

School of Mining Engineering



UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

**THE INCORPORATION OF UNMANNED AERIAL VEHICLES IN A
SLOPE STABILITY MONITORING SYSTEM: A RÖSSING URANIUM
MINE CASE STUDY**

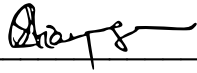
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A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science.

Johannesburg, 2023

DECLARATION

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“Just type Love.”

Erastus Nashima

ABSTRACT

Slope stability monitoring is a safety critical input in the Slope and Dump Management Plan (SDMP) at Rössing Uranium Limited (RUL) mine. The SDMP was adopted to satisfy the requirements of the D3 standard – management of slope geotechnical hazard at the operation. Through this standard, RUL aims to provide an injury-free and safe working environment for the operation. This is achieved by proactive identification and management of slope risks and instabilities onsite.

This research is a case study of the incorporation of unmanned aerial vehicle (UAV) technology into the slope stability monitoring system (SSM) at RUL, towards conformance to the D3 standard. The study highlights the safety benefits gained by removing personnel from hazardous areas and substituting them with UAVs. The utilisation of UAV data in geotechnical processes such as; the final wall assessment, crack detection and monitoring, as well as dump advancement rate calculations are also discussed.

The study further investigated the use of UAVs for SSM prism inspections and proposes the incorporation of UAVs into the trigger action response plan (TARP). A concept of UAV modification for prism-cleaning operations has been developed through this research, to alleviate the challenges of prism loss in inaccessible areas due to dust accumulation on the prism surfaces.

Key words: UAV, SSM, prism-cleaning, prism-inspections, TARP.

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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviation	Description
3D	Three-Dimensional
AVDS	Aero Vision Drone Services
BIPA	Business Intellectual Property Association
BRMP	Business Resilience Management Plan
EDM	Electronic Distance Measurement
GCP	Ground Control Point
GeoMoS	Geodetic Monitoring System
GPS	Global Positioning System
HSSEC	Health, Safety, Security and Communities
LoMe	Life of Mine Extension
m	Metre
NCAA	Namibian Civil Aviation Authority
PPK	Post Processing Kinematics
RPA	Remotely Piloted Aircraft
RTS	Robotic Total Station
RUL	Rössing Uranium Limited
SDMP	Slope and Dumps Management Plan
T4D	Trimble 4-Dimensional Monitoring System
TARP	Trigger Action Response Plan
UAV	Unmanned Aerial Vehicles

Symbol	Description	Units
%	A ratio expressed as a fraction of 100	Percentage

1 INTRODUCTION

Slope stability monitoring (SSM) is a process of measuring ground movement to detect slope instability before a slope failure. SSM is a safety-critical system and a crucial input in mitigating operational and safety risks. The key objective of the SSM system is to ensure the safety of mine personnel and equipment, by maintaining safe operating conditions (Read & Stacey, 2009).

An effective SSM system must be reliable, robust and defensible, continuously acting as a verification cycle and confirming the validity of the SSM design. The feedback loops within the cycle are crucial in enabling the user to identify areas of improvement in the design and calibrate the model as more data is acquired (Stacey, 2007).

A comprehensive SSM system enables the mine management to adopt mining strategies for maximising ore extraction with a reduction in waste stripping, by steepening the slopes, that is, slope optimisation. This is done with the confidence that any slope instabilities will be well managed and an appropriate warning is given timeously, to evacuate personnel and equipment to safety, and aid in risk mitigation (Mphathiwa, 2012).

Prism monitoring forms an integral part of SSM, comprising Robotic Total Stations (RTS) and reflective prisms (Read & Stacey, 2009). An RTS is a Total Station with remote operation capabilities. RTS provides increased field productivity and efficiency in comparison to the traditional Total Stations. This is due to their ability to perform increased calculations and inspections with minimal manpower and in less time than a traditional Total Station (Crumal, 2019).

The RTS is used for surveying and measuring three-dimensional (3D) coordinates of reflective prisms installed along the slopes and ramps being monitored (Read & Stacey, 2009). Thomas (2011) listed the factors contributing to the optimal functionality of a prism monitoring system as:

- The RTS's suitability for the required accuracy specifications;
- Regular calibration of the RTS;
- The stability of the control beacons;
- The design of the survey control network, enabling a clear line of sight between the RTS and monitoring prisms, and;
- Maintenance and cleaning of the monitoring prisms.

Of the factors mentioned, the main focus of this research is the maintenance and cleaning of the monitoring prism. Maintenance and cleaning of prisms in open pit mines is an ongoing challenge mainly due to:

- The amount of dust generated by various mining activities settling on the prisms, hence affecting the reflectivity of the prism to the RTS prism recognition and measurement signal;
- The loss of access to prisms installed on upper benches as the mining progresses as per the open pit design; and
- Prisms located close to a highwall may compromise the safety of personnel attempting to clean prisms.

Trimble 4-Dimensional (T4D) control system is used at Rössing Uranium Limited (RUL) for the prism monitoring system. The mine survey team is the custodian of the T4D system and bears responsibility for the installation and maintenance of the monitoring equipment and hardware. This includes the installation and maintenance of the prisms. The mine survey team is also responsible for the quality control and quality assurance of the prism monitoring data acquired, that is, data accuracy and integrity.

Figure 1-1 shows a monitoring prism installed close to an open edge (highwall), exposing mine survey personnel to a fall from height risk if they physically approach the prism for cleaning or inspection. Thus, rendering the prism unsafe to access by mine survey personnel for cleaning and maintenance.



Figure 1-1: A prism installed at an open edge (highwall) (RUL Internal Data, 2022).

The inability of the RTS to locate the monitoring prism may result in data gaps and blind spots in SSM data. Vital indications of slope movement may go unnoticed or undetected, resulting in unanticipated slope failure.

The safety and economic impacts of an unpredicted or poorly managed slope failure may be catastrophic for the mine employees and the operation. The potential consequences may be fatalities, injuries, damage to equipment and infrastructure, company reputational damage, as well as ore sterilisation (University of the Witwatersrand, 2019).

The size and location of the failure will determine the rehabilitation cost. If a considerable amount of failure material has buried areas of high-grade ore or has obstructed open pit access, the operation may be forced into premature mine closure.

In a bid for continuous process improvement, RUL employed the services of unmanned aerial vehicles (UAV) in 2019. The operation has since observed seamless incorporation of UAV data into mining processes on-site such as volumetric surveys, stockpiles, and waste dump management, as well as SSM systems. The resultant process efficiency is attributed to the technology's ability to safely gather multitudes of datasets timeously, and in varying formats for absorption into differing processes.

This research focused on the incorporation of UAV technology into the SSM processes at RUL. The research highlighted the safety benefits acquired by substituting personnel with UAVs in hazardous areas and identified opportunities for further process improvement and safety.

1.1 Research Background and Context

The case study is based on RUL, an open pit mine situated on a low-grade uranium deposit in the Namib Desert in Erongo Region, Namibia as shown in Figure 1-2.



Figure 1-2: The location of Rössing Uranium Mine in Namibia (Google Maps, 2023).

The company, through its health, safety, security, environment, and communities (HSSEC) policy, and slope and dump management plan (SDMP), aims to uphold the commitment to zero harm and corporate citizenship. The zero-harm strategy aims to mitigate incidents and create a work environment that ensures every employee returns home safely.

Seeking continuous sustainable improvements in HSSEC performance (China National Nuclear Corporation Rössing Uranium, 2020), and the management of slope geotechnical hazards at the operation (RUL, 2020a) are some of the approaches to achieving these goals.

One of the safety management systems at RUL is critical risk management (CRM), which is a fatality prevention tool. There are 18 critical risks identified and managed through the CRM process at RUL, including slope failure, (which is inclusive of rockfalls and slope failures). Slope failure's high-risk rating is derived from a risk matrix assessment, which considers the likelihood of the occurrence against the severity of the consequences (RUL, 2020a).

