UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Designing a Multi-Sensor Cluster for Monitoring Ventilation Risks Using a Micro Aerial Vehicle (MAV) in Underground Mining

Student Name: Mosima Precious Matlhwana

Student Number: 562484

School of Mining Engineering

University of the Witwatersrand

Johannesburg, South Africa.

MSc (50/50)	MSc by Research Only	PhD
	X	

Supervisors: Dr Tariq Feroze

A research dissertation submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in fulfilment of the requirements for the degree of Masters in Engineering.

Date: October 12, 2020

Declaration

I declare that this dissertation is my own, unaided work. I have read the University Policy on Plagiarism and hereby confirm that no plagiarism exists in this dissertation. I also confirm that there is no copying nor is there any copyright infringement. I willingly submit to any investigation in this regard by the School of Mining Engineering and I undertake to abide by the decision of any such investigation.

Signature of Candidate

12 October 2020

Date

Abstract

The integration of fixed sensors and portable instruments on the same telemetry network enable mines to monitor wider regions and detect airborne hazards more quickly than before. The advent of the micro-unmanned aerial vehicle (MAV) presents an alternative mobile platform for transporting portable air sampling instruments into hazardous environments without endangering mine personnel. Therefore, development of a suitable ventilation sensor cluster is required to enable a MAV to serve as a monitoring platform focused on detecting airborne hazards in underground mining environments. Hence this research was carried out to identify a conceptual design of a ventilation multi-sensor cluster for attachment to a MAV frame. The research applied the systems engineering process (SEP) in a simulated mining environment to conceptualize a suitable design, operational scenarios, and key functionality for the ventilation sensor cluster to be constructed for a MAV.

Acknowledgements

I would like to acknowledge my supervisor Dr Tariq Feroze for his contribution of ideas, advice, guidance, and support during this research. Dr Tariq's expertise and assistance in structuring and executing this work was invaluable. I appreciate his patience and commitment.

I would also like to thank and acknowledge the financial support provided by the Mine Health and Safety Council (MHSC) through the Sibanye-Stillwater Digital Mining Laboratory (DigiMine), Wits Mining Institute (WMI).

I would like to thank the DigiMine researchers for their enthusiasm which kept me encouraged and their useful input.

Table of Contents

Acronyms

2D	Two Dimensions
3D	Three Dimensions
API	Application Programming Interface
BBE	Bluhm Burton Engineering
BLE	Bluetooth Low Energy
CAD	Computer-Aided Design
CFD	Computational Fluid Dynamics
CO	Carbon Monoxide
CO^2	Carbon dioxide
CoE	Centre of Excellence
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CSV	Comma-Separated Values
DigiMine	Wits Sibanye-Stillwater Digital Mining Laboratory
DMS	Database Management System
FCC	Flight Control Computer
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPIO	General Purpose Input/Output
HIRA	Hazard Investigation and Risk Assessment
I2C	Inter-Integrate Circuit
ICT	Information Communication Technology
IDC	International Data Corporation
IEEE	Institute of Electrical and Electronic Engineering
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
IP	Internet Protocol
IR	Infrared
ISM	Industrial Scientific and Medical
LAN	Local Area Network
LiDAR	Light Detection and Ranging

LOS	Line of Sight
MAC	Media Access Control
MAV	Micro Aerial Vehicle
MHSC	Mine Health and Safety Council
MOS	Metal Oxide Sensors
MTW	Maximum Total Weight
N_2	Nitrogen
NDIR	Non-Dispersive Infra-Red
NIOSH	National Institute for Occupational Safety and Health
NO_x	Nitrous oxides
O_2	Oxygen
OEL	Occupational Exposure Limits
OSI	Open System Interconnection
OTA	Over the air
PCB	Printed Circuit Board
PHY	Physical layer
PID	Proportional Integral Derivative
RAM	Random Access Memory
RDMS	Relational Database Management System
RF	Radio Frequency
RGB	Red Green Blue
RPAS	Remotely Piloted Aircraft System
SACAA	South African Civil Aviation Authority
SCADA	Supervisory Control and Data Acquisition
SDK	Software Development Kit
SEP	Systems Engineering Process
SLAM	Simultaneous Localisation and Mapping
SPI	Serial Peripheral Interface
SQL	Structured Query Language
SUMO	Small Unmanned Meteorological Observer
TCP	Transmission Control Protocol

UART	Universal Asynchronous Receiver/Transmitter
UAS	Unmanned Aircraft System
UAV	Unmanned Aerial Vehicle
UHF	Ultra-High Frequency
UWB	Ultra-Wide Band
VOC	Volatile Organic Matter
WLAN	Wide Local Area Network
WMI	Wits Mining Institute
WSN	Wireless Sensor Network
XLM	Extensible Markup Language

List of Figures

List of Tables

1 INTRODUCTION

Ventilation is defined as the provision of fresh air into a building, underground tunnel or archaeological cave (Lexico, 2018). The application of the theory of ventilation became increasingly used in underground mining environments in an effort to reduce the frequency of catastrophic accidents experienced in collieries since the 18th centuries (McPherson, 1993). Although the frequency of accidents caused by fires and explosions has significantly reduced in present day, ventilation remains crucial to maintaining safe workplaces. However, a deterioration in the safety performance of South African (SA) mining during 2017 marked the first regression in 10 years (Phakathi, 2018). Despite these challenges, clear improvements have been made towards providing a healthier, safer, and more efficient working atmosphere in underground mining environments.

In present day, the provision of an adequate ventilation system is enforced by regulations which have widened the scope to environmental control. As the law which enforces and promotes health and safety in SA mining, the Mine Health and Safety Act No. 29 of 1996 (MHSA) (Mine Health and Safety Council, 2018; Rautenbach, et al., 2013) requires the employer to ensure that employees are protected from prominent hazards encountered in a mine's atmosphere. This includes "provision of an early warning system where there is significant risk of a fire, explosion, toxic gas release and any atmosphere which presents an immediate danger to life" (Conti, et al., 2005; Mine Health and Safety Council, 2018).

Strengthening of monitoring and early warning systems has been identified by several authors (Holding, 1994; Spencer, et al., 2000; Conti, et al., 2005; Zhang, et al., 2014) as a key element of preventing accidents. Traditional techniques of monitoring a mine's atmosphere are being redefined through rapid advances and a declining cost of portable sensing technology. Advancements in information communication technology (ICT), miniaturized sensors and robotic platforms are creating opportunities for miners to optimise existing instrumentation and enable the integration of digital infrastructure into risk management systems (CSIRO, 2017). Digital technology now makes it possible to control an entire mining environment in a manner that can eventually lead to predictive response (IDC, 2016).

Development of remotely operated products, such as real-time sensors and autonomous robots is one of the target goals of 2020 focused on driving modernisation in the SA mining sector (Minerals

Council South Africa, 2018). Remotely operated systems for monitoring airborne hazards in a mine are currently implemented using sensors fixed at strategic locations in an underground mine. There is a trend of embracing the latest developments in sensing, wireless communication devices and robotics to increase the regional coverage of environmental monitoring in underground mining. A convincing case is made to support wireless sensing communication architectures in mine ventilation monitoring and control (Witrant, et al., 2008; Fischione, et al., 2008). Similar research has encouraged developments of ventilation instruments with the ability to support advanced services such as localisation and wireless connectivity. Such implementations create opportunities for integration with heterogeneous communication medium for application-specific solutions.

This research is interested in using autonomous robots, specifically a micro aerial vehicle (MAV) in conducting mine ventilation surveillance tasks. The MAV presents an alternative remote sensing platform which can safely extend the regional coverage of existing hazard monitoring systems. To detect airborne hazards using a MAV as an autonomous remote sampling tool, a sensor system that can measure physical changes in ventilation conditions is required for attachment onto the aerial robot. Hence there is a need to design a multi-sensor cluster for monitoring ventilation risks using a MAV.

1.1 Purpose of the Study

This research investigated modern trends that are changing the methods of collecting and analysing air samples in a mine's atmosphere. The contribution of this research was aimed at informing performance expectations of a MAV being developed to serve as a remote sensing tool for automated ventilation monitoring in an underground mining environment. This research was aimed at identifying the most suitable design of a multi-sensor array with the ability to gather information about the status of a mine's atmosphere and deliver that information to decision makers in near-real time. The study investigated supporting digital technologies including wireless communication and autonomous navigation systems that would be practical for implementation in underground mining for facilitating connectivity and control of the MAV during flight missions from a remote computer operated on surface.

There is a limitation in the hardware and computational processes that can be assigned for execution on-board the MAV during flight. Therefore, the selection of a suitable multi-sensor arrangement and processing capabilities for integration with a MAV for ventilation surveillance in underground mining needed to be compatible with existing technology that is currently implemented. The objective of using a remotely piloted MAV for safety surveillance in this study was focused on increasing the distance between mine workers and airborne hazards in an underground mine during risk assessments for enforcing safety compliance and investigating accidents or dangerous occurrences.

1.2 Research Background/Context

The term unmanned aerial vehicle (UAV), also referred to as remotely piloted aircraft system (RPAS) or a drone, is a small flying robot which can serve as a remote sensing platform to automate risk inspection and hazard monitoring processes (Deloitte, 2017). Different types of UAVs are classified according to their maximum take-off weight (MTW), flight range capability and frame design (fixed wings or multirotor) (Singhal & Bansod, 2018). This research looked at the category of a micro-sized UAV often called the MAV or micro-drone. MAVs are classified by a MTW of 2 kg, maximum flight time of 30 minutes and have frames available as fixed-wings and multi-rotors (Schwartz, 2014). This research was interested in MAVs with four rotors which are termed quadcopter or quadrotor micro-drones.

A key benefit of using MAVs in surveillance is the ability to remove personnel from hazardous environments while capturing valuable data at a reduced cost and time (Freire & Cota, 2017; Edwards, 2017; Extance, 2019; Emesent, 2019a). Hence, the Wits Digital Mining (DigiMine) laboratory sponsored by Sibanye-Stillwater is in the process of testing the use of a MAV for monitoring multiple health and safety risks encountered in underground mining. There are several MAV prototypes being tested at the DigiMine facilities for different safety surveillance tasks mandated in emergency response and compliance monitoring (Miningmx, 2019). Thus far, the use of a MAV in subsurface environments has been demonstrated in the construction of survey plans. This research planned to advance features of the MAV by including the ability to detect harmful gases and poor ventilation with sensors attached to the aircraft.

Villa et al (2016) preferred a quadrotor over the fixed-wing type of MAV in atmospheric analysis due to its capability for autonomous take-off and landing, high manoeuvrability, ability to maintain very low speed and hover close to sources of risk. Custom sensor packages using anemometry, pitot-static tubes or multi-hole probes have been developed for attachment on MAV frames used as sampling tools in the open atmosphere (van den Kroonenberg & Martin, 2008; Lawrence &

Balsley, 2013; Witte, et al., 2017). Sensors attached to MAVs have been used to measure wind speed, temperature, relative humidity, and atmospheric pressure. Although MAV tests in meteorological studies took place in outdoor environments, the robot has been shown to work in indoor spaces as well as in underground mining environments (Emesent, 2019a; Edwards, 2017).

This research focused on air sampling instruments of a miniature design and low weight for attachment to a MAV platform. The objective of integrating air quality sensors with a MAV was to offer the ability to assess the atmosphere of an underground mine particularly in hazardous environments without the need for personnel to be near risk. The MAV offers an alternative and safer means of transporting air sampling instruments to assess a mine's atmosphere in excavations which may be not be accessible to humans and larger ground-based equipment e.g., in ventilation shafts, ore-passes or sub-level stopes.

Portable instruments used for collecting air samples in underground mines needed to be reviewed in this research to determine a suitable multi-sensor array that can be carried by the MAV. Smaller sensors have become more advanced due to integration with processing and communication capabilities. Modern air sampling instruments used currently in underground mines can wirelessly transmit the measurements captured over a communication network and deliver the data to a surface control station (Schauenburg Systems, 2017; Testo SE & Co, 2019; Drägerwerk AG & Co., 2019). The goal of this research was therefore to evaluate elements of the system design used in the development of handheld air quality instruments traditionally provided to mine personnel to formulate a design that can be carried by a micro-drone or MAV payload.

1.3 Research Motivation

This research was part of multi-disciplinary post-graduate studies coordinated by the Wits Mining Institute (WMI) in the development and testing of MAVs for safety surveillance in underground mining. The MAV research was housed at DigiMine, which is a 21st, century state of the art, mining laboratory with the aim of using digital technologies to make mining safer and sustainable (University of the Witwatersrand, 2017). The laboratory's research agenda is focused on transferring surface digital technologies into the underground environment and support processes that automatically observe, evaluate, and take action to protect the health and safety of mine workers. The ability to detect dangerous atmospheric conditions using air sampling instrumentation was among safety surveillance functionality under on-going research for the development of the next MAV prototype to be tested at DigiMine.

1.4 Problem Statement

Traditional implementations of air monitoring systems have been through fixed devices which are hardwired, therefore any damage to the cable can disrupt their operation. Fixed sensor systems provide limited regional coverage and are unable to track hazards encountered by moving assets (people and equipment).

Portable instruments are available for monitoring air conditions, but they require a carrier to sampling locations. Supervisors are often the ones who carry portable sampling instruments to examine air conditions at hazardous locations beyond the reach of fixed devices.

The use of a MAV as an alternative air sampling platform would eliminate the need for mine personnel to carry portable devices into hazardous environments to assess the quantity and quality of the ventilation flow. MAVs offer an affordable mobile remote sensing platform that can be used during dangerous situations such as a fire due to their high manoeuverability and capability for autonomous localisation.

Although MAVs and supporting technologies are commercially available, they have been largely tested in open environments where air behaves differently to confined spaces such as underground tunnels. Therefore, the integration of air quality sensors with a MAV needed to be carefully evaluated for the specific conditions and risk scenarios encountered in an underground mining environment. Furthermore, analysis of real-time information systems to facilitate connectivity and control of the MAV during ventilation assessments in underground mining was required as it is an integral part of the implementation of real-time environmental monitoring systems.

1.5 Research Questions

The key questions this dissertation aimed to answer were the following:

1. What are the common risks encountered in an underground mine’s atmosphere?
2. What are the common sensors, communication and software technologies adopted in monitoring airborne hazards?

3. How can MAV systems be customised for the task of monitoring risks in a mine's atmosphere?
4. Advantages of using a MAV instead of a stationary sensor to monitor air conditions in underground mines?

1.6 Hypotheses

A MAV or micro-drone is a remotely piloted system with the potential to perform automated safety surveillance tasks in underground mines. Therefore, a MAV can be integrated with miniaturised sensors to measure the quantity and quality of air in an underground mine's atmosphere and wirelessly transmit real-time information to a computer station on surface for post-analysis, display, and response action.

1.7 Research Objectives

The aim of this dissertation was to detail components of a multi-sensor cluster being designed for attachment on MAV to be used for collecting air samples needed for ventilation monitoring in an underground mining environment. This research aimed to achieve the following objectives:

a) Investigate hazards managed through the implementation of ventilation controls in underground mining;

b) Evaluate implementation of wireless ventilation monitoring systems currently adopted in underground mining; and

c) Identify components for designing a multi-sensor system to monitor ventilation risks using a MAV.

The following chapter of this research begins the literature review which is broken down into two chapters. The first part is concerned with airborne hazards encountered in underground mining environments and the methods used to manage them.

2 AIRBORNE HAZARDS IN UNDERGROUND MINES

An underground ventilation system is primarily concerned with supplying enough air for breathing and the dilution of harmful pollutants to safe concentrations in all parts of a mine where mine personnel are required to work or travel. Once an adequate ventilation system is in place, regular assessments are necessary to determine whether atmospheric conditions comply with legislative requirements of a healthy, safe and productive working environment. In most mineral producing countries, regulatory standards are mandated for minimum air velocity required at strategic locations of a mine.

2.1 Need for Ventilation Monitoring

Systematic and periodic surveys to collect physical measurements of airflow samples are necessary to show actual conditions of a mine's atmosphere. The information is used to plan incremental adjustments of ventilation controls in compliance with guidelines. McPherson (1993) explained that the objective of a ventilation survey in underground mining is to obtain the pressure differences and corresponding air flowing through a ventilation network and quantify the distribution and magnitudes of air volume flow.

Belle (2013) indicated that implementing real-time air velocity monitors in mining provides mine officials with non-bias data for evaluating atmospheric conditions and determining the effectiveness of a mine's ventilation system. Remotely operated instrumentation offers an alternative method of continuously tracking hazards in a mine's atmosphere without the reliance on manual observations which are demanding and have practical limitations. Continuous monitoring enhances traditional ventilation observations for more effective control of air quality and facilitates efficient emergency response. Airflow measurements are a mandatory practice in the coal mining industry (Unwin, 2007), however the practice is becoming widely adopted in metalliferous mining as a result of safety benefits realised in collieries.

Instrumentation used for obtaining airflow measurements have been studied by researchers such as Casten (1995), McElroy (1935) and Unwin (2007). Measurements collected during ventilation surveys are used to quantify the airflow in each ventilation airway of a mine's network. Velocity measurements are required for comparison with minimum air velocity design standards. Minimum air velocity mandated in strategic locations of a mine are determined based on environmental factors, the maturity of an individual operation, as well as regulatory standards which vary across different countries. South African regulations mandate a minimum velocity of 0.5 m/s in all areas of a mine where flammable gas is being freely released (Holding, 1994). Air velocity remains an important design parameter used to evaluate the adequacy of a ventilation system implemented to control airborne hazards in underground mines.

2.2 Airborne Hazards in Underground Mining

Different hazards encountered in a mine's atmosphere are controlled using a variety of ventilation equipment. This research is focused on the monitoring techniques for hazards due to fires, explosions, gas emissions, heat, and humidity. Although dust and radiation are part of the hazards managed by the ventilation department, they will not be included in the scope of this research.

Records of occupational exposure measurements for hazards such as airborne pollutants due to gas emissions and thermal stress (temperature and humidity) must be reported to the regional Inspector of Mines on a monthly, quarterly and on an annual basis depending on the level of risk (Mine Health and Safety Council, 2018). Additionally, mines must report all dangerous occurrences and accidents including fires and explosions (Rautenbach, et al., 2013). A discussion of ventilation hazards that are the focus of this research is next.

2.2.1 Gas Emissions

Normal dry air mixture which enters a mine consists of nitrogen (78%), oxygen (20.95%), argon (0.93%), carbon dioxide (0.03%) and water vapour (Toppr, 2018). Harmful gases are introduced into the ventilation airstream by strata emissions released by breaking rock and chemical reactions taking place throughout the mining process. Major sources of emissions in a mine are influenced by the nature of the rock strata, method of mining or metal recovery, and unscheduled occurrences such as fires in a mine. Other contributors to gas emissions in an underground mine's atmosphere are blasting activities, diesel exhaust fumes, worked out sections, fissures, battery charging bays and welding operations (Greig, 1989).

When there is insufficient ventilation to dilute emissions, lighter gases tend to form layers against the hanging wall of a mine. The formation of gas layers along the hanging wall is dependent on the rate of emission, density of the gas, dip of an airway and the turbulence of a ventilation airstream (Greig, 1989). Therefore, to prevent the accumulation of dangerous gases in a mine's atmosphere, ventilation needs to be supplied at a velocity that is sufficient to dilute pollutants and carry them out of the mine's workings.

While some gases are highly toxic, others can create flammable air mixtures. The accumulation of flammable gases such as methane, hydrogen and ethylene are considered dangerous because they can lead to the creation of an explosion. Methane is especially associated with coal mines and has caused some of the world's deadliest mining accidents. High concentrations of hydrogen are a unique occurrence in metalliferous mines located in Carletonville, South Africa (Greig, 1989). Gases such as carbon dioxide (CO_2), carbon monoxide (CO), and nitrous oxides (NO & NO_2) are released by fires, explosions, blasting and diesel exhaust emissions. Worked out areas of a mine tend to be susceptible to deficient oxygen which gets consumed during oxidation of decaying timber material in metal mines.

