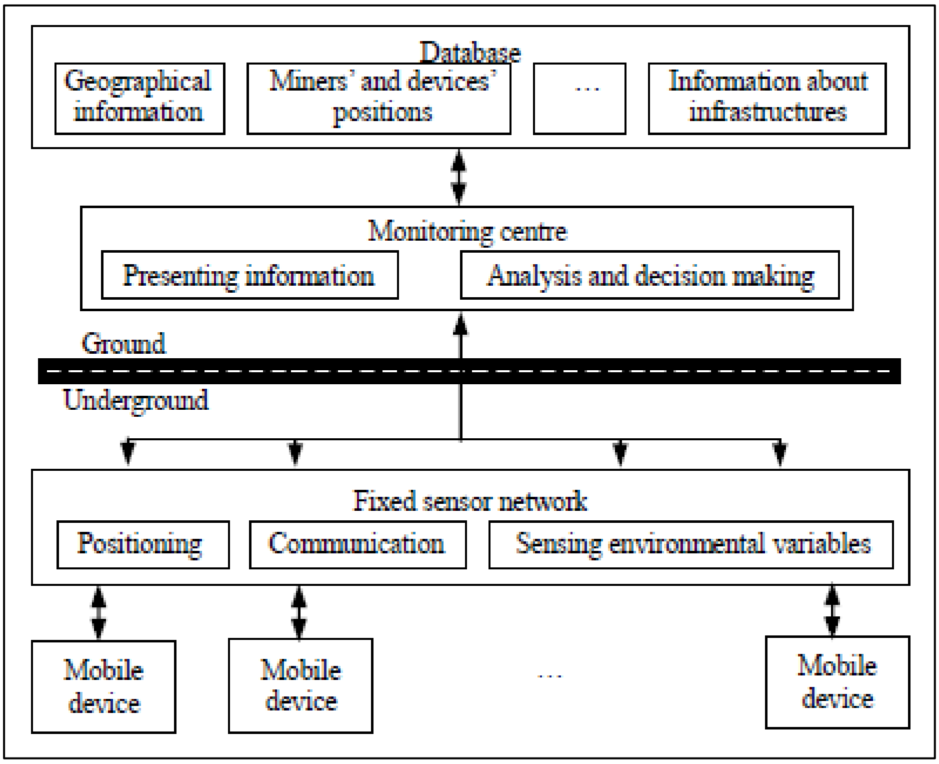


Figure 2- 6 Structure of an intelligent and integrated response and rescue system (Zhang et al.*, 2009)*

c) Integrated Underground Mine Monitoring Systems

Aimed at achieving economical and productive mines, a variety of technological systems and mechanisation technologies have been implemented (Mitchell & Steen, 2017; Leach, 2014). Examples of these implementations includes systems for ventilation and refrigeration monitoring and management, communication systems with wired and wireless sensor networks for environmental attributes monitoring (Moridi *et al.*, 2015; Moridi *et al.*, 2015), access control and surveillance systems, emergency communications, collision avoidance systems (Schauenburg, 2017), just to mention a few. Such systems find application within the mines at different levels of the mining process and are also managed by different departments.

Lately, mining companies have discovered the benefits that come with all these systems being integrated and sharing their data (Clarke & E. E. Publishers, 2016). Some of these benefits, in addition to data sharing for informed decision making, include reduced costs that would come about due to complete overhaul of existing systems and bridging of the gap in technology considering the ages and development platforms to existing systems (RAMJACK, 2016). This eliminates the need for acquisition of new software and applications and the need subject current employees to technological training on the new systems. Instead, through integration of the existing systems, only relevant information can be retrieved and shared across the integrated systems, which will provide a necessary input towards better analysis and information derivation.

This goal towards integrated systems, information sharing and analysis can be achieved through integration technologies such as use of web services (Qifeng & Zhangjian, 2011; Machado *et al.*, 2006), data or application level integration (Chilcott, 2015; Buchinski, 1986) or even through the use of the ‘internet of things’ technology (Ahmed *et al.*, 2017; Shah & Yaqoob, 2016; Samaniego & Deters, 2016).

3. METHODOLOGY

3.1. Introduction

This section provides in-depth information on the chronology leading to the development of a proof of concept (POC) system. This POC mainly functions to provide real-time data viewing, analysis and management capabilities aimed at ensuring that the underground mine working environment is properly monitored and that the personnel present are exposed to a healthy and safe working environment.

The overall goal of this research project was the demonstration of the capabilities of Integrated Enterprise GIS and GeoEvent Management Systems for real-time monitoring, analysis and management of digital sensor data for improved health and safety in an underground mine. The methodology workflow was divided into two major sections, i.e.

1. Determination of factors or causes of health and safety risks in an underground mine;
2. Development and of an integrated and real-time monitoring and spatial analysis system, targeting provision of a healthy and safe working environment.

3.2. Scenario Establishment and Modelling

The prototype system developed with this research study was aimed at promoting and improving health and safety in an underground mine. In order for the system to be functional in real time monitoring and management of data about the underground mine environment, the dangers, factors and risk scenarios causing harm to personnel leading to casualties, health deterioration and even death needed to be determined. Other than identification of such factors and risks in an underground mine, the specific sensor systems and hence parameters about the underground mine environment that need to be measured or monitored also needed to be identified to facilitate the development of fully functional real-time monitoring system.

In establishment of these factors and risk scenarios, focusing on underground mines, the methods used included:

- Informal (personal discussions and via e-mail) brainstorming sessions with colleagues and professionals at the School of Mining Engineering. These communications provided guidance on how to carry out this research in the context of the South African mining industry, especially on the various disasters that have struck the industry

- Research and information gathering from existing publications, journals, books and even from websites belonging to companies and parastatals in the mining industry, such as the Department of Mineral Resources (DMR) of South Africa.

In addition to this, two meetings were also held with stakeholders in the DigiMine Project, on the 17th and 24th of May, 2016. Participants included ESRI staff led by Mr. P. McKivergan, representatives from MineRP led by M. Woodhall, representation from IBM led by M. Honey, staff from Anglo American (South Africa) led by A. Portia and Wits DigiMine team, led by Prof. F. Cawood. One of the agenda in these meetings was determination of the most prevalent health and safety risks and factors in underground mine environment. Other than determining of the most common risks and scenarios in underground mines, a limit to the research was put up in relation to what scenarios to focus on, their courses and even how to provide a solution through systems integration. A discussion on how to monitor and model such factors and risks was also covered by looking at the various scenarios that pose danger to mine personnel and how to manage such scenarios.

Underground mine incidents are a combination of hazards and causes and any of the risk factors can initiate a domino effect in the mine that could lead to a major disaster. Presence of explosive gases in a mine could be triggered, with the resultant explosion leading to collapse of the mine or even flooding of the mine tunnels (Dolozme, 2016). To avoid or prevent such a disastrous extent to damages and injuries or deaths to mine personnel, continuous monitoring of the underground mine environment and the management of the environment is necessary, so that at all times, the environment is safe and healthy.

Modeling of the risks and hazards in an underground mine is possible through the continuous collection and analysis of sensor data about the different parameters in a mine environment. Such models can also be used to predict and quantify the occurrence of life-threatening incidents in the mine. Health and safety risks and factors can thus be monitored and predicted through analysis of data from sensors such as smoke detectors, rock stress meters, water pH meters, temperature sensors, humidity sensors, gas sensors, wind speed and direction sensors and even through use of video and still photo cameras.

WMI mock underground mine has sensors already implemented and accompanying software installed. For the purposes of this research exercise and POC development, these sensor systems and data obtained from them were used. These sensors, including their purpose and locations within the mock underground mine, data format and purpose are presented in table 3-1 below.

Table 3- 1 A table with a list of sensors present at the Wits Mine Institute's mock underground mine (source: Author)

EOH Camera System				
Sensor	**Purpose**	**Location**	**Data Format**	
Video Camera	Capture and storage of pictures and videos	3 x MDL Lab 1 x Third Floor 4 x Second Floor 2 x Stairs 1 x South-western Entrance, Lower ground 7 x Tunnel area 1 x Control Room 6 x Genmin Lab	Still picture format in JPEG Video file format in SCP	
Vibra Tech System				
Sensor	**Purpose**	**Location**	**Source Data Format**	
			Before Data Logger	**After Data Logger**
Crack Meters	Measure crack expansion and contraction	2 x Ceiling of 2nd Floor 1 x wooden support in stope 1 x concrete ceiling outside stope area	Vibrating wire signal from sensor in Digits Digits = $Hz^2/1000$	Displacement = current digits – Initial Digits * Gauge Factor
Rock stress meters	Measures stress changes	1 x Concrete block placed near the stope 1 x wooden support in stope	Vibrating wire signal from sensor in Digits Digits = $Hz^2/1000$	Displacement = current digits – Initial Digits * Gauge Factor
Convergence meter	Measures convergence and divergence in the tunnel	1 x Tunnel	Vibrating wire signal from sensor in Digits Digits = $Hz^2/1000$	Displacement = current digits – Initial Digits * Gauge Factor
Seismographs	Measure vibration	1 x Roof 1 x Near entrance to tunnel	Integrated in the data logger - Volts	Velocity
Web Cameras	Captures still images and video	1 x Roof 1 x Near entrance to tunnel	.jpg files	.jpg files

Temperature and relative humidity sensor	Measures temperature and relative humidity	1 x Roof	Voltage	Voltage * Gauge factor for correct units for Temperature and Relative Humidity
Rain Gauge	Measures precipitation	1 x Roof	Pulse Count	Pulse counts * 0.01” rain per pulse
Water Level (pressure) sensor	Measures water level	1 x Roof	Voltage	Voltage * Gauge Factor for water level
pH Sensor	pH measurement	1 x Roof	Voltage	Voltage * gauge factor for pH

NOTE: All vibrating wire sensors output a frequency signal to a small spectrum analyzer in the remote box. The spectrum analyzer then resolves the signal and converts this to a reading of digits. Digits = Freq^2/1000. The data logger stores the value in digits and then multiplies digits by gauge factor to convert digits to an engineering value such as mm of displacement. All other sensors, except cameras do output a voltage which goes through the A-D to convert to digital signal.

Schauenburg system

Sensor	**Purpose**	**Location**	**Source Data Format**	
			Before Data Logger	**Before Data Logger**
Cap lamps	Light source, paging and tracking, SOS message, gas warning message and access control	10 x Lamp Room	Binary	Value
Sentinel gas detection station (GDI)	Measuring gas levels	2 x lamp room	Binary	Value
Sentinel calibration station	Calibration of GDI	1 x Lamp Room	Binary	Value
Sentinel test Station (Auto)	Test GDI	1 x Lamp Room	Binary	Value
Sentinel test Station (manual)	Test GDI	1 x Lamp Room	Binary	Value
Rescue Packs	Oxygen source, paging and tracking, access control	10 x Lamp Room	Binary	Value
Intellisens CH_4 sensor	Measuring CH_4 levels	1 x Tunnel	Binary	Value
Intellisens CO sensor	Measuring CO levels	1 x Tunnel	Binary	Value

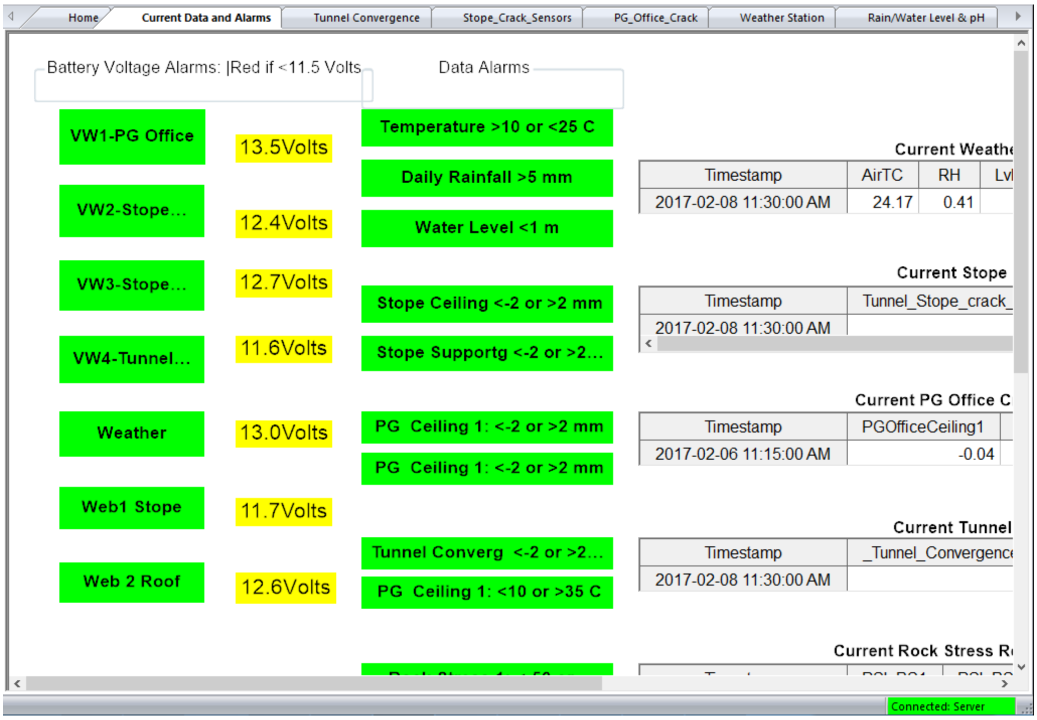
3.3. Data Acquisition and Processing

To facilitate system development for real-time monitoring and management of the underground work environment, test data was required.

a) Data download from the existing server system

WMI mock mine is equipped with mining sensors commonly used in underground mines, from which data were obtained and used for this research. All the sensor systems and their accompanying software systems are installed and transmit recorded data onto the server system. These systems are presently configured to query and transmit data recordings from the sensors to the servers every 15 minutes, though this time span is configurable and can be set to shorter or longer periods. The data used with this research were therefore downloaded from the server system present at the control room, located at the Chamber of Mines building.

The server system provides a web interface from which the sensor systems, that is, a camera system and its recordings; Schauenburg System; and as well, Vibratech System, can be managed and configured. This web interface (see figures 3-1, 3-2 and 3-3 below), also functions as a one-stop-shop from which information from the sensors can be retrieved from the databases; and warnings and/or alarms as configured in the system can be viewed and necessary actions or corrective measures can be taken.