The general slope failure zones at RUL are in the weak amphibole schist formations, while the rockfall risks across the open pit are increased by weak zones within competent rock formations. These weak zones may be due to weathering, fracturing and geotechnical features such as faults. The engineering controls in place to manage the slope failure risk is a robust SSM system, which includes a prism monitoring network.

The maintenance of the SSM system requires the installation of new slope monitoring prisms on the open pit benches as mining progresses, and ideally, the cleaning of all the prisms in the open pit. The loss of access to the upper open pit benches as mining progresses creates a challenge for effective cleaning, inspection and maintenance of prisms. In most cases, the cleaning of the few prisms left that are accessible is unsafe as it exposes mine survey personnel to highwalls and potential rock falls.

A near-miss incident occurred at RUL in the first quarter of 2020, where a minor rockfall occurred in the vicinity of a team that was installing prisms. No injuries were recorded, however, it highlighted the potential risk that mine personnel installing and/or cleaning prisms are exposed to.

Figure 1-3 shows an image of a damaged prism (SMP501) from a prism-focused inspection UAV flight. This damage may have been caused by fly-rock from a blast.



Figure 1-3: A prism-focused UAV inspection showing a damaged prism (RUL Internal Data, 2022).

1.2 Problem Statement

The loss of access to certain in-pit areas at RUL such as the upper benches or waste dumps has created various challenges to the SSM system. The loss of access is due to either the open pit design, inability to approach the high wall or waste dump due to poor high wall conditions and/or unsafe slopes. These challenges are:

- Lack of physical inspections of benches or waste dumps for crack detection and/or monitoring,
- Uncertainty of prism status when it is no longer being measured; and
- The inability to clean and inspect prisms installed on inaccessible benches.

The loss of access to some prisms makes it impractical to perform regular maintenance of the prisms as required, such as replacing, cleaning and inspecting the prisms, thus potentially losing them from the slope monitoring network. The lack of a regular prism-cleaning and inspection regime reduces the reliability, effectiveness and defensibility of the slope monitoring data, as dust accumulations on prisms affect the ability of the RTS to track the prism (Jooste & Cawood, 2006). This undermines the confidence in the data provided and threatens the reliability and defensibility of the monitoring data and the SSM system at RUL. The resultant heightened safety risk may reduce the system's ability to provide early detection and timeous warning of instabilities and slope failures.

Physical visual inspections are crucial for an ongoing safe operation of dumps on operations and are a key input into the successful management of a monitoring program. Limited physical inspections due to safety concerns prevent the relevant mine personnel from assessing slope faces for the early detection of instabilities (Read & Stacey, 2009).

1.3 Justification for Research

A prism (in an open pit mine) is a sensor installed in a discrete position on a slope face or bench, that is positioned strategically to monitor geological/geotechnical elements of its host rock (Read & Stacey, 2009). Prism monitoring is currently the only slope monitoring tool that measures the 3D vector movement of a slope and it is therefore imperative to ensure the optimum performance of the system. Prism availability is one of the crucial inputs into the performance of the SSM system (Read & Stacey, 2009).

The key motivation for this research is to investigate the potential safety value to be gained by removing mine personnel from working in slope-hazardous areas and deploying UAVs. Additionally, to improve data integrity and the overall effectiveness of the SSM system with prisms that can be monitored. This will be achieved by the following:

- Integration of UAV data into geotechnical processes;
- Regular prism inspections using UAVs;
- Development of the concept of modifying a UAV to use as a tool for prism cleaning; and
- A proposal to incorporate UAVs into the trigger action response plan (TARP).

This research has also investigated the benefits of utilising UAV technology in identifying, monitoring and managing slope hazards at RUL. Recent studies by Lee and Choi (2016) and Javad *et al.* (2020), clearly outline the benefits of adopting UAV technology in various mining operations, particularly for safety through risk mitigation. The use of UAV technology to capture and provide high-resolution video footage and images from multiple views in areas that are no longer accessible eliminates the need for mine personnel to enter unsafe areas (Airobotics, 2020). Figure 1-4 shows the monitoring Prism 229 fully covered by dust accumulation on the prism.



Figure 1-4: A monitoring Prism 229 covered with dust.

A properly maintained SSM system provides full monitoring coverage and reliable data for movement trend analysis by frequently providing various datasets, at scheduled intervals, over a long period of time. The data is available for current use, building a historical archive for analysing trends, as well as for back analysis when required.

UAV technology has the potential of bridging the gaps identified in the prism monitoring system by providing information on inaccessible prisms and areas of interest. This is achieved through prism inspection flights, providing images and videos of the prisms in areas that mine personnel cannot access.

Additionally, UAVs have the potential of providing a prism-cleaning solution, by modifying or adopting a UAV for use in prism-cleaning projects. This solution will potentially strike a balance between safety, cost and practicality, due to the UAV's ability to access and manoeuvre in areas not accessible or safe for mine personnel access.

1.4 Research Objectives

The main aim of this research was to investigate and evaluate the potential value, primarily in safety, that has been gained by incorporating UAV technology in the SSM system at RUL. The research further identified areas of opportunity for further utilisation of UAVs in the SSM workflow. The research also highlighted the anticipated value addition in the form of improved safety of mine personnel, while maximising economic gain by:

- Providing the guidance required in selecting a prism-cleaning solution that is most practical and better combine cost, safety and effectiveness;
- Increasing confidence in the monitoring data, which when coupled with the necessary SSM controls can improve slope optimisation;
- Incorporating UAVs in the TARP, to provide data and surveillance, hence accelerating the decision-making for remedial action; and
- Developing a concept of modifying a UAV to be used for prism-cleaning projects.

The findings of the research will be shared with the mining community globally, contributing towards the foundation for future research in the modification of UAVs for prism cleaning. The knowledge shared aims to improve safety beyond RUL, by removing mine personnel from slope stability hazards as far as possible while maximising the effectiveness of the SSM systems. The report in general will be an invaluable addition to the body of knowledge in the field of SSM and UAV technology for future research.

1.5 Research Methods

The research approach for this study is based on a hybrid method and has included both qualitative and quantitative research methods. A combination of empirical and developmental study methods was employed to tailor a procedure for UAV modification for prism cleaning projects. A case study approach was taken for evaluating the use of UAVs in geotechnical processes. The results of the prism-cleaning experimental component will feed into the development of the theoretical concept model. An in-depth discussion of the research methodology adopted is discussed in Chapter 3 of this report.

1.5.1 Qualitative Research

The development of a theoretical model concept for modification of UAVs for prism cleaning, as well as the desktop analysis of the current prism-cleaning methods. A desktop study of UAVs that are currently on the market was conducted, by looking at various manufacturer websites for UAV specifications and information.

1.5.2 Quantitative Research

Part of the research data for prism inspections and the geotechnical applications of UAVs in SSM was collected through field research, as well as experience and observations. Experimental work, using a pressure washer to clean a prism was done to assess key inputs for the prism-cleaning concept.

The initial attempt for sourcing the pressure washer was done through price comparison from different suppliers, however, the funding constraints delayed the purchase of the unit. A site-wide search of any mine section that may have a washer was undertaken, and eventually, a pressure washer was found and borrowed from the mine's transport department for use in the experiment.

1.6 Sources of Data

RUL will be the main source of data for the research, with UAV data obtained from the site's UAV service provider, as well as data from the company's policies and geotechnical and mine survey experts. The additional sources of data for desktop studies will be acquired from reputable websites, reports, as well as journals.

1.7 Research Validation

The publications used for the research are peer-reviewed. Non-peer-reviewed sources such as the Namibian Civil Aviation Authority, (2020), and China National Nuclear Corporation Rössing Uranium (CNNC) Rössing Uranium (2020) are reliable websites and sources of relevant information. The research data will be in cloud-based storage and backed up on an external hard drive.