Given the dangers presented by harmful gases in a mine's air supply, it is crucial to obtain immediate estimates of the composition of air in a mine. Air samples offer a means to measure compliance with environmental engineering guidelines and enable detection of dangerous atmospheric conditions. In South Africa, all mining operations are mandated to establish a system of monitoring airborne pollutants where gas emissions have reached or exceeded 50% of occupational exposure limits (OELs). Unsted (2001) documented various airborne pollutants, their occurrence, or origins in underground mines, as well as occupational exposure limits (OELs) as a chapter in the Handbook on Occupational Health Practice in the SA Mining Industry (Guild, et al., 2001). Table 1 is an extract from the chapter on airborne pollutants and provides a list of OELs prescribed for hazardous gases commonly released in a mine's atmosphere.

Table 1: Mine gases, chemical properties, their sources and OELs (Unsted, 2001).

Name	**Chemical Symbol**	**Specific Gravity Relative to Air**	**OEL (ppm)**	**Sources or origin**
Carbon dioxide	CO_2	1.5	5000	Breathing, oxidation, blasting, diesel exhaust, fires
Carbon monoxide	CO	0.97	25	Blasting, diesel exhaust, fires
Hydrogen sulphide	H_2S	1.2	10	Fissures, stagnant water
Nitrogen	N_2	0.97		Normal air
Nitrous fumes	NO, NO_2, NO_3.	1.04, 1.6	25, 3	Blasting, diesel exhaust, welding, burning of explosives
Methane	CH_4	0.55	Simple asphyxiant Explosive Hazards	Fissures, coal seams
Oxygen	O_2	1.0	>19%	Normal air
Sulphur dioxide	SO_2	2.22	2	Smelting operations, diesel exhaust fumes, Sulphur in coal seams
Hydrogen	H_2	0.07	Simple asphyxiant Explosive Hazards	Battery charging, sometimes from fissures with methane
Chlorine	Cl_2	2.5	-	Chlorination of water
Aldehydes	HCHO, etc.	1.04	-	Diesel exhaust
Ammonia	NH_3	0.6	25	Cooling plants, blasting
Acetylene	C_2H_2	0.93	-	Welding and cutting

The pollutants monitored in an atmosphere depend on the activities that release emission sources into the environment. Measurements of gas concentrations are useful in compliance analysis; however, they become crucial for informing effective fire response measures.

While flammable gases are prioritised in collieries, deeper metalliferous mines are more concerned with the effects of toxic gases and excessively hot rock temperatures that heat up the air supplied for breathing and pollution dilution (Encyclopaedia of Occupational Health & Safety, 2011).

Gas emission are only one of the hazards encountered in a mine's atmosphere. The next discussion looks at sources, phycological effects and control methods for thermal stress which can affect the health and safety of underground mine workers.

2.2.2 Thermal Stress

Metalliferous mines, particularly operations that are deeper, encounter rock temperatures that raise the temperatures of air to excessive levels. Thus, mechanical refrigeration systems become necessary to cool down the air and prevent adverse effects of heat stress. Common sources of heat in underground mines include auto compression, geothermal gradient, blasting, the use of electrical and diesel equipment, the human metabolism, oxidation processes and ground movement (Bardswich, 1965)

Management of heat stress in underground mining is necessary to provide a comfortable environment for mine personnel to work and equipment to operate at maximum efficiency. Studies have been done to show the effect of cold and heat stress on productivity and accidents (Stewart, 1989). Prevailing heat stress is well correlated with higher accident rates as it has been found to diminish a person's ability to concentrate. The performance of tasks is found to be adversely affected at heat stress levels above 27°C effective temperature. Effects of heat stress on an individual can range from less serious symptoms such as heat rashes, heat cramps and heat exhaustion to more dangerous effects of heat stroke which can cause death. Heat stroke is caused when the body's internal temperature rises to over 40°C (Anderson & De Souza, 2017).

In practical mining, wet bulb temperature and air velocity are found to have the greatest effect to cooling powers required to adequately manage the hazard of heat stress (Encyclopaedia of Occupational Health & Safety, 2011). The danger of heat stress can be minimized by ensuring compliance with OELs defined for dry and wet bulb air temperature. South African regulations mandate implementation of a system for measuring hazards where the mean wet bulb temperature exceeds 25°C and/or dry bulb temperature exceeds 32°C. Heat stress management becomes more challenging as mining expands in size, depth and equipment usage. The use of continuous monitoring stations in strategically selected locations of an underground mine is found to be the most effective control for planning and preventing exposure to heat stress (Anderson & De Souza, 2017).

Information about a mine's atmosphere is not only important for compliance monitoring but required to respond to emergencies cause by fires and explosions. The discussion on fires and explosion is next.

2.2.3 Fires and Explosions

Information gained from ventilation observations becomes crucial during a mine fire which can cause catastrophic losses in an underground operation. Regulations of the MHSA require every underground mine to prepare a ventilation plan for emergency response containing the following details:

- Boundaries of ventilation districts;
- Direction of air currents in each district;
- Quantity of airflow in each ventilation district; and
- The position of ventilation controls, e.g., fan, door, regulators, etc.

Regular monitoring is necessary to measure gas concentration for detecting dangerous conditions such as a fire in an underground mine. Manual observations are sometimes the most cost-effective and practical means of monitoring the status of a mine's atmosphere. Fire patrols are mandatory in any mine where there is an interval of six hours between shifts or during extended periods without activity in a mine. Holding (1994) highlighted that providing instruments to measure concentrations of CO to employees selected for fire patrols enhances the exercise.

Fires and explosive air mixtures in the mine atmosphere can be detected using multi-sensor monitoring systems to obtain measurements of concentrations of gases such as CO_2, CH_4 and N_2O (Villa, et al., 2016). In a confined underground metal mine, oxygen-deficiency may occur in the combustion by-products, therefore peaks in CO are used as indicators of an underground fire (Timko, 1900). Basic fire detection systems in underground mines include multiple gas instruments with sensors for airflow, temperature and smoke (NIOSH, 2012). Requirements for the implementation of detection systems are specified by guidelines on mine fire prevention (Mine Health and Safety Inspectorate , 2017a) and require the following information to be made available in the event of a fire:

- prevailing airflow;
- oxygen feed to the fire;
- rate of contamination in downstream airways;
- spread of fire beyond the source; and
- the potential of employees being trapped by the fire.

Miners have developed a variety of techniques to identify dangerous conditions in the air. As technology advanced, these methods have improved. Earlier methods of detecting airborne hazards are discussed in the following section.

2.3 Earlier Method of Detecting Airborne Hazards

Methods of identifying the presence of firedamp air in underground mining were developed as early as the 18th century (McPherson, 1993). By observing changes of a candle flame on a miners' hat shown in Figure 2.1.a, miners could identify danger when the flame would change its colour (The Rams Horn, 2010).

a. *Miners wearing flame cap lamps (The Rams Horn, 2010)*

b. *Canary inside cage (Pollock, 2016)*

Figure 2.1: Early techniques of detecting flammable gases in an underground mine's atmosphere

Early warning methods advanced to use warm-blooded animals to detect hazards in the mine's atmosphere. A canary kept in the cage shown in figure 2.1.b, were considered the best species for detecting the presence of flammable gas conditions, specifically carbon monoxide (CO). The bird would warn miners by showing visible signs of physical illness and faint about 20 minutes before humans would be overcome by the same gas concentration (Pollock, 2016). Techniques for detecting unsafe condition and providing an early warning to miners underground have advanced significantly since the days of the canaries in coal mines. Mines are now able to use technology to monitor air conditions in real time. The next discussion looks at implementations of real-time monitoring technology in underground mining.

2.4 Real-Time Monitoring System Implementations

The nature of mining is risky therefore, the implementation of real-time monitoring systems to provide a warning of danger in a mine's atmosphere is indispensable to ensuring compliance and detecting the occurrence of fires underground. Monitoring is defined by the Mine Health and Safety Inspectorate (2017b) as "the repetitive and continued observation, measurement and evaluation of health and/or environmental data in accordance with regulatory OELs, using normally acceptable methodologies". The need for monitoring in mine ventilation has been discussed in preceding sections which covered a variety of hazards encountered in the environment of an underground mine.

Modern technological advancements are redefining the way air samples are gathered from an underground mining environment. The developments of instantaneous (direct-reading) monitoring instruments and communication systems for underground mining now enable comprehensive sensing on a mine-wide scale. Automatic ventilation devices provide the ability to perform large-scale atmospheric analysis using regular measurements gathered from multiple air sampling sensors. Monitoring changes in the quality and quantity of airflow enables the detection of anomalies in the atmosphere of an underground mine. Continuous observations of atmospheric hazards are possible using distributed networks of sensors fixed at strategic locations in underground mines. South African Instrumentation & Control (2017) noted that distributed sensor networks are gaining widespread acceptance in underground mines for ventilation applications focused on the following aspects:

- ensuring safe working environments for humans;
- early detection of underground fires;
- tracking explosive atmospheres in fiery mines; and
- optimisation of ventilation system performance.

Distributed sensor clusters for detecting CO, temperature and low airflow velocity may be integrated with a telemetry system to transmit measurements to a remote computer station located on surface (NIOSH, 2012). Figure 2.2 shows a simplified multi-sensor environmental monitoring system for implementation in underground mining.

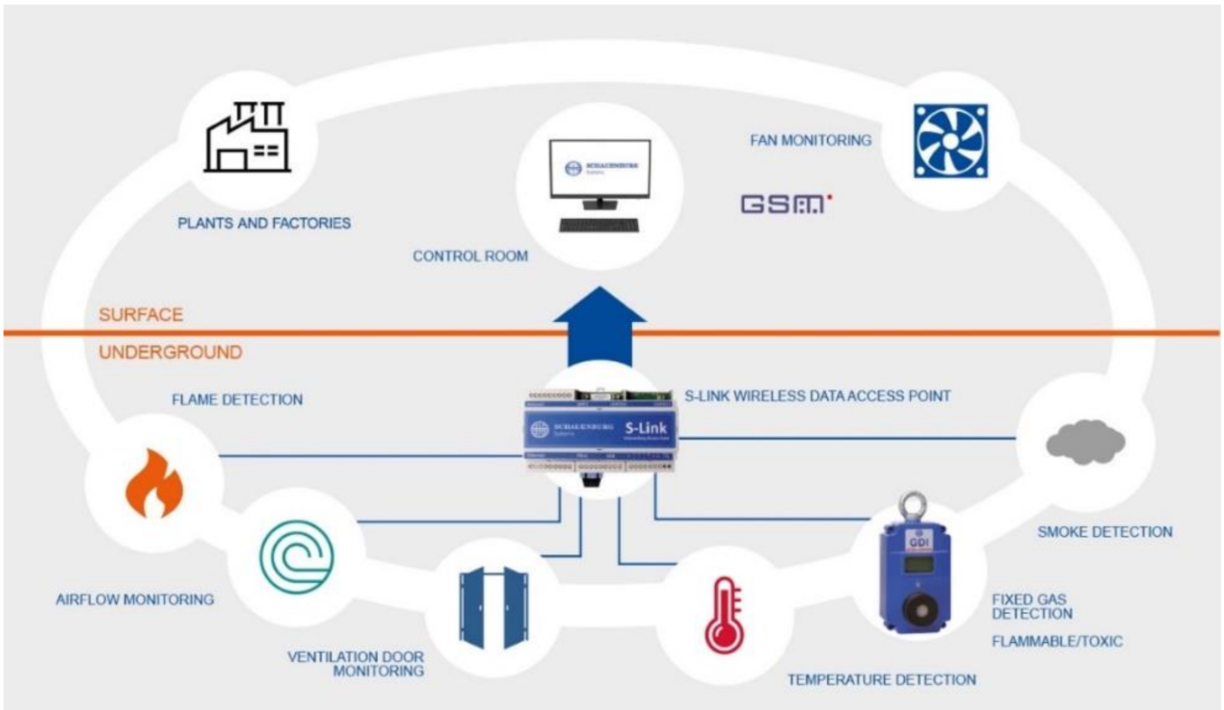


Figure 2.2: Multi-sensor system for monitoring air conditions in underground mines (Schauenburg Systems, 2017)

Automatic environmental monitoring systems enable historic measurements of physical conditions to be displayed as a graphical representation in a remote-control room on surface. In addition to sensors for gases, airflow and temperature, a comprehensive environmental monitoring system can monitor fan operation, pressure difference across doors, as well as detect smoke and flame in the event of a fire. Information is delivered over a telemetry system to a computer station on surface. Figure 2.3 provides a simplified diagram of the implementation of mobile gas sensing devices.

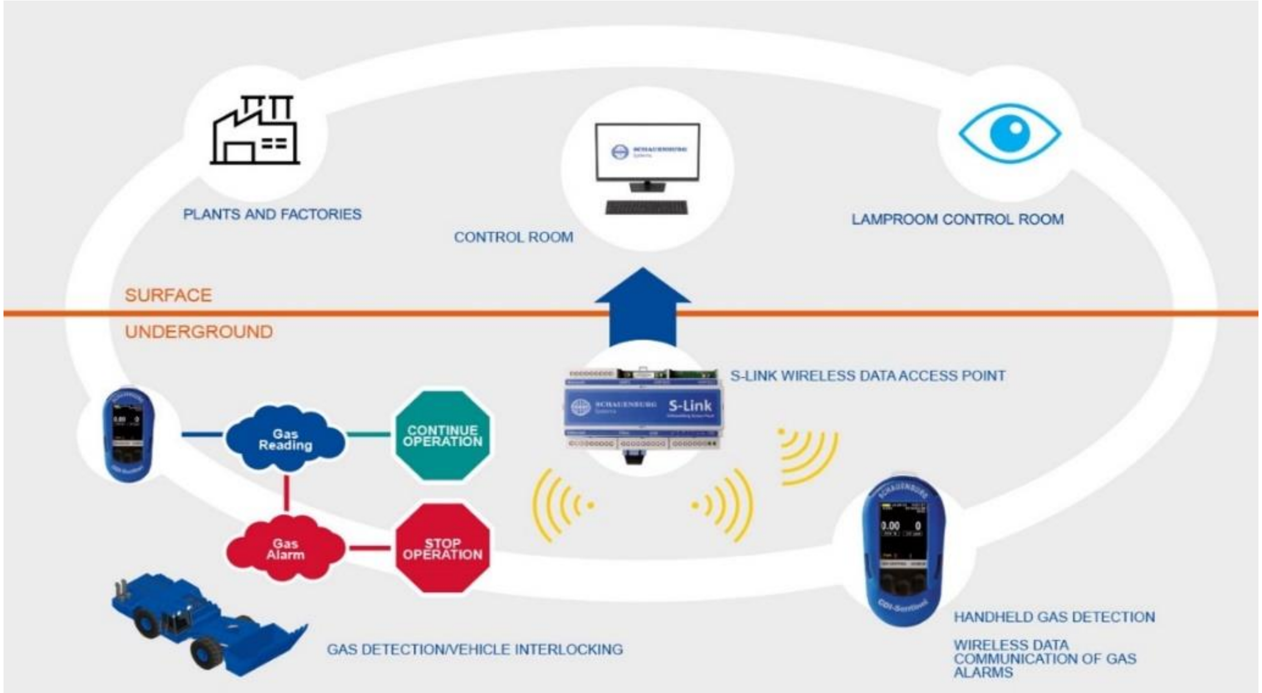


Figure 2.3: Mobile gas detectors linked with vehicle interlocking system (Schauenburg Systems, 2017)

Rugged gas monitors may be mounted on machines and integrate into a mine's telemetry system to provide a visual-audio alarm when a hazard is detected. Mobile gas detectors increase the regional coverage of large-scale ventilation monitoring by tracking hazards beyond the reach of permanently fixed instruments. However, mobile instruments have practical limitations when mounted on ground-based equipment as they are unable to access smaller spaces with uneven floors and vertical tunnels. Handheld instruments are therefore provided to trained mine personnel to perform gas testing routines which exposes them to potentially dangerous atmospheres.

Although the use of mobile sensor clusters overcome some of the practical limitation of fixed instruments, they need a transportation medium to move between different sampling locations. Collecting air samples in hazardous environments using handheld instruments places the lives of mine personnel at a high risk which is evident in some of the recent fatalities that have taken place in South Africa. In 2018, the lives of five employees were lost due to a heat-related accident at a gold mine and six lives were taken by a fire accident at a copper mine (South African Government, 2019). The elimination of such accidents requires automatic detection devices that can collect air samples from hazardous environments without the need for mine personnel to be in proximity of dangerous conditions.

In the next chapter, this study evaluates the application of MAVs in collecting air samples and delivering them to a remote computer. This chapter forms the second part of the literature reviewed to inform the functional requirements for the MAV that will serve as a ventilation monitoring instrument.

3 MONITORING AIRBORNE HAZARDS USING A MAV

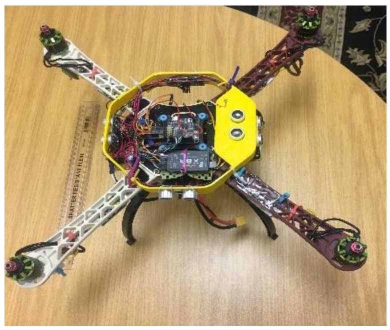
The term unmanned aircraft system (UAS) is also referred to as a drone, unmanned aerial vehicle (UAV) or remotely piloted aircraft system (RPAS). The application of UAS for sensing reconnaissance and scientific data collection are considered in Watts, et al. (2012). UAV platforms are classified based upon characteristics such as size, flight endurance, and payload capacity. A classification of UAS based on weight and flight range is given in (Singhal & Bansod, 2018). This study was focused on the category of micro-sized UAS called MAV and classified by a maximum take-off weight of 2 kg. The type of MAV considered in this dissertation is a multirotor, specifically referred to as a quadrotor or quadcopter. Reasons for using a quadcopter MAV for this research are provided in the following section.

3.1 Functional Analysis of MAVs for Ventilation Surveys

Quadrotor MAVs are found to be desirable remote-sensing platforms for air sampling particularly in hazardous atmospheres. Villa, et al. (2016) noted that quadcopters have capability for autonomous flight, high maneuveribility, can maintain very low speeds and hover closer to target sources. MAVs have potential to provide sampling platforms that enable environmental monitoring to be carried out in a way that was not possible with the use of ground based instruments. Figure 3.1 shows different quadcopters which have been successfully tested at DigiMine for survey mapping.

DJI quadcopter used for demonstrations at DigiMine

Hummingbird quadcopter previously tested at DigiMine



Current quadcopter used for testing new functionality at DigiMine

Figure 3.1: MAVs tested at DigiMine for the construction of survey plans

The quadcopters shown in figure 3.1 all share performance characteristics as well as technical constraints of micro-drones. They can carry a payload capacity of 250 g and endure a flight of 30 minutes. Performance specifications of MAVs being tested at DigiMine are an important design parameter to consider in the development of other functionality for this survaillance platform. For now, the only function offered is the ability to construct three-dimensional (3D) maps ustilizing photogrametric sensors such as a light detection and ranging (LiDAR) scanners or a red, green, blue (RGB) camera.

MAVs being tested at DigiMine are capable of maintaining communication when the pilot has line of sight. This research will require the ability to maintain communication and control of the drone without the need for line of sight. As part of the MAV project at DigiMine, a Masters candidate from the Wits School of Electrical Engineering is researching solutions to overcome this challenge. In this research the focus was on advancing current functions of the MAV system by integrating a ventilation sensor cluster to enable the aerial robotic platform to assist in ventilation surveys. MAVs being tested at DigiMine are customizable with the use of mounting brackets that can be interchanged to suit funtional requirements.

MAVs offer an attractive sampling platform for detecting forests fires (Yuan, et al., 2015) due to their high manoeuverability, extended operational range and improved personnel safety. A MAV equipped with an infrared camera and sensors for smoke, gas and thermal heat can assist in monitoring the behaviour of a forest fire (Krüll & Willms, 2012). Semiconductor gas sensors with high-sensitivity and fast response times are preferred for measuring volatile products produced during fires, however there are a variety of alternative sensing techniques available to users.