Current Weathe

Timestamp	AirTC	RH	Lvl
2017-02-08 11:30:00 AM	24.17	0.41	

Current Stope

Timestamp	Tunnel_Stope_crack_
2017-02-08 11:30:00 AM	

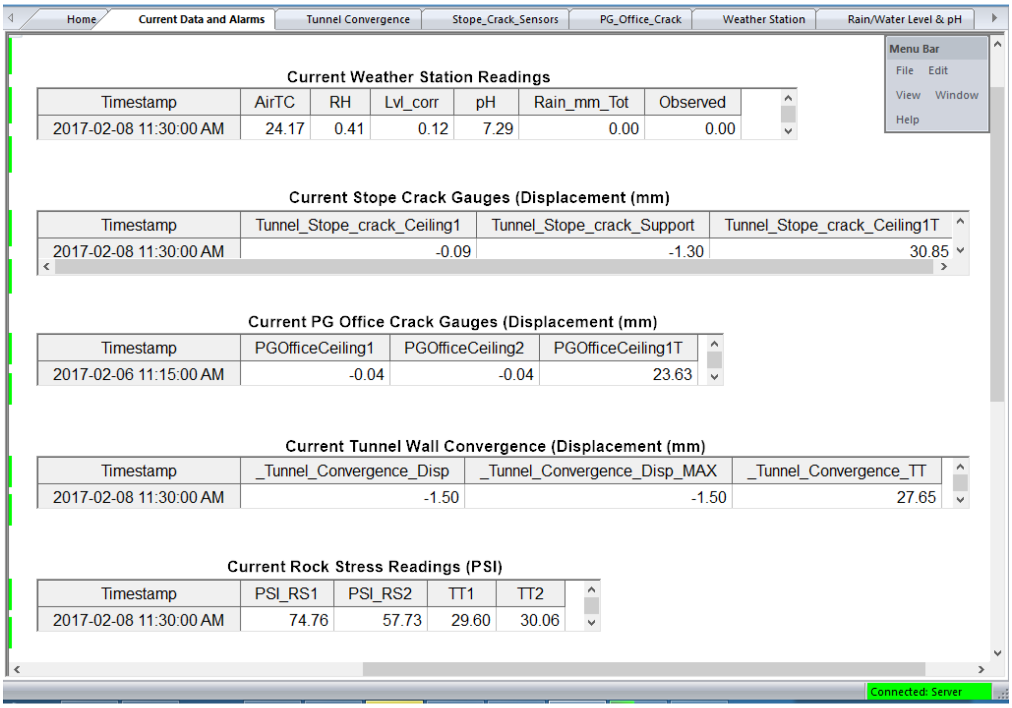
Current PG Office C

Timestamp	PGOfficeCeiling1
2017-02-06 11:15:00 AM	-0.04

Current Tunnel

Timestamp	_Tunnel_Convergence
2017-02-08 11:30:00 AM	

Figure 3- 1 Current VibraTech System's web dashboard interface (source: Author)



Current Weather Station Readings

Timestamp	AirTC	RH	Lvl_corr	pH	Rain_mm_Tot	Observed
2017-02-08 11:30:00 AM	24.17	0.41	0.12	7.29	0.00	0.00

Current Stope Crack Gauges (Displacement (mm)

Timestamp	Tunnel_Stope_crack_Ceiling1	Tunnel_Stope_crack_Support	Tunnel_Stope_crack_Ceiling1T
2017-02-08 11:30:00 AM	-0.09	-1.30	30.85

Current PG Office Crack Gauges (Displacement (mm)

Timestamp	PGOfficeCeiling1	PGOfficeCeiling2	PGOfficeCeiling1T
2017-02-06 11:15:00 AM	-0.04	-0.04	23.63

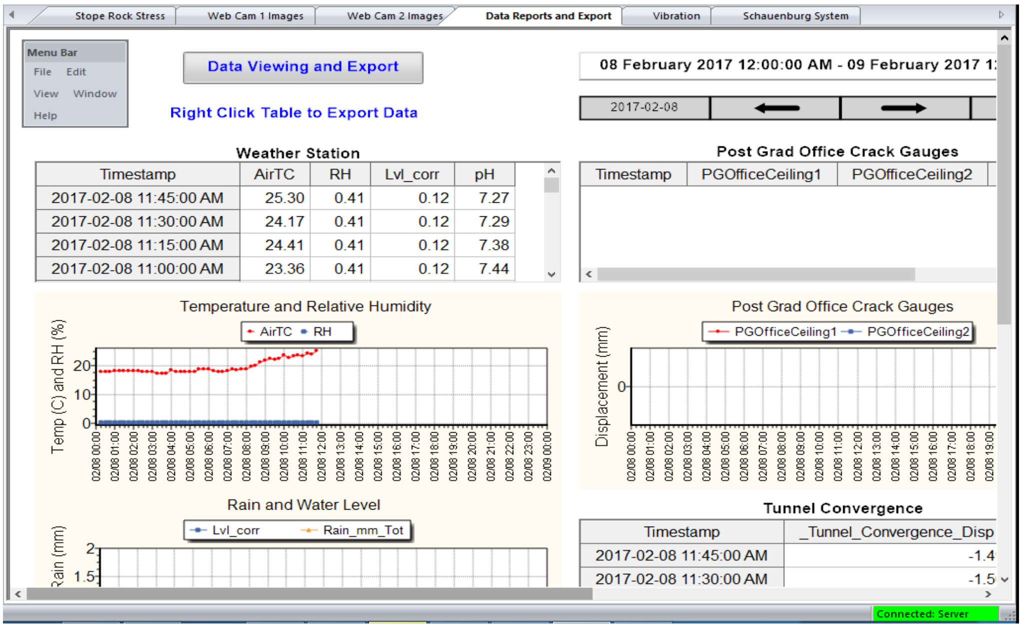
Current Tunnel Wall Convergence (Displacement (mm)

Timestamp	_Tunnel_Convergence_Disp	_Tunnel_Convergence_Disp_MAX	_Tunnel_Convergence_TT
2017-02-08 11:30:00 AM	-1.50	-1.50	27.65

Current Rock Stress Readings (PSI)

Timestamp	PSI_RS1	PSI_RS2	TT1	TT2
2017-02-08 11:30:00 AM	74.76	57.73	29.60	30.06

Figure 3- 2 Web interface showing current data recorded from the VibraTech sensor systems (source: Author)



Weather Station

Timestamp	AirTC	RH	Lvl_corr	pH
2017-02-08 11:45:00 AM	25.30	0.41	0.12	7.27
2017-02-08 11:30:00 AM	24.17	0.41	0.12	7.29
2017-02-08 11:15:00 AM	24.41	0.41	0.12	7.38
2017-02-08 11:00:00 AM	23.36	0.41	0.12	7.44

Post Grad Office Crack Gauges

Timestamp	PGOfficeCeiling1	PGOfficeCeiling2

Tunnel Convergence

Timestamp	_Tunnel_Convergence_Disp
2017-02-08 11:45:00 AM	-1.4
2017-02-08 11:30:00 AM	-1.5

Figure 3- 3 Web interface platform for exporting of VibraTech sensor data, reports and charts (source: Author)

This web interface was used to access and download data recorded by the sensors. Sensor recordings from 1st September, 2015 to 1st May, 2016 were retrieved from the server system. For the purposes of this project and a case study of mine health and safety at WMI mock underground mine, Vibratech System and data obtained from its sensors, were used.

The data downloaded from Vibratech system's database, with samples provided below in tables 3-2, 3-3, 3-4, 3-5 and 3-6, were used as is with no dummy data being created owing to the stable nature of the data. The data is used as is, because at this stage of the research, the aim was integration of the two systems and displaying of the real-time streaming data on a dashboard application. Events simulation or identification is a possibility of this integrated system, which will be the focus of the next level of this research, just not part of the scope of this exercise.

These datasets downloaded, in comma delimited csv file format, were from the following Vibratech System sensors:

1. Convergence meters - located in the tunnel

This sensor records and transmits data on the minimum and maximum measured displacements, in millimeters (mm) as exemplified in table 3-2.

Table 3- A sample of the tunnel convergence meter dataset (source: Author)

Timestamp	**Disp (mm)**	**Disp MIN**	**Disp TMx**	**Temp**	**Temp MIN**	**Temp MAX**
4/1/2016 0:00	-1.53	-1.53	2016-03-31 11:52:00 PM	27.26	27.26	27.32
4/1/2016 0:15	-1.53	-1.53	2016-04-01 12:10:30 AM	27.19	27.19	27.25
4/1/2016 0:30	-1.53	-1.53	2016-04-01 12:18:00 AM	27.11	27.11	27.19
4/1/2016 0:45	-1.53	-1.53	2016-04-01 12:42:00 AM	27.05	27.05	27.11
4/1/2016 1:00	-1.53	-1.53	2016-04-01 12:49:00 AM	27.01	27.01	27.06
4/1/2016 1:15	-1.52	-1.53	2016-04-01 01:12:00 AM	26.92	26.92	27
4/1/2016 1:30	-1.52	-1.53	2016-04-01 01:28:00 AM	26.84	26.84	26.92
4/1/2016 1:45	-1.53	-1.53	2016-04-01 01:40:00 AM	26.73	26.73	26.84
4/1/2016 2:00	-1.52	-1.53	2016-04-01 01:54:30 AM	26.65	26.65	26.73
4/1/2016 2:15	-1.52	-1.52	2016-04-01 02:11:00 AM	26.56	26.56	26.65

2. Crack gauge – located under the stope

This sensor functions to monitor measure and transmit displacements or movements of the stope, as exemplified in table 3-3.

Table 3- 2 Sample data from the stope crack gauge (source: Author)

Timestamp	**Tunnel_Stope crack_Ceiling1**	**Tunnel_Stope crack_Support**	**Tunnel_Stope crack_Ceiling1T**	**Tunnel_Stope crack_SupportT**
4/1/2016 0:00	-0.13	-1.29	29.53	29.14

4/1/2016 0:15	-0.13	-1.29	29.4	29.04
4/1/2016 0:30	-0.14	-1.3	29.85	29.65
4/1/2016 0:45	-0.13	-1.29	29.85	29.45
4/1/2016 1:00	-0.13	-1.29	29.32	29.01
4/1/2016 1:15	-0.14	-1.3	29.68	29.5
4/1/2016 1:30	-0.13	-1.29	29.62	29.26
4/1/2016 1:45	-0.13	-1.29	29.1	28.89
4/1/2016 2:00	-0.13	-1.29	28.91	28.74
4/1/2016 2:15	-0.13	-1.29	28.9	28.64

3. Rock stress meters – located under the stope

This sensor system, located at the stope in an underground mine measures the amount of stresses acting on the stope, which provides valuable information that can be used to determine the status of the stope structure. The measurements recorded are captured in table 3-4.

Table 3- 3 Sample data from the stope rock stress meters (source: Author)

Timestamp	**PSI_RS1**	**PSI_RS2**	**TT1**	**TT2**
4/1/2016 0:00	84.44	93.36	29.06	29.44
4/1/2016 0:15	85.25	93.49	28.98	29.38
4/1/2016 0:30	82.63	92.41	29.14	29.69
4/1/2016 0:45	84.94	93.43	29	29.43
4/1/2016 1:00	86.92	93.73	28.81	29.31
4/1/2016 1:15	83.41	92.79	29.01	29.58
4/1/2016 1:30	86.68	93.74	28.83	29.32
4/1/2016 1:45	87.7	93.95	28.72	29.24
4/1/2016 2:00	88.17	94.14	28.65	29.15
4/1/2016 2:15	88.36	94.25	28.62	29.09
4/1/2016 2:30	85.5	93.22	28.8	29.39

4. Weather station sensors – located at the entrance

Located on the roof of the Chamber of Mines (representing the mock underground mine entrance/surface), the weather station is made up of a number of sensors that measure different parameters about the out of mine environmental and weather conditions. These include parameters such as air temperature, relative humidity, rainfall measurements and pH levels, as shown in table 3-5.

Table 3- 4 Sample of the weather station dataset (source: Author)

Timestamp	**AirTC**	**RH**	**Lvl_corr**	**pH**

4/1/2016 0:00	20.22	0.41	1.25	NAN
4/1/2016 0:15	19.74	0.41	1.25	NAN
4/1/2016 0:30	19.63	0.41	1.25	NAN
4/1/2016 0:45	20.15	0.41	1.25	NAN
4/1/2016 1:00	19.77	0.41	1.25	NAN
4/1/2016 1:15	19.43	0.41	1.25	NAN
4/1/2016 1:30	18.99	0.41	1.25	NAN
4/1/2016 1:45	18.82	0.41	1.25	NAN
4/1/2016 2:00	18.64	0.41	1.25	NAN

5. Crack gauge – located in the Post-Graduate Office, Chamber of Mines

This sensor measures and transmits recordings of minute displacements or movements from within the Post Graduate Office on the 2nd floor of the Chamber of Mines building. An example of transmitted data is in table 3-6.

Table 3- 5 Sample data from the PG Office crack gauge sensor (source: Author)

Timestamp	**PG Office Ceiling1**	**PG Office Ceiling2**	**PG Office Ceiling1T**	**PG Office Ceiling2T**
4/1/2016 0:00	-0.01	-0.06	23.47	24.39
4/1/2016 0:15	-0.01	-0.05	23.37	24.05
4/1/2016 0:30	-0.01	-0.05	23.46	24.25
4/1/2016 0:45	-0.01	-0.06	23.41	24.22
4/1/2016 1:00	-0.01	-0.05	23.44	24.15
4/1/2016 1:15	-0.01	-0.06	23.45	24.36
4/1/2016 1:30	-0.01	-0.05	23.39	24.03
4/1/2016 1:45	-0.01	-0.06	23.5	24.33

In addition to the extracted and downloaded digital sensor recordings obtained from the mock mine, other datasets that were required to accomplish the objectives of this research were also obtained. These include:

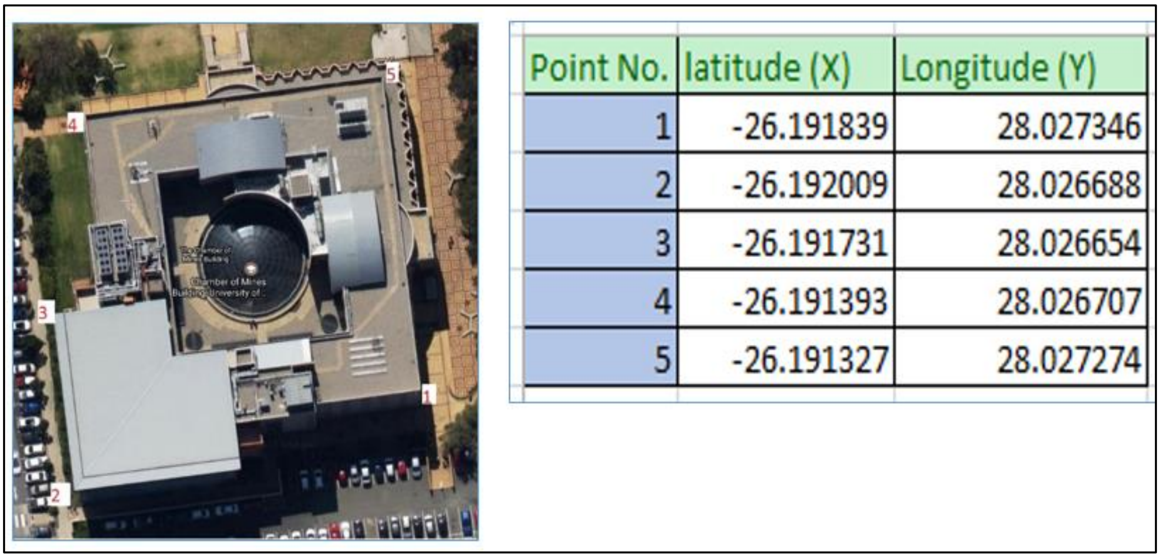
- CAD drawings for the mock mine (Chamber of Mines Building);
- Location and descriptive information about the various features and facilities present at the mock mine.

b) CAD Data and 3D mine Development

A 3D spatial map and design of the mock mine (CM Building) is one of the deliverables for this research study. To achieve this, 2D CAD drawings were obtained from the digital repository at the WMI, together with elevation and inter-level measurements of the CM building to elaborate a 3D design of the mock mine. This conversion from 2D to 3D involved the following processes:

Step 1: Georeferencing and Conversion of the AutoCAD drawings to ArcGIS feature layers:

To facilitate georeferencing of the AutoCAD drawings, Google Earth was used to obtain coordinates for the Chamber of Mines building. These coordinates were used to georectify the CAD drawings for each and every floor.

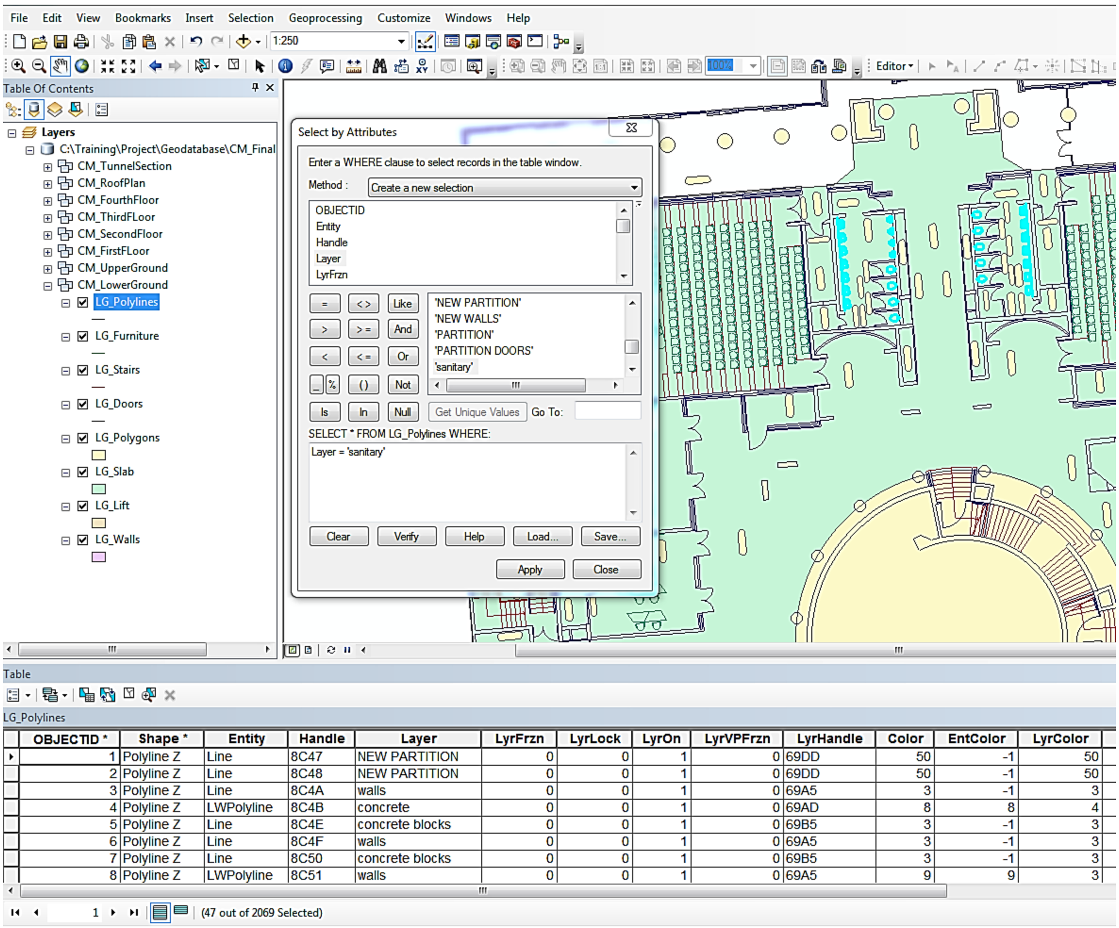


Point No.	latitude (X)	Longitude (Y)
1	-26.191839	28.027346
2	-26.192009	28.026688
3	-26.191731	28.026654
4	-26.191393	28.026707
5	-26.191327	28.027274

Figure 3- 4 A Google image of teh CM building and a table with coordinates used to georectify AutoCAD files (source: Author)

Step 2: Vectorization and creation of the individual feature layers for the mapped features:

This step mainly involved the identification of the features mapped on the AutoCAD drawing and hence the converted spatial features on the geodatabase. This was done through *attribute querying* of the feature layers, for instance *polylines* layers i.e.