1.8 Structure of the Research Report

This report consists of six chapters where Chapter 1 is the introduction and covers the background of the research topic, the problem statement, the justification for the research and the research objectives.

The research methodologies followed by this study and the sources of the information are introduced. The research validation criteria, as well as the contribution to knowledge, are discussed.

Chapter 2 reviews the literature in the fields relevant to this research, starting with the introduction of the fields surveyed, the key concepts, theories and studies, and finally outlines the key debates and controversies in the literature.

Chapter 3 gives an overview of the research approach. It is an in-depth description of the design type of the research, the methods used for data collection and validation, as well as the process used for analysing the data.

Chapter 4 is a presentation of the data for the study. This chapter showcases the collection of information used and attained during the research process, from which the analysis and findings in chapter five are derived.

Chapter 5 is the presentation of a thorough analysis and findings for the research. It is a fusion of all the results of the inputs such as experiments, field observations, desktop studies, data acquired, assessed and analysed to answer the research questions.

The final Chapter 6 is a presentation of the conclusions and recommendations that emanated from this research. The discussion on key findings and observations from the study, limitations encountered during the research, as well as recommendations for future research work, are discussed in this chapter.

2 LITERATURE REVIEW

2.1 Introduction

A review and analysis of the existing literature that is relevant to the utilisation of UAVs in SSM systems was conducted and has been discussed in depth in Section 2.2. The fields reviewed in the research are SSM, its importance for a safe continuous mining operation and the potential dire safety and economic consequences if the system is not well managed. Dust settlement and its accumulation on surfaces, as well as UAV technology and its increasing utilisation in the mining industry, were also researched.

2.2 Key Concepts, Theories and Studies

2.2.1 Slope stability monitoring

The ability of any system to perform to its optimum potential is highly influenced by the quality control of all the inputs into the system. Accurate data input into the SSM system is crucial in ensuring the safety of the operation, by preserving the integrity of the system results (Mphathiwa, 2012).

Prism monitoring forms an essential part of the SSM system and remains a primary slope monitoring tool in the mining industry, due to the system's potential to provide accurate and reliable data over large open pit slopes. Implementation and maintenance of the prism monitoring system is the mine surveyor's responsibility, ensuring data accuracy and defensibility before distribution to the geotechnical team for slope stability analysis. Furthermore, the mine surveyor should ensure appropriate archiving of the data, for trend analysis, and continuous use as a feedback loop for continuous improvement of the system (University of the Witwatersrand, 2019).

The theory of prism monitoring is based on a continuous calculation and comparison of the distance between two points. This is achieved by measuring the distance between the instrument, such as an RTS and a prism installed at a fixed known point at specified time intervals. The specified intervals between measurements and the threshold of movement criteria are determined by the geotechnical engineer (University of the Witwatersrand, 2019).

The measurement intervals for different areas may vary depending on the risk and level of exposure and the rockmass properties. Some of the instruments used to measure this distance such as Trimble and Leica RTS use electronic distance measurement (EDM), electromagnetic radiation, microwave radiation, infrared or visible light (Read & Stacey, 2009).

Measurement data (horizontal angle, vertical angle, slope distance, ambient temperature and atmospheric pressure) is transmitted to the software and the software "calculates" coordinates and these are compared to the given coordinates. 3D movement can then be determined from the differences between the coordinates. The quality of these measurements can be affected by numerous factors such as:

- The velocity of the EDM signal;
- The amount of dust in the atmosphere;
- Application of accurate ambient temperature and atmospheric pressure corrections to the final readings; and
- The ability of the RTS to locate the prisms (Read & Stacey, 2009).

The Trimble S9 RTS used on site is equipped with an "auto lock" and "long fine range lock" that enables the instrument to locate prisms on the open pit slopes (Trimble, 2023). The main factors that reduce or eliminate the ability of the RTS to locate prisms are:

- The loss of prisms due to slope failure or poor installation;
- Prism destruction by mining activities or equipment; and
- Accumulation of dust and dirt on the prisms (Read & Stacey, 2009).

The mining activities in open pit environments such as drilling, blasting, loading and hauling of the blasted material generate large amounts of dust. This dust settles on the prisms and the settling rate is exacerbated by the atmospheric moisture content and the lack of prism-cleaning and maintenance.

A key component in a prism monitoring system is the targets, in the form of retro-directive optical reflectors/prisms. There is a wide variety of prism types on the market for different areas of application. The decision of the type of prism to use is dependent on the unique monitoring requirements of each site, such as measurement distance (range) and general environmental conditions.

Good survey practice requires the use of genuine manufacturers' prisms for monitoring systems to meet the accuracy and durability requirements for a long period. Imitation prisms, despite being economically appealing, fall short of the high-performance standards set by genuine manufacturers' prisms (University of the Witwatersrand, 2019). Figure 2-1 shows a Leica GPR112 monitoring prism - a large-diameter monitoring prism, suitable for long-range measurements (Leica Geosystems, 2023).



Figure 2-1 Leica GPR112 monitoring prism - large diameter monitoring prism.
(Leica Geosystems, 2023).

The installation preference of the prisms on the slopes is also site dependent, however, the most common preferences are:

- Permanently fixing the prism into the bench, mounted on prism poles or pipes, securely grouted into the bench floor; and
- Mounting the prism into the slope face/wall.

The second option has been removed from RUL's prism installation practices due to improving safety regulations and highwall approach procedures to remove mine personnel from working directly against high walls. RUL has opted for installing prism poles into the bench floor as illustrated in Figure 2-2.



Figure 2-2: A prism installed on a pole grouted into the bench floor (Source: RUL Internal Data, 2022).

2.2.2 Slope optimisation

Slope optimisation is the process of increasing operational returns by maximising ore extraction and reducing waste stripping. This is achieved by steepening the slopes and recovering the ore with less waste stripping, at an acceptable level of slope stability; this concept is illustrated in Figure 2-3.

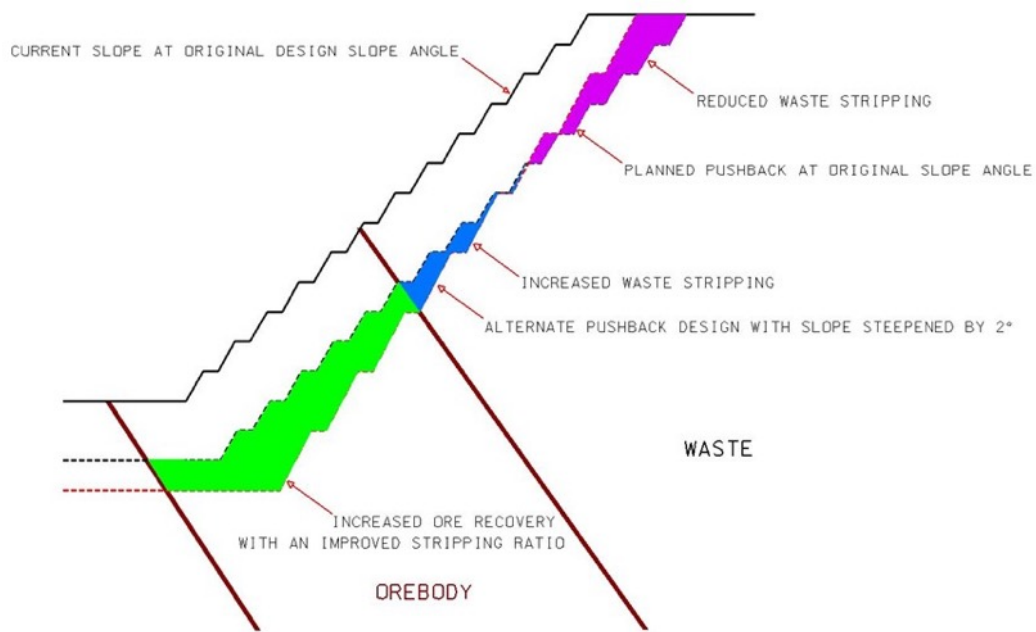


Figure 2-3: The potential results of slope optimisation (Read & Stacey, 2009).