Sensor packages for MAVs have been developed to measure multiple atmospheric variables which include airborne pollutants and airflow velocity. Air velocity sensors packages include instruments to capture ambient parameters of airflow i.e. temperature, pressure and humidity which are required in evaluating the dispersion of pollutants and thermal heat in an environment. MAVs seem to be feasible remote-sensing solutions for atmospheric analysis, which means that in principle the aerial robotic platform can be used for ventilation observations in underground mining environment.

3.2 MAV Sensors for Wind Speed Measurements

Field tests of MAVs for the collection of wind turbulence data have developed laboratory sensor packages using either hot-wire anemometry or multi-hole pressure probes to collect data sets with high spatiotemporal resolution. Examples of systems evaluated by Witte, et al (2016) include a multirotor MAV used with hot-wire anemometers and fixed-wing MAVs using a 5-hole probe to analyse mean wind velocity.

The small unmanned meteorological observer (SUMO) is a fixed-wing MAV system with a weight of approximately 600g which was equipped with meteorological sensors and successfully tested for gathering atmospheric measurements in the earth's atmosphere (Reuder, et al., 2008). On-board sensors were used to capture measurements of temperature, humidity, and pressure. SUMO did not include any special equipment on-board for measuring wind velocity, however, the MAV system had to be flown in helical or spiral patterns to estimate horizontal wind speed profiles.

Lawrence & Balsley (2013) developed a MAV called the DataHawk which was tested for collecting measurements of multiple atmospheric variables. Custom lightweight high-resolution sensors were developed by researchers and mounted on the DataHawk's airframe at a location with access to free air streams and adequate protection from damage. The custom sensor cluster included a pitot-static probe, a cold-wire probe, as well as inexpensive sensors calibrated to measure temperature, pressure, and relative humidity.

A meteorological sensor system for a MAV tested for air quality analysis (Allen, et al., 2019) included a five-hole probe weighing 98 g and a pitot-static tube of 15 g in a sensor cluster arranged to measure static and total pressures used in the determination airflow speed. An ultrasonic anemometer on the ground was used to provide reference values of wind speed in further tests of the MAV systems using a five-hole probe for turbulence measurements in the earth's atmosphere (Witte, et al., 2017). Measurements from the MAV were found to be in good agreement with the sonic anemometer on the ground.

Field tests of MAV systems have validated the capability of the aerial robotic platforms to serve as a remote sensing tool for atmospheric sampling. The next discussion looks at MAVs applications in the analysis of air pollution. Air pollution is assessed in mine ventilation to manage health hazards encountered daily.

3.3 MAV Sensors for Pollution Analysis

An analysis of capabilities of MAVs for air pollution monitoring was done (Chwaleba, et al., 2014) and identified near-infrared (NDIR) and thermographic cameras as desirable devices for air quality analysis. Miniature photogrammetric devices applicable to air quality monitoring are relatively expensive, provide indirect measurements, and would present complexities in data analysis for the current skills training of mine ventilation engineers. Therefore, the focus of air pollution sensors in this study was limited to the techniques which are used in gas detection instruments already accepted for mine ventilation monitoring.

MAVs have been identified to be useful for detecting forests fires (Yuan, et al., 2015) due to their high manoeuverability, extended operational range and improved personnel safety. A MAV equipped with an infrared camera and sensors for smoke, gas and thermal heat can assist in monitoring the behaviour of a forest fire (Krüll & Willms, 2012). Semiconductor gas sensors with high-sensitivity and fast response are preferred for measuring volatile products produced during fires, however there are a variety of alternative sensing techniques available to users.

The review of MAV capability in meteorological studies is relevant to understanding the characteristics of sensor packages which must be matched against hazards discussed in previous the chapter. This leads the research to the description of the methodology used that was used to design a feasible ventilation multi-sensor cluster for a MAV.

4 RESEARCH METHODOLOGY

A preliminary title, objectives and questions for this research were developed after reviewing WMI's documented plans for the MAV project and published literature related to the research tittle. A presentation was prepared, and its contents were discussed through a proposal workshop facilitated by WMI to bring academic researchers, mining professionals and vendor partners into the same room to reach agreement on the functional requirements for the MAV system in the task of ventilation monitoring.

The proposal workshop was attended by Schauenburg Systems, Bluhm-Burton Engineering (BBE), lecturers and post-graduate students from the Wits School of Mining Engineering, School of Geography and School of Electrical Engineering. The outcome of the proposal workshop was a mind map which provided the author a detailed plan to follow during the research. The author broke down the mind map into developmental stages of the design using the systems engineering process described in the next section.

4.1.1 Systems Engineering Process

A diagramatic representation of a SEP is provided in figure 4.1 and shows the various developmental stages which guided this research.

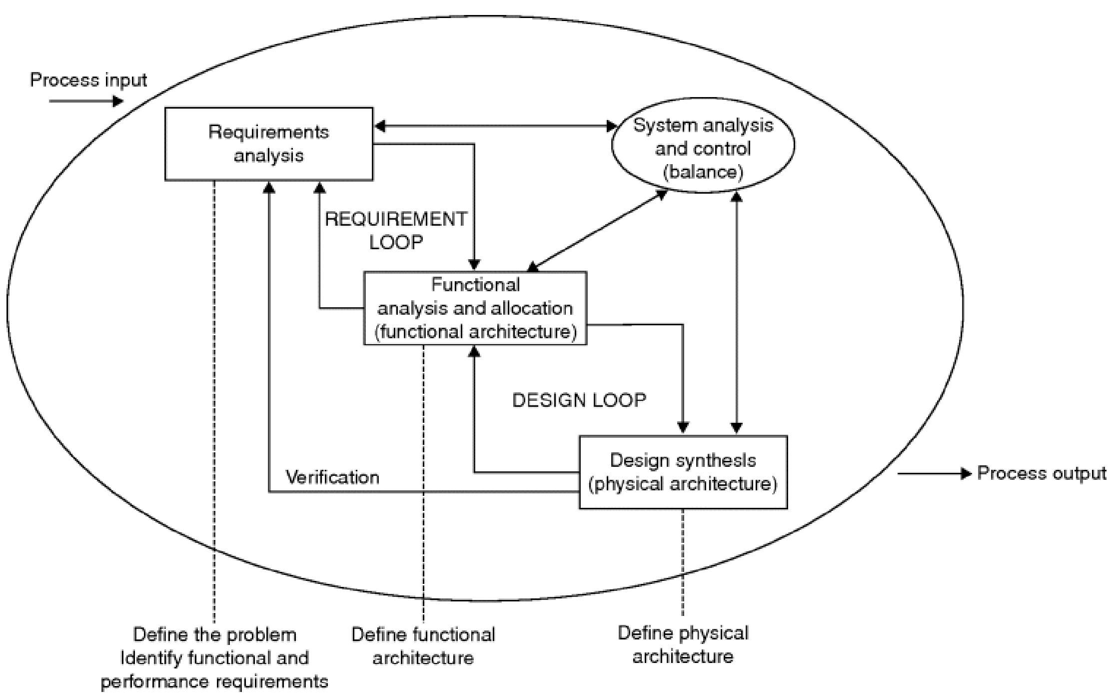


Figure 4.1: *Representation of systems engineering process (System Management College, 2001).*

The Systems Engineering Process (SEP) is a high-level project management approach that is used to transform functional requirements of air quality sensors for an MAV platform into a practical configuration that meets objectives of this research. The ability to measure airborne hazards discussed in chapter two is the main function that the MAV is required to execute. Performance capabilities and the physical design of the MAV established a technology baseline considered when identifying compatible sensing instruments that would suit the functions identified for missions in underground mines. These were inputs discussed during the proposal workshop which analyzed the requirements of the system.

The requirements gathered led to the allocation of functions for the ventilation multi-sensor cluster and involved more workshops and follow-up meetings with partners such as the Mine Health and Safety Council (MHSC), Adroit Technologies, Sperosens, and vendors who were part of the proposal workshop. Feedback gathered during the functional analysis phase helped the author develop a functional architecture for the ventilation multi-sensor design to be constructed for a MAV.

The functional architecture was transformed into a physical architecture for the contemplated ventilation sensor cluster. The physical architecture was discussed with the supervisor, fellow researchers, and project partners. Once agreement was reached regarding the physical architecture, specification of hardware, software and communication were identified for a more detailed design. Follow-up meetings were held with project partners throughout the developmental stages of the SEP. The feedback gathered helped the author in selecting existing technologies with the capability to achieve the functionality expected from the MAV operating in an underground mining environment.

Following is a description of the case study that was used to help the author gain a practical understanding of the operational expectations of the ventilation sensor systems. The case study enabled the author to identify use cases for the ventilation sensor cluster to be constructed for a MAV. This case study was particularly important to enable the author to consider how the effectiveness of the design would be impacted by current levels of technology in underground mining environments. The case study also included observations of MAV demonstrations which helped the author see how well the platform would perform as an autonomous air sampling instrument. Furthermore, the case study provided access to facilities, information and guidance that helped the author in documenting an implementation plan for the contemplated technology in a simulated underground tunnel.

4.1.2 Ventilation Monitoring Case Study

This research was carried out at the DigiMine laboratory located inside the Chamber of Mines building at the University of the Witwatersrand's Braamfontein West Campus. DigiMine is a simulated underground mining environment developed to enable students to obtain training in 21st century mining skills and test digital systems installed in the laboratory. The laboratory has real-time sensor technologies transmitting data to a control room and assigns each student in the multi-disciplinary group a live system to operate, manage and oversee its maintenance. Figure 4.2 shows pictures of the mock underground mine and some of the equipment used by post graduate student to set up case studies and collect data for on-going research work.

Mock mine tunnel

Mock mine stope

DigiMine control room

Roof installation of sensors for rain, wind and ambient conditions

Figure 4.2: Facilities and technologies available at DigiMine

The laboratory includes fixed and mobile gas detection instruments as well as lamproom facilities. There is a representation of a narrow reef stope and a staircase in the building has been converted into a vertical shaft with the roof of the building representing the surface of a mine. Sensors measuring different environmental conditions are fixed near the face of the development tunnel, and the roof of the Chamber of Mines building. Mobile gas detectors and portable airflow monitors are available for traversing ventilation surveys.

During this research, the author was assigned the role of managing a real-time mine ventilation simulation software installed in a control room and linked with multiple sensors placed in a mock underground mine tunnel for measuring airflow velocity and gases. The author received practical training in digital skills required to operate real-time ventilation monitoring systems for underground mines. All details, learnings and challenges related to the live ventilation simulation system installed at DigiMine were recorded and reviewed regularly using a standard system document template developed for each of the digital technologies at the laboratory. The system documents made up an important part of recording learnings from digital technologies being tested at the laboratory.

Technologies that were reviewed during this research included portable atmospheric sensors, underground navigation systems, wireless communication, information processing and display interfaces. Access to DigiMine facilities enabled the author to evaluate digital technologies in a laboratory environment, facilitate consultation within the multi-disciplinary research group and provided observations through demonstration of MAV operations conducted by WMI partners. The SEP was used in this case study to organise and guide activities required in this research.

This research required training in digital mining skills to enable the author to operate the real-time ventilation simulator which combines different hardware, software, and communication methods. A portion of time during this research involved consultations, meetings, training and demonstration events from which observations were documented according to the structure developed during the proposal workshop and the SEP. Drafts for chapters planned for this research during the proposal workshop were written, reviewed and corrected in consultation with the supervisor. Reviewed and corrected chapters were compiled into a single document for the final dissertation.

4.1.3 Criteria for Validation

Following were the considerations for evaluating the validity of this research:

- Did the research review existing theories and practices for monitoring airborne hazards in underground mining?
- Did the research carry out workshops, interviews, or prepare reports for classifying and analysing ventilation monitoring technology?
- Did the research examine the use of multi-sensor clusters with MAVs in observations of the air conditions?

4.1.4 Ethical Issues/Clearance

No ethical clearance is required as this study does not perform any experiments on humans or animals

4.1.5 Deliverables

The outcome of this research had to provide a detailed design specifying a selection of atmospheric sensor instruments, communication hardware and software to facilitate ventilation monitoring using a MAV in underground mining. The design was detailed for the construction of a ventilation sensor cluster for attachment to a MAV being tested in a simulated underground mining environment.

4.1.6 Project Budget

This research was funded by a bursary provided by the WMI who keep record of budget allocations for the MAV project and may be contacted for specific information related to the finances of this study. The bursary was sponsored by funding from the MHSC center of excellence (CoE).

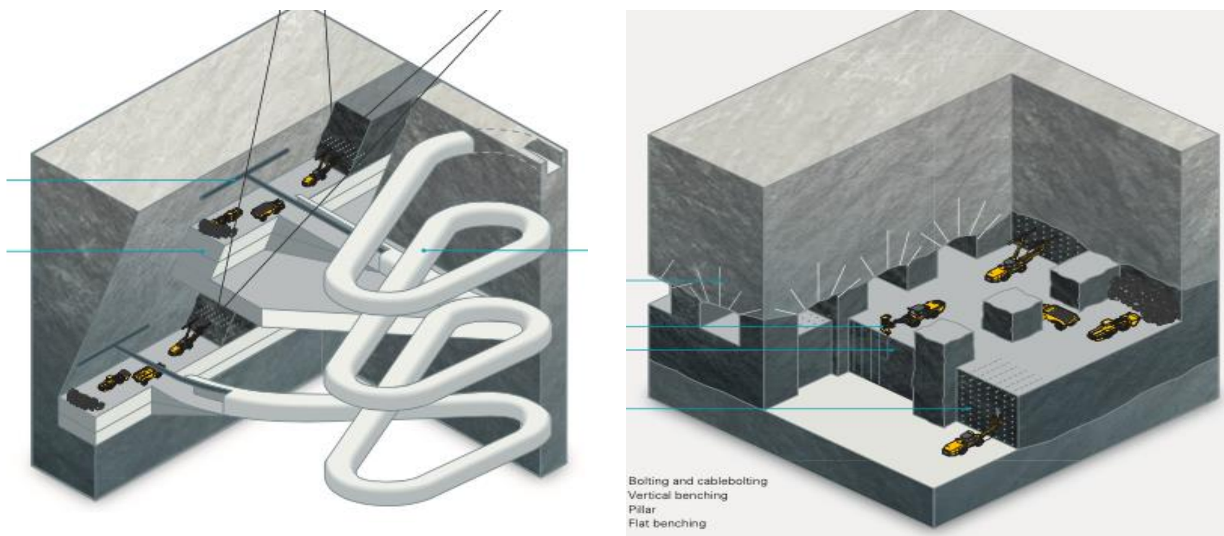
Following is a chapter focusing on the requirements analysis of mine ventilation monitoring. The chapter is the beginning of the discussion of the developmental stages of the SEP.

5 REQUIREMENTS ANALYSIS FOR MINE VENTILATION MONITORING

Chapter 5 begins a discussion of the SEP carried out after considering inputs gathered from workshops, consultations and meetings held during the research. An analysis of requirements in terms of the SEP needed the researcher to analyse the environment for the mission, identify functions and define performance and design constraints. The following section covers the analysis of the nature of the underground mining environment where a MAV could be used for ventilation monitoring.

5.1 Analysis of the Environment

Airborne hazards prioritized in a mine are influenced to a great degree by the type of commodity being extracted. This study focuses on mechanized metalliferous mining to avoid the need to acquire equipment protection accreditation for MAV operation at such early stages of development. Depictions of different mechanized metalliferous mining methods are shown in figure 5.1.



a. Cut and fill method used for mining vertical orebodies

b. Room and pillar used for mining horizontal orebodies

Figure 5.1: Depictions of mechanized metal mining operation (Atlas Copco , 2014)

Although there are varying degrees of automation in mechanized metal mines, humans are still required in the mining process. Therefore, the likelihood of collisions would be high if the MAV is flown in proximity of moving mine personnel and vehicles. The decision of whether a specific mining operation needs a MAV in ventilation surveillance would have to be taken by the ventilation department in consultation with the mine surveying office, the financial department, and mine management. The next section discusses the need for ventilation monitoring specifically for metal mines.

5.2 Identification of Functionality Requirements

Significant health hazards encountered in metalliferous mines depending on the depth of the operation include exposure to toxic fumes from diesel equipment and overexposure to heat and humidity (Mining Review, 2019a). Therefore, ventilation remains important in mechanized mining operations to minimize exposure to hazards and maintain a healthy, safe, and comfortable environment for humans. Ventilation is essential to maintain an environment required to keep equipment in good condition for maximum efficiency and operational life.

Metal mines detonate explosives to break the rock hosting a mineral orebody. Mechanized equipment is deployed during mucking, scaling, shotcreting, bolting and drilling for a blast. An ideal blast releases fumes and gaseous products such as water vapour (H_2O), carbon dioxide (CO_2) and nitrogen (N_2). However, conditions in real-life are never ideal, therefore, carbon monoxide (CO) and oxides of nitrogen (NO_x) are also produced from detonating explosives (Richard , et al., 2007).

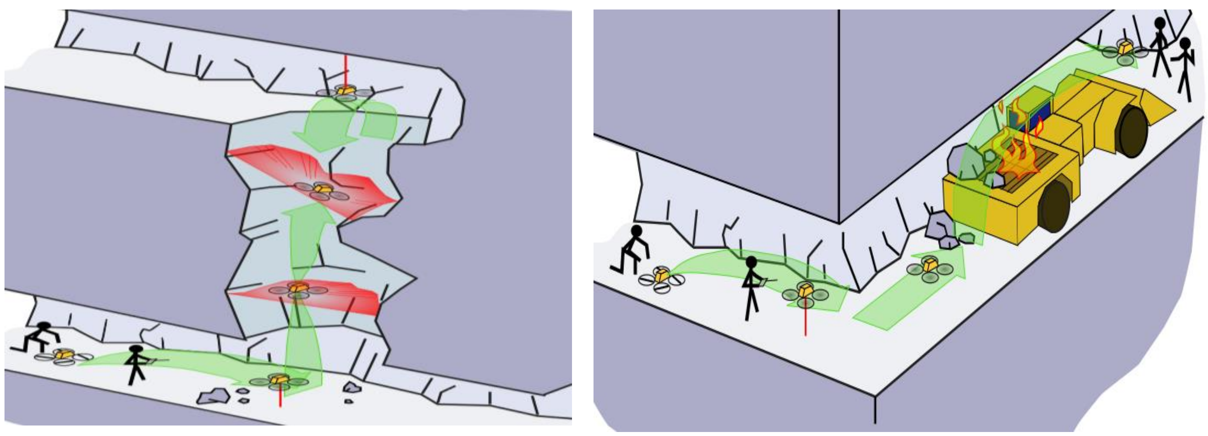
Monitoring levels of gases such as CO_2, CO and NO_x after blasting enables mine operators to establish safe re-entry times which ensures that all harmful gases are removed from the atmosphere before the next shift can begin. Peaks in gas emissions may also be an indicator of excessive emissions of diesel exhaust fumes. Gas testing is mandatory in early-entry examination to declare whether a workplace is safe before a shift can begin. Critical times to monitor gases include after blasting and during peak productivity periods.

Mandatory ventilation surveys must be conducted every month to assess airflow for compliance (Holding, 1994) as well as to quantify the pressure differences across airways in a mine’s layout. Monitoring intervals can be established based on a mine’s shift production schedule and knowledge of peak emission periods. With the introduction of real-time instruments, it is now possible to continuously monitor a ventilation system.

Real-time ventilation monitoring systems in underground mining can be installed as hybrid networks comprising of wired and wireless air quality sensing nodes measuring fan operation, airflow speed, pressure differences, air temperature, gas and smoke concentration (Schauenburg Systems, 2017). Wireless mobile devices are implemented to extend the reach of real-time multi-sensor clusters being transported by humans and vehicles to secondary tunnels and production zones (Fischione, et al., 2008). The objective of installing a real-time ventilation monitoring system is to track changes in significant airborne hazards and enable early detection of risk. Therefore, for the MAV ventilation sensor cluster needs to offer functions which are available in existing monitoring solutions. However, the MAV is limited by its payload capacity and design.