Enter a WHERE clause to select records in the table window.

Method : Create a new selection

SELECT * FROM LG_Polylines WHERE:

Layer = 'sanitary'

LG_Polylines

OBJECTID *	Shape *	Entity	Handle	Layer	LyrFrzn	LyrLock	LyrOn	LyrVPFrzn	LyrHandle	Color	EntColor	LyrColor
1	Polyline Z	Line	8C47	NEW PARTITION	0	0	1	0	69DD	50	-1	50
2	Polyline Z	Line	8C48	NEW PARTITION	0	0	1	0	69DD	50	-1	50
3	Polyline Z	Line	8C4A	walls	0	0	1	0	69A5	3	-1	3
4	Polyline Z	LWPolyline	8C4B	concrete	0	0	1	0	69AD	8	8	4
5	Polyline Z	Line	8C4E	concrete blocks	0	0	1	0	69B5	3	-1	3
6	Polyline Z	Line	8C4F	walls	0	0	1	0	69A5	3	-1	3
7	Polyline Z	Line	8C50	concrete blocks	0	0	1	0	69B5	3	-1	3
8	Polyline Z	LWPolyline	8C51	walls	0	0	1	0	69A5	9	9	3

1 (47 out of 2069 Selected)

Figure 3- 5 A screenshot showing 'select by attributes' process to feature selection, from which new layers are derived (source: Author)

From the selected features, a new layer was thus created and exported to the geodatabase. This was done for all different layers present on the CAD drawings which represented each floor of the building. A feature dataset was created for each floor of the CM building and the exported layers from the query stored in the relevant feature dataset, representing the floor/level.

Step 3: Creation of a 3D map scene of the mock mine using Arc Scene

Arc Scene, a 3D application for visualization of GIS data, allowing for overlaying of GIS layers of data, was used to develop a 3D scene of the underground mine. This 3D scene was developed using the CAD derived spatial layers stored in the geodatabase. For each layer, a base height was set, representing its altitude, with all layers on the same floor being set to the same base height. This resulted in layering of the layers, as seen in figure 3-6 below.

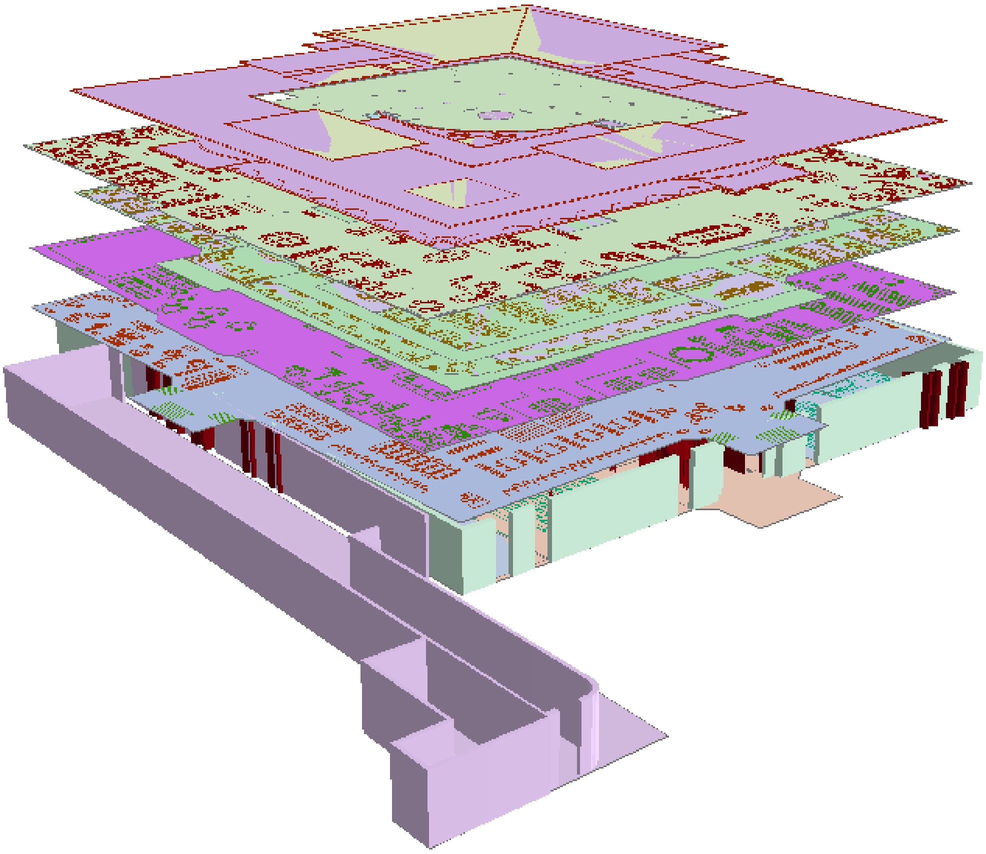


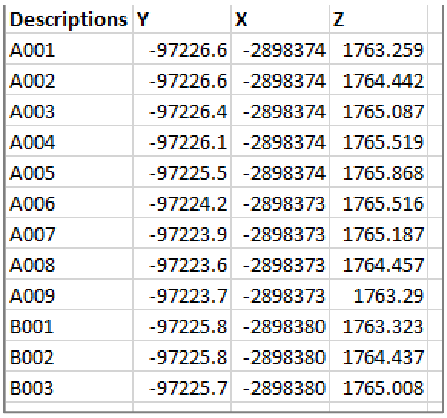
Figure 3- 6 A 3D model of the underground mine at the CM building CM Building (source: Author)

c) Surveying and Mapping of Mock Mine Features

The final dataset used in this research study includes information on other features, such as fire extinguishers, emergency exits and routes, that are essential to health and safety. To obtain the following information, features from the CAD drawings play a significant role. However, majority of these features are not included in the AutoCAD drawings, therefore surveying was used to spatially locate, map and obtain descriptive information about these features.

A reflector-less total station was used to conduct the mapping survey of the features present in the underground mine, with special focus on the tunnel section. The tunnel's already set control points were used to set the total station, after which observations to different features inside the tunnel was made and 3D coordinates measured, as shown in table 3-7. These coordinates and the descriptions – codes representing the features mapped – were then imported to ArcMap and a layer generated.

Table 3- 6 Sample of the coordinate information for the features at the tunnel (source: Author)



Descriptions	Y	X	Z
A001	-97226.6	-2898374	1763.259
A002	-97226.6	-2898374	1764.442
A003	-97226.4	-2898374	1765.087
A004	-97226.1	-2898374	1765.519
A005	-97225.5	-2898374	1765.868
A006	-97224.2	-2898373	1765.516
A007	-97223.9	-2898373	1765.187
A008	-97223.6	-2898373	1764.457
A009	-97223.7	-2898373	1763.29
B001	-97225.8	-2898380	1763.323
B002	-97225.8	-2898380	1764.437
B003	-97225.7	-2898380	1765.008

With all these information and datasets obtained and studied, a map document was created in ArcMap with its 3D equivalent in Arc Scene. The information obtained from the sensor data and location/descriptive information about the features present at the CM building was used for the design and development of the real-time management system, including design and administration of the accompanying geodatabase, as discussed in the sections below.

3.4. System Design, Development and Integration

The three basic components that make up a sensor-based underground mine monitoring system includes:

1. A sensor system – installed in an underground mine, recording data about different mine parameters
2. Communication network – can be either wired or wireless and functions to relay the recorded data from the sensors to the control room
3. Control Room Server Systems – This represents a central server system with installed software and databases to store, analyze and manage data recorded and transmitted from the underground mine work environment

For the purposes of this research study and meeting of its objectives, attention is mainly given to the control room server system component. This is because sensor systems and communication networks have already been implemented at the mock mine, as part of the larger DigiMine Project. Data is thus collected by the sensors and transmitted to the control room, where the prototype system developed was installed and used to analyse and monitor, in real time, information about the underground mine environment and its conditions.

Before the development of the POC system, prerequisite environmental setup and installation of software is conducted. ESRI's ArcGIS platform is used with this research exercise through installation of both desktop and server version of the software. Default installation of this platform and hence software provides capabilities for map creation through addition, styling and organisation of spatial features. This platform also allows for the use of geoprocessing tools and configurable widgets to be used to further develop and deploy map-based applications and services or solutions. An example of such functionality is the development of workflows for process modelling. Through use of the model builder tool in the GeoEvent Extension for ArcGIS Server, a process workflow involving data input, processes and data output can be configured and implemented *ad hoc*. As discussed in section 3.4 (c) below, input configurations involve defining data fields, data types, data sources and formats – csv, excel, geojson, just to mention a few; process configurations involving isolation of specific fields for specific processes, such as generating a geometry field from combining latitude and longitude fields from data input widget based on a predefined coordinate reference system; and as for data output, the processed input data and its fields are mapped to a table in a spatial database. Such a process workflow reduces the default multi-step processing time through use of a single tool that combines multiple geoprocessing tools into a single tool.

The additional configurations and use of widgets, representing functionalities beyond the default software setup, are discussed in the subsections below, especially focusing on feature service publishing to server and portal environments, GeoEvent services development and eventually the development and configuration of an operations dashboard application specific to the DigiMine project.

The stages used for the development of the system involved:

a) Development Environment Setup

This stage involved mainly the preparation and installation of prerequisite software that were used for this research. In developing the system, a multi-tier architecture, defined as a client-server architecture in which components of the system are organized into layers and providing dedicated functionality (Schuldt, 2009), was used. Specifically, a 3-tier architecture was used and is made up of the following layers:

- *Data Management Layer* –which houses the database servers for data and information storage

- *Application Layer* – also referred to as middle tier, logic tier or business logic tier and controls the applications functionality by performing detailed processing
- *Client or Presentation tier* – which mainly includes the user interface which displays data and information to the users and accepts input too, as a platform through which the user interacts with the system and its functionalities.

A database server system, making up the data tier, was implemented through installation of Microsoft SQL Express 2012 RDBMS and ArcSDE, providing a central and robust data storage for both spatial and non-spatial data and information.

Application tier is actualized through the installation of ArcGIS for Server system. ArcGIS for Server functions to make the geographic information available enterprise-wide through internet connections. These information is accomplished through the use of web services allowing the server computer to receive and process requests for information sent from other devices, such as tablets, smartphones or laptops.

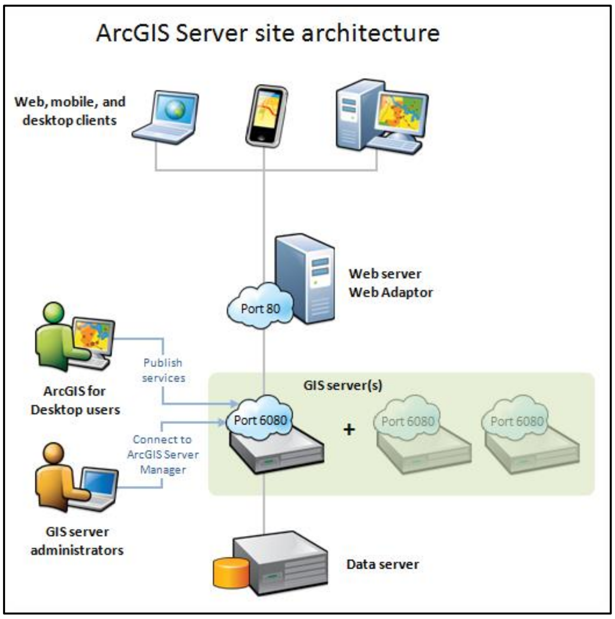


Figure 3- 7 General representation of an ArcGIS Server site architecture and components. Source -(ESRI, 2016b)

Additional extensions were also installed alongside ArcGIS for Server, providing additional functionality to the system. These extensions included *GeoEvent Extension for Server* which functions in handling of streaming real-time data from the sensors; *ArcGIS 3D Analyst* which provisions for creation, visualization and analyzing of GIS data in a 3D context and *Data Interoperability extension* which enables integration of data from multiple sources and formats e.g. csv, their use within geoprocessing tools and publishing the data to ArcGIS Server.

To facilitate and provide a platform through which the users of the system can interact with and provide commands to the system and derive information from analysis of the data, the presentation layer of the architecture has the following software and application development tools installed:

- ESRI's ArcGIS for Desktop (ver. 10.4.1) – with ArcMap, ArcCatalog, Arc Scene and ArcGlobe, for creation of maps, performing spatial analysis, managing geographic data and sharing of the results/maps
- Python 2.7 and Jupyter notebook– for development of custom scripts for analysis and data management
- Operations Dashboard for ArcGIS– for monitoring of activities and events and assessment of status and performance of daily operations through a dashboard application.

The software and tools listed above provide a desktop-based environment/platform, through which users of the system can view, analyse, interpret and manage data about the underground mine. Other than the desktop environment, a web portal platform is also provided through the installation of *Portal for ArcGIS*. This collates all the spatial data in a ArcGIS environment and shares it within the whole organization and therefore allowing for creation, saving and sharing of web maps; creation and hosting of web mapping apps; searching for GIS content within the organization; creation of groups for sharing GIS information with coworkers; sharing of links to the GIS applications; and sharing of maps and layer packages for used in desktop environment (ESRI, 2016d).

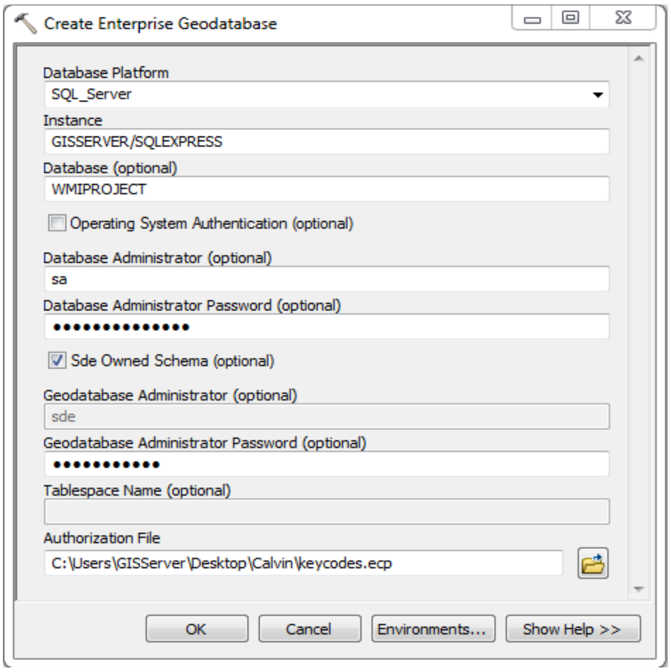
Installation of ArcGIS, both on desktop and server environments provides for an application development platform without the need to use or apply coding or programming skills. This platform mainly uses widgets and 'drag and drop' functionalities for application development, which are essential especially for non-developers (ESRI, 2012). This approach to development is used in this research for the development of the POC system, in particular the GeoEvent Services Manager and Operations Dashboard for ArcGIS.

b) Map & Feature Services Publishing

Up to this point, the stages covered have been preparation of data and installation of prerequisite software for the development of the system. At this stage, the tasks to be carried out entailed exporting of the spatial and attribute data to an enterprise database and publishing of the same data and maps created to ArcGIS server environment, followed by the creation and configuration of real-time data streaming and analysis system through the ArcGIS GeoEvent Processor.