The optimised configuration of the open pit in the context of safety, ore recovery and financial return is the main objective of an open pit slope design (Read & Stacey, 2009). Increasing the slope angles reduces the stability of the slopes, hence maintaining an effective and reliable monitoring system is crucial for ongoing operational safety.

Read and Stacey (2009) also recognised that the operators and investors expect that the highwalls will be stable for the life of the open pit. The expectation of investors for stable highwalls for the life of the open pit is contrary to the reality of slope behaviour. An ideal expectation would be for operations to ensure a qualified staff complement and an SSM system for effective management of slope instabilities.

Stacey (2007) discusses the importance of back analysis in an SSM system and stresses that "the ability to carry out quality back analysis depends heavily on the availability of good monitoring and observation data" (Stacey, 2007, p.196). Bamford *et al.* (2020) state that the UAV approach can increase data coverage timeously. Post-failure analysis of events leading to the failure can assist with confirming design assumptions and capabilities as well as areas of SSM improvement (Thomas, 2011).

On the economic consequences of geotechnical instabilities in mines, Young *et al.* (2020, p.145) discuss the importance of "quantifying the direct and indirect economic consequences of geotechnical hazards on the operation, as these costs inform appropriate exploration and mine planning decisions". Prism monitoring is an important factor in understanding geotechnical instabilities and predicting failures, and should, therefore, be introduced at the early stages of mine development.

2.2.3 Trigger action response plan

A TARP is a set of planned reactions to an event that is likely to happen. Most slope management plans include a TARP, which when triggered by a change in slope conditions, highlights the appropriate actions, and the responsible parties (Read & Stacey, 2009). An example of a generic SSM strategy is shown in Figure 2-4, illustrating the TARP's position in the strategy, which is under Risk Management Tier 3 to Tier 5 (SRK Consulting, 2019).

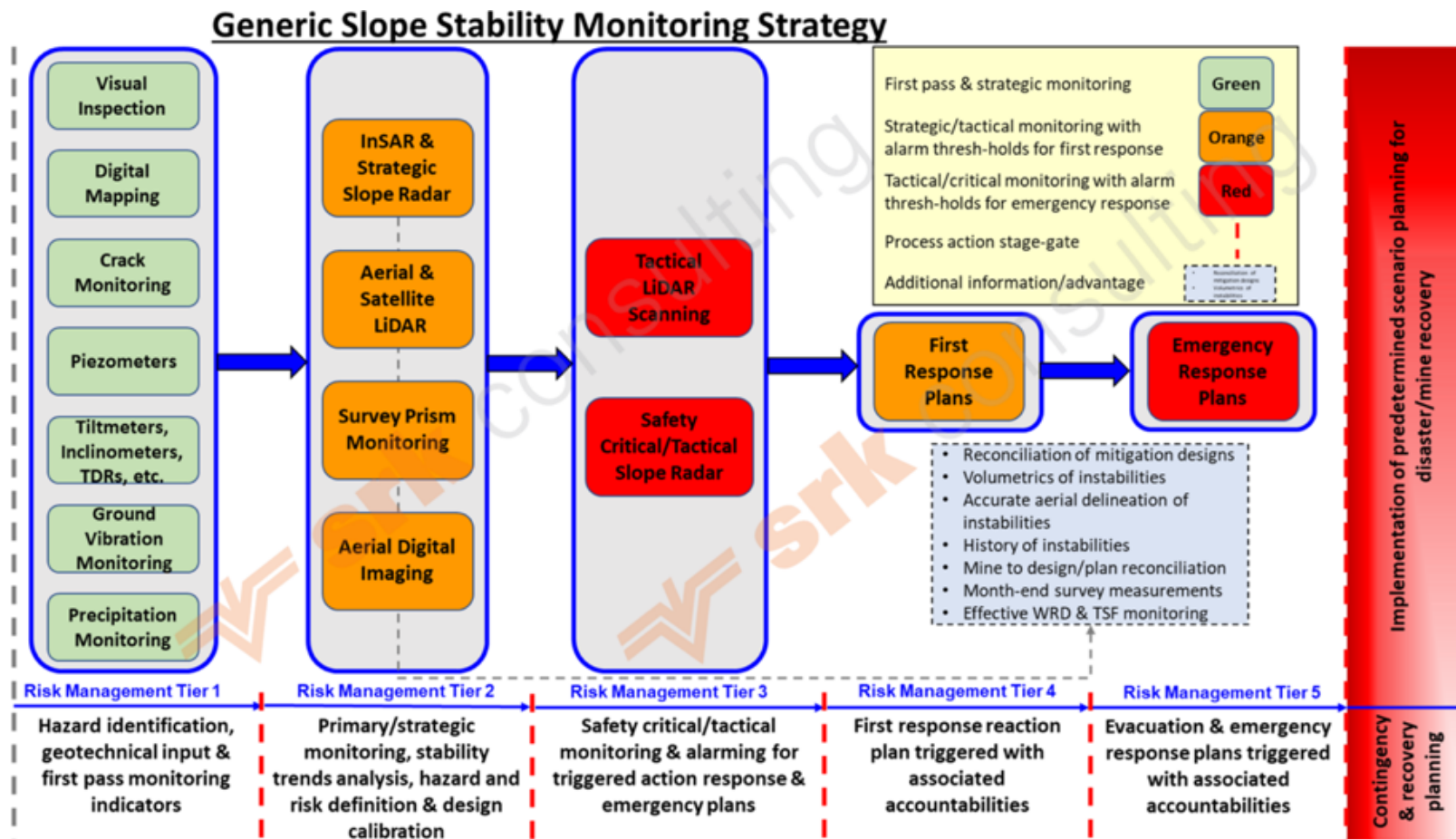


Figure 2-4: A Generic Slope Stability Monitoring strategy (SRK Consulting, 2019)

A well-defined TARP is crucial for an operation to ensure prompt and appropriate action for disaster management. Research into technological advances and continuous analysis of the TARP performance allows for improvement opportunities for the plan. This research has identified an opportunity to officially incorporate UAV technology into the RUL TARP, which is further discussed in the recommendations section. The TARP for open pit and dump instabilities currently employed at RUL is shown in Figure 2-5.

TRIGGER ACTION RESPONSE PLAN			
Response Level	Characteristics) / Trigger*	Operational Response	Management Response
0 (Blue)	No movement	Routine operations and planning	Routine activities
	Stable condition(s)		
1 (Green)	Steady movement of velocities less than 1 mm/day with consistent low levels of monitored increase over the past 1-5 days	Routine operations	Routine activities
	Movement in the mass	Operational planning activities for failure	Daily management meetings
	Minor to limited deviation in the behaviours of the failure	Activate Business Resilience Management Plan (BRMP).	Maintain normal scheduling and shift rosters
		Infrastructure removal from failure zone	BRMP
2 (Yellow)	Significant deviation in the monitored behaviour of the mass - A confirmed doubling of average mass movement rates (Rates between 1 mm/day to 5 mm/day over a 24-hour period)	Modified mine operations plan	Activate management team on call- within 1 hour response time to the mine
	Rock falls/dust reported coming from the instability zone	Modified mine management plan	Reschedule off-site activities and shift rosters to meet business
	Active failure expected within days based upon significant acceleration in monitored rates	Restricted access to area - spotters and berms in place	Regular updates to the BRMP, increase meeting frequency as required.
	Any Radar alarm is triggered originating from exposure area		
	Any blasting adjacent (within a 300 m radius) to the rock fall zone.		
	Any break or malfunction in the Radar systems		
	Any significant rainfall event (where the pit has been closed)	Evacuation of rock fall zone. Barricading established	Increased geotechnical coverage.
3 (Orange)	Active failure expected within hours based upon significant acceleration in monitored rate	Closure of access to the failure area	Mine management team made aware of imminent failure, but incident command not required due to controlled response
	Active failure occurring within controlled limits, failure zone is controlled and operational plans are failure behaviour requiring complete closure of area	Temporary stoppage of operations	BRMP team placed on standby, daily updates
	Clear and defined deviation in failure mass behaviour	Modified Mine operations and asset management plans implemented	
4 (Red)	Active failure at high/accelerated rate, unexpected causing emergency evacuation	Emergency Evacuation of the mine and support areas	Mine Management Team immediately reports to site.
		Operations halted and Mine Senior Leadership Team notified	BRMP activated
		Incident Command established	
		Emergency Response Planning	
*Triggers will be reviewed daily and modified as required by the geotechnical team			

Figure 2-5: RUL Trigger Action Response Plan for open pit or dump instability (RUL, 2020a).