5.2.1 Operational Scenarios for the MAV Ventilation Monitoring System

Multiple MAVs would be required to operate in underground mines as depicted in Figure 5.2. by Mitchell & Marshall (2017) who recognised the platforms to be a feasible solution in underground mine surveying as well as in search and rescue missions.



a. UAVs in a routine inspection mission *b. UAVs in mine post-disaster analysis*

Figure 5.2: Potential MAV applications in underground mining (Mitchell & Marshall, 2017)

In terms of mine ventilation surveys, the MAV's missions would be used for routine inspection and post-disaster analysis of the underground mining atmosphere. The multi-sensor cluster to be attached onboard the MAV therefore requires the ability to adapt to risk scenarios encountered in normal operations and in search and rescue operations.

The integration of portable sensors with a MAV can enable the platform to be used to inspect ventilation conditions during pre-entry examinations, post-blasting, for alarm validation, for assessing accident-scenes and any dangerous occurrences or near-misses. The MAV can traverse the mine to conduct regular inspections of hazardous environments such as electrical substations, diesel fuel bays, and sealed off sites. Smaller, low-cost MAVs can be used in some of the most dangerous situations in underground mining to collect atmospheric samples. When operated by a pilot from a safe environment, using the MAV will eliminate the need for workers to enter dangerous atmospheres to carry out risk assessments.

The MAV platform can enter dangerous mine excavations in it is difficult to install fixed instruments. The MAV can also increase the regional coverage of air quality monitoring by traveling fixed monitoring stations

Using MAVs in ventilation monitoring can be an alternative to sending expensive production equipment with sensor clusters into hazardous atmospheres. In a catastrophic event, it would be cheaper to lose an MAV than a mine's production asset. Although the MAV offers the ability to function as a ventilation monitoring tool, it has some performance and design constraints.

5.3 Performance and Design Constraints

There are currently MAV systems developed as remote sensing platforms in atmospheric analysis of outdoor environments. The basic design thinking process used in previous MAV developments for atmospheric analysis applies to the development of the multi-sensor cluster for ventilation surveillance in confined underground mining environments. Air pollution mapping systems developed for MAVs by authors such as Kersnovski, et al., (2017); Villa , et al., (2016); Chwaleba, et al., (2014); Malaver, et al., (2015) and Rossi & Brunelli, (2016) were reviewed and used to guide the development of a suitable design for mine ventilation monitoring using a MAV as a remote sensing tool.

Based on response time of commercial gas detection instruments, at least 30 seconds needs to be spent by the MAV at each sampling location to allow sensors sufficient time to respond. With a flight of 30 minutes which a single quadcopter can sustain, a complete flight mission using a stop-measure-move strategy can record up to 60 measurements at different locations in a mine. The final strategy and measuring intervals for the MAV's ventilation inspection missions can only be determined from practical testing of the system. More than one MAV platform is needed to surveil an entire mining operation. Furthermore, MAVs can only serve in periodic ventilation surveys to supplement fixed and portable ventilation monitoring instruments.

Performance specification of the MAVs tested at DigiMine's mock mine tunnel form the basis of constraints requirements for this design of a multi-sensor cluster. In other words, the main limitation to the design is the payload capability of 250 g which is the maximum weight of sensors that can be mounted on a MAV platform based on the quadcopter utilized by Edwards (2017). An additional constraint on the multi-sensor design is the location to attach the cluster such that there is shielding from interference between sensor signals. As the MAV sensors would need to measure samples while flying, it will be important to design an appropriate sensor casing to house selected instruments and position the cluster such that the effect of turbulence from flying rotors is minimized.

According to Sørensen, et al. (2017), MAV frame are designed with standard mounting points underneath the frame originally designed to support a camera gimbal. The mounting brackets would have to be modified for the design of the selected ventilation multi-sensor cluster. It is important that modifications to mounting brackets and the method of fitting the sensors' bracket to the MAV frame does not interfere with the structural integrity of the system. Once the physical design has been constructed then testing of the performance of the sensor cluster can begin. The following chapter is a discussion of the functionality requirements of the ventilation multi-sensor cluster being designed for a MAV platform to serve as a remote air sensing tool in underground metalliferous mines.

6 FUNCTIONALITY ANALYSIS FOR VENTILATION MONITORING USING A MAV IN AN UNDERGROUND MINE

This chapter is a discussion of functional requirements of the ventilation multi-sensor cluster that is being designed for attachment on a MAV platform. It forms part of the developmental stages of the SEP. The chapter evaluates different handheld instruments used for ventilation analysis with an aim of identifying the most suitable instruments that can be arranged into a multi-sensor package for attachment onto a MAV. It also considers complementary electronic hardware that is needed for the integration of different air sampling instruments. The chapter begins the analysis with a decomposition of lower-level functions for the MAV ventilation monitoring system.

6.1 Function Allocation for MAV System

The use of MAV's as automated air sampling platforms has been validated in meteorological experiments. Trials in subsurface environments have shown that MAV technology has potential to increase the spatial coverage of existing ventilation monitoring in underground environments without endangering personnel or mine production assets. Monitoring critical systems such as ventilation conditions in an underground mine is part of controlling hazards which cannot be eliminated or substituted. It will therefore continue to be a crucial aspect of maintaining healthy and safe working conditions.

The use of MAVs can advance existing wireless ventilation sensing in underground mines when used as mobile sensing carriers to gather and disseminate information for the following purpose:

- mine-wide situational awareness of ventilation conditions;
- monitoring, forecasting, and early warning system for airborne hazards;
- stand-alone communication for search and rescue mission; and
- mapping pollution distribution in underground mining.

The multi-sensor cluster needs to include sensors to capture measurements for analysis of airflow quantity and quality. This requires sensing instruments for ventilation flow speed, gas emissions and ambient conditions. Next is a discussion on airflow velocity instruments as they are used in underground mining for estimating the quantity of ventilation flowing through different districts of an operation.

6.1.1 Airflow Velocity Measurements

Schmitz & Drummond (1989) indicated that to obtain accurate measurements of airflow velocity in underground mines requires readings to be taken along the complete area of an airway. For better accuracy, an airway can be divided into several geometric areas with a cross-sectional shape like that of the main access tunnels. Air velocity can be measured during a moving traverse, at a single point or over a series of points (Casten, 1995). Schmitz & Drummond (1989) recommended the speed of moving during traversing velocity measurements to be kept below 0.2 m/s to minimise errors due to motion. Thus, the MAV would be required to maintain the recommended speed while flying to ensure the highest accuracy of air samples is maintained.

Anemometry is the most common instrumentation used for measuring airflow velocity in underground mining. Types of anemometers are vortex shedding, hot-film or hot-wire, laser Doppler, rotating vane and ultrasonic (Unwin, 2007). Alternative instruments used for measuring air velocity in mining include velometers, smoke tubes, olfactory devices and tracer gas methods (Casten, 1995). Example of anemometers embedded with wireless communication are provided in figure 6.1.

a. Hot-wire anemometer with Bluetooth (Testo SE & Co, 2019)

b. Pitot-static tube for UAV systems (UAV Factory LLC, 2019)

c. Ultrasonic anemometer for quadcopter (Unmanned System Technology , 2019)

Figure 6.1: Air velocity measuring instruments

Modern anemometry embedded with Bluetooth or radio connectivity enables wireless transmission of captured measurements. Personal devices for measuring airflow have interchangeable probes and include sensors for measuring temperature and humidity within the instrument (Testo SE & Co, 2019). The measuring probes have a fixed cable with pins that can connect to a digital reader.

The pitot-static tube shown in figure 4.2.b has been designed specifically for MAV systems and eliminates the weight of a digital reader included as part of traditional air velocity meters currently used in mining. The pitot-static tube weighs only 41 grams (UAV Factory LLC, 2019). Martikainen, et al. (2010) recommended using the ultrasonic anemometer in very low air velocity. The ultrasonic anemometer shown in figure 4.2.c is specifically designed for a quadcopter MAV system to provide measurements of airflow speed, its direction and temperature (Unmanned System Technology , 2019).

Specialized mounting brackets and other accessories would be necessary to attach air velocity instruments to a MAV frame. In addition to a sensor for airflow velocity, the cluster needs to include sensors for hazardous mine gases. Sensing instruments used for measuring concentrations of airborne pollutants as part of pollution analysis are discussed in the next section.

6.1.2 Pollution Analysis

Risk is presented by any situation involving exposure to danger. When risk is detected, employees are required to evacuate from their workplaces to a place of safety, thus putting a halt on production activities. Significant risks encountered in metalliferous mines include fires which can have catastrophic consequences. Real-time measurements of gas and smoke enables sudden concentration peaks to be detected early for effective mitigation. Toxic fumes including CO_2 and NO_2 are produced by blasting, diesel exhausts, and released from the combustion process in combination with smoke, hydrocarbons and oxygen-deficient by-products such as CO.

A review of sensing techniques for toxic gases identified infrared (IR), electrochemical, photoionization (PID) and semiconductor sensors for measuring concentrations (Szulczyński & Gębicki , 2017). Metal oxide semiconductor (MOS) type sensors are preferred for integration with portable devices such as smart phones and wearable technology (Burgués, et al., 2019). An additional advantage of MOS sensors is the sensitivity to low concentrations of toxic gas and low-power consumption. Sensors are packaged into portable gas detectors shown in figure 6.2.

a. Detector for measuring up to 6 gases (Dräger, 2010)

b. Dual-gas detector (Dräger, 2010)

c. GDI-sentinel measures up to 4 gases (Schauenburg Systems, 2017)

Figure 6.2: Personal gas detection instruments for hazardous environments

Portable detectors are used by miners to measure up to six different gas species including flammable, toxic and combustible gases, vapours and oxygen. Devices can be equipped with IR or electrochemical sensors which simultaneously measure two different gas combinations e.g., CO/O_2. IR sensors are preferred in explosive environments while PID is used for detecting low concentration of volatile organic compounds (VOC). Sensors are enclosed in a robust casing that is water-tight and provides accurate, reliable measurements (Schauenburg Systems, 2017).

Important considerations during the selection of sensors for a specific application include the expected gas concentration, whether the emission source is stationary or mobile, and other gases present which can influence the readings. A review of gas sensor (Yunusa, et al., 2014) defined an ideal sensor based on properties which include high sensitivity, selectivity, and fast response.

Modern detectors for hazardous environments have a response time between 10 – 30 seconds (Dräger, 2010; Schauenburg Systems, 2017). Gas sensing techniques are miniaturized through microfabrication techniques that have allowed the development of small sized, low-cost and low-power hardware which is ideal for large-scale mobile monitoring (Anas , et al., 2017). The next section provides a selection of sensors for the system design to be attached on a MAV tasked with ventilation sampling in underground metal mines.

6.2 Ventilation Sensor Selection

The main measurements which are required to be collected for ventilation analysis in an underground metal mine include gas concentrations (CO NO_2 and O_2), airflow velocity and ambient conditions (air temperature and humidity). For gas sensing, hardware used for portable detectors is suitable for this integration. However, for measuring airflow, the user has a choice between commercially available anemometry (ultrasonic or hot-wire) and custom design pitot static. Table 2 provides a list of sensors selected in this work for attachment onto the MAV to carry out ventilation monitoring tasks in underground hard rock mines.

Table 2.: Air sampling sensor selection for integration with MAV

Sensor type	Electro-chemical	Electro-chemical	Electro-chemical	Ultra-sonic	Digital	Digital
Risk Indicator	CO	NO_2	O_2	Air velocity	Temp.	Relative humidity
Range	0 – 200 ppm	0 - 2000 ppm	20.9 – 0%	0-50 m/s	-25°C to +80°C	0-100% RH
Accuracy	±0.5 ppm	±0.1 ppm	± 0.1%	±0.1 m/s	±2°C	±3%
Response time (sec)	25	30	20	1Hz, 2Hz, 5Hz	1Hz, 2Hz, 5Hz	1Hz, 2Hz, 5Hz
Mass (g)	5	5	7	50	-	-
Sensor name	CO-CF sensor	4-NO2	O2-G2	TriSonica Mini	Inside TriSonica	Inside TriSonica

Sensors selected in table 2 have a small-size, consume low-power, and need to be connected to an integrated circuitry. The ultrasonic sensor also measures ambient conditions which minimizes the sensor weight. Sensing hardware needs to establish a physical connection with the MAV's flight controller to access power and transfer converted signal values to a local memory to be synchronized with the robot's location at regular intervals. Figure 6.3 shows a depiction of the circuitry for a ventilation multi-sensor cluster adapted from a MAV system designed for visualizing air pollution by (Koutroumpas, 2017).

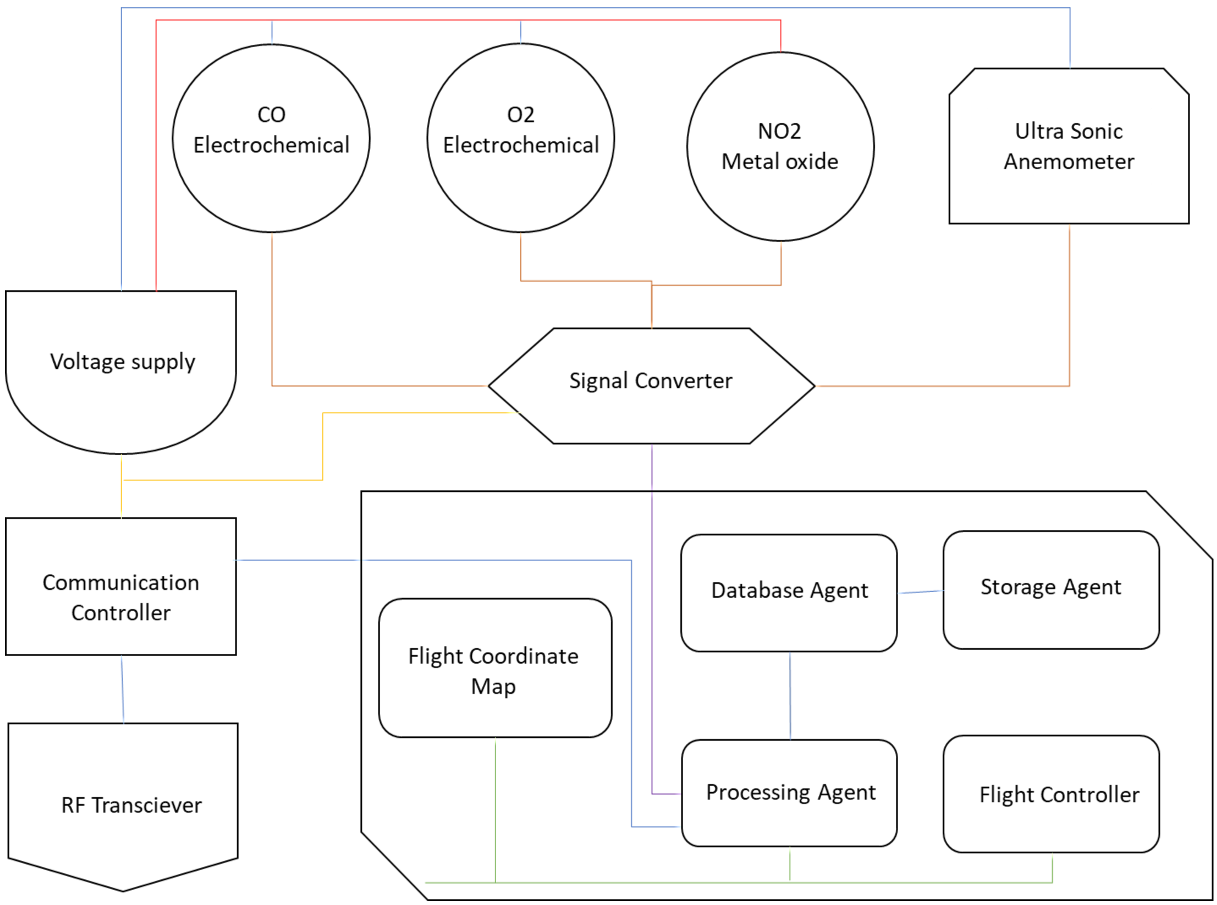


Figure 6.3:Conceptual design of a mine ventilation sensor cluster for attachment on a MAV

The next discussion focuses on complementary functional electronics required in the design to support functionality allocated to the MAV system for ventilation monitoring in underground mining environments.

6.3 Complementary On-Board Hardware Requirements

This design requires different air sampling instruments to be integrated onto the same control interface and function as a unified system. Therefore, electronic circuit boards are an essential element of designing the ventilation multi-sensor cluster as they can be used as a platform to pin different sensors together. An electronic board integrating multiple gas sensors is shown in figure 6.4.

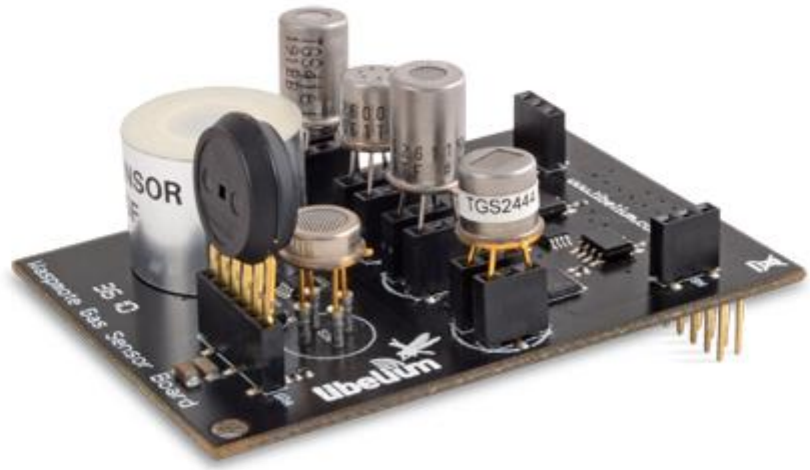


Figure 6.4: Electronic sensor board for detecting changes in air (Libelium, 2019)

Gas boards enable users to design modular multi-sensor arrays that are customizable for application-specific needs. Gas sensor boards are currently used in handheld detection instruments. Modern designs offer computational processing capability to check for errors and transfer multiple sensor measurements at pre-defined intervals to a main command controller (Libelium, 2019). Additional functionality included in modern detection instruments is the ability to transmit captured measurements over radio signals and efficient energy consumption.

For this research, the main control computer is the flight control computer (FCC) of the MAV platform. Therefore, the FCC circuitry is required to connect with the ventilation cluster which would interface with sensors for measuring gas emissions, airflow speed and ambient conditions in a mine's working. As such, multiple electronic boards may be necessary to support the allocated functions. The FCC will also be control of navigating the MAV during flight missions.

6.3.1 On-Board Navigation

Complimentary hardware modules required on the MAV need to enable the platform to fly on pre-defined pathways, collect multiple air quality variables and synchronize them with the robot's position (X-Y-Z) before the data can be being transmitted to a central data center. Synchronizing measurements of air samples with the MAV's position is required to enable quick identification of where hazards are located throughout a mining operation. Expansion ports exposed from the MAV's flight control microcomputer provide users with the capability to integrate external hardware without the need for significant physical modifications (Burgués, et al., 2019). The ports would enable air sampling sensors to be combined with the circuitry of the MAV's FCC.

The MAV requires a map of its target environment and the knowledge of its own position within that map in order to navigate autonomously (Edwards, 2017). However, due to the limited payload and energy efficiency of the MAV, this research does not recommend the use of laser scanners or photogrammetric cameras as external sensory input for the navigation system in ventilation inspection missions.

In environments without access to global navigation satellite system (GNSS), an inertial measurement unit (IMU) or inertial navigation system (INS) is the alternative solution to self-localization in robotic platforms (Bartholmai, et al., 2014). Bartholmai, et al. (2014) described the IMU as a multi-sensor devices that consists of 3-axes accelerometers, gyroscope, magnetic fields, and barometric pressure sensors. The IMU calculates motion sequences of the robot using inputs from external sensor data to allow the MAV to find its current position and navigate itself to the next target.