To initiate the process, an enterprise geodatabase was created on SQL Server Express from ArcMap environment. This was done through the ‘Create Enterprise Geodatabase’ geoprocessing tool (figure 3-8 below) available on ArcMap, which connects to the SQL Server Express instance installed on the server allowing for creation of a database with spatial capabilities to manage spatial data.

After creation of an enterprise geodatabase, a connection was made to the geodatabase from ArcMap or ArcGIS Pro environment, enabling the transfer of the spatial and attributes data for storage. Figure 3-9 below shows the database connection geoprocessing tool used to connect to the geodatabase on SQL Server Express RDBMS.


Create Enterprise Geodatabase

Database Platform
SQL_Server

Instance
GISSERVER/SQLEXPRESS

Database (optional)
WMIPROJECT

☐ Operating System Authentication (optional)

Database Administrator (optional)
sa

Database Administrator Password (optional)
●●●●●●●●●●●●●●●

☑ Sde Owned Schema (optional)

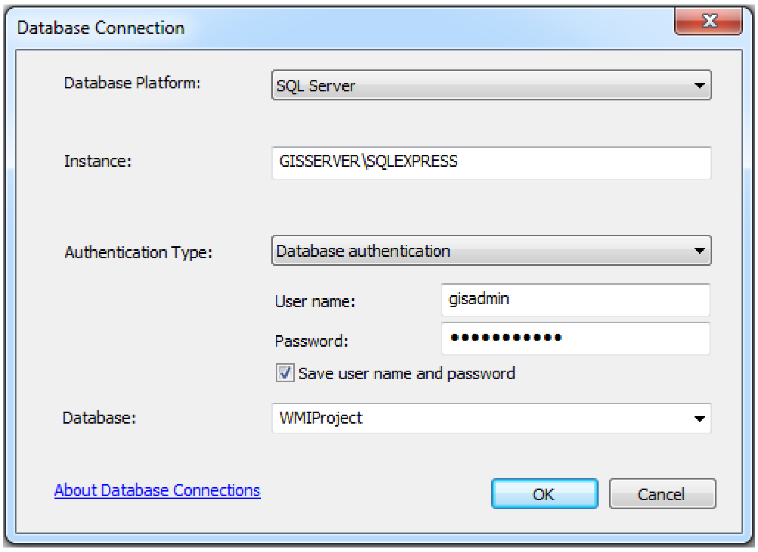
Geodatabase Administrator (optional)
sde

Geodatabase Administrator Password (optional)
●●●●●●●●●●●●

Tablespace Name (optional)

Authorization File
C:\Users\GISServer\Desktop\Calvin\keycodes.ecp

Figure 3- 8 A screenshot of a geoprocessing tool for Enterprise Geodatabase creation (source: Author)



Database Platform: SQL Server

Instance: GISSERVER\SQLEXPRESS

Authentication Type: Database authentication

User name: gisadmin

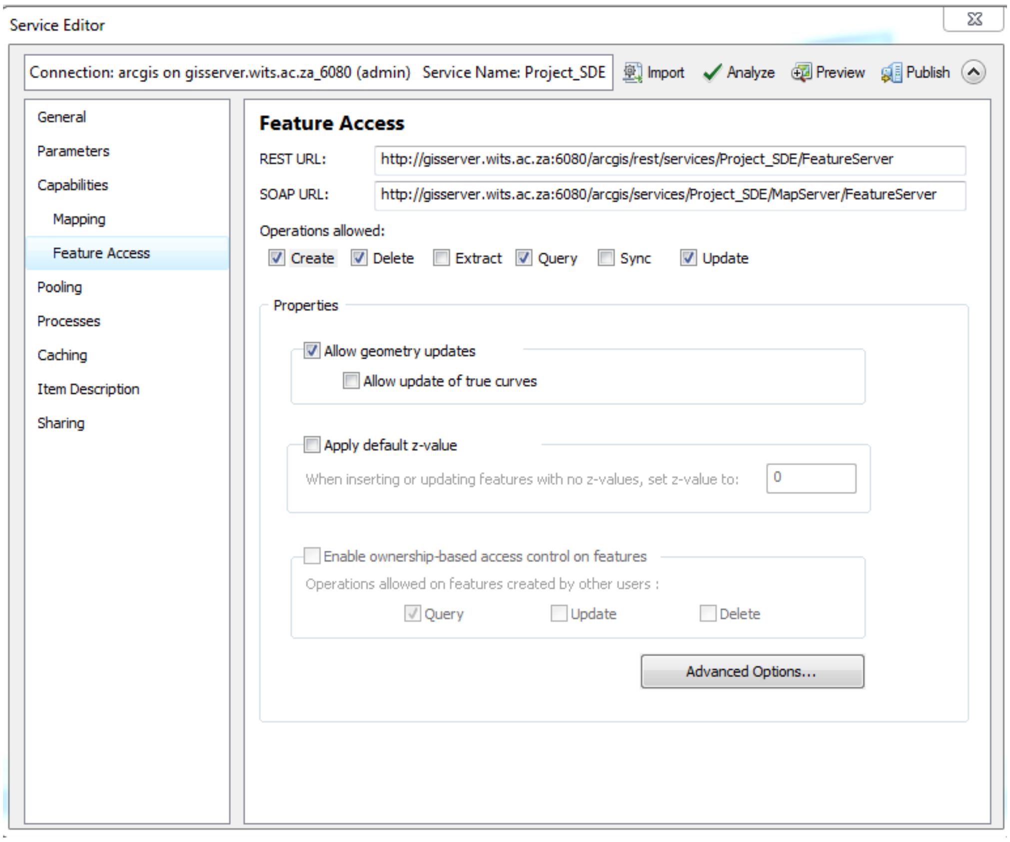
Password: ●●●●●●●●●●●●

☑ Save user name and password

Database: WMIProject

Figure 3- 9 A screenshot of a geoprocessing tool for connecting to an Enterprise Geodatabase from ArcMap (source: Author)

A map document of the underground mine, both in 2D and 3D was then created from the data collected by the researcher through survey of the mine and stored on the enterprise geodatabase. This map shows the layout of the underground mine (for each level), the locations of the sensors and the features/facilities present in the mine. With the map created, it was published to ArcGIS for Server environment as a map service. Publishing of the map service facilitates information access, updating and sharing within the organisation. ArcGIS platform provides for a mechanism to share maps and map features, through publishing of the map features to a hosted platform – either to ArcGIS online which is hosted by ESRI, or to an in-house ArcGIS Server or ArcGIS Portal environment. The process of map service publishing involves configuration of parameters, capabilities, map description and sharing properties as shown in the service editor window (figure 3-10) below.



Connection: arcgis on gisserver.wits.ac.za_6080 (admin) Service Name: Project_SDE

Feature Access

REST URL: http://gisserver.wits.ac.za:6080/arcgis/rest/services/Project_SDE/FeatureServer

SOAP URL: http://gisserver.wits.ac.za:6080/arcgis/services/Project_SDE/MapServer/FeatureServer

Operations allowed:

☑ Create ☑ Delete ☐ Extract ☑ Query ☐ Sync ☑ Update

Properties

☑ Allow geometry updates
☐ Allow update of true curves

☐ Apply default z-value
When inserting or updating features with no z-values, set z-value to: 0

☐ Enable ownership-based access control on features
Operations allowed on features created by other users :
☑ Query ☐ Update ☐ Delete

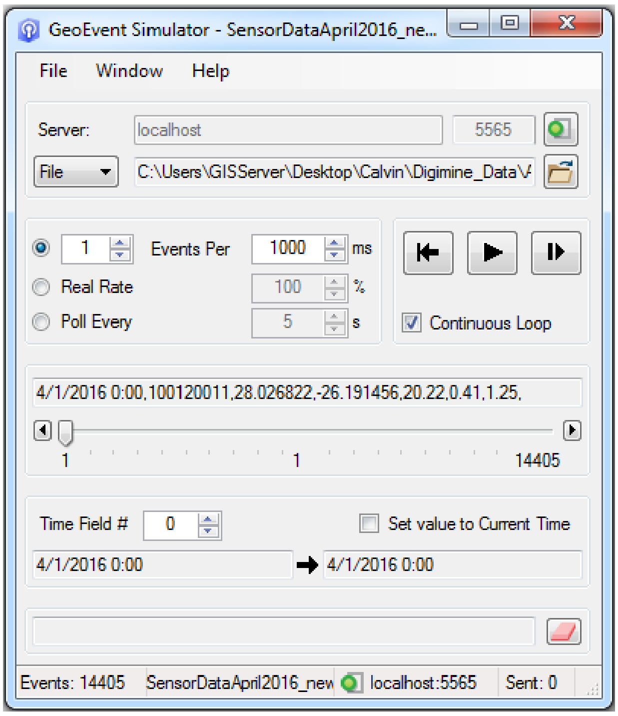
Figure 3- 10 A map service editing window used to analyze map features before their publishing to a GIS server (source: Author)

c) GeoEvent Services Publishing and Data Streaming

The maps developed and features published function to provide a spatial and visual orientation on the location of features and location of sensors within the mock mine. These features and especially the locations of the sensors in the mine remain static, yet record data about parameters such as temperature, relative humidity, seismicity and stream the data to the server system for analysis in real time.

To replicate this real time data streaming process, a simulation of the data downloaded from the existing system was done using GeoEvent Simulator (shown in figure 3-11 below). This application was used to connect to the data and stream the data through a port on a computer or to a streaming web service application, representing transfer of data from the sensor system.

To facilitate the streaming of the data from the simulator and data transfer to a web streaming service, a GeoEvent Service (see figure 3-13 below) is developed, using the GeoEvent Manager. A GeoEvent Definition (see figure 3-12 below) was created, containing and representing the schema of the data being simulated and received as input, via a TCP port. The GeoEvent Service created and published isolates data specific to an identified sensor, through the unique sensor identifier, and conducts a join with the feature service for that specific sensor, acting as the output and thereby updating the feature service layer with the streaming sensor data.



Server: localhost 5565

File C:\Users\GISServer\Desktop\Calvin\Digimine_Data\

● 1 Events Per 1000 ms

○ Real Rate 100 %

○ Poll Every 5 s

☑ Continuous Loop

4/1/2016 0:00,100120011,28.026822,-26.191456,20.22,0.41,1.25,

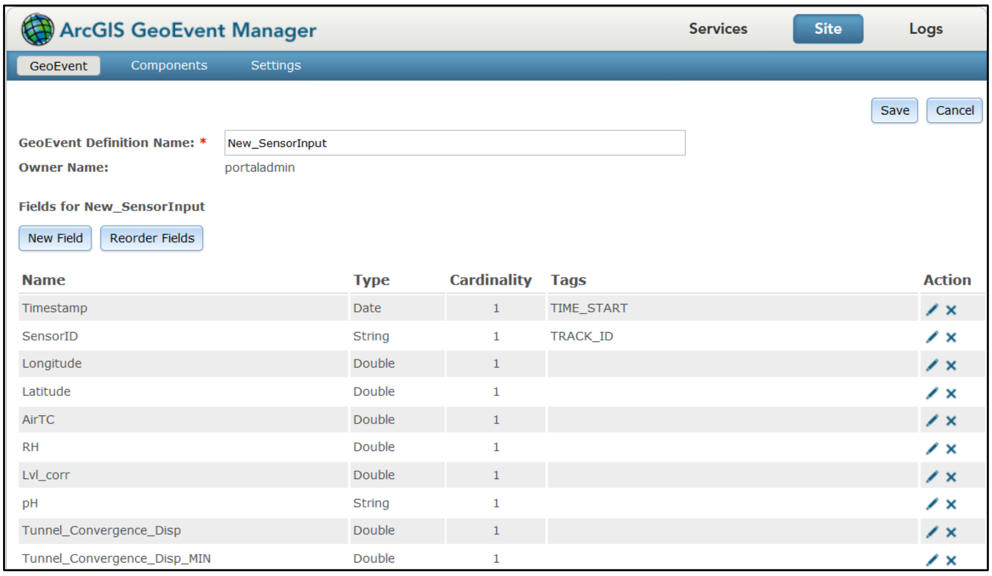
1 1 14405

Time Field # 0 ☐ Set value to Current Time

4/1/2016 0:00 → 4/1/2016 0:00

Events: 14405 SensorDataApril2016_new localhost:5565 Sent: 0

Figure 3- 11 A GeoEvent Simulator application that is available with the GeoEvent Extension for ArcGIS for Server (source: Author)



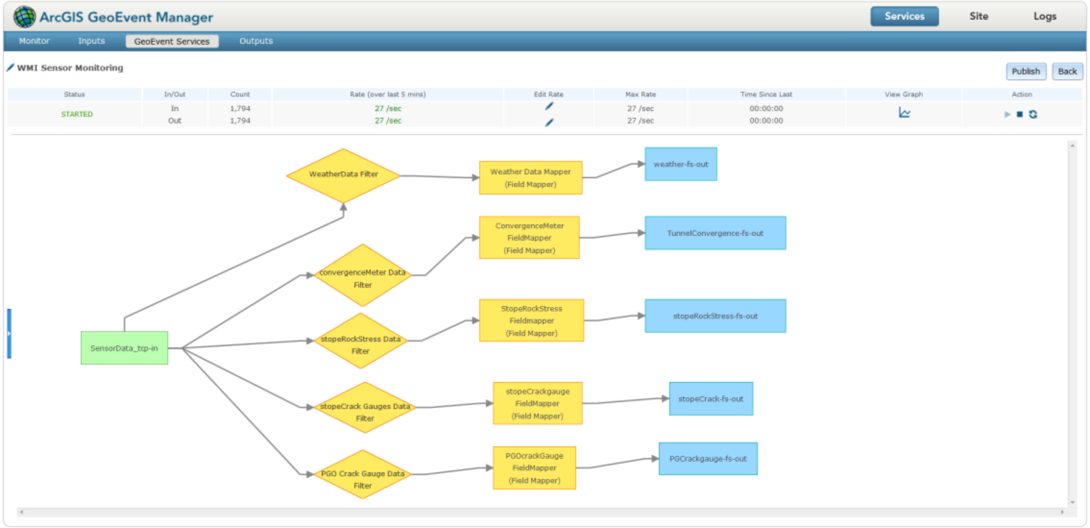
GeoEvent Definition Name: * New_SensorInput

Owner Name: portaladmin

Fields for New_SensorInput

Name	Type	Cardinality	Tags	Action
Timestamp	Date	1	TIME_START	✎ ✕
SensorID	String	1	TRACK_ID	✎ ✕
Longitude	Double	1		✎ ✕
Latitude	Double	1		✎ ✕
AirTC	Double	1		✎ ✕
RH	Double	1		✎ ✕
Lvl_corr	Double	1		✎ ✕
pH	String	1		✎ ✕
Tunnel_Convergence_Disp	Double	1		✎ ✕
Tunnel_Convergence_Disp_MIN	Double	1		✎ ✕

Figure 3- 12 A sample screenshot of a GeoEvent definition and properties as used to represent the schema of the incoming streaming sensor data (source: Author)



Status	In/Out	Count	Rate (over last 5 mins)	Edit Rate	Max Rate	Time Since Last	View Graph	Action
STARTED	In	1,794	27 /sec		27 /sec	00:00:00		
	Out	1,794	27 /sec		27 /sec	00:00:00		

Figure 3- 13 GeoEvent Service showing the workflow through which input data is received, filtered and used to update a feature service with real-time streaming sensor data (source: Author)

c) Dashboards Development

This was the last step to development of the POC system for real-time monitoring and management of sensor data streaming from the underground mine. Operations Dashboard for ArcGIS, a desktop application developed by ESRI, was used for development of a single operational view with summarized information about the streaming data, and therefore about the status of an underground mine environment.

A requirement for development of a dashboard operations view is a web map with feature layers about the features and facilities in the mine, including layers to which the streaming data is stored. A web map was therefore created containing the published map with spatial features about the underground mine, represented as layers.

Creation of an operations view application using Operations Dashboard for ArcGIS involved the use of widgets, such as map, charts, performance indicators and gauges to provide and display an interactive map application. The widgets added to the dashboard view are linked to the layers from the web map application, such that their data sources are the individual layers on the web map.