2.2.4 Challenges with prism inspections and maintenance

Slope stability is a well-researched field and identifies prism maintenance as a challenge associated with prism monitoring. On operations such as RUL, the cleaning and maintenance of prisms have almost been non-existent due to inaccessibility and the fall from height risks resulting from the proximity of prisms to open crests (highwalls). Mining operations such as Kolomela Mine in the Northern Cape employ the services of abseilers for cleaning, maintenance and replacing damaged prisms.

The abseiling solution may, however, not be easily adoptable by all mining operations due to cost limitations, as well as safety policies. Thomas (2011), Jooste and Cawood (2006) and Mphathiwa (2012), all refer to prism-cleaning and maintenance as a shortcoming of the prism monitoring system. However, there is a knowledge gap in the peer-reviewed literature that suggest suitable solutions for this challenge with the development of UAV technology.

Mphathiwa (2012) discusses the safety and economic risks of poorly predicted and unmanaged slope failures, as well as the economic benefits of steepening slopes. Tommaso *et al.* (2018) highlight the following as key components of the effectiveness of an evacuation strategy:

- A comprehensive implementation of the monitoring systems employed; and
- The system's ability to detect instabilities timeously, as well as to derive reliable predictions of the slope time of failure.

Prism monitoring is a proactive measure towards ensuring the safety of the slopes. When well-managed, SSM can provide timeous warning for the safe evacuation of mine personnel and machinery when a failure is imminent.

The importance of the inputs of an effective prism monitoring solution into operational safety plans warrants an investigation into finding a solution for an ongoing challenge that has been identified by multiple researchers, including those mentioned above.

2.3 Dust Settling Analysis

Dust in open pits is a by-product of drilling, blasting and loading and hauling activities. At RUL, this challenge is more prevalent throughout the winter months, as a result of little to no rainfall to assist with washing down dust accumulation on the prisms. For inaccessible prisms, dust accumulation may result in interrupted measurements, until the next rainfall assists in the cleaning of the prisms (Afeni & Cawood, 2013).

The Central Namib Desert where RUL is located has a hyper-arid environment with an average annual precipitation of, for the most part, less than 50 mm per year. Rainfall is sporadic and very unpredictable, with a variation coefficient exceeding 90%, implying that the average may be produced from a single shower while experiencing years of very little rainfall (RUL, 2021). RUL experiences strong prevalent west-south-westerly winds between April and October transporting dust from the active mining areas onto prisms and scarce rainfall is experienced as shown in Figure 2-6.

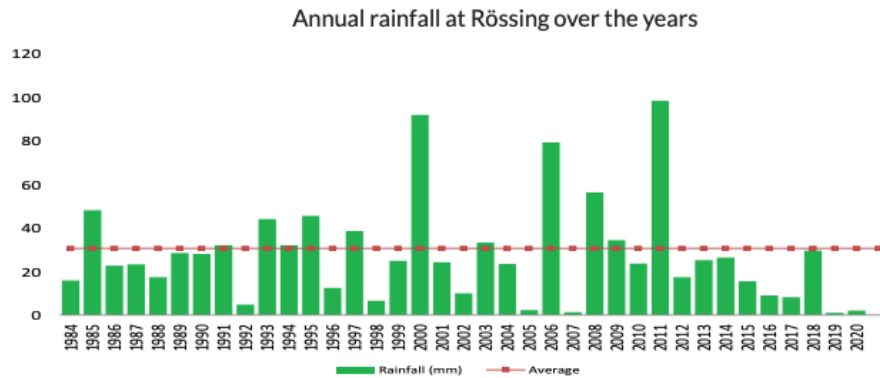


Figure 2-6: Annual rainfall at Rössing over 36 years (RUL, 2020b).

The rainfall relief that other mines may have to assist with prism cleaning only has a minimum benefit on the RUL prism network. Additionally, the direction of the prisms limits the rain from direct contact with the prism surface, reducing the possibility of cleaning the surface even further.

An investigation by Pennetta *et al.* (2016) on the factors influencing dust accumulation on concentrated solar power (CSP) mirrors was carried out for one year in Collinsville, Queensland, Australia. The study examined the correlation between dust concentration and various weather variables. The findings by Pennetta *et al.* (2016) indicate a strong relationship between dust concentration, and wind speed and direction. This provides the potential for developing a model-based prediction for dust concentration in the air, at different locations and during different periods. The dust predictions from the model would allow for optimised cleaning plans by indicating the settling rates per location for each period. Analysing these trends will enable tailoring the appropriate cleaning frequency to suit the dust accumulation rates per location and period (Pennetta *et al.*, 2016).

In a study of dust mitigation by rolling water droplets from hydrophobic surfaces, Yilbas *et al.* (2021) discuss the implications of the settlement of dust particles on hydrophobic surfaces and the resultant reduced optical transmittance efficiencies. Numerous techniques including self-cleaning, air jet blowing, water jet splashing and electrostatic repelling have been adopted to repel dust particles from surfaces. Yilbas *et al.* (2021) highlight cost efficiency and preservation of the surface's unique qualities as major concerns for surface cleaning applications.

Furthermore, Yilbas *et al.* (2021) analysed the size, shape and elemental composition of the dust particles. Understanding the elemental dust composition for individual sites and the potential resultant chemical reaction and their effects on surfaces is crucial. This was a key consideration for the research in identifying the appropriate prism-cleaning solution, that preserves the prism surface qualities.

2.3.1 Unmanned aerial vehicles technology

The increased efficiency improved operational safety and high-cost savings are some of the key reasons that have attracted mining houses to invest in the incorporation of UAV technology in their operations. UAVs offer solutions in the mining industry in areas such as:

- Stockpile management;
- Geotechnical modelling;
- Industrial inspections;
- Drilling and blasting performance and fragmentation analysis;
- Tailings dam monitoring; and
- Project oversight for compliance reporting and data provision for insurance claims and verifications (Airobotics, 2020).

Figure 2-7 illustrates the use of UAV imagery in tracing material from an in-pit composite to the respective stockpiles, the data was used to rectify an incorrect booking incident at RUL.