Autonomous navigation techniques in underground mining environments are challenging to implement due to the confined nature of excavations which create multi-path signal interference, poor or lack of signal propagation and the requirement for large capital investment to achieve robust and high-precision localization needed to track mobile platforms (Sathyan, et al., 2011).

Information captured by the IMU is prone to errors. The IMU system therefore requires inputs from external sensory hardware such as ultrasound or radio frequency (RF)-based systems to correct for errors in the estimated position of the MAVs. Burgués, et al., (2019) indicated that although RF-based positioning systems are cheaper and provide larger coverage without the requirement of line of signt (LOS), they can only achieve an accuracy within 10 cm error. Figure 6.5. shows a picture of a Bluetooth low energy (BLE) node and an alternative wireless node currently being tested for underground positioning at the DigiMine laboratory.

a. BLE wireless reference node for real-time positioning (Qin, 2017)

b. WASP wireless positioning node for hazardous environments (Sathyan, et al., 2011)

Figure 6.5: Wireless positioning system hardware

The latest generation of positioning systems for underground environments use wireless technologies to trilaterate/triangulate the location of an asset using communication signals (Li, et al., 2016). Such a system uses radio-based access points or antennas to estimate the position of a moving entity from the received signal strengh (RSS).

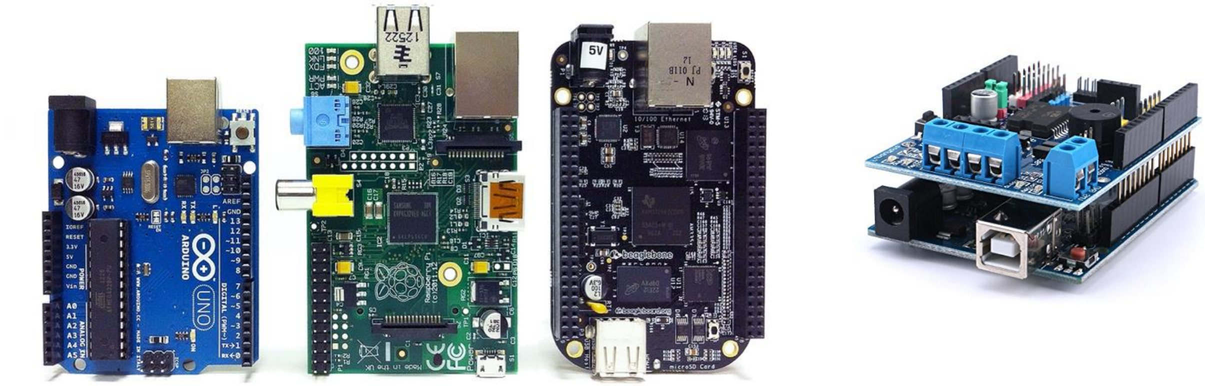
The MAV’s position estimated from RSS may be checked against an existing map of the environment loaded on the MAV’s memory. Imlementatation of fusion algorithms such as the Kalman filter is therefore neccessary to account for uncertainty in the estimated position. The estimated position of the MAV needs to be regulalrly transmitted to the control room to update the MAV’s path map in real-time.

Practical testing of various types of low-cost wireless localization and navigation technologies is currently an interest of many research studies as it is crucial to accelerating further development of large-scale mobile monitoring systems. Qin (2018) is testing high-precision real-time positioning systems using small-sized wireless technology at DigiMine. Some of the applications scenarios identified for wireless positioning systems in underground mining include navigating mobile entities such as scanners, mining vehicles, MAVs and locating rescue teams during evacuations. The accuracy of MAV navigation in underground environments has been shown to be sufficient in practical experiment for generating survey maps (Edwards, 2017; Emesent, 2019b; Freire & Cota, 2017). Next is a discussion on the method used to control mission commands onboard the MAV during flight.

6.3.2 Flight Control Computer (FCC)

Edwards (2017) controlled a quadcopter's navigating along DigiMine's mock tunnel by integrating an autopilot system, with a proportional-integral-derivative (PID) onto a flight controller running a local coordinate system. The navigation control could support both autonomous and semi-autonomous operation. For this application, the navigation control system can be modified to access ultrasound or RF-based sensors to feed into the systems’s decision making process. The PID was used to stabilizes the position of the MAV during flight which prevented the robot from drifting towards the side walls. A dedicated curcuit board for flight control is required to integrate all navigation components and be separated from the circuit board interfacing with multiple ventilation sensors. Commercial printed circuit boards (PCB) such as the examples shown in figure

6.6.a. intergrate multiple microcrocontrollers or microcomputers onto a single programmable circutry.



a. Open-source microcontroller boards *b. Stacked electronic boards*

Figure 6.6: Examples of microcontroller boards for modular sensor integration

A typical microcomputer comprises of a processing core, RAM and an operating system which can be programmed with software by connecting the device to a keyboard and mouse (Schuyler & Guzman, 2017). The alternative to commercial PCBs would be to create a custom design using software such as Fritzing and have them 3D printed.

The FCC need to access energy from battey on-board the MAV which can be selected once all the hardware and software requirements for the mission have been identified. The flight control circuitry board also needs to interface with multiple PCBs which can be stacked up as shown in figure 6.6.b such that all circuitry may be powered from the main energy supply connected to the flight controller. A PCB gives the user the option to store data locally on an SD card to be retirived after flight. The alternative is to wirelessly transmit the data in real-time to an online database.

Open source PCBs are compatible with commercial autopilot systems which can be programmable with different navigation software to meet application-specific requirements of the user (Gu, et al., 2018). The PixHawk and ArduPilot are open-source autopilot software kits designed for copters and other aerial vehicles. Autopilot software development kits (SDKs) provide application programming interfaces (APIs) for transmitting data and controlling commands. MAV commands are generated using MAVLink protocol which facilitates open-sorce communication as described in the following section.

6.3.3 On-Board Communication

MAVLink is an open-source protocol designed to support different wireless and wired communication modules. Meier, et al. (2011) indicated that MAVLink protocol can be used to communicate with external transmission units as well as for transferring data between the flight computer and peripheral sensory circuits mounted on the MAV's control circuit. Dedicated ports provided to connect peripherals to a MAV's FCC include digital general-purpose input/output (GPIO) pins, dedicated universal asynchronous receiver/transmitter (UART) buses, serial peripherals interfaces (SPIs) and inter-integrated circuits (I2C). Using an I2C is found to be the best solution for connecting sensors to microcomputers. In a low cost and flexible MAV systems developed for air pollution assessments (Sørensen, et al., 2017) I2C ports were used to connect wires to the flight control board for accessing measurements, synchronizing values with a clock, and supplying power.

A MAVLink protocol is needed to communicate with the FCC connected to expansion boards interfacing with sensors that are measuring physical changes in the environment. Conformity is necessary in the data format to be shared across different hardware onboard the quadcopter. Data synchronization functions can be pre-programmed on the flight controller using a pre-defined data format. Once measurements are captured by the sensor cluster on-board the MAV, they need to be transmitted to a central control room for post analysis and decision making.

6.4 Simplified MAV architecture

This chapter has discussed the functional elements required to enable the MAV to accomplish its mission. The architecture in figure 6.7 shows where different processes are executed, and which hardware is responsible for each function in the information system.

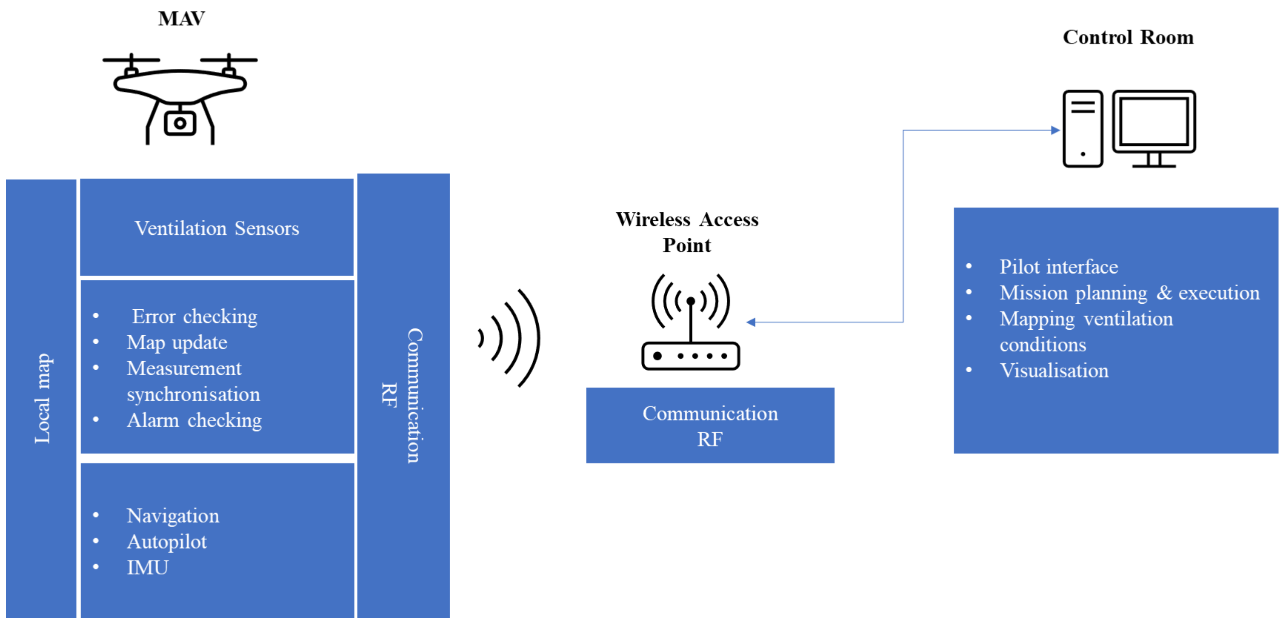


Figure 6.7: Simplified MAV architecture for ventilation monitoring

Figure 6.7 shows that the MAV needs a central microprocessor that interfaces with a microprocessor interfacing with ventilation sensors. The central processor should also interface with another microcomputer that controls navigation and orientation. The central microcomputer needs a local map to be loaded in its memory for positioning. Comunication through radio frequecy (RF) needs to also be controlled by the central proccesing board.

The central processor is responsible for checking errors in measurements, synchronising them, checking for alarms, updating the local map and transmitting the data to the nearaest access point. When alarm conditions are detected by the processor, an LED light can be activativated to immediately warn personnel in the workplace. All the data collected is sent via wireless access points to the mine's communication infrastructure which transports the information to a control room.

The control room executes processes that allow the operator to control the mission from a remote and safe place. The control room needs a computer server for the pilot to load commands for the drone's mission. The server needs software for planning the MAV's mission as well as for maping ventilation conditions. All the information needs to be visaulised using dashboards deployed in the control room.

The communication network is an important link between the MAV in an underground envvironment and the control room where the pilot and operator sit. The discussion of communication network for transmitting data for this apliccation is covered in the next chapter.

7 DATA TRANSMISSION NETWORK

Data captured by ventilation monitoring systems is currently being delivered over wired communication network media such as ethernet or fiber optic cables. However, communication with the MAV's on-board hardware requires a wireless medium. Requirements for the communication architecture to facilitate data transmission from an MAV operating in an underground mine to a surface control station is discussed in this chapter. The chapter begins by focusing on the format of data needed to enable computational processing on-board the MAV before readings can be delivered to a surface control station.

7.1 Data Acquisition Format

A data format needs to be pre-defined on the circuit board interfacing directly with sensors measuring changes in the physical environment. The signal received by sensors will have to be converted into readable values before being transferred for syncronization with the coordinate position accessed from the FCC. The MAVLink protocol used for command control is provided with an open-source flight control SDK (Gu, et al., 2018). MAVLink enables communication using encoded messages generated with XLM protocol specification files.

XLM files can be coded using programming languages such as C, Python and Java (Meier, et al., 2011; Schuyler & Guzman, 2017). The XLM files need to contain all messages defining functions and measuring intervals for the mission. A default XLM file provided with the flight control SDK can be edited with custom messages to run automatically during the flight mission. The pilot on the surface countrol station needs to have the ability to overide automatic commands pre-programmed on the FCC anytime during the flight mission.

The software driver programmed on the PCB interfacing with atmospheric sensors needs to be modified by pre-defining data acquisition rules. A basic structure or format needs to be specified for retrieving data from the ventilation sensor board to synchronize it with location data from the FCC. A microprocessor can be added to the flight control board for synchonizing ventilation measurements with position. Therefore, modification of the sensor software driver is needed to create placeholders for values from gas sensors and the anemometer. An example of the format required in the structure of the XLM file describing a complete point measurement during a MAV ventilation survey mission is as follows:

Time: 00:00:00, Date: DD:MM:YY; O_2: %vol; CO: PPM; NO_2: PPM; X-Y-Z; Temperature: ºC; Humidity: %; Barometric Pressure:Pa

The XLM file is a portable format and can be shared across different microprocessors included on the MAV system. Software drivers for sensor boards and the MAVLink communication protocol are supplied to support open-standards development. Once the data has been collected, it needs to be delivered to decision makers by linking to a mine wide network. The requirements for the data transmission network are covered in the next section.

7.2 Data Transmission Network

Global Mining Guideline Group (2019) stated that the design of communication network in underground mining is based on the Open-System-Interconnection (OSI) model which ensures that devices can communicate over different types of wireless transmission which are in-turn linked to high-transmission infrastructure such as fiber optic or copper local area network (LAN) cables. OSI models developed to support communication in underground mining categorize the network into seven separate layers. Layers 1-4 consider the physical infrastructure responsible for moving data from one point to another and are therefore relevant to this research. The following subsections discuss roles of each of the layers 1-4 in the OSI model, with a specific focus on facilitating the transmission of data captured by MAVs functioning as sensor carriers for real-time ventilation monitoring in underground mines.

7.2.1 Physical Layer

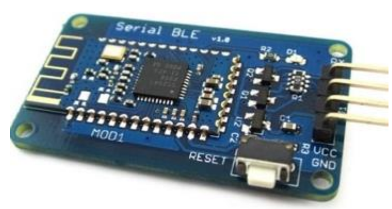
The physical layer is concerned with the means of transmitting raw bits of data through a physical link connecting network nodes and is responsible for converting data to wireless signals over-the-air (OTA) (Global Mining Guideline Group , 2019). Wireless transmission is an attractive communication medium for connecting a quadcopter to a fixed wireless access points to establish a dynamic network that supports real-time transmission of measurements captured by sensors mounted on the flying robot. Wireless mesh networks were found to offer flexible solutions that can be easily deployed with reduced infrastructure (Moridi, et al., 2015). Wireless transmission networks are robust for emergency communication due to their capability to resort to battery operation in the event of a cable failure.

Wireless mesh networks operate at ultra-high frequency (UHF) (300 MHz 3000 MHz) bands of the electromagnetic spectrum (NOISH, 2014). Standards of broadcast frequencies available for wireless local area network (WLAN) use 2.4, 3.6 and 5 GHz. The 2.4 GHz frequency band has been designated as the Industrial, Scientific, and Medical (ISM) radio band (Wired, 2010). ISM frequency bands are unlicensed standards, and support Wi-Fi and RF-based communication.

7.2.2 Data Link Layer

WSN enable mobile sensing nodes within an environment to interact by interlinking with routing nodes though data transmitters. The resulting network can achieve reliable transmission with small nodes that have low power requirements and low complexity (Moridi, et al., 2015). Wireless communication technologies available for implementation underground mine include Bluetooth, ultra-wideband (UWB), Wi-Fi and ZigBee technology. Images of various transceivers integrated into wireless monitoring technology for underground mines are shown in figure 7.1.

a) *Wi-Fi module*



b) *Bluetooth low energy Module*

c) *UWB module*

d) *ZigBee module*

Figure 7.1:Wireless communication nodes applicable to underground mining communication

Investigations of WSN applicable to underground mining (Moridi, et al., 2015) has found BLE and UWB to be inadequate solutions for wireless transmission due to their limited communication range. Griffin (2013) attributed the popularity of wireless mesh networks in underground mining to their redundancy and self-healing abilities. Wireless nodes can establish a mesh network by interacting directly with each other without the need for access points in between end devices.

Wireless mesh networks are preferred in dynamic environments which present difficulties to the operation of cabled infrastructure, e.g., during an emergency evacuation process. However, the Global Mining Guideline Group (2019) highlighted that the implementation of wireless networks in underground mining is not yet capable of replacing hard-wired communication technology entirely.

7.2.2.1 Wi-Fi Communication in Underground Mining

Wi-Fi is the most commonly used wireless computer network standard in micro-drone systems developed for pollution monitoring (Yungaicela-Naula, et al., 2017; Schuyler & Guzman, 2017). Wi-Fi is based on the 802.11 protocol developed by the Institute of Electrical and Electronic Engineers (IEEE). Global Mining Guideline Group (2019) does not consider Wi-Fi as a feasible communication medium for underground mining environments anticipating increased automation. This is because s Wi-Fi network needs access points to be connected via cable to a communication backbone infrastructure. Wi-Fi access points require a continuous power supply and do not have multi-hop network topology (Moridi, et al., 2015). Complexities in installing and maintaining Wi-Fi access points disadvantages this type of WSN for underground mining applications.

7.2.2.2 ZigBee Radio Communication

ZigBee radio technology based on the IEEE 802.15.4 communication protocol has been proposed for environmental monitoring systems in underground mining environments (Zhang, et al., 2014; Minhas, et al., 2017; Jo & Khan, 2017; Tiantian & Zhanyong, 2011; Qandour & Ahmad, 2016; Moridi, et al., 2015). The ZigBee technology operates at the ISM frequency band of 2.4 GHz to transmits information using regional bands of 868/915 MHz depending on the country specification (Pothuganti & Chitneni, 2014). According to Moridi, et al. (2015) and Tiantian & Zhanyong (2011) ZigBee technology has cost-effective nodes that are less complex to install and maintain compared to other WSNs for underground communication.

The redundancy and self-healing capability offered by multi-hop pathways in ZigBee technology make it an attractive solution for wireless transmission especially in emergency situations (Moridi, et al., 2015). ZigBee communication has been integrated into mobile sensing nodes for wireless pollution monitoring in underground mines (Jo & Khan, 2017). ZigBee transceivers have also been used on MAV systems to establish a dynamic wireless connection with a ground computer station receiving measurements during flight (Edwards, 2017; Koutroumpas, 2017).

The implementation of ZigBee wireless mesh networks for monitoring pollution in underground mining has been shown to have the capability to support communication during normal operation and promises to be a feasible option for emergency response. It is compatible with MAV platforms which makes it a suitable solution to facilitate real-time transmission of data collected using quadcopters in underground mining environments. Therefore, ZigBee presents a viable alternative for wireless communication to support transmission from mobile monitoring platforms.

7.2.3 Network Layer

ZigBee networks nodes are categorized according to their functions which include coordinator (gateway), full function (router) and end-devices that are usually mobile. The functions for communication nodes are described by (Moridi, et al., 2015) as follows:

- A gateway (coordinator) node establishes and controls the networks, stores information, and operates as a terminal for data acquired from other nodes in the network.
- A routing (full function) node relays data transmission between the coordinator/gateway and participating end devices. It is responsible for extending network coverage over large areas and maintains communication paths despite network congestion or possible node failure.
- End-device is a node that can only receive or transmit data and needs to interlink with a routing node or gateway to relay its data.

ZigBee-based communication makes it possible to arrange nodes into a star, cluster-tree, and mesh (peer-to-peer) network topologies. ZigBee routers enable multi-hop communication and relay data from end devices via routers to the sink node where all data is parked. ZigBee nodes offer the flexibility to be placed anywhere in underground mining within space and environmental constraints. Nodes have the ability for self-organization and self-healing which can be optimized to rebuild wireless networking when there is high potential for node failure such as in an emergency event.