For development of this real-time monitoring and management system's operations view dashboard, a map widget was used to load and display the already created web application. For every level of the underground mine, a map widget was used to add the web map application and linked to the layers representing features on the specific levels, including a layer of the sensor present on that level or floor.

Additional functionality, for interactivity with the operations view dashboard included addition of tools such as a layer lists tool, for toggling visibility of feature layers; a bookmarks tool, to allow for easy return or zooming to study areas or areas of interest; changing of basemap layers through a basemaps switcher tool; feature pop-up functionality to get more information about the plotted (point, line or polygon) feature; filtering of incoming data and querying of a layer feature.

4. RESEARCH RESULTS AND DISCUSSION

This section covers a discussion on the results obtained from undertaking of this research exercise. These include a discussion on the results from environment setup and architecture, data simulation and basic real-time monitoring and integration testing. This section also covers results obtained from researching on the various risk factors and dangers in underground mines.

4.1. System Environment and Architecture

Figure 4-1 below represents the architecture of the system developed. It also shows the different software installed during system development, based on the 3-tier system architecture.

The components of the developed system, as depicted in the server-client architecture below, include:

- ✓ A relational database management system, achieved through installation of Microsoft SQL Server Express 2012
- ✓ An implementation of ArcGIS platform’s Spatial Data Engine (ArcSDE) for management of spatial data stored within the RDBMS
- ✓ An implementation of ArcGIS for Server and Portal for ArcGIS, which function to make the spatial system and data available and shared within the enterprise or organization
- ✓ A desktop platform with ArcGIS for Desktop, Python and Operations Dashboard is also implemented within the system to allow for connection to the database and the GIS server portals for data retrieval and management
- ✓ The system is developed to allow for web access through mobile clients and through web browsers through with the data streaming from the sensors and information about the mine can be obtained. This web access to the data is made possible through the presence or installation of a web server and web adaptor on Microsoft Internet Information Services (IIS).
- ✓ The developed system is also compatible with a variety of browsers available today, such as Microsoft Edge (latest version of Internet explorer available and shipped with windows 10), Mozilla Firefox, Google Chrome, Safari and Opera Mini.

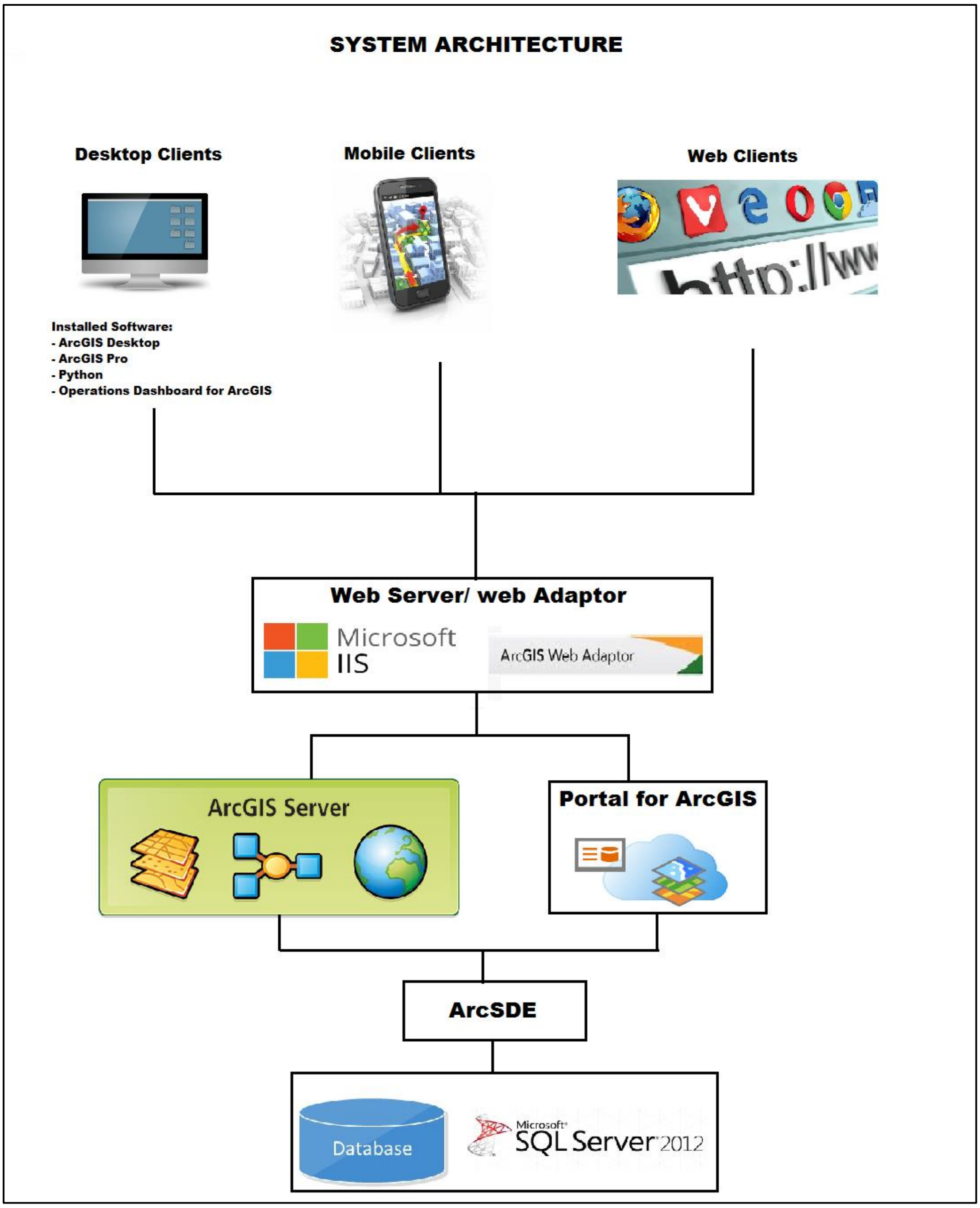


Figure 4- 1 System architecture of the WMI DigiMine: Real-Time Mine Monitoring and Management System (source: Author)

A three-tier architecture was implemented with this research as it facilitates implementation of a centralised data repository. Such a repository is essential in data sharing and database-level integration of systems, which was used in this research for the integration of legacy mining solution from VibraTech and ArcGIS. This architecture also encourages data and information sharing, which a core foundation for enterprise systems.

4.2. Data Simulation, Basic Integration and System Testing

Testing of the system and its basic functionalities was done through simulation of sample historical data obtained from the current server system. Sample data for the month of April 2016 was used to test the real-time solution. The aspects of the real-time monitoring and management system tested include:

a) Ability to connect to and retrieve streaming data from a streaming service
b) Computation of geometry in real-time from the incoming streaming data
c) On the fly filtering of sensor data based on the Sensor ID as the unique identifier
d) Real-time updating of the feature classes with incoming streaming sensor data
e) Real-Time analysis of incoming data for status determination of the underground mine environment through use of a dashboard

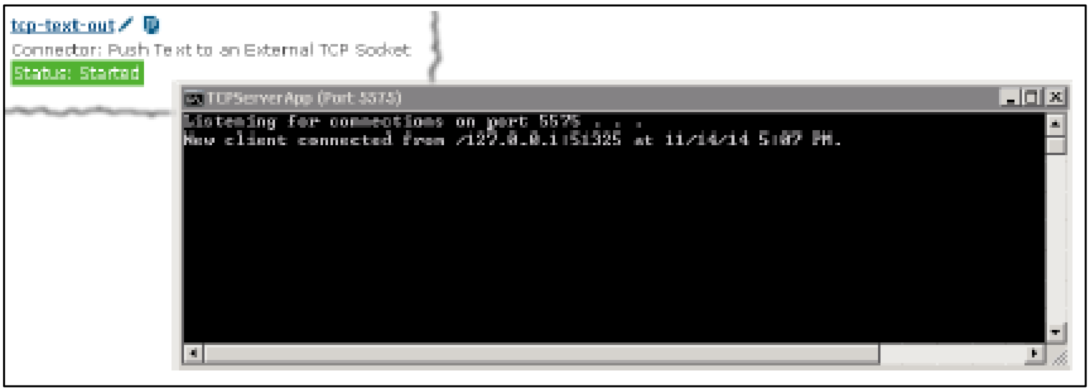
The above 5 test cases are mainly motivated by the functional and integration requirements (Belete *et al.*, 2017) of the system. These tests, though selected by the author, are mainly influenced by the fundamental requirement that integrated systems can communicate and share data and allow for interoperability between/among the systems (Arsie *et al.*, 2014), with expected results being presented on the configured dashboard application. More sophisticated tests can also be carried out, especially with a fully integrated system to ensure achievement of desired technical and functional requirements of the integrated system.

In development of the system, properties of the sample data for April 2016 and specifically data obtained from the weather station at the surface of the mine (in this case, the roof level of the Chamber of the Mine) was used to determine schema and characteristics of the system. Characteristics in terms of the processes involved from streaming of data, processing of input data and use of the data to update the sensor's feature services.

a) Connection to Streaming Services Tests

The success of the solution is dependent on its ability to connect to and obtain data from a streaming service. Due to time constraints and because of the proprietary nature of the current system, obtaining links and ports to the streaming data was not possible. Therefore simulation of the downloaded historical data from the same existing system was carried out to emulate a streaming service.

The GeoEvent Simulator application was used to stream the sample data through a TCP/IP port on the server. Using a TCP Server application, developed on java platform by ESRI and shipped with GeoEvent Processor training materials, a connection was successful made to TCP port 5575, as shown on figure 4-2 below. A successful connection was reported by the application and therefore indicating that the solution is able to receive incoming streaming data.



```
Listening for connections on port 5575 . . .
New client connected from /127.0.0.1:51325 at 11/14/14 5:07 PM.
```

Figure 4- 2 Successful connection to the streaming service through a TCP port (source: Author)

b) Computation of Geometry on Real-Time Streaming Data

Within an underground mine environment, most sensor systems are stationary. There are however some sensors that are portable and may be carried by mine workers as they move around in the mine. In most cases, these sensor systems stream their data measurements accompanied by their 2D or 3D spatial locations. In some situations, the 3D locations of these stationary sensors are pre-determined during installation and therefore only transmit data accompanied by its unique identifier.

Sensor implementations at WMI mock underground mine that were used for this research are all stationary. Through a survey exercise carried out at the mine, coordinate information was added to the data, which was simulated through this test exercise. The inclusion of this coordinate data therefore calls for computation of a geometric property to allow for plotting of the incoming data on a GIS-based web map platform.

Tests for real-time computation of geometry, on the incoming streaming data, was conducted through use of a field calculator processor available with the GeoEvent Services application. This processor tool runs in the background and is linked to the Events Definition, which calculates geometry using coordinate data on Longitudes and Latitudes fields available with the streaming data.

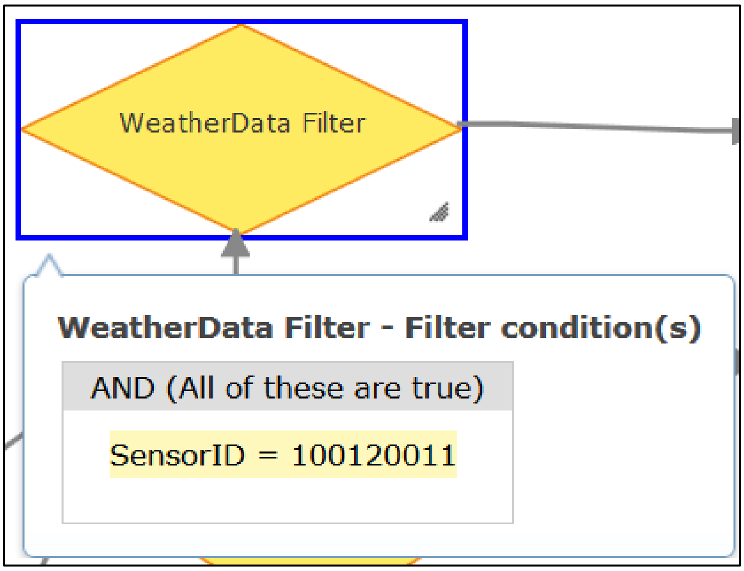
The success of this calculation was achieved in the creation of a new point geometry field, as shown and highlighted in *table 4-1* below, with the last field/column showing a geometry field with a comma delimited combination of longitude and latitude coordinates alongside weather stations data. This success was also achieved with the plotting of a point feature on a web map application.

Table 4- 1 A csv text output of the streaming weather station data with the highlighted portion representing geometry field (source: Author)

weatherStream	2016-04-01 T00:00:00.000 +02:00	100120011	20.22	0.41	1.25	NAN	28.026822, -26.191456
weatherStream	2016-04-01 T00:15:00.000 +02:00	100120011	19.74	0.41	1.25	NAN	28.026822, -26.191456
weatherStream	2016-04-01 T00:30:00.000 +02:00	100120011	19.63	0.41	1.25	NAN	28.026822, -26.191456
weatherStream	2016-04-01 T00:45:00.000 +02:00	100120011	20.15	0.41	1.25	NAN	28.026822, -26.191456
weatherStream	2016-04-01 T01:00:00.000 +02:00	100120011	19.77	0.41	1.25	NAN	28.026822, -26.191456
weatherStream	2016-04-01 T01:15:00.000 +02:00	100120011	19.43	0.41	1.25	NAN	28.026822, -26.191456
weatherStream	2016-04-01 T01:30:00.000 +02:00	100120011	18.99	0.41	1.25	NAN	28.026822, -26.191456
weatherStream	2016-04-01 T01:45:00.000 +02:00	100120011	18.82	0.41	1.25	NAN	28.026822, -26.191456
weatherStream	2016-04-01 T02:00:00.000 +02:00	100120011	18.64	0.41	1.25	NAN	28.026822, -26.191456
weatherStream	2016-04-01 T02:15:00.000 +02:00	100120011	18.3	0.41	1.25	NAN	28.026822, -26.191456

c) On the fly filtering and isolation of sensor data

The system was also tested for its ability to filter and isolate the incoming streaming data for data that is specific for an identified sensor. Each sensor in the mine can be uniquely identified through a unique set of codes. Isolation of the streaming data based on this unique sensor identification code enables association of the observed parameter values to the right sensor. Thus a filter tool was created with the GeoEvent Service and applied to the streaming sensor data with the output directed towards a csv text output. Figure 4-3 below shows a filter used to isolate weather station data, which is transmitted with the unique identifier, *SensorID = 100120011*.



WeatherData Filter - Filter condition(s)

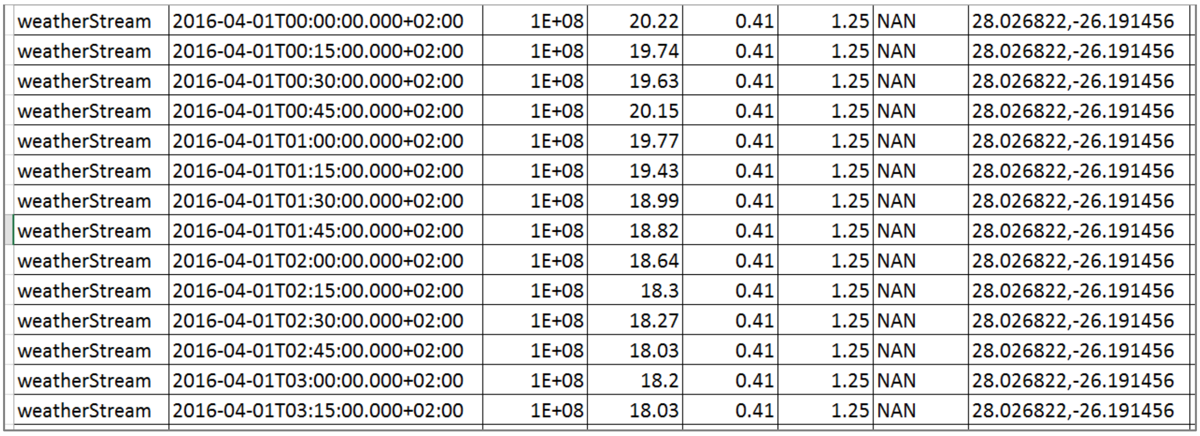
AND (All of these are true)

SensorID = 100120011

Figure 4- 3 Snippet of the filter tool created and applied with the GeoEvent Services Processor to isolate data (source: Author)

To test this filtering functionality, all the sample data from all the sensors were combined into a single simulation file and streamed. The filtering tool was then connected to the incoming streaming data with the output directed to the text output file.