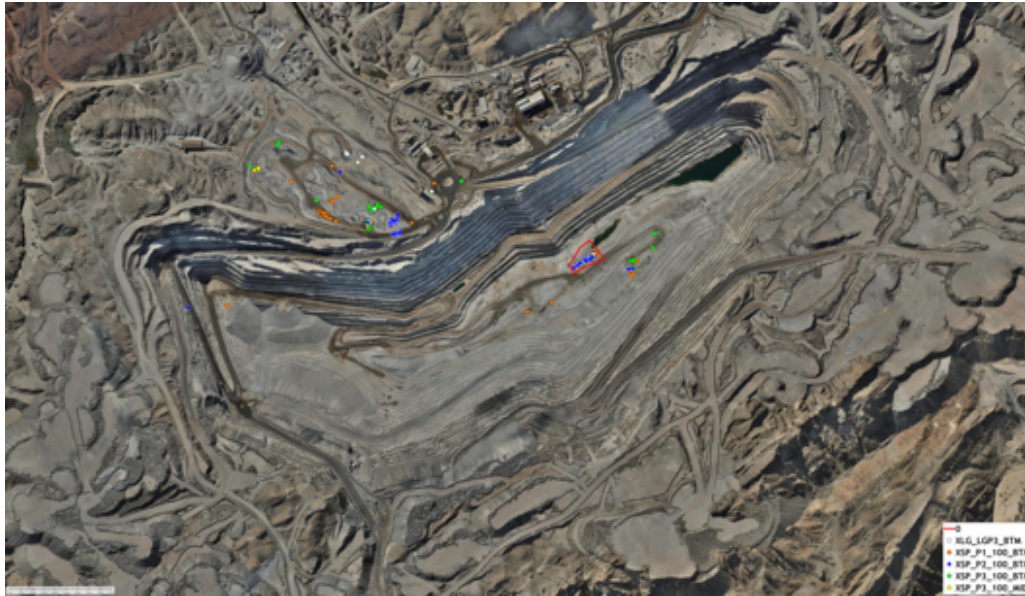


Figure 2-7: UAV imagery utilised for tracing material movement (Source: Aero Vision Drone Services, 2022).

The accuracy of the geo-referenced 3D data is achieved by a precise technique of placing and surveying of ground control points (GCP) network in the area of interest. GCPs are used to support triangulation during data processing (Padro *et al*, 2019).

Post-processing kinematics (PPK) was adopted at RUL as a preferred method of referencing in recent years. PPK is a Global Positioning System (GPS) technique that enables data referencing after the completion of the surveys (Padro *et al*, 2019). The PPK process allows accurate data referencing with limited use of GCPs, increasing safety and productivity, by reducing exposure in hazardous areas and time taken for GCP placement.

Lee and Choi (2016) reviewed the applications of UAVs in the mining industry, highlighting their incorporation in the mine survey, mining and safety sections in the industry. Some of the findings discussed in their study include UAV application for the open pit, dumps and stockpile management; surveys of inaccessible steep inclines, surface stability monitoring, as well as a slope stability analysis (Lee & Choi, 2016).

Lee and Choi (2016) further discuss the specifications of various UAVs, such as weight, battery life, maximum flight times, and radio link range with examples of their major applications in several industries. This information is vital input for the selection and recommendation process of the most suitable UAV for the research project (Lee & Choi, 2016).

Knott *et al.* (2019) refer to a case study where the use of UAVs for observations proved to be a safer alternative to physical observations by the staff or by abseiling. They further highlight the additional benefit of prompt risk management of risks and the rapid development of appropriate remedial actions (Knott *et al.*, 2019)

Javad *et al.* (2020) identified the rapid deployment capability of UAVs for inspections in emergencies and hazardous situations as a key advantage. Highlighting the capability to provide hazard warnings and accelerate search and rescue missions despite communication breakdowns. Their use for transporting medical supplies to inaccessible areas is an additional advantage (Javad *et al.*, 2020).

The Civil Aviation regulations 101.05.2(8) in Namibia state that "*A person who is in charge of the operation of a RPA or a RPA system carrying goods, including:*

(a) any articles or equipment installed in or attached to the aircraft; and

(b) cargo, at the commencement of its flight, may not allow such an aircraft to be flown, unless the person has been granted approval by the Executive Director to do so and subject to such conditions as are required by such approval " (Namibian Civil Aviation Authority (NCAA), 2020).

This regulation is directly applicable to the research aspect of using UAVs for cleaning prisms, as it requires dispensing a cleaning solution from the payload attached to the UAV. All additional legal approvals must be granted before the utilisation of the prototype.

Bamford *et al.* (2020) discuss the integration of UAV photogrammetry in design compliance and structural modelling of open pit walls highlighting several limitations of remote sensing that can be reduced by the use of UAVs. The limitations include vegetation or occlusions, as well as the lengthy duration of the processes.

The aforementioned limitations can be addressed by the ability of the UAV approach to conduct frequent surveys, over large areas in a short period (Bamford *et al.*, 2020). This capability aligns with the motive of removing mine personnel from unsafe areas at RUL by incorporating UAVs in the SSM system on site.

Vergrouw *et al.* (2016) discuss various types of UAV specifications in terms of type, size, weight and payload. The importance of understanding these specifications are the key elements in determining the UAV capabilities such as flight duration and loading capacity (Vergrouw *et al.*, 2016).

Vergrouw *et al.* (2016) further discuss the current applications of UAV technology, as well as future development. There is a likely trend of UAVs becoming smaller and lighter, more efficient and cheaper. This trend will result in increased public accessibility and autonomy, as well as an increased range of purposes, highlighting the possibility of UAVs operating in swarms (Vergrouw *et al.*, 2016).

Adopting UAV swarm operations for SSM processes in the near future is worth considering and will provide great benefits, especially towards the prism-cleaning and inspection tasks. The swarm operations will alleviate the battery constraints and the short hovering periods of the current UAVs on the effectiveness of the process.

This will be achieved by reducing the need for constant battery changing and charging when using only one UAV. Hence, shortening the duration of the process by covering a wider area range in a short time, attending to different prisms at the same time, as well as the increasing payload capabilities of the combined fleet. A cost-benefit analysis is advisable for each operation prior to employing the swarm concept for the prism cleaning project.

2.4 Key Debates and Controversies

The most prominent debate in this review is highlighting prism monitoring as the only reliable 3D SSM system that has been challenged by various mining professionals. In recent years, reflectorless slope monitoring has been proposed as a better alternative for slope monitoring.

The method proposes a prism-less system, which would do away with the cost and safety risks associated with prism installation, cleaning and maintenance. Hope and Dawe (2015), highlight the challenges associated with precise monitoring using a reflectorless RTS and support the reservations towards reflectorless slope monitoring:

- There is uncertainty about what happens to the laser during the measurement process, there is no confirmation on whether the laser has indeed hit the right surface. In contrast, prism monitoring would not return any readings if it does not locate the prism, therefore providing higher credibility in this regard; and

- Reflectorless control points need to be on smooth surfaces, a requirement that is not practically attainable for an open pit mining environment. The roughness of the high walls will increase background noise, thus increasing the potential errors in the measurements.

2.5 Chapter Summary

Chapter 2 reviews the literature in the fields relevant to this research, such as slope stability monitoring and discusses the purpose of slope monitoring. The review specifically assessed the safety and the economic impacts associated with slope instabilities and their management.

One of the challenges to SSM is the loss of prisms in the prism monitoring network, mainly due to dust accumulation on the prism surfaces. Therefore, the chapter further referred to publications on various properties of dust, to understand the settlement properties of dust on surfaces. A study that highlighted the function of understanding dust elemental compositions and their reaction to cleaning solutions was also reviewed.

Additionally, the chapter covers literature on UAVs, their uses in the mining industry, as well as the benefits gained from their incorporation into multiple operations in the industry. The key controversy and theory regarding reflectorless slope monitoring as a better alternative to prism monitoring are discussed at the end of the chapter. The accuracy of the reflectorless option was highlighted as the main area of concern.

3 RESEARCH APPROACH

3.1 Introduction

RUL's first fixed-term contract for UAV services commenced in September 2019, since then, the technology has been successfully adopted throughout processes on-site, including the SSM system. The scope of this research was focused on highlighting the applications of UAV technology in the SSM system in the open pit mining operation at RUL.