According to Qandour & Ahmad (2016), a ZigBee node needs to be embedded with a logic that controls Over-The-Air (OTA) transmission between wireless nodes in the network. Routing protocols available for ZigBee communication technology can be either proactive or reactive. Moridi et al. (2015) preferred the reactive routing protocol for on-demand route discovery required for mobile devices which must alter communication paths over time. The reactive type of routing protocol was found to consume less energy and bandwidth while achieving longer transmission times.

The transmission logic is responsible for defining the address and routes or paths over which data packets will be broadcasted from sensor nodes in the Physical (PHY) and Media Access Control (MAC) layer of the network (Moridi, et al., 2015). The logic ensures that data packets are received by the intended destination node and that wireless nodes can join the WSN securely. The IEEE 802.15.4 alliance defines specifications of the transmission logic which provides functions to distributed devices facilitating wireless transmission in an OSI communication model. The next discussion focusses on the fourth layer of the OSI model which is responsible for transporting data packets to the storage server.

7.2.4 Transport Layer

The ZigBee-based networks are not subjected to specific protocols in the upper layers of the OSI model, therefore, existing communication media such as fibre or Ethernet can be interlinked with wireless mesh networks to deliver the data to the main storage database on surface. Communication technology in underground mining currently relies on backbone infrastructure such as, leaky feeders, power line, copper twisted pair, coaxial cable, Ethernet, or fiber optics (Griffin, 2013; Global Mining Guideline Group, 2019). A wired backbone infrastructure already available in underground mines may be interlinked with the WSNs to improve the robustness of heterogeneous communication under normal operational conditions.

In traditional communication systems, the backbone infrastructure is the transport layer used to move data packets from wireless routing nodes to a local storage server. When a WSN gateway node is connected to a LAN on surface via Ethernet, a transmission control protocol (TCP) based on internet protocol (IP) applies to the communication network.

The backbone infrastructure can provide charging facilities to wireless nodes placed in underground mining spaces during normal operations. However, wired communication is not a practical solution during emergency events as the cable can easily get damaged. In any event which may results in physical damage to the wired infrastructure, wireless coordinators and routing nodes placed underground can resort to a back-up battery for energy supply and enable the network to operate without need for a wired backbone within the mine. On surface an Ethernet link would still be required to transfer data parked on the terminal node to the LAN connected to computers in a control room.

7.3 Data Transmission Architecture

A network architecture to facilitate connectivity and data transmission between the MAV and control station on surface is provided in figure 7.2.

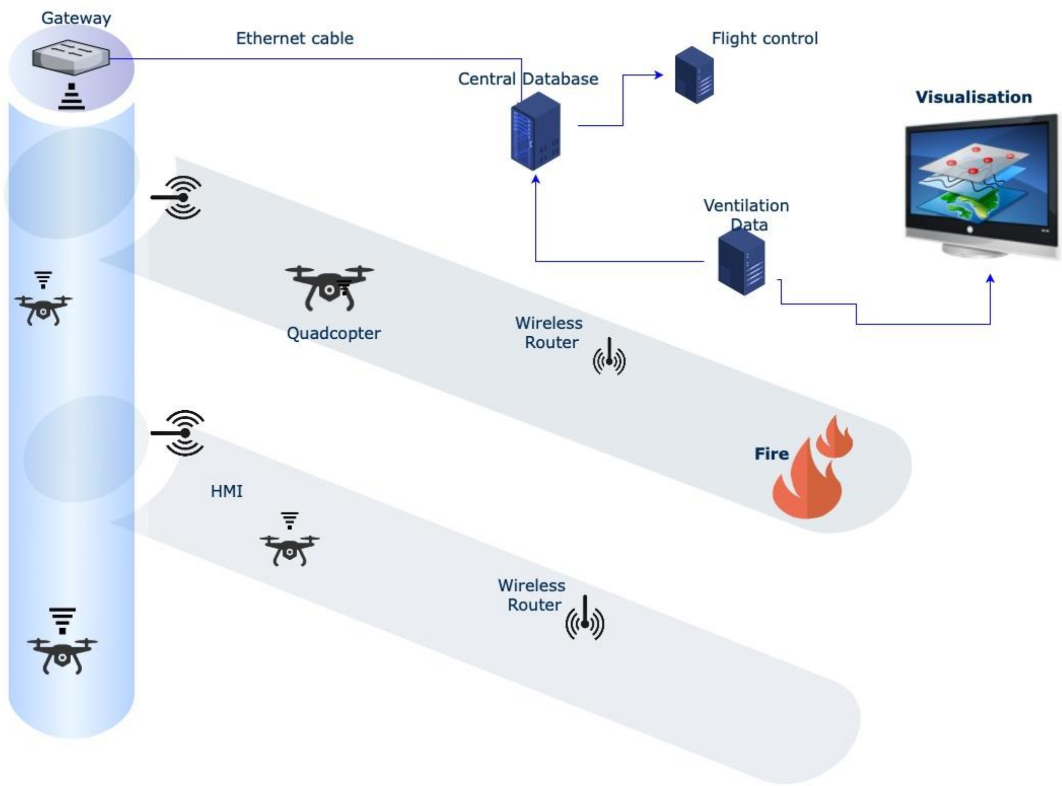


Figure 7.2: Mine-wire transmission network for communication with MAV during mission

Data packets would be transmitted via radio-based communication until they reach the terminal node. Communication with the MAV is made possible using an open-source protocol which is optimized for transmission via a radio telemetry network. Custom messages may be encoded to send commands to the flight controller which communicates with the ventilation sensor system on-board. The telemetry module on the MAV needs to establish connection with the nearest routine node using radio signals. The routing node would then relay data packets using multi-hop paths in the network until they arrive at the gateway node(s) where data is to be parked.

The terminal gateway node is preferred to be placed closer to a surface control station and connected to a wired infrastructure such as Ethernet. To ensure network security, it is good practice to avoid connecting sensor networks directly to the internet, therefore data may be saved to a local database server on site. This chapter completes the allocation of functions for the communication infrastructure required to deliver information gathered using a MAV to a central database for post-analysis. The next chapter looks at the software applications which will be needed to control the MAV operations during its missions and analyze the information stored on the operational database.

8 DATA ANALYSIS REQUIREMENTS

In this chapter, the study looks at control room facilities and investigates software applications required to control the flight mission and access ventilation measurements for analysis and display. Each of the hardware components discussed is essentially treated as an asset which participates in the monitoring networks to execute specific commands required during the mission. Each device is supported by specific software that enables the user to configure commands according to the needs of the mission. The discussion of software is the last part of the requirements for designing the ventilation multi-sensor cluster for attachment to a MAV for underground monitoring tasks. The consideration of software begins with requirements for the management of an operational database for this application.

8.1 Operational Database Management

Information gathered by a MAV during ventilation inspection missions will be delivered to a local database for storage. To manage data storage facilities for geo-located ventilation measurements transmitted by the MAV in real-time, a reliable database management system (DMS) is required. Geographic information, also known as spatial data or geospatial information is used to describe the physical location of a feature which will in this case be ventilation parameters registered by multiple sensors carried by an MAV during its flight mission.

The DMS needs to organize the data in a structured manner that makes it easy to access the information and update it. A relational database management system (RDMS) which uses table structures to arrange data sets that are related to each other is an attractive solution for this application. Structured Query Language (SQL) is a programming language used to communicate with data stored on a RDMS (Codecademy, 2019). SQL uses syntax which is like the English language and it is easy to write, read, and interpret.

Management of spatial data in SQL categorizes objects into a geometric or a geographic data sets with a local coordinate system using X and Y to represent lines, points, and polygons in two dimensions (Ernest, 2015). An SQL database can make spatial information available to third party applications that request the data. DMS such as IBM, DB2, and Oracle have been able to handle spatial data, with Microsoft SQL Server having recently added advanced features including cost-based optimization in spatial analysis (Ernest, 2015). Following is a discussion of third-party software that will need to access information stored on a RMDS to perform analysis and display the data.

8.2 Geographic Modelling

The MAV will not provide a visual feed of the environment in which it will be sent to assess ventilation conditions. It will only include a navigation system that uses light-weight sensory input to estimate its current position and orient the robot to its next target. The MAV needs to therefore be provided a pre-planned flight plan to follow when assessing ventilation conditions in an underground environment.

Burgués, et al. (2019) indicated that A 2D map of the survey area is required to predefine a path for the MAV to travel during its flight mission. Experiments used 2D models to define a pathway with enough clearance from obstacles, set the target flight height and speed for the MAV to follow during its mission. As the MAV navigated the pre-planned pathway, air quality measurements were transmitted to a ground control station. Geo-located measurements were then computed into a 3D simulation which displayed conditions as shown in figure 8.1.

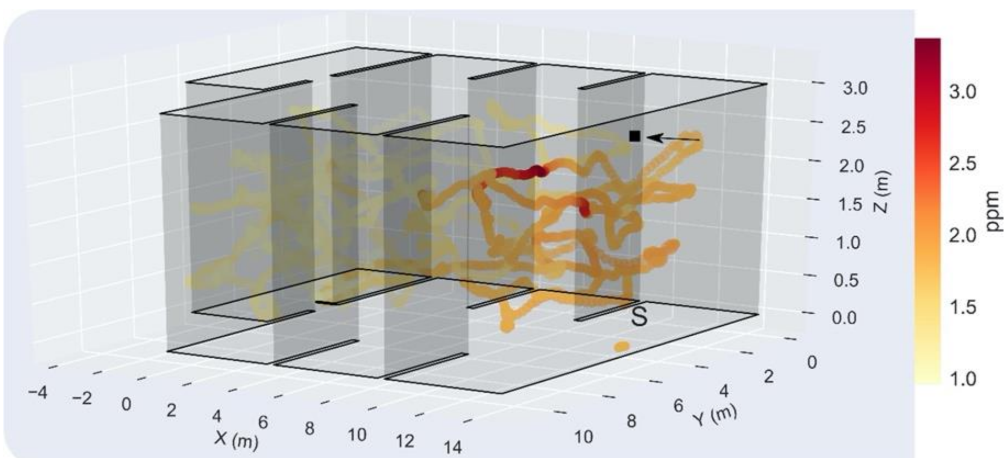


Figure 8.1: 3D simulation of pollution measurements collected using MAV (Burgués, et al., 2019)

The simulation programme used enabled the MAV to track gas pollution plumes in real-time. For comprehensive ventilation assessments, pollution analysis needs to account for the influence of airflow speed and ambient conditions on the behaviour of pollutants. Therefore, the simulation of measurements needs to not only provide an analysis of airborne pollution but also incorporate airflow behaviour, temperature, pressure, and humidity into the solution.

Some MAV systems for air quality assessments have used open source software to develop custom ground station applications to access the local database from a web-based display (Gu, et al., 2018;

Sørensen, et al., 2017). Software offered for visualizing MAV data superimposes geo-located measurements over a surface map that represents the sampled area. A surface analysis will not be adequate for underground mining environments that are confined within a rock structure. To perform a comprehensive analysis of ventilation conditions and display results in a manner that is easy to interpret requires specialized simulation software that can analyse the air behaviour within a 3D environment.

8.3 Computer-Aided Design (CAD)

In preparing the MAV mission, a realistic representation of the study area must be made available. Accurate 3D representations of structures can be created using computer-aided design (CAD) applications. CAD model development is a necessary part of preparing survey maps to be used for visualisation of environmental changes. A CAD model is required to be imported into the mission planning software to plan the flight path.

CAD modelling is used in many applications such as in animation, architecture, and engineering for creating design such as mine plans. According to Koutroumpas (2017) flight planning software provided for MAVs can import 3D models of the study environments where the MAVs will be sent to survey. The flight planning software is used to define parameters for the mission such as:

- Regional boundaries
- Flight height
- Start position
- Acceptable clearance from walls, etc.

Once a flight plan is configured, the settings may be encoded into commands to be executed automatically by the MAV during flight. A separate software is required to control the MAV manually and track the aircraft's position in real time. While the MAV's position can be visualized in real-time on a location tracking software, air quality measurements may be stored directly to a spatial database which requires them to be exported and analyzed on a different visualization tool. Data processing for ventilation analysis is discussed next.

8.4 Ventilation Data Processing

Additional preparation is required for processing the ventilation measurements collected using MAVs. Some of the processes that will be required for data preparation include exporting data from a SQL database and transferring it to an excel software to process the file by selecting variables of interest and removing any additional information that is unnecessary. Thereafter the comma separated variable (CSV) file needs to be exported from excel to a 3D visualization tool. To facilitate a reliable data exchange process for near real-time analysis will need an automated process to be implemented. The automated data exchange software needs to be compatible with the operational database structure and third-party software. The data exchange processes adopted for sharing information across large enterprises can enable automation of this process.

Techniques for automating data sharing between third-party software include email and CSV. Recently, application program interfaces (APIs) are used for data exchange however, programming skills are needed to implement the code (ServiceNow, 2019). An industrial data exchange software called the supervisory control and data acquisition (SCADA) system was used to automatically transfer data files from real-time sensor networks to a ventilation simulation software (Willemsen, et al., 2017). It would simplify the integration of ventilation sensing with MAVs in mining operations when existing tools can be incorporated into the implementation. Once the user has selected a data exchange process to suit their needs and cyber environment, a display interface is required to visualize the information.

8.5 Data Visualization

The most popular 3D visualization package is ArcGIS (Koutroumpas, 2017; Opiti, 2017) which uses surface interpolation algorithms to perform spatiotemporal analysis of environmental conditions by referencing XY coordinates. An analysis of ventilation in confined spaces can be simulated with computational fluid dynamics (CFD) programs, however, conventional tools tend to be slow and computationally demanding to be performed for real-time analysis.

Specialized software packages are preferred to perform visual analysis of air quality conditions specifically in an underground mining environment. Marx, et al. (2001) explained that ventilation simulation software applies principles used in the mining industry to calculate air pressure drop, changes in thermodynamic behaviour of air and concentrations of contaminant (gas and dust). Recent advances in mine ventilation simulation software makes it possible to update the model with real-time data sets.

8.5.1 Live Ventilation Simulation

Willemsen, et al. (2017) gave a detailed account of installing a monitoring system which enabled a ventilation simulation program to correlate data from real-time instruments in an underground platinum mine. A live ventilation simulation software program called Vuma 3D-live was developed by Bluhm and Burton Engineering (BBE) for this purpose. The model shown in the screen shot provided in figure 8.2 has been created by the researcher for DigiMine's mock tunnel using Vuma 3D-live.

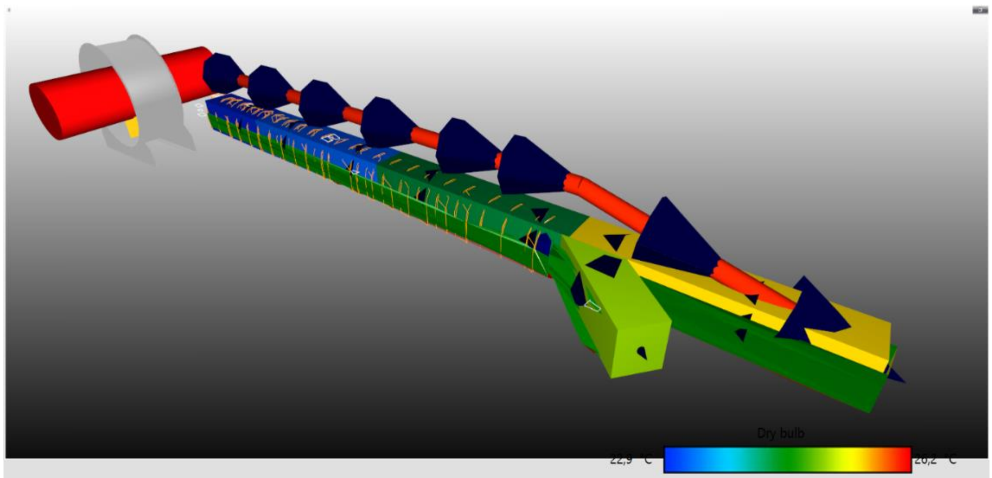


Figure 8.2: Vuma-live ventilation simulation model of DigiMine mock tunnel

Vuma 3D-live allows a high-accuracy survey map generated using LiDAR scanning to be imported into the simulation. Implementations of live ventilation simulation systems have only incorporated data collected from sensors fixed in single location of an underground mine as part of continuous monitoring system. The position of sensors in ventilation simulators is defined by the branch name in which a monitoring station is placed. The location of each monitoring station can be easily identified from the mine plan which is configured with the suitable inputs for the simulation. To enable ventilation simulators to analyze measurements captured in motion by a MAV, each value needs to be treated as a point-measurement with a known location that can be referenced to given point in a mine's branch. This would require geo-referencing to be matched between the database and simulator.

8.5.2 Geographic Referencing

Data sets shared with the ventilation simulator will need to specify the branch to be updated along with the measurements to input into a solution. The file extracted from the spatial database to update the ventilation simulation model will need a method to synchronize XY coordinates in the data file with a reference used in the simulation program. Using an identical mine design plan for flight mission planning and ventilation simulation will minimize the processing time required for geo-referencing. Once coordinates on the data file are matched to the reference used in the simulation model, built-in algorithms can then be activated to solve the results by predict conditions for the rest of the branches in the mine's network. Results may be continuously updated on a dedicated user interface.

Chapter 8 completes the discussion of functional requirements to manage information about a mine's ventilation conditions obtained using a MAV as a sampling platform. The next chapter will consider the steps that need to be taken to ensure that the MAV ventilation sensor cluster described in this research can be tested practically.

9 SYSTEM IMPLEMENTATION PLAN FOR DIGIMINE

DigiMine is identified as the facility where further research and development to advance and test functionalities of the MAV for safety surveillance in underground mining will be carried out (Cawood, 2016). DigiMine facilities are a simulated mining operation built in the Wits Chamber of Mines Building with a mock mine underground tunnel, a vertical shaft and a control room (University of the Witwatersrand, 2019). DigiMine lab has installed advanced software, sensors and real-time monitoring infrastructure for learning and applied research focused on the development of intelligent mine safety systems (Creamer, 2016).

The MHSC MAV project is well-aligned with DigiMine's mission to develop 21st century technologies that enable an underground mine to automatically observe, evaluate, and action safety measures in real-time without posing any danger to mine workers. The key advantage of the MAV is to provide a monitoring tool for hazardous environments that does not require personnel to be in proximity with danger.

This chapter documents the steps to be taken by DigiMine for implementing and testing the MAV ventilation monitoring system design synthesised in this research. There are currently MAV prototypes being tested at DigiMine, but the focus has been on map construction. The hardware, software and processes considered in this research are specifically focused on enabling the MAV to conduct ventilation survey in an underground mining environment. First the implementation plan needs to think about regulatory landscape to identify whether they present a risk to acceptability of the MAV for operating in mining.

9.1 Regulatory Environment

DigiMine is a laboratory simulated inside a building structure, therefore, flying the MAV during field tests does not require regulatory compliance. Definitions, acceptable uses, and dangers of remotely piloted aircraft systems (RPAS) are provided by (South African Civil Aviation Authority (SACAA) (South African Civil Aviation Authority, 2017). There is a requirement to register a RPAS under national civil regulations to be allowed to fly in an open atmosphere. The restriction does not apply for underground mining as they are in a closed space. In open spaces, the aircraft system is prohibited from flying near any property without permission.

SACAA's approval for pilot status for the aircraft is not necessary because the underground environment is beyond their jurisdiction and does not have any civil airspace activities. Furthermore, the MAV with its payload will weigh less than 7 kg and flown in a controlled environment from a remote mission controller. The key to avoiding SACAA's pilot approval is to optimize the navigation algorithm for confined underground mining environments. The navigation problem is being addressed through simultaneous localization and mapping (SLAM) algorithms which forms part of the work in the MAV project.

Contrast to coal mining, hard rock mines that have high levels of mechanisation and not restrictions in the type of equipment used in the mining process if it is safe. A careful hazard identification and risk assessment (HIRA) process is required before introducing any equipment or material into a mining environment in terms of section 11 of the MHSA (Safety in Mines Research Advisory Committee , 2009). Considerations of the HIRA process required for introducing an airborne robotic platform in an underground mining environment for the tasks of ventilation sampling are discussed in the following section.