The filtering process was a success in that, based on the sensor id as the unique identifier for the sensors; only relevant data from the sensors were isolated and stored on the text file outputs. Figure 4-4 below displays data on a text file output with only isolated weather station data, as a result of the data filtering process on the streaming sensor data.



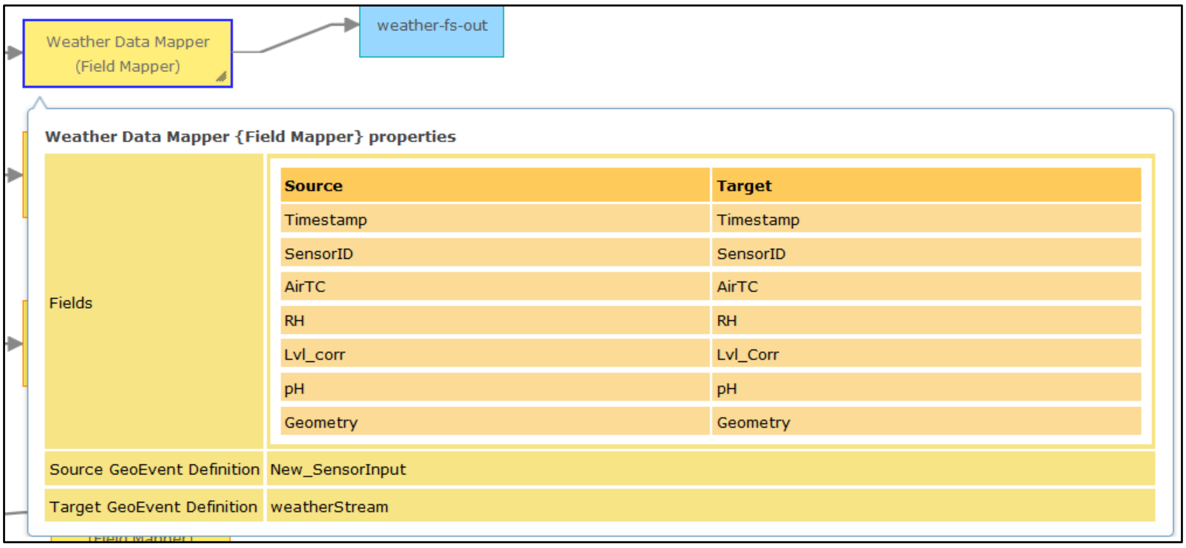
weatherStream	2016-04-01T00:00:00.000+02:00	1E+08	20.22	0.41	1.25	NAN	28.026822,-26.191456
weatherStream	2016-04-01T00:15:00.000+02:00	1E+08	19.74	0.41	1.25	NAN	28.026822,-26.191456
weatherStream	2016-04-01T00:30:00.000+02:00	1E+08	19.63	0.41	1.25	NAN	28.026822,-26.191456
weatherStream	2016-04-01T00:45:00.000+02:00	1E+08	20.15	0.41	1.25	NAN	28.026822,-26.191456
weatherStream	2016-04-01T01:00:00.000+02:00	1E+08	19.77	0.41	1.25	NAN	28.026822,-26.191456
weatherStream	2016-04-01T01:15:00.000+02:00	1E+08	19.43	0.41	1.25	NAN	28.026822,-26.191456
weatherStream	2016-04-01T01:30:00.000+02:00	1E+08	18.99	0.41	1.25	NAN	28.026822,-26.191456
weatherStream	2016-04-01T01:45:00.000+02:00	1E+08	18.82	0.41	1.25	NAN	28.026822,-26.191456
weatherStream	2016-04-01T02:00:00.000+02:00	1E+08	18.64	0.41	1.25	NAN	28.026822,-26.191456
weatherStream	2016-04-01T02:15:00.000+02:00	1E+08	18.3	0.41	1.25	NAN	28.026822,-26.191456
weatherStream	2016-04-01T02:30:00.000+02:00	1E+08	18.27	0.41	1.25	NAN	28.026822,-26.191456
weatherStream	2016-04-01T02:45:00.000+02:00	1E+08	18.03	0.41	1.25	NAN	28.026822,-26.191456
weatherStream	2016-04-01T03:00:00.000+02:00	1E+08	18.2	0.41	1.25	NAN	28.026822,-26.191456
weatherStream	2016-04-01T03:15:00.000+02:00	1E+08	18.03	0.41	1.25	NAN	28.026822,-26.191456

Figure 4- 4 Snippet of the resulting weather data obtained after filtering process on the streaming sensor data (source: Author)

d) Real-time updating of the feature classes

Having conducted the tests above, that is, ability to make a connection to streaming service and isolation of sensor-specific data, the system was then tested to check is ability in updating feature layers with the incoming sensor-specific data in real-time.

A field mapper tool (example shown in figure 4-5 below) was created with the GeoEvent Services processor to link the incoming isolated sensor-specific data with the schema of the sensor's feature layer. A feature service for the sensors, initially empty, was published to the server and was used to hold the incoming streaming data. The success of the updating capability was determined with auto-plotting of the incoming data on a web application.



Weather Data Mapper {Field Mapper} properties

	Source	Target
Fields	Timestamp	Timestamp
	SensorID	SensorID
	AirTC	AirTC
	RH	RH
	Lvl_corr	Lvl_Corr
	pH	pH
	Geometry	Geometry
Source GeoEvent Definition	New_SensorInput	
Target GeoEvent Definition	weatherStream	

Figure 4- 5 An example of a field mapper tool that links isolated weather station data to a published weather data feature service (source: Author)

These feature layers were also set to refresh after every 6 seconds to retrieve and update itself with the latest data. This was tested through clicking on the plotted point features and checking the information on the pop up features, as shown in figure 4-6 with the pop up feature displaying data obtained from the streaming data.

Every time the point feature was clicked on, the web map’s pop up box feature had new data with a more recent timestamp, thereby confirming the solutions ability to update the feature classes with the latest set of streaming information.

Weather Data: 100120011

Timestamp	April 15, 2016
Sensor ID	100120011
Air Temperature °C	18.75
Relative Humidity %	0.41
Water Level (mm)	1.19
pH	NAN

Figure 4- 6 A web map of the WMI underground mine, hosted on Portal for ArcGIS, showing a pop up feature with data from the weather station streaming serviceReal-Time analysis of incoming data for status determination (source: Author)

The goal of this project and hence the development of the solution was to provide a system that can provide real-time underground mine monitoring and analysis of digital sensor data. The system was developed and tested to verify its capabilities and functionalities in retrieving and displaying real-time streaming sensor data from deep below the surface in an underground mine.

Using the operations dashboard application, basic analysis output and summarized views of the real-time analysis were made possible. The dashboard application developed contains widgets that connect to the streaming data, allowing for carrying out basic analysis of the data and the determination of the real-time status and conditions of the underground mine environment.

The operations dashboard developed with this research project uses or connects to the previously developed web map applications. Each level in the mock underground mine, including the tunnel area has a specific web map showing the features present, inclusive of the purpose to which the rooms and spaces in that level are used for. On the same level-based web map, the sensors available on that location are also mapped and provide information on the real-time streaming data as collected by the sensors.

4.3. Results

The success of this research exercise and the subsequent development of a POC application for underground mine health and safety were dependent on:

- Determination of scenarios, risks and factors prevalent in underground mines that endanger the health and safety of mine workers; and
- The application of system development and testing techniques for development of the real-time monitoring and managements system within the ESRI environment.

a) Underground Mine Risks and Hazards

Following the stakeholder meetings as indicated at section 3.2 of this research report and the informal brainstorming sessions, a discussion involving the implementation of technology in underground mines took place. This was mainly with regards to improving on the safety and health of underground mine employees. The outcome of these sessions, other than getting acquainted with the current status and updates on SA mining industry, included:

- Determination of the common health and safety risks and dangerous hazards that are associated the underground mines.
- Determination of ways to prevent illegal miners from accessing an underground mine facility, through the implementation of access control systems and triggers or notifications on unauthorized access attempts.
- Determining and limiting specific scenarios to which the research exercise will be confined to, based on time constraints, though with a possibility of further improvements at PhD level, later on.

These sessions therefore resulted in the following three scenarios being of main focus for research:

i. Implementation of access control systems with swipe access cards, fingerprint or biometric scanners being implemented to facilitate authorized entry into the mine by employees. This was to be further improved on by implementation of facial recognitions systems, with an aim of ensuring only authorized personnel gain entry to the mine, while keeping track on the count of miners in the miners to allow for rescue and emergency personnel responding effectively in the case of an emergency at the underground mine.

ii. Implementing a system to monitor and manage lamp room equipment and especially Personal Protective Equipment (PPEs) and Gas Detector Equipment (GDIs) and provide report at the control room in case of malfunctions and improper use. Such a system should also be able to trigger an alert at the control room and deny access to any miner trying to access the mine with incomplete PPEs or equipment that are not fully charged or malfunctioning equipment.

iii. Implementation of an integrated GIS-based solution for real-time monitoring of environmental parameters in an underground mine and reporting on the status of the mine on a dashboard application at a control room.

This research is mainly focused on the third scenario from the above list of outcomes of the stakeholder meetings, while the other two were taken up my different researchers at the Institute. Based on research carried out in identifying risk factors and dangerous scenarios in underground mines, through existing literature review and brainstorming sessions, various factors and causes were identified. The most common accidents that occur in underground mines are as a result of and/or include factors or risks such as:

- Explosions due to CH_4 and coal dust: Methane is an explosive gas present and trapped within coal. Due to mechanical errors on machinery or equipment (such as faulty safety lamps or electrical equipment) or the use of improper explosives can initiate explosions of the coal dust (Smith & du Plessis, 1999)
- Accidents due to blasting: use of explosives could lead to dangers such as:
    - *Rock falls* – where mining personnel can be injured by flying or falling rocks during blasting
    - *Premature blasts* - due to accidental percussions, carelessness, faulty fuses or degenerated explosives, just to mention a few, which could result into death and injuries, especially to miners close to the blast sites or working with the explosives
    - *Misfires* – refers to complete or partial failure of the charge to explode as intended, which if left in the ground, could be triggered during mining and causing injuries or fatalities
    - *Mine-induced seismicity* – this could cause instability and collapse mini workings, trapping miners.
- Fires which could be as a result of faulty electrical connections, presence of explosive and/or combustible gases within the mine (Dolozme, 2016).

- Flooding within the underground mine tunnels in situations where a tunnel is dug close to water bodies (van Zyl, 2011; Wolkersdorfer, 2008). This hazard can lead to miners drowning or being trapped underground
- Mine collapse due to explosions during rock blasting or through seismic activities. These could shake and weaken mine support, leading to mine collapse and as a result, injuring of killing miners
- Presence of toxic contaminants and gases such as methane (CH_4), nitrogen dioxide (NO_2), hydrogen sulphide (H_2S), carbon dioxide (CO_2), and carbon monoxide (CO) (Othmani *et al.*, 2015; Altun *et al.*, 2010).

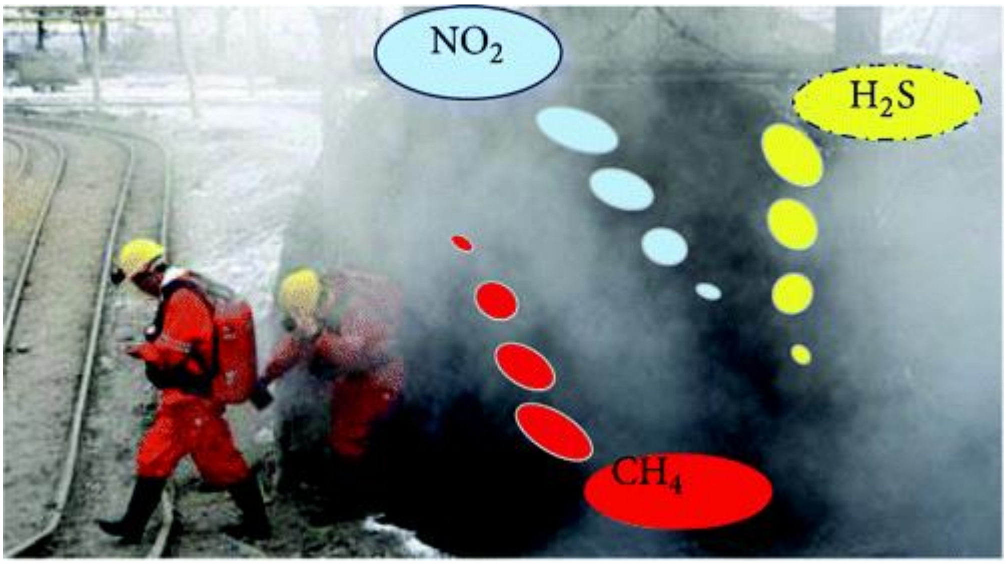


Figure 4- 7 A sample underground mine explosion due to build-up of toxic gases (Osunmakinde, 2013)

The other hazards identified within underground mines include noise and vibrations. These could be from the mining activities and machinery, such as rock drilling, diesel engines, transport equipment and even during rock blasting. Miners being exposed to high noise levels may develop occupational hearing loss due to neurosensory deafness, rapturing of the tympanic membrane or even hemorrhaging in the middle or inner ear.

Gas poisoning or intoxication is also a prominent hazard to underground miners. There is the risk of miners running out of oxygen while working underground, as a result of poor ventilation, oxidation of exposed coal seams, decay in timber, burning of open lights and breathing of men. Presence of Carbon dioxide in the air results into laboured breathing when in high concentrations.

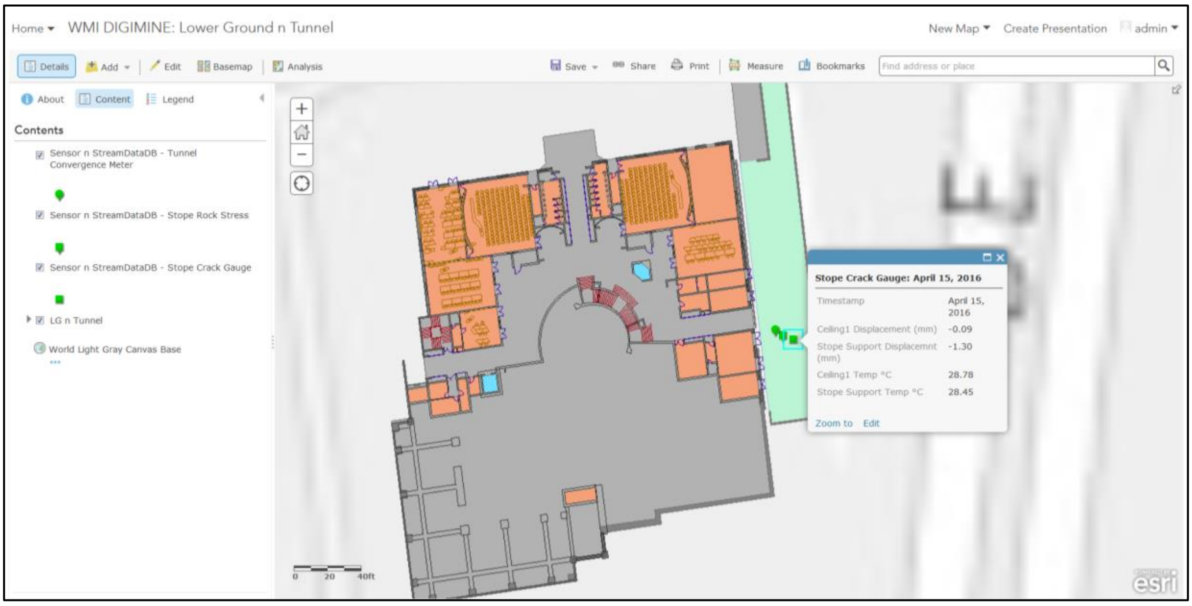
Identification of the above risks and factors that affect the health and safety of workers in underground mines is a necessary step in determining the necessary remedies to their effects to the miners. In order to provide for remedies to the scenarios, monitoring and making of real-time measurements of the factors causing said hazardous scenarios needs to be done.

This research was however limited to integration of ArcGIS and Vibratech systems and the used of only weather data so as to prove the capability and hence the success of integrating both systems with real-time streaming data being displayed in a dashboard application. This limitation to use of weather data, despite being as a result of achieving the project's aim of integration, was also due to time constraints for completion of the research and submission of the research report.

b) Web Map Applications

Having carried out data acquisition pre-processing stages of the project and development of a map document for the WMI mock underground mine, the map features were published to ArcGIS for Server as a map service. Publishing of a map services enables internet or intranet users to use the maps for web applications development.