3.2 Research Design

The research approach is classified as a flexible design, which is a combination of descriptive, experimental and review research. The main approach is a case study of the incorporation of UAVs in the RUL SSM system. The research analysed areas of UAV data implementation in the system and identified potential areas for further adoption of the technology.

To assist in answering questions for key considerations for undertaking the proposed UAV modification for prism cleaning, the following complimentary studies were undertaken:

- Complimentary studies were completed through data collection for studying the dust settlement rates in the vicinity of in-pit Haul Road 11; and
- Prism cleaning experiment using a pressure washer.

3.3 Data Collection Process

Data accuracy is a crucial aspect of an SSM system, as incorrect data input in the system affects the overall system performance and decision-making. Thus, exposing the operation to potential unpredicted failures or misallocation of resources in the event of false movement predictions (University of the Witwatersrand, 2019).

The mine survey team is the custodian of the UAV data onsite and ensured the accuracy and integrity of all data before distribution to its stakeholders. This was achieved by performing the set quality control and assurance practises on the data capturing and processing at RUL.

3.3.1 The use of 3D UAV meshes in geotechnical inspections

The information for the use of 3D UAV data in geotechnical inspections was acquired from the geotechnical team onsite through observations and images from their processes. Additional information from RUL's internal policies and procedures related to SSM such as the SDMP and HSSEC were also utilised as inputs to this research.

Exporting break-lines for slope conformance measurements and waste dump advancement monitoring

Global Mapper or Riegl RiMINING software was used onsite for the extraction of crest and toes from UAV point clouds. Global Mapper software is utilised by Aero Vision Drone Services (AVDS) in their data processing procedures, while Riegl RiMINING software is used by the mine surveyors for further UAV data manipulation and break-line extraction.

Riegl RiMINING software was acquired with the Riegl VZ-4000 for laser scanning at RUL, however, this scanning process was halted in 2020 for internal reasons. The Riegl RiMINING software onsite is currently used solely for importing and manipulating UAV data, such as for break-line extraction, or exporting lighter point clouds for fast import into other survey software.

Break-line extraction is a survey function, however, in the absence of sufficient mine survey manpower, AVDS utilises Global Mapper for break-line extraction. The crest and toes of waste dumps extracted were used for calculating the waste dump advancement rates. This is necessary to prevent overloading the dump foundation, as well as to ensure that the dumping rate allows the material sufficient time to settle and compact.

Geotechnical Mapping – remote mapping of structures on inaccessible walls

The effect of geotechnical structures on the final highwall was assessed to provide ongoing precautions for current and future mining activities in the same or similar areas. AVDS provided geo-referenced 3D terrain meshes and models in RUL local coordinate system (Geo-reserve) as used by the geotechnical team, as well as in the global coordinates system. This enables efficient and seamless data transfer between the team on-site and other stakeholders. The use of UAV data in geotechnical inspections is discussed further in the subheadings below.

The outputs of the data captured by UAVs include high-resolution imagery and geo-referenced 3D terrain models. These outputs are used by the geotechnical team for highwall mapping, especially of inaccessible slopes. Mapped structures are exported in various file formats such as .obj, .dxf and .dwg files. These outputs are imported into Sirovision software for incorporation into structural, geological, and geotechnical models. They are also utilised for kinematic analysis to determine factors of safety and probability of failure of high walls.

The stereoplot as shown in Figure 3-1 provides a simplified view of different structure sets in the open pit and is used in the kinematic analysis processes by the geotechnical team. This is utilised to predict the likelihood of the occurrences of certain kinds of failures, by analysing the wall angles and structure orientations, as well as their interaction with each other.

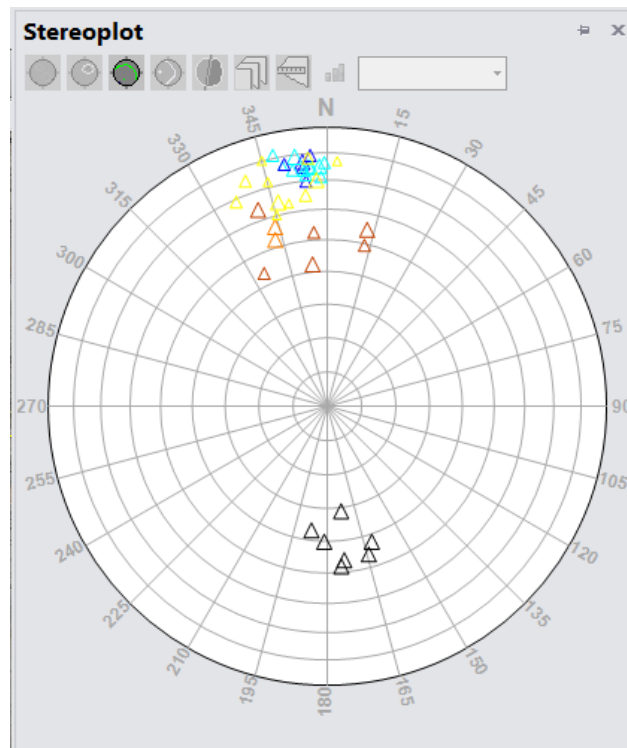


Figure 3-1: A stereoplot from Sirovision used in the kinematic analysis (Pearce, 2022).

Other beneficiaries of the geotechnical data such as the geo-referenced 3D models include the RUL Project teams, for initiatives such as the highwall meshing project, (lateral highwall support/rockfall management). The Phase 4 Life of Mine Extension (LoME) team, as well as the external service providers, use the data for analysis, and/or interpretation in the final wall design recommendations (Pearce, 2022). The LoME project aims to extend the life of mine for an additional 10 years, from 2026 to 2036.

Crack detection and monitoring

Crack detection and monitoring are traditionally done through visual inspections and observations by the geotechnical personnel onsite. However, with the evolving company safety policies and outlook, access to hazardous areas referred to as “red zones” have been strictly discouraged. The use of UAV data has been a safer substitute in the crack visualisation and analysis process.

The Geotechnical risk assessment at RUL is based on the 5x5 risk matrix. “*The matrix combines the maximum reasonable consequence with the maximum reasonable likelihood of an event happening to assign a risk score (RUL, 2020a).*” The colour codes used for ease of identification of risk category are listed and illustrated in Table 3-1.

- Green – Low risk;
- Yellow – Moderate risk;
- Orange – High risk; and
- Red – Critical risk.

Table 3-1: The 5x5 risk matrix utilised at RUL (RUL, 2020a)

LIKELIHOOD	CONSEQUENCE				
	1 – Minor	2 – Medium	3 – Serious	4 – Major	5 – Catastrophic
A – Almost Certain	Moderate	High	Critical	Critical	Critical
B – Likely	Moderate	High	High	Critical	Critical
C – Possible	Low	Moderate	High	Critical	Critical
D – Unlikely	Low	Low	Moderate	High	Critical
E – Rare	Low	Low	Moderate	High	High

Blast monitoring

Blasting is a crucial stage in the mining process that is frequently employed in both open pit and underground mines, for fragmentation of the rock mass into the appropriate rock sizes (Bamford *et al.*, 2020). The process results in significant ground vibration in the vicinity of the blasting site. These vibrations could compromise the stability of mine slopes, jeopardising safety and posing a risk to people's lives and property (Bazzi *et al.*, 2020).

The UAV incorporation in the continuous monitoring of the blasting process concerning slope management at RUL is implemented by conducting pre-blasts, blast process monitoring, as well as post-blast surveys. The data output is in the form of videos, high-resolution imagery, and 3D models. The pre-blast data is utilised for assessing the condition of the highwall before the blast, and if required for further investigation and is used to evaluate as-drilled hole alignment.

Video recordings of the blast process, not only assist the blasting engineers to evaluate the blast performance but also aid the geotechnical team to identify potential causes of blast-induced damage on final open pit walls. This is particularly important for the trim blocks closest to the high wall, as they are designed to be blasted in a manner that safeguards and minimises blast damage to the final high wall (Pearce, 2022).