9.2 Risk assessment

The most obvious hazard to the operation of MAVs in underground mines is the presence of other moving objects including people and equipment involved in the mining process. To minimise the chances of collision the MAV may be operated only during times when there is minimum activity such as during fire patrols. Immediately after a blast has been detonated, a MAV may be sent to validate whether all noxious fumes have cleared before personnel may be allowed to re-enter mine workings. The MAV may also be sent in an underground mine just before a shift is sent down the cage for conducting pre-entry assessments of the workings and declare their safety before personnel can be allowed to enter.

In the event of an emergency alarm, people must be withdrawn from underground and production stops. In such scenarios, the MAV offers a quick way of assessing the environmental status and locating the source of the problem. The MAV will be beneficial for inspecting a mine's safety compliance as the data collected is not subject to intentional or accidental human interference. In an emergency, the MAVs presents a safe and affordable method of air sampling in hazardous environments.

By operating the MAV during times of minimal traffic in an underground mine and focusing on mechanized operations which have larger openings, airborne robotic sampling may be a feasible solution for automating mobile ventilation assessments. The feasibility of the solution for operation in underground environments can only be validated through practical testing which is on-going at DigiMine.

9.3 Stage of MAV Development

The UAV project plan is shown on the innovation curve provided in figure 9.1 with a yellow star marking the position this study fits in the curve.

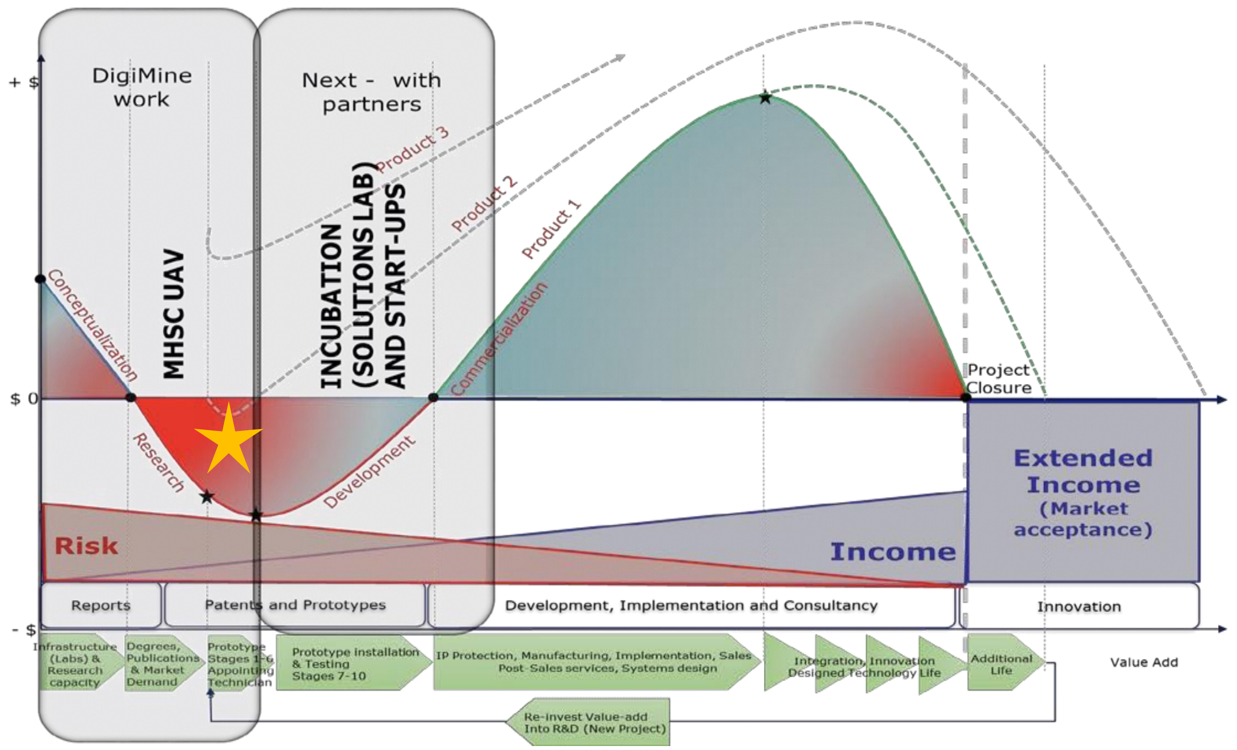


Figure 9.1: WMI's innovation curve for the MHSC UAV project (Cawood , 2019)

This study forms part of DigiMine's research work on the MHSC UAV project. The research is conducted by a post graduate student in pursuit of a Masters degree. The research aims to create publications and evaluating market demand for the planned product. Findings of this study will inform development of prototypes of the MAV system.

There are currently two MAVs being tested at DigiMine for various mine safety surveillance tasks. The next phase planned in the MAV project is construction and testing of new sensor arrays including the design developed in this research. Practical testing of the system's performance will be conducted in a laboratory environment. If tests are successful, then development may be further refined to prepare the prototype for further testing in more challenging environments.

Development of the MAV project brings together multi-disciplinary post-graduate skills to carry out applied research facilitated by WMI. All research work including the MAV development are aligned with themes outlined for DigiMine. The laboratory's research themes are specifically focused on applications in underground mine environments and categorised as follows:

- wireless communication systems;
- surveying, mapping and navigation;
- health, safety, and security; and;
- system integration for smart mining.

Following is a discussion on how the MAV project is aligned with each research themes. The consideration of the MAV according to the focus of DigiMine's research agenda will determine whether the laboratory is adequately equipped for practical testing to be carried out.

9.4 Wireless Communication

Geo-referenced ventilation measurements may be accessed using a wireless communication network that is connected to a local database server on a mine site. Wireless hardware is one of the technologies being tested at DigiMine for tracking the localisation of mobile assets operating in underground mines. This technology is important for controlling MAV navigation from a remote location, maintaining connectivity with the pilot and for transmitting information in real-time. Most wireless communication in underground mines use radio-based tags to establish a dynamic network between mobile and stationery nodes for reliable transmission (Global Mining Guideline Group , 2019). However, BLE is another alternative being tested.

Including a compatible radio communication module on the MAV's controller would enable the platform to connect with an existing wireless network already implemented in an underground mine. Using existing mine infrastructure can minimize the capital investment required and maximise the use of available resources. DigiMine has several wireless options that it can evaluate for integrating ventilation sensing with MAV for operation in underground mining.

Wireless communication signals are also required for localisation of the MAV. Localization is part of mapping which in robotics, informs navigation decisions. DigiMine's research agenda combines surveying, mapping, and navigation under the theme discussed next.

9.5 Surveying, Mapping and Navigation

Advanced mapping technologies are part of 21st century digital systems being tested at DigiMine. Mapping and navigation techniques are being incorporated into mining applications with the objective of putting distance between mine workers and typical risks encountered on a daily basis (University of the Witwatersrand, 2019). DigiMine is involved in the testing of mobile laser scanners including portable systems developed for quadcopters (Edwards, 2017). Current work on the MAV include development of an algorithm to optimize collision-avoidance in underground mining environments.

This research has discussed the relevance of maps of mine environments for mission planning and flight control of the MAV. On-going work at the laboratory under the theme of survey mapping and navigation will have a significant influence on the success of MAV's development. A key focus of the research at DigiMine is incorporating accurate maps into risk analysis models which get updated with real-time information. Risk analysis is focused on minimizing health and safety hazards in a mining environment. Research on health and safety at DigiMine is incorporated into a single theme with security. Work under the theme is discussed in the next section.

9.6 Health, Safety and Security

Data obtained from continuous environmental monitoring systems installed in DigiMine facilities is being used to perform spatiotemporal modelling of significant risk factors encountered in a typical mining environment (Opiti, 2017). Risk analysis has incorporated 3D modelling and spatial algorithms to predict and quantify the occurrence of life-threatening incidents in an underground mine. The outcome of the model was an interactive dashboard with the capability to display critical data in a control room display.

In the case of mine ventilation, DigiMine has developed a model to simulate ventilation conditions of its mock mine by correlating real-time measurements from monitoring instruments. The model requires a 3D survey model to animate conditions by accessing data sets from an automated data exchange software that manages the environmental network. This method is also adopted in underground hard rock mining. The simulation software presents the best method of managing real-time information for ventilation analysis.

Ventilation simulation software will have to be tested for managing measurements captured in motion if it is to be considered for the integration of MAV. The alternative is to visualize the data during MAV testing using on an open-source platform such as the MathWorks Simulink application with the intention of programming a new display interface at a later stage. Whichever alternative is opted for needs to simulate the information as a 3D structure. Following are considerations of the MAV under the theme of systems integration for smart mining at DigiMine.

9.7 Systems integration for Smart Mining

The integration of environmental sensors and spatial algorithms for analysing risk factors in underground mines can be performed using GIS software and/or specialized ventilation simulators which have both been tested at DigiMine. The integration of ventilation sensing with a MAV for safety surveillance in underground mines is facilitated by automated data exchange across a heterogeneous communication network to third party software used for risk analysis. Implementation of a RDMS and automated server extensions or APIs to manage data transfer to processing applications is the leading practice of integrating disparate third-party systems in large enterprises computer network. Systems integration for smart mining and the rest of DigiMine's research themes are applicable to the information management architecture discussed in the next section.

9.8 Information Management Architecture for the MAV

All the themes of DigiMine's research apply to the management of information gathered by the ventilation multi-sensor cluster to be carried by the MAV. A multi-disciplinary approach adopted for all research at DigiMine cannot be avoided in the development of this technology. A diagram depicting the information management architecture required for the systems is provided on figure 9.2.

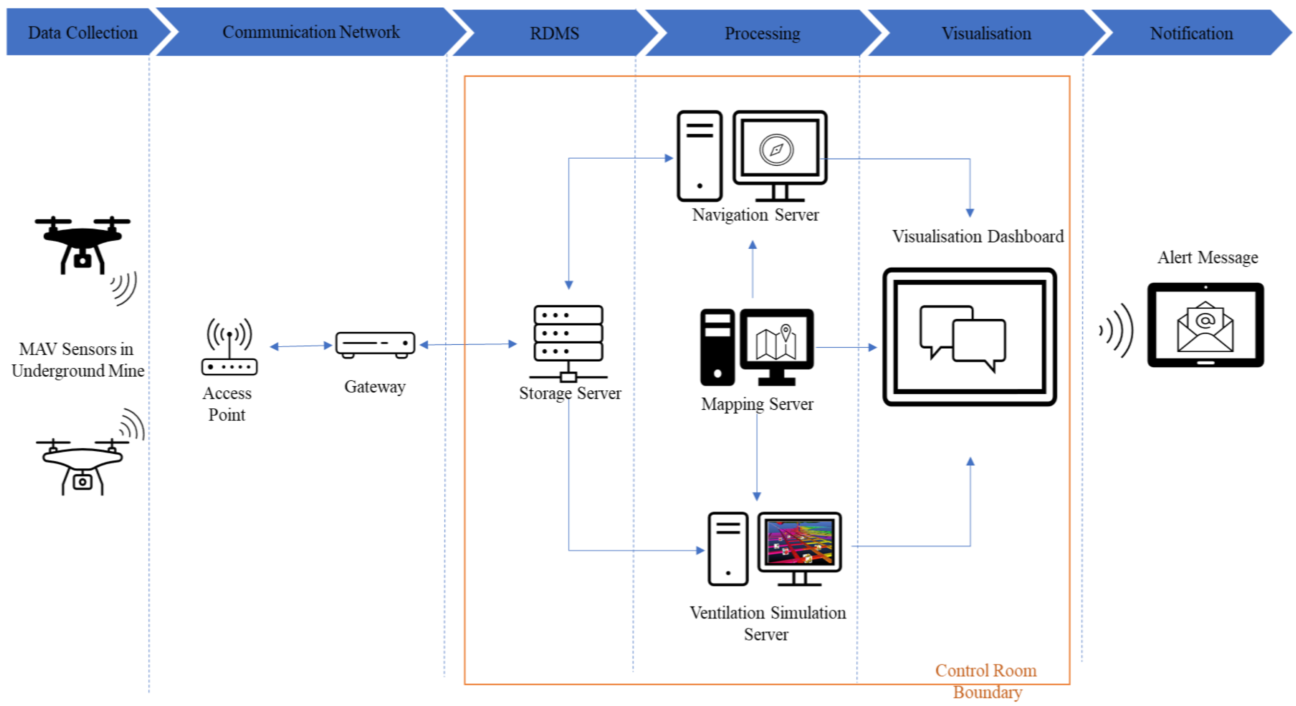


Figure 9.2: Information management architecture for MAV ventilation system

The control room would be the central point of control and data processing. Data from the MAV sensors in an underground mine can be streamed over radio frequency to the nearest access point. The access point sends the data over the mine's communication infrastructure via wired links to a network gateway. The gateway is connected to the local server which is responsible for storing the data. The local sever needs a relational database management system to store data and allow the navigation server and the ventilation simulation server to have access to the data.

A mapping server which host all survey maps of the underground mine is required in the control room. Processed maps should be accessed by the navigation server for path planning and controlling the MAV during missions. Underground mine maps should also be accessed by the ventilation simulation server for processing of geo-located ventilation data. Whenever an anomaly is detected by the navigation server and/or the ventilation simulation server, it should be displayed on the main visualization dashboard. When an anomaly is detected, an email message should also be sent to a decision maker to initiate an appropriate response to address the issue.

The information management architecture shown in figure 9.2 is deployable at DigiMine's facilities and well aligned to the research themes of the laboratory. The next step is to acquire the hardware identified in this research, construct and test the performance of a ventilation sensor systems integrated with a MAV as described in this research. This chapter leads to the conclusion of this dissertation.

10 CONCLUSION AND RECOMMENDATIONS

For as long as people work in underground mines, ventilation systems cannot be avoided. Ventilation supply is the most effective way of controlling airborne hazards and maintaining an environment in which mining equipment can operate with maximum efficiency. From as early as the 19th century, miners have looked for ways of identifying risk and warning each other when danger approached. These methods have not always been safe. However, techniques used in present day have been advanced through the discovery of new knowledge, enforcement of health and safety regulation and rapid developments in monitoring instruments.

Despite advances in ventilation monitoring instruments, their effectiveness is limited during practical applications particularly in the harsh mining environment. Now this can be changed by using MAVs controlled from a remote location. Hence this research was conducted to inform a design of a multi-sensor cluster for monitoring ventilation risks using MAV in underground mines.

This research investigated health and safety hazards managed through implementation of a ventilation system. Automatic monitoring systems installed to manage airborne hazards were analyzed to put together a functional design for this product. The research found that the development of MAV ventilation monitoring system had to focus on operation in mechanized hard rock mines which do not required equipment to be certified for intrinsic safety. Location of hazards was found to be an important consideration in identify targets for the MAV mission.

A SEP was used to analyze functional requirements and select components required for the system design. The investigation determined that portable sensors for gas concentrations and airflow speed embedded with wireless communication capability based on radio frequency (RF) or BLE would be suitable for the design. Although existing wireless communication only supports low-data rate transmission, it is suitable for text-based communication and monitoring environmental changes. Functional modules for which hardware was selected for this integration covered the following aspects:

- multiple sensors to measure changes in ventilation conditions;
- navigation and orientation control on-board the MAV;
- a wireless transmission network to deliver the data to surface; and
- software for flight control, data analysis and visualization

Low cost sensors identified for the design were based on instruments currently used in ventilation sampling. Single board circuits are found to be an important hardware to enable connectivity and control of ventilation sensors on-board the MAV from a remote computer station. MAVs can be easily integrated with different sensors, most commonly cameras. However, other portable hardware kits can be connected to an MAV's flight controller using expansion ports provided on the FCC. On-board hardware requirements for the MAV include a circuit board to interface with the ventilation sensor board, navigation system and communication module.

This research focused on sensors that are already accepted in the mine ventilation practice. Hence an ultra-sonic sensor that also measures humidity and temperature as well as three different gas sensors (CO, NO_2 and O_2) were found to be an adequate arrangement for assessing the status of ventilation conditions in mechanized hard rock mining. Measurements of pressure difference may be estimated using the MAV's IMU data and compared to reference instruments fixed in a mine. Sensor instrument, communication and control hardware selected for this design will enable the MAV to be useful for compliance analysis and assessment of dangerous occurrences such as fires in underground mining.

An information management architecture was proposed for the system. The architecture shows how data would stream from MAV's in underground mines to a display interface in a control room. Storage and processing resources should be in the control room which needs a visualization screen to display important information gathered by the MAV during missions. The information architecture proposed for the MAV system needs to send all events of anomalies to decision makers to initiate appropriate response measures.

10.1 Recommendations

Following are recommendations of this research:

- Hardware identified in this study will need to be acquired and assembled into a design of the multi-sensor cluster before being attached to a MAV platform.
- A new MAV platform may be required as current prototypes were developed for a different function.

- Several iterations of the design may be constructed for comparative performance analysis in a simulated environment. Once the design has been validated to be successful in a laboratory environment, it can be considered for testing in a mine site.
- Geo-referencing of measurements needs to be programmed on-board the MAV system to minimize processing time during post-analysis. Existing data management methods and visual analysis are found to be adequate for handling spatial measurements from the MAV and sharing information with third party software for processing.
- The development of optimized algorithms is crucial to drive acceptability and adoption of MAV for mine safety surveillance as well as to discover new functions for the technology. Algorithms are essential to optimize a stop-measure-move strategy of the MAV and maximize its flight endurance time. Algorithms embedded in the MAV software need to enable navigation control and ventilation analysis using disparate third-party software to maintain the integrity of the central database.
- Automation of data exchange is the most optimal way of managing data processing for real-time analysis of the measurements captured.

10.2 Limitations

More than one MAV platform is needed to surveil an entire mining operation. Furthermore, MAVs can only serve in periodic ventilation surveys to supplement fixed and portable ventilation monitoring instruments. The MAV would be required to maintain the recommended speed of 0.2 m/s while flying to ensure the highest accuracy of air velocity samples is maintained.

This development has a significant need for electronic and programming skills. Near-term application of the MAV technology is in risk assessment, although, there is potential to enable the MAV to add more value towards enhancing overall mine health and safety. At present, energy efficiency is the main limitation to the MAV's flight endurance, but this challenge can be overcome with improvements in battery technology. Based on developing trends, the technology is expected to improve current performance with smaller hardware.

In conclusion, this study has provided details of a design that may be used in the integration of ventilation sensing with a MAV being developed for safety surveillance in underground mining environments. The next phase is to construct the design for practical tests at DigiMine laboratory.

The only way to determine if the design proposed is a feasible solution is through practical testing of sensor performance which is planned to take place at DigiMine.

WMI is in a unique position to facilitate multi-disciplinary research using one-of-a-kind research facilities at DigiMine. The laboratory and Institute plan to continue to provide vital knowledge to accelerate the transfer of surface technologies into underground environments. This MAV project is one example of the impact of focused research in modernizing mining with digital technology that can enhance health and safety of mine personnel. If the MAV integration project is executed successfully, this development can result in commercial products that can become part of leading monitoring practices for underground mining in the future.

11 REFERENCES

Allen, G. et al., 2019. The development and trial of an unmanned aerial system for the measurement of methane flux from landfill and greenhouse gas emission hotspots. *Waste Management,* Volume 87, pp. 883-892 .

Anas , M., Haider, S. M. & Sharma, P., 2017. Gas Monitoring and Tesing in Underground Mines Using Wireless Technology. *International Journal of Engineering Research & Technology (IJERT),* 06(01), pp. 412 - 416.

Anderson, R. & De Souza, E., 2017. Heat Stress Management in Underground Mines. *International Journal of Mining Science and Technology* , 27(04), pp. 651 - 655.

Atlas Copco , 2014. *Underground Mining: A Global Review of Methods and Practices.* First ed. s.l.:Atlas Copco .