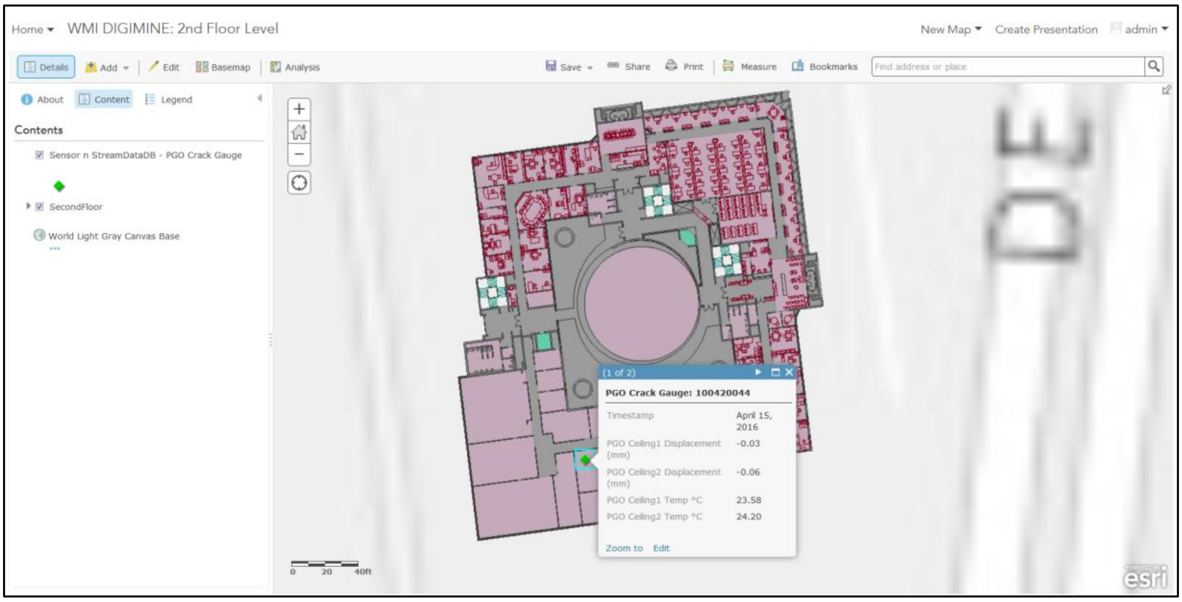
These published map services were therefore used to develop web maps for the different levels of the WMI mock underground mine. Each of these levels shows cartographic representations of the features and their locations. Locations of the sensors are also shown on these web maps (figures 4-8, 4-9 and 4-10 below).



Stope Crack Gauge: April 15, 2016

Timestamp: April 15, 2016
Ceiling1 Displacement (mm): -0.09
Stope Support Displacemnt (mm): -1.30
Ceiling1 Temp °C: 28.78
Stope Support Temp °C: 28.45

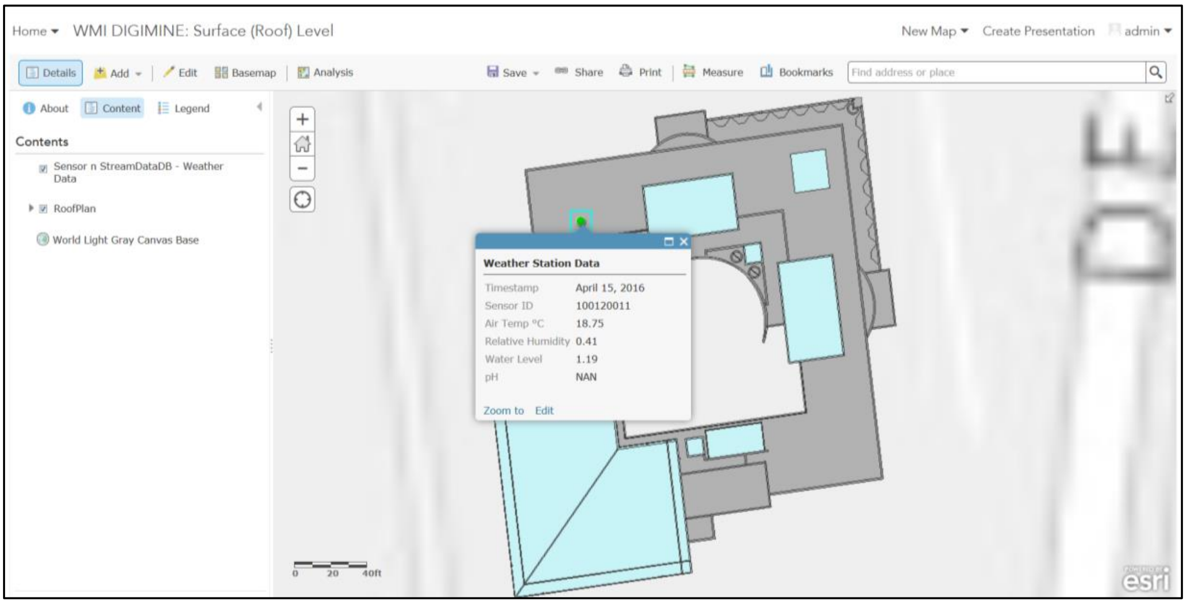
Figure 4- 8 Web map showing features and sensors at the lower ground level and tunnel section of the WMI mock underground mine (source: Author)



PGO Crack Gauge: 100420044

Timestamp	April 15, 2016
PGO Ceiling1 Displacement (mm)	-0.03
PGO Ceiling2 Displacement (mm)	-0.06
PGO Ceiling1 Temp °C	23.58
PGO Ceiling2 Temp °C	24.20

Figure 4- 9 A web map showing features and sensor locations on the 2nd floor level of the WMI mock underground mine (source: Author)



Weather Station Data

Timestamp	April 15, 2016
Sensor ID	100120011
Air Temp °C	18.75
Relative Humidity	0.41
Water Level	1.19
pH	NAN

Figure 4- 10 A web map showing features and sensor locations at the surface (roof) level of the WMI mock underground mine (source: Author)

c) WMI DIGIMINE: Real-Time Monitoring Dashboard

A web map widget was used within the operations dashboard application. It was used to load the web map applications for each floor and as well, determine query able layers to which the other widgets can connect to and be used for analysis and underground mine health and safety status determination. The operations dashboard – WMI DIGIMINE: Real-Time Monitoring Dashboard – is made up of 3 web maps representing 3 different levels within the mock underground mine. These levels and the description of the configurable contents as present in the dashboard above include:

a) **The mine's surface (CM building's roof) level**:- This level shows the floor plan of the Chamber of Mines building's roof, which represents the mock underground mine's surface level. Present on the surface is a weather station with sensors for temperature, humidity, rain gauge or water levels and water pH measurements.

   The location of the weather station sensor is stationary and is plotted on the web map with a point feature. This point feature is styled and configured such that, upon clicking on it, information about the last queried and transmitted information from the sensor is displayed. This is through the use of a pop up window, containing a title and attribute data representing the sensor recordings or measurements.

   Other than the pop up feature, indicator and gauge widgets are used. These widgets are linked to the streaming data from the weather station sensor. They provide a graphical representation of the sensor recordings, which based on the set and configurable scale and threshold, are used to provide real-time status of the roof level. In this case the status are reported by the widgets are used to determine the atmospheric conditions of the environment around the underground mine – that is atmospheric temperature, relative humidity, rainfall amounts and rain water pH levels.

   Relative humidity indicator widget is configured such that, readings of between 20% and 60% are considered tolerable and comfortable for human beings. Based on this configuration, the RH indicator widget lights up green for readings between 20% and 60%, red for readings below 20% and orange for readings above 60%.

   For temperature indicator widget, ideal temperatures in this case are configured to be below 20°C. Therefore the indicator widget lights up red for temperatures above 20°C and green for temperature below the set threshold.

b) **The 2nd Floor level**: **-** The middle section on the dashboard application contains information about the 2nd floor level of the Chamber of Mines building. A web map for that level is loaded and features present on the level are also plotted. A single sensor, at the Post Graduate (PG) Office, which is used to measure, record and transmit crack displacements is also plotted.

The plotted point feature representing the PG office Crack gauge sensor location has a pop up functionality enabled. On click, information on the latest sensor recordings is displayed on a pop-up window, which includes displacement measurements and the temperature readings as recorded by the sensor.

Bar chart widgets are also used to provide real-time plots of the displacement and temperature measurements. These configurable widgets tap into the sensor feature service layer for the latest sensor recording and subsequently plot those values on the column charts.

c) **The lower ground and tunnel section**: - This section, occupying the left side of the dashboard screen shows all the features and sensor locations, as plotted on a web map for the lower ground and tunnel region. There are three (3) sensor systems present inside the tunnel, namely tunnel convergence meter, crack gauge on stope and a rock stress meter present on the stope.

Pop-up functionality is also enabled on the point features representing the locations of the sensors inside the tunnel. Each feature is configured to display values of the different parameters as recorded by the sensors in the tunnel.

The tunnel convergence meter records millimeter displacements and as well, temperature of the tunnel. Therefore on click of this feature, a pop-up window displays the latest recorded readings from the sensor, including the timestamp for the readings.

Rock stress meter sensor on the stope, measures stresses (in terms of PSI) on the stope and reports back these readings to the server. This sensor also has the ability to measure temperatures which is also displayed on the pop-up window, alongside the timestamp for the measurements.

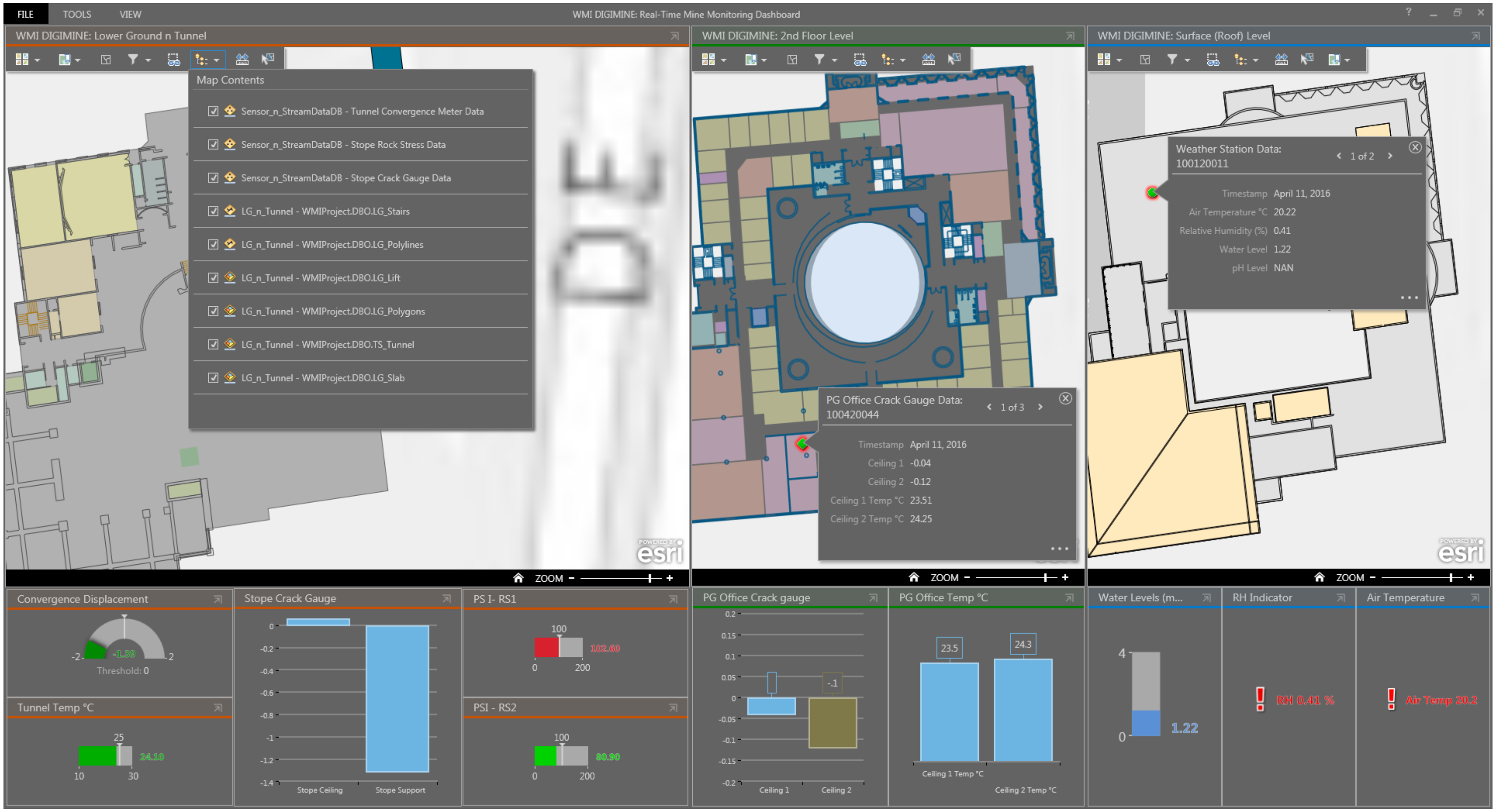
Stope crack gauge sensor, also available on the stope, functions to measure displacements (in millimeters) on the stope, alongside temperatures on the stope. Displacement readings on the stope ceiling and stope support are recorded and reported by the sensor.

Gauge widget is used with readings from the convergence meter and the stope rock stress meter. Here, the gauges are used to plot convergence meter displacement readings, ranging from -2 – 2 mm with a threshold set at 0 mm.

As for temperature measurements inside the tunnel, a gauge is also used. This widget is configured to plot measurements ranging from 10 - 30°C, with a threshold set at 25°C, thereby providing both numerical and color-coded representation of the status of the tunnel.

With regards to the stresses on the stope, a gauge widget is also used and configured to range from 0 – 200PSI, with a threshold configured at 100PSI. This gauge widget also indicates PSI readings at any given timestamp and a color-coded representation of these measurements to give a status indication about the stresses acting on the stope.

The dashboard application developed to provide real time visual status information about the mine, based on the readings from the sensors, was configured to auto-update after every 6 seconds. This is in tandem with the rate at which the simulated data is being streamed in and used to update the feature services of the mapped sensors.