Bardswich, W. A., 1965. *Ventilation of deep mines in Northern Ontario,* Toronto: Proceedings of annual general meeting.

Bartholmai, M., Koeppe, E. & Neumann, P. P., 2014. Monitoring of Hazardous Scenarios using Multi-Sensor Devices and Sensor Data Fusion. *International Journal on Advances in Systems and Measurements,* 7(3 & 4), pp. 193 - 200.

Burgués, J., Hernández, V., Lilienthal, A. & Marco, S., 2019. Smelling Nano Aerial Vehicle for Gas Source Localization and Mapping. *Sensors* , 19(03), pp. 478 - 503.

Casten, T. P., 1995. *Air Velocity Measurements in Underground Mining,* Reno: University of Nevada.

Cawood , F. T., 2019. *Digital Systems for 21st Century ining* , Johannesburg: The Wits Mining Institute .

Cawood, F. T., 2016. *The Wits Mining Institute: DigiMine (Unmanned Aerial Vehicle) Business Plan*

Chwaleba, A., Olejnik, A., Rapacki, T. & Tuśnio, N., 2014. Analysis of Capability of Air Pollution Monitoring from an Unmanned Aircraft. *Aviation,* 18(1), pp. 13 -19.

Codecademy,2019.*Articles:Codecademy.*[Online]Availableat:https://www.codecademy.com/articles/what-is-rdbms-sql[Accessed 14 June 2019].

Conti, R. S., Chasko, L. L., Wiehagen, W. J. & Lazzara, C. P., 2005. *Fire Response Preparedness for Underground Mines* , Pittsburgh, PA: National Institute for Occupational Safety and Health (NOISH).

Creamer,M.,2016.*Mining:EngineeringNews.*[Online]Availableat:http://www.engineeringnews.co.za/article/new-wits-mining-institute-to-focus-on-innovation-2016-06-30[Accessed 24 October 2019].

CSIRO, 2017. *Mining Equipment, Technology and Services: A Roadmap for unlocking future growth opportunities for Australia,* CSIRO.

Deloitte, 2017. *The Fourth Industrial Revolution is here - Are you ready?,* London: Deloitte Insights.

Dräger, 2010. *DrägerSensors XXS,* Lübeck, Germany: Drägerwerk AG & Co. KGaA.

DrägerwerkAG&Co.,2019.*draeger.com.*[Online]Availableat:https://www.google.com/url?sa=i&rct=j&q=&esrc=s&source=images&cd=&ved=2ahUKEwjxjo6m9LlAhUuzoUKHfBoBjIQjB16BAgBEAM&url=https%3A%2F%2Fwww.draeger.com%2Fen-us_us%2FApplications%2FProductselector%2FPortable-Gas-Detection%2FMulti-Gas-Detectors&psig=AOvVaw1VdX[Accessed 01 August 2019].

Edwards, S., 2017. *Autonomous 3D Mapping and Surveillance of Mines with MAVs,* Johannesburg: University of the Witwatersrand.

Edwards, S., 2017. *Autonomous 3D Mapping and Surveillance of Mines with MAVs,* Johannesburg: University of the Witwatersrand.

Emesent,2019a.*Mining:Emesent.*[Online] Available at: https://emesent.io/industries/mining/ [Accessed 21 March 2019].

Emesent,2019b.*Emesent.io.*[Online] Available at: https://emesent.io/wp-content/uploads/2019/01/Emesent-Hovermap-Flyer-Mining-lr.pdf[Accessed 24 June 2019].

Encyclopaedia of Occupational Health & Safety , 2011. *Encyclopaedia of Occupational Health & Safety: Ventilation and Cooling in Underground Mines.* [Online] Available at: https://www.iloencyclopaedia.org/part-xi-36283/mining-andquarrying/item/604-ventilation-and-cooling-in-underground-mines[Accessed September 09 2018].

Extance, A., 2019. *velodynelilidar.com.* [Online] Available at: https://velodynelidar.com/newsroom/wp-content/uploads/2019/04/041019-Electro-Optics.pdf [Accessed 2019 June 27].

Fischione, C. et al., 2008. *Mining Ventilation Automation: Wireless Sensing, Communication Architecture and Advanced Services.* Berkeley, CA, HAL, pp. 44-51.

Freire, G. R. & Cota, R. F., 2017. *Capture of Images in Inaccessible Areas in an Underground mine using an Unmanned Aerial Vehicle,* Perth: Australian Centre for Geomatics.

Global Mining Guideline Group , 2019. *Underground Mine Communications Infrastructure Guidelines Part III: General Guidelines,* s.l.: Global Mining Guidelines Group (GMG).

Greig, J. D., 1989. Gases Encountered in Mines. In: J. Burrows, R. Hemp, W. Holding & R. M. Stroh, eds. *Environmental Engieering in South African Mines.* Johannesburg: Mine Ventilation Society of South Africa, pp. 714 - 740.

Griffin, K. R., 2013. *Utilization and Implementation of Atmospheric Monitroing Systems in United States Underground Coal Mines and Application of Risk Assessment,* Blacksburg, Virginia: Virginia Polytechnic Institute and State University.

Gu, Q., Michanowicz, D. R. & Jia, C., 2018. Developing a Modular Unmanned Aerial Vehicle (UAV) Platform for Air Pollution Profiling. *Sensors,* 18(12), pp. 43 - 63.

Holding, W., 1994. *Review of Practices for the Prevention, Detection and Control of Underground Fires in Coal Mines.* COL 031 ed. Pretoria: Safety in Mines Research Advisory Committee (SIMRAC).

IDC, 2016. *Energy Insights.* [Online] Available at: http://idccema.com/dwn/SF_152048/digital_transformation_in_mining.pdf [Accessed 23 July 2018].

Jo, B. W. & Khan, R. A., 2017. An Event Reporting and Early-Warning Safety System Based on the Internet of Things for Underground Coal Mines: A Case Study. *Applied Science* , 07(09), pp. 925 - 100.

Koutroumpas, A., 2017. *Use of UAV for 3D in visualization of air pollutants in urban areas,* Chania, Greece: Technical University of Crete.

Krüll, W. & Willms, I., 2012. Early Forest Fire Detection and Verification using Optical Smoke, Gas and Microwave Sensors. *Procedia Engineering* , Volume 45, pp. 584 - 594 .

Lawrence, D. A. & Balsley, B. B., 2013. High-Resolution Atmospheric Sensing of Multiple Atmospheric Variables Using the DataHawk Small Airborne Measurement System. *Journal of Atmospheric and Oceanic Technology,* 30(10), pp. 2352 -.

Lexico,2018.*Ventilation.*[Online] Available at: https://www.lexico.com/en/definition/ventilation [Accessed 24 June 2018].

Li, B., Zhao, K., Saydam, S., Rizos, C., Wang, Q., 2016. Third Generation Position System for Underground Mine Environments: An Update on Progress. [Online] Available at: http://www.ignss2016.unsw.edu.au/sites/ignss2016/files/u80/Papers/non-reviewed/IGNSS2016_paper_28.pdf

Libelium, 2019. *Connecting Sensors to the Cloud.* [Online] Availableat:https://whizgig4.rssing.com/chan-3949116/all_p2.html[Accessed 13 September 2019].

McPherson, M. J., 1993. *Subsurface Ventilation and Environmental Engineering.* Volume 1 ed. California: Springer.

Meier, L., Tanskanen, P., Fraundorfer, F. & Pollefeys, M., 2011. The PixHawk Open-Source Computer Vision Framework for MAVs. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* XXXVIII(01), pp. 13 - 18.

Mine Health and Safety Council , 2018. *Mine Health and Safety Act, (Act No. 29 of 1996) and Regulations,* Pretoria: Department of Mineral Resources.

Mine Health and Safety Inspectorate , 2017a. *Guideline for the Compilation of a Mandatory Code of Practice for the Prevention of Fires at Mines,* Pretoria: Department of Mineral Resources.

Mine Health and Safety Inspectorate , 2017. *Guideline for the Compilation of a Mandatory Code of Practice for the Prevention of Fires at Mines* , Pretoria: Department of Mineral Resources

Minerals Council South Africa, 2018. *Facts and Figures Pocketbook* , Johannesburg : Minerals Council South Africa.

Minhas, U. I. et al., 2017. A WSN for Monitoring and Event Reporting in Underground Mine Environments. *IEEE Systems Journal* , pp. 1937-9234.

Mining Review, 2019a. *Feature Analysis: 7 Common Risks to Protect Yourself Against.* [Online] Available at: https://www.miningreview.com/features-analysis/mining-health-safety-7-common-risks-to-protect-yourself-against/
[Accessed 22 May 2019].

Miningmx, 2019. *Drones: The Next Frontier in Mine Safety.* [Online] Available at: https://www.miningmx.com/special-reports/mining-indaba/mining-indaba-2019/35899-drones-the-next-frontier-in-mine-safety/
[Accessed 24 July 2019].

Mitchell, J. & Marshall, J., 2017. *Design of a Novel Auto-Rotating UAV Platform for Undergound Mine.* Denver, Colorado, USA , Society of Mining Metallurgy and Exploration.

Moridi, M. A., Kawamura, Y., Sharifzadeh, M. & Chanda, E. K., 2015. *Underground Spaces Communication and Monitoring Systems integrated ZigBee and GIS.* Lacroma Valamar Congress Center, Dubrovnik, Croatia, ResearchGate .

NIOSH, 2012. *Centre for Disease Control and Prevention.* [Online] Availableat:https://www.cdc.gov/niosh/mining/topics/fires.html[Accessed 30 June 2018].

NOISH, 2014. *Mine Communication and Tracking Glossary: NOISH.* [Online] Availableat:https://www.cdc.gov/niosh/mining/content/commglossary.html#veryhighfrequency(VHF)system[Accessed 24 April 2019].

Opiti, C. O., 2017. *A Spatio-Temporal Modelling and Analysis of Digital Sensor Data for Underground Mine Health and Safety* , Johannesburg : University of the Witwatersrand .

Phakathi, S., 2018. *The Management of Occupational Health and Safety in the South African Mining Industry: The Role of the Minerals Council.* s.l., Minerals Council South Africa.

Pollock, C., 2016. The Canary in the Coal Mine. *Journal of Avian Medicine and Surgery,* 30(4), p. 386–391.

Pothuganti, K. & Chitneni, A., 2014. A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi. *Advance in Electronic and Electric Engineering.,* 4(6), pp. 655-662.

Qandour, A. & Ahmad, E., 2016. *Applied application of sensor networks in underground mines,* Perth, Australia: ResearchGate .

Qin, C., 2017. *Seamless Underground/outdoor Positioning System Based on Beidou andWireless Signals*, Johannesburg : Wits Mining Institute, University of the Witwatersrand .

Rautenbach, S. et al., 2013. *Manual Two: Enforcing the Mine Health and Act and Regulatios: Conducting Investigations and Inquries in terms of the Mine Health and Safety Act.* Johannesburg, South africa: Centre for Sustainability in Mining & Industry .

Red Gate Software Ltd, 2015. *Introduction to SQL Server Spatial: Red Gate Software Ltd.* [Online] Available at: https://www.red-gate.com/simple-talk/sql/t-sql-programming/introduction-to-sql-server-spatial-data/
[Accessed 17 March 2019].

Reuder, J. et al., 2008. The Small Unmanned Meteorological Observer SUMO: A new tool for atmospheric boundary layer research. *Meteorologische Zeitschrift,* 2(141-147), p. 2009.

Richard , J., Harris, M. L. & Rowland III, J. H., 2007. *Works: CDC Noish Mining.* Nashville, Tennessee, Proceedings of the 33rd Annual Conference on Explosives and Blasting Technique.

Safety in Mines Research Advisory Committee , 2009. *Practical Guide To Risk Assessment Process.*[Online]Available at: https://www.sanire.co.za/sanire-documents/archive/technical-papers-archive/154-practical-guide-to-the-risk-assessment-process/file[Accessed 22 June 2018].

Sathyan, T., Humphrey, D. & Hedley, M., 2011. WASP: A System and Algorithms for Accurate Radio Localization Using Low-Cost Hardware. *IEEE Transactions on Systems Man and Cybernetics Part C (Applications and Reviews),* 41(02), pp. 211 - 222.

SchauenburgSystems,2017. [Online] Available at: http://schauenburg.co.za/wp-content/uploads/2017/03/Schauenburg-MIMACS-Brochure-2017.pdf[Accessed 02 April 2018].

Schmitz, B. & Drummond, J. A., 1989. Measurements of Airflow. In: J. Burrows, R. Hemp, W. Holding & R. M. Stroh, eds. *Environmental Engineering in South African Mines.* Johannesburg, South Africa: Mine Venstilation Society of South Africa, pp. 49 - 81.

Schuyler, T. J. & Guzman, M. I., 2017. Unmanned Aerial Systems for Monitoring Trace Tropospheric Gases. *Atmosphere,* Volume 8, pp. 206 - 222.

Schwartz,E.,2014.*NetHope.*[Online]Availableat:https://solutionscenter.nethope.org/resources/uavs-in-humanitarian-response-the-advantages-of-open-source-development [Accessed 22 September 2019].

ServiceNow, 2019. *ServiceNow: Intergration with third-party applications and data sources.* [Online] Available at: https://docs.servicenow.com/bundle/newyork-platform-administration/page/integrate/concept/c_IntegrateWThirdPartyAppsDataSrces.html [Accessed 08 August 2019].

Sørensen, L. Y., Jacobsen, L. T. & Hansen, J. P., 2017. Low Cost and Flexible UAV Deployment of Sensors. *Seensors* , Volume 17, pp. 154 - 167.

Sørensen, L. Y., Jacobsen, L. T. & Hansen, J. P., 2017. Low Cost and Flexible UAV Deployment of Sensors. *Sensors,* Volume 17, pp. 154-167.

South African Civil Aviation Authority , 2017. *South African Civil Aviation Authority: Remotely PilotedAIrcraftSystems.*[Online]Availableat:http://www.caa.co.za/Pages/RPAS/Remotely%20Piloted%20Aircraft%20Systems.aspx [Accessed 13 November 2018].

South African Government , 2019. *South African Government : Media Statements.* [Online] Available at: https://www.gov.za/speeches/mineral-resources-releases-2018-mine-health-and-safety-statistics-1-mar-2019-0000 [Accessed 22 March 2019].

Spencer, K. C., Walters, D. M., Page, T. T. & du Plessis, A. G., 2000. *The Management of Inrushes, Fires, Explosions, and other Emergencies* , s.l.: Safety in Mining Research Advisory Committe (SIMRAC).

Stewart, J., 1989. Fundamentals of Human Stress. In: J. Burrows, R. Hemp , W. Holding & R. M. Stroh, eds. *Environmental Engineering in South African Mines.* Johannesburg: The Mine Ventilation Society of South Africa, pp. 495 - 533.

System Management College, 2001. *Systems Engineering Fundamentals.* Fort Belvoir, Viginia: Department of Defense.

Szulczyński, B. & Gębicki , J., 2017. Currently Commercially Available Chemical Sensors Employed for Detection of Volatile Organic Compounds in Outdoor and Indoor Air. *Environments,* 04(10), pp. 21 - 36.

TestoSE&Co,2019.*testo.com*.[Online]Availableat:https://staticint.testo.com/media/14/25/8a58715128ab/testo-Air-velocity-IAQ-probes-with-fixed-cable-Instruction-Manual.pdf[Accessed 01 August 2019].

TheRamsHorn,2010.*Minerslamps.*[Online]Availableat:https://www.ramshornstudio.com/miners_lamps.htm[Accessed 04 November 2018].

Tiantian, J. & Zhanyong, Y., 2011. Research on Mine Safety Monitoring System Based On WSN. *Procedia Engineering* , Volume 26, p. 2146 – 2151.

Timko, R. J., 1900. *Methods to Determine the Status of Mine Atmospheres - An Overview.* [Online] Available at: https://www.cdc.gov/niosh/mining/UserFiles/works/pdfs/mtdts.pdf [Accessed 14 September 2018].

Toppr,2018.*ComponentsofAir*.[Online] Available at: https://www.toppr.com/guides/science/air-around-us/components-of-air/[Accessed 09 December 2018].

UAV Factory LLC, 2019. *Combined Pitot-Static Tube Datasheet 2.0,* New York: Irvington.

University of the Witwatersrand, 2017. *DigiMine.* [Online] Availableat:https://www.wits.ac.za/wmi/digimine/[Accessed 06 June 2018].

University of the Witwatersrand, 2019. *General news: University of the Witwatersrand.* [Online] Available at: https://www.wits.ac.za/news/latest-news/research-news/2019/2019-04/digimine-strikes-gold.html
[Accessed 22 October 2019].

Unmanned System Technology , 2019. *TriSonica Mini 3D Ultrasonic Anemometer: Unmanned SystemTechnology*.[Online]Availableat:https://www.unmannedsystemtechnology.com/company/anemoment/[Accessed 25 July 2019].

Unsted, A. D., 2001. Chapter 4: Airborne Pollutants. In: R. Guild, R. I. Ehrlich, J. R. Johnston & M. H. Ross, eds. *A Handbook on Occupational health Practice in the South African Mining Industry.* Johannesburg: The Safety in Mines Research Advisory Committee (SIMRAC), pp. 85 - 118.

Unwin, I. D., 2007. *The Measurement of Air Flow in British Coal Mines: A Historical Review*. [Online]Availableat:https://pdfs.semanticscholar.org/8b2f/070984e0e566f04406704bd13405c426c804.pdf[Accessed 20 January 2019].

van den Kroonenberg, A. & Martin, T., 2008. Measuring the Wind Vector Using the Autonomous Mini Aerial Vehicle M2AV. *Journal of Atmospheric and Oceanic Technology,* 25(11), pp. 1969 - 1981.

Villa , T. F. et al., 2016. An Overview of Small Unmanned Aerial Vehicles for Air Quality Measurements: Present Applications and Future Prospectives. *Sensors,* 16(07), p. 1072.

Villa, T. F. et al., 2016. An Overview of Small Unmanned Aerial Vehicles for Air Quality Measurements: Present Applications and Future Prospectives. *Sensors,* 16(07), p. 1072.

Willemsen, T. et al., 2017. *Installing a Live Ventilation Network Monitoring System to Improve Safety.* Johannesburg, South Africa , BBECosulting .

Wired,2010.*Gear:Wired.*[Online] Available at: https://www.wired.com/2010/09/wireless-explainer/[Accessed 13 August 2016].

Witrant, E. et al., 2008. *Mining ventilation control: A new industrial case for wireless automation.* Washinigton, DC, United States., HAL.

Witte, B. M., Singler, R. F. & Bailey, S. C., 2017. Development of an Unmanned Aerial Vehicle for the Measurement of Turbulence in the Atmospheric Boundary Layer. *Atmosphere,* Volume 08, pp. 195 - 210.

Witte, B. M., Smith, S. W. & Bailey, S. C., 2016. *Measurement of Atmospheric Surface Layer Turbulence using Unmanned Aerial Vehicles,* University of Kentucky Lexington, KY, USA: College of Engineering .

Yuan, C., Liu, Z. & Zhang, Y., 2015. A Survey on Technologies for Automatic Forest Fire Monitoring, Detection and Fighting Using UAVs and Remote Sensing Techniques. *Canadian Journal of Forest Research ,* Volume 10, p. 1139.

Yungaicela-Naula, N. M., Garza-Castañón, L. E. & Minchala, I., 2017. *Design and Implementation of an UAV-based Platform for Air Pollution Monitoring and Source Identification.* Monterrey, Nuevo León, Research Gate.

Yunusa, Z., Hamidon, M. N., Kaiser, A. & Awang, Z., 2014. Gas Sensor Review. *Sensors & Transducers,* 168(04), pp. 60 - 75.

Zhang, Y., Yang, W., Han, D. & Kim, Y., 2014. An Integrated Environment Monitoring System for Underground Coal Mines - Wireless Sensor Network Subsystem with Multi-Parameter Monitoring. *Sensors* , Volume 14, pp. 13149-13170.