Map Contents

- ☑ Sensor_n_StreamDataDB - Tunnel Convergence Meter Data
- ☑ Sensor_n_StreamDataDB - Stope Rock Stress Data
- ☑ Sensor_n_StreamDataDB - Stope Crack Gauge Data
- ☑ LG_n_Tunnel - WMIProject.DBO.LG_Stairs
- ☑ LG_n_Tunnel - WMIProject.DBO.LG_Polylines
- ☑ LG_n_Tunnel - WMIProject.DBO.LG_Lift
- ☑ LG_n_Tunnel - WMIProject.DBO.LG_Polygons
- ☑ LG_n_Tunnel - WMIProject.DBO.TS_Tunnel
- ☑ LG_n_Tunnel - WMIProject.DBO.LG_Slab

PG Office Crack Gauge Data: 100420044 ‹ 1 of 3 ›

Timestamp	April 11, 2016
Ceiling 1	-0.04
Ceiling 2	-0.12
Ceiling 1 Temp °C	23.51
Ceiling 2 Temp °C	24.25

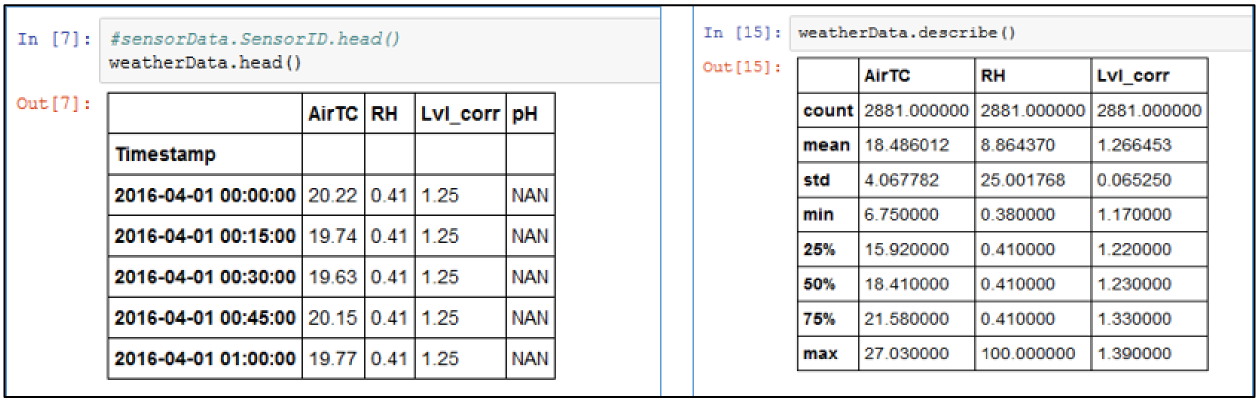
Weather Station Data: 100120011 ‹ 1 of 2 ›

Timestamp	April 11, 2016
Air Temperature °C	20.22
Relative Humidity (%)	0.41
Water Level	1.22
pH Level	NAN

Figure 4- 11 An operations dashboard view of the different levels of the underground mine, showing some of the basic features and functionalities (source: Author)

4.4. Python Platform for Data Analysis

In addition to the querying and analysis of the spatial sensor data through the widgets available on Operations Dashboard for ArcGIS, Python was also used to conduct statistical analysis of the sensor data. The streaming data from the sensor systems are time stamped and therefore are treated as time series data. Time series analysis methods were employed to the analysis of the incoming sensor data, such that information such as trend in sensor measurements, faults in sensors, mean measurements (i.e. mean hourly, daily or weekly) and correlations with measurements from other sensors could be determined.



```
In [7]: #sensorData.SensorID.head()
        weatherData.head()
```

Out[7]:

	AirTC	RH	Lvl_corr	pH
Timestamp				
2016-04-01 00:00:00	20.22	0.41	1.25	NAN
2016-04-01 00:15:00	19.74	0.41	1.25	NAN
2016-04-01 00:30:00	19.63	0.41	1.25	NAN
2016-04-01 00:45:00	20.15	0.41	1.25	NAN
2016-04-01 01:00:00	19.77	0.41	1.25	NAN

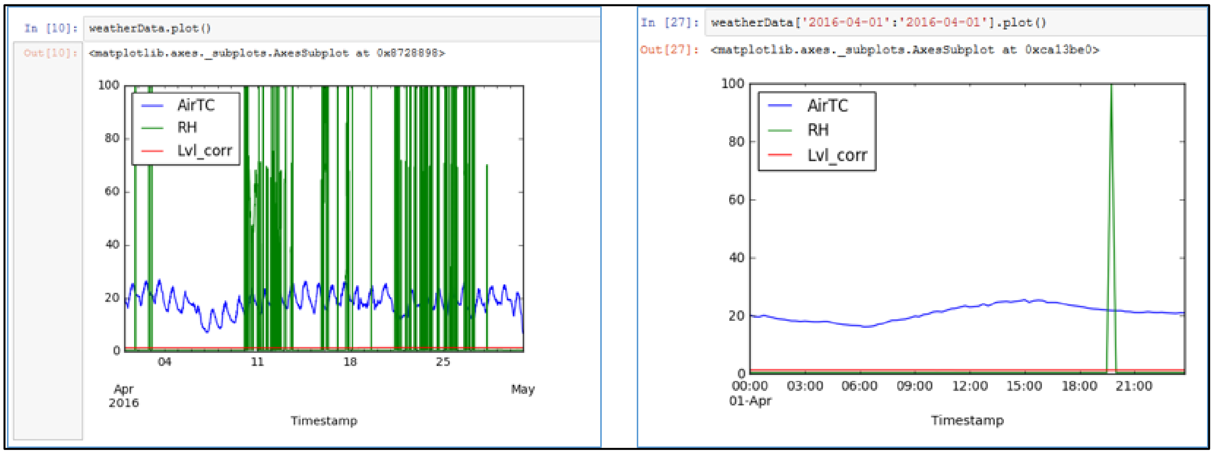
```
In [15]: weatherData.describe()
```

Out[15]:

	AirTC	RH	Lvl_corr
count	2881.000000	2881.000000	2881.000000
mean	18.486012	8.864370	1.266453
std	4.067782	25.001768	0.065250
min	6.750000	0.380000	1.170000
25%	15.920000	0.410000	1.220000
50%	18.410000	0.410000	1.230000
75%	21.580000	0.410000	1.330000
max	27.030000	100.000000	1.390000

Figure 4- 12 A snapshot of the historical weather data and descriptive statistics (source: Author)

The above statistics on figure 4-12 show that for the month of April 2016 recorded temperature readings at the surface ranged from 6.75°C to 27.03°C with a mean of 18.486°C and standard deviation of 4.068°C. That of relative humidity range from 0.41% to 100%. There are no reported readings from the pH sensor, which could indicate malfunctioning of the sensor system.

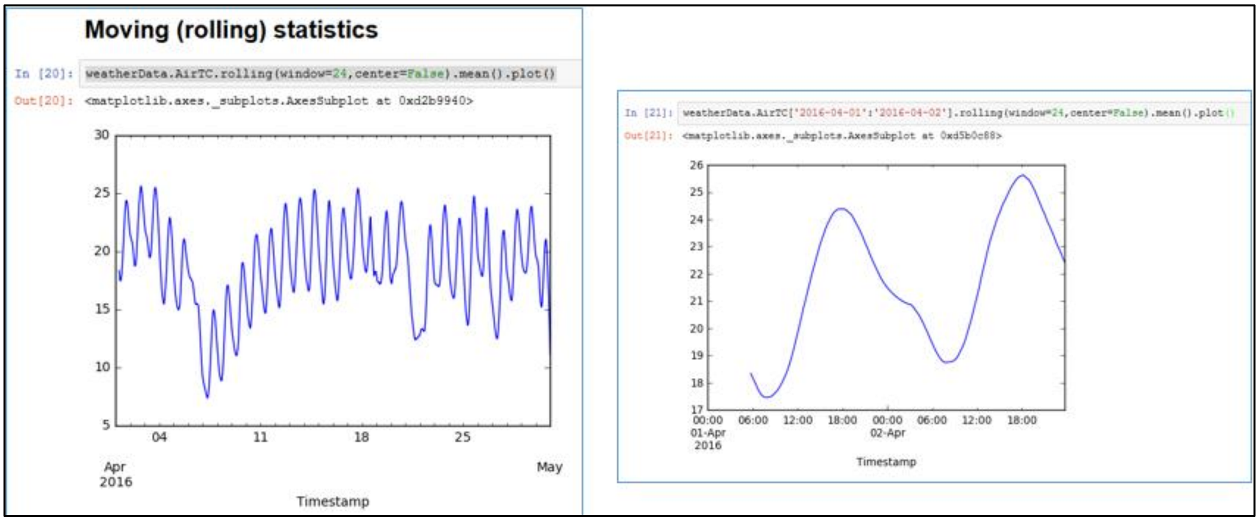


```
In [10]: weatherData.plot()
Out[10]: <matplotlib.axes._subplots.AxesSubplot at 0x8728898>
```

```
In [27]: weatherData['2016-04-01':'2016-04-01'].plot()
Out[27]: <matplotlib.axes._subplots.AxesSubplot at 0xca13be0>
```

Figure 4- 13 A plot of the monthly weather station sensor data and plot of a single day's data (source: Author)

The above plots about the weather station data (Figure 4-13) shows the fluctuations on the readings of parameters like air temperature and relative humidity. The reported data on relative humidity has wide fluctuations, which can be attributed to summer as a season which is experienced in South Africa at that time of the year. A finer plot of the received data, on a 24-hour period is also plotted, and shows a finer trending line in temperature recordings while that of relative humidity is constant at 0.41% before overshooting to 100% around 9PM. These fluctuations in relative humidity readings could suggest errors or malfunctioning of the sensor, or a problem with its configuration.



Moving (rolling) statistics

```
In [20]: weatherData.AirTC.rolling(window=24,center=False).mean().plot()
Out[20]: <matplotlib.axes._subplots.AxesSubplot at 0xd2b9940>
```

```
In [21]: weatherData.AirTC['2016-04-01':'2016-04-02'].rolling(window=24,center=False).mean().plot()
Out[21]: <matplotlib.axes._subplots.AxesSubplot at 0xd5b0c88>
```

Figure 4- 14 A smoothing model of air temperature data based on 6-hour averages showing trend in recorded readings, with the left image showing temperature trends for the month of April, while right graph is a 2 days trend plot (source: Author)

Python tools applied to time series analysis allows for determination of trend in the distribution of data. Based on the recorded air temperature readings, application of moving or rolling averages on the data, as in figure 4-14 above, shows clearly the existing trend and change in the measurements over the 24 hour period. The data shows a decreasing trend in air temperature readings between 1800 hours and 0800 hours and an increasing trend from 0900 hours and 1800 hours. This brings out the seasonality in air temperature readings, a factor that can help in accurate forecasting of sensor readings.

4.5. Conclusion

To conclude, this research set out with the objectives listed at section 1.6, which mainly involve investigating and determination of the most prevalent risks and hazardous factors in underground mines. From the outcome of this objective, an implementation of a GIS-based integrated solution for monitoring and managing of such risks and factors was looked into. This implementation is mainly to provide a real-time status and representation of the underground mine vis-a-vis provision of a safe and healthy working environment.

Through literature review and stakeholder meetings during the course of this research, prominent and most dangerous underground mine risks were identified. This included environmental conditions within the underground mine, which was the main focus of this research and hence the development of an integrated real-time system and operations dashboards using ArcGIS platform, as a proof of concept. This research was conducted at the Wits Mining Institute (WMI) research facility which includes a mock underground mine with a control room.

This proof of concept application was mainly limited to integration of ArcGIS with VibraTech Systems and specifically the use of weather station data. This is mainly owed to the issues faced during carrying out of the research, which included:

- Sensors installed in the mine not being fully operational, with related systems at the control room not being adequately configured and operational to retrieve data from the sensors
- Adequate data for the analysis not being present. As for the obtained data from Vibratech Systems, there wasn’t much variability of the data to warrant implementation of advanced data analysis techniques
- No access to the live and streaming data from the sensors installed at the mine, owing to the proprietary nature of the systems, therefore a remedy being put in place to instead simulate streaming of the downloaded data using GeoEvent Simulator application on ArcGIS.

In spite of the above listed problems faced during development of the integrated system and specifically the operations dashboard application (see figure 4-11), the developed system has functional and operation advantages to dealing with the scenarios as identified by stakeholders. The system is capable of interpreting and providing real-time status reports based on the data streaming in, which is useful in determining the current situation in the mine. Due to implementation of a spatial aspect to the system, reports and triggers displayed on the dashboard application can be located precisely, and when necessary informed decisions can thus be made and emergency services directed to the right locations in the mine. Some of the disadvantages of the system include absence of a prediction module and not enough sensors in the mine to allow for better spatial analysis of the data.

Interoperability with other applications or solutions in underground mining can be achieved through the integration with ArcGIS platform, which is an enterprise application. ESRI's ArcGIS platform enables configuration of widgets and web service applications through which data can be shared and integration achieved, independent of the solution in question or operating system platform of the mine system or solution. ArcGIS platform can also be connected to a central database system through which data obtained from other systems can be analysed with the results displayed on a map environment, as was the case with this research exercise.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

Health and safety in underground mines are critical for the mining industry. Through implementation of modern and advanced technological systems to mining, improved operational environments and health and safety for underground miners are being witnessed. Modern technologies and applications like intelligent response and rescue systems, underground 3D positioning and modelling, RFID/INS integrated positioning, just to name a few, have greatly reduced the number of fatalities and deaths in underground mines (Zhang *et al.*, 2009).

The application of technological developments, especially in the fields of sensor systems, spatial analysis and real-time data management were the main motivating factors towards carrying out this research exercise which resulted in the development of a prototype system for health and safety monitoring in underground mines. An underground mine environment is rich with information that can be used to accurately determine the prevailing conditions. Sensor systems provide a means of collecting such data in real-time for analysis and development of models that can be used to make predictions of the underground mine environment. These data collected from the mine come with a spatial aspect to them, thereby enabling carrying out of spatial analysis and mapping of environmental factors and conditions within the mine space.

An underground mine environment has plenty of factors that could trigger hazardous situations leading to injuries to mine workers and in some cases, even death. The most frequent and common health and safety risk factors and scenarios in an underground mine, as identified from this research exercise, include exposure to toxic/harmful gases; accidents that come about due to rock blasting and resultant seismicity; high noise levels and vibrations from machinery in the mine; unfavourable environmental factors like high temperatures, very low/high humidity; absence of clean and sufficient oxygen in the mine; flooding; occurrence of fires.

The implementation of sensor systems and real-time monitoring and data analysis applications helps in determining a round-the-clock health and safety status of the underground mine environment. Such systems enable collection of data from an underground mine environment, which is analysed in real-time to determine the prevailing conditions on the underground environment. These data can also be used in the prediction of future occurrences or determination of near and/or far-future health and safety status of the mine. This information when acted upon in time, in conjunction with protocols already put in place as remedies for an occurrence of a hazardous event in the mine, could result in saving of many lives at the mine.

A dashboard application was also developed with this research exercise as an output. This dashboard application displays the results of real-time analysis carried out on the streaming sensor data. These results, which represent the status and prevailing conditions of an underground mine environment, in real-time, are in the form of widgets that display colour–coded and graphical output of the analysis results. This dashboard and the data it displays provide proof in application of real-time spatial-temporal analysis of digital sensor data in determination, monitoring and prediction of health and safety risks.

A real-time monitoring and analysis system with integrated enterprise GIS provides additional advantages over other monitoring systems. GIS-based monitoring systems enable determination and plotting of locations of sensors and tracking of personnel within the mines. Implementation of such a system prove to be useful, especially in times of disasters, as better emergency response and evacuation procedures can be implemented. Through integrated enterprise GIS, data, analysis reports and information from an underground mine environment can be updated and shared with every department in the mining company for in-depth analysis, leading to safer, healthy and efficient mining process and running of operations.

This research exercise set out to investigate and determine prevalent dangers and health risks in underground mines. It also set out to determine how legacy mining systems can be integrated with ESRI GIS and as well, determines the best integration methods alongside determining functional capabilities that come about from such integration.

The first objective, involving the identification of the most frequent and dangerous scenarios and the determination of their causes was achieved as the most frequent dangers in underground mine were determined and can be broadly categorised as fires, floods, rock falls or fracturing and toxic chemical composition within the mine tunnels. Objective three (3) was also achieved, involving the development of a real-time monitoring and management POC system with a dashboard. A dashboard application was developed showing real-time graphical status reports as data streams in from the sensors in the mine, as discussed in section 4.3 (c) of this report. Partial satisfaction of the objectives two and four were achieved with this research and POC development. Integration from the database level and through use of web services – achieved through published web maps and features services on ArcGIS platform – were used. As for the fourth objective on determination of functional capabilities of an integrated system, the resultant POC system and dashboard application showed the basic but very important functionality of real time status determination and reporting based on the streaming data.

Partial fulfilment of these two objectives of this research thus opens us areas for further research and development of a fully integrated system for underground monitoring. This further research could include the implementation of better, tried and tested integration approaches, customised and properly designed database environment, implementation of machine learning approaches to continuous data analysis and implementation of additional functionalities beyond the control room scenario.

5.2. Recommendations

The developed system for the real-time monitoring and management of an underground mine environment with regards to health and safety, has been tested using simulated historical data. These test results with simulated data show success in analysis of real-time digital sensor data. Improvements of the system, better analysis results and development of suitable models can be achieved through the implementation of the following recommendations:

- System development and testing has been carried out using simulated historical data obtained from the existing system. Better results and testing of the system should be done through connection to the relevant TCP/IP port(s) on the Vibratech system on the server for live streaming data from the sensors at the mock underground mine
- Additional sensor systems should be installed to allow for carrying out of spatial and statistical analysis of the sensor data. Analysis such as 3D distribution or spread of the harmful gases, dusts, temperature can only be carried out if there are a good number of sensor systems in the mine, strategically and spatially spread in the mine.
- The current dashboard system on Operations Dashboard for ArcGIS has limited functionalities in terms of available widgets for displaying reports and warnings. Therefore additional widgets can be developed for additional functionalities.

- A web-based dashboard application built on HTML5 can be developed, with additional functionality included, to allow for access to information about the mine to personnel and stakeholders, even on mobile devices as opposed to just using a desktop environment
- Analysis of historical data, collected over a predefined period of time can be subjected to data/machine learning algorithms to determine trends in the data from these sensors in the mine. Such trends can be used to better predict danger in an underground mine.
- Development of a comprehensive system for health and safety monitoring and management, based off the results obtained from this research and POC development should be done. This system should include and integrated with the other systems, such as Schauenburg and EOH's Camera system
- Monitoring and tracking of mine personnel, moving equipment and wearables in the mine should also be incorporated in the system to facilitate determination of positions and numbers at a given location in the mine, for better and informed decisions and emergency responses.

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