UAV systems can approach the rock mass or blasted muck piles more closely, enhancing the potential resolution of the 3D models that can be created (Bamford *et al.*, 2020). By studying the performance of the blast, the geotechnical team is on occasion able to anticipate where blast damage or blast-related issues can affect the final stability or condition of the high wall. They use this information to proactively advise the load and haul team on any additional precautions required for the loading and scaling activities in the area (Pearce, 2022).

3.3.2 Utilising UAVs for prism inspections

The inability to conduct physical prism inspections and maintenance is one of the challenges posed by the loss of safe access to prisms for a monitoring system. A manner in which UAVs are bridging this gap is by providing imagery and videography as a visual aid for prism inspections. The process for these inspections at RUL is outlined in Figure 3-2.

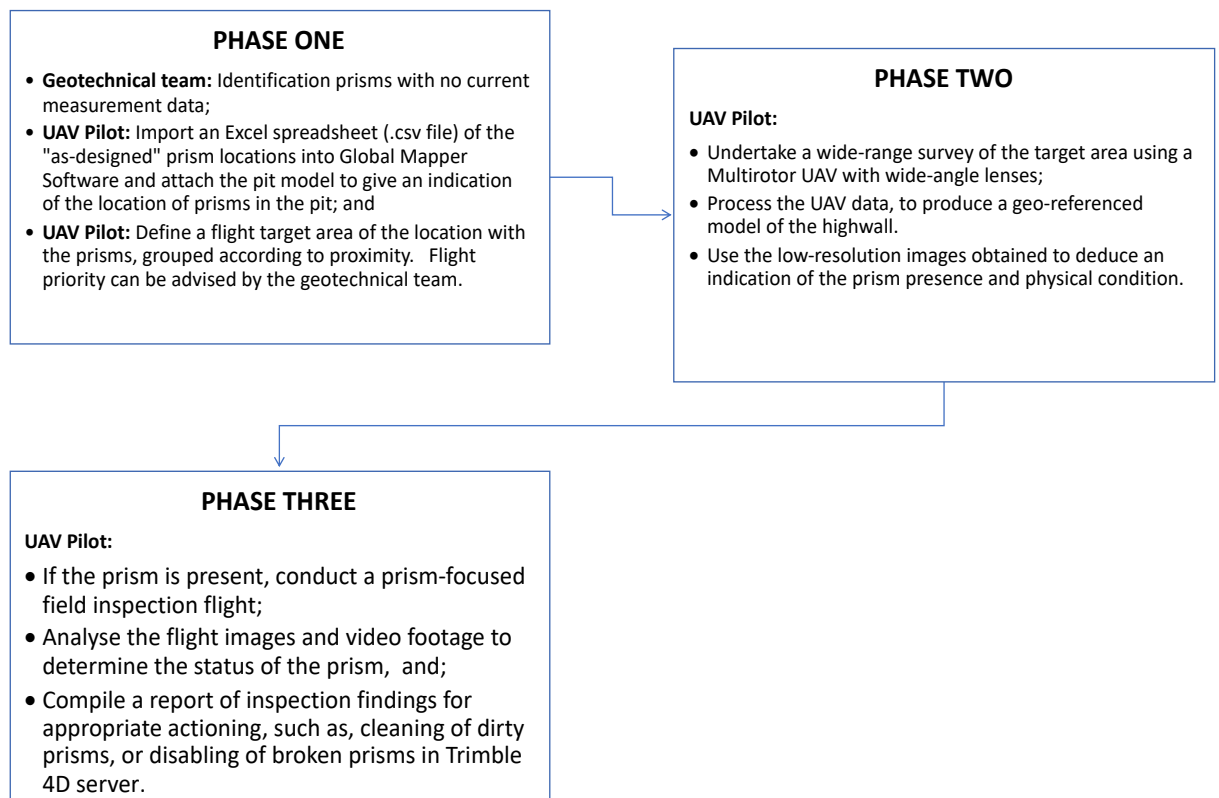


Figure 3-2: A – three-phase approach for prism inspections at RUL.

Data collection for the assessment of UAV utilisation for prism inspections on-site was done through three-phased field experimentation with AVDS and the geotechnical team. Datasets from the flights conducted during the initial experiment and the inspections that followed the successful trial were obtained from AVDS.

Phase one

Phase one of the process is initiated by the geotechnical team, with the identification of prisms of interest, prompted by either a loss of data from the prism or sudden data abnormalities picked up from the T4D monitoring system. The geotechnical team requests the UAV pilot for flight scheduling and data analysis of the prisms in question.

Phase two

Figure 3-3 illustrates the plotted prism locations, imported into Global Mapper software from a .csv file, and appended to an open pit image. The prisms are colour coded based on their functional status, with red prisms such as 520, 507, 506, and 518 being prisms of concern and the green-coloured prisms being in normal functionality. The red prisms are then targeted for a prism-focused flight, for further inspection.

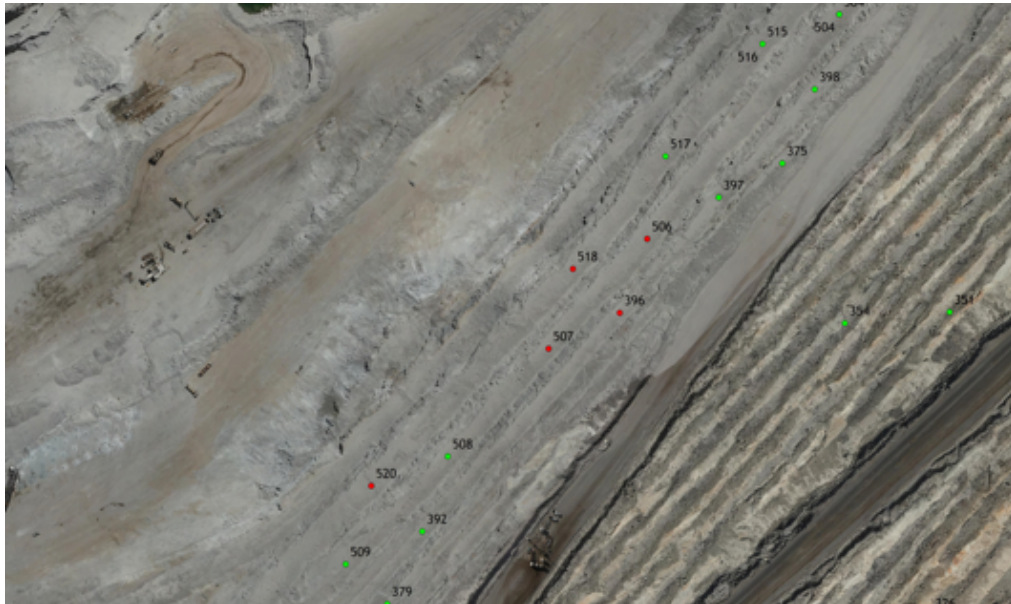


Figure 3-3: Prism locations on an open pit image in Global Mapper software (Aero Vision Drone Services, 2022).

Phase three

The images taken during the third phase of the inspection process are utilised in the assessment for determining the final prism status. The results of the inspection are presented in a report format to the survey team and the geotechnical engineer for relevant actioning.

3.3.3 Dust settlement on prisms

Dust accumulation on prisms has been identified as one of the main contributors to the loss of prism readings (Read & Stacey, 2009). Prism 229 installed near Haul Road 11, was decommissioned in 2018, due to the RTS's inability to locate it. The prism was recovered in 2022, undamaged, but fully covered in dust.

This presented an opportunity to install a new test prism on the prism pole, to study dust accumulation rates near access roads; Haul Road 11 is one of RUL's main in-pit access roads. Figure 3-4 and Figure 3-5 illustrate the location of the prism in relation to Haul Road 11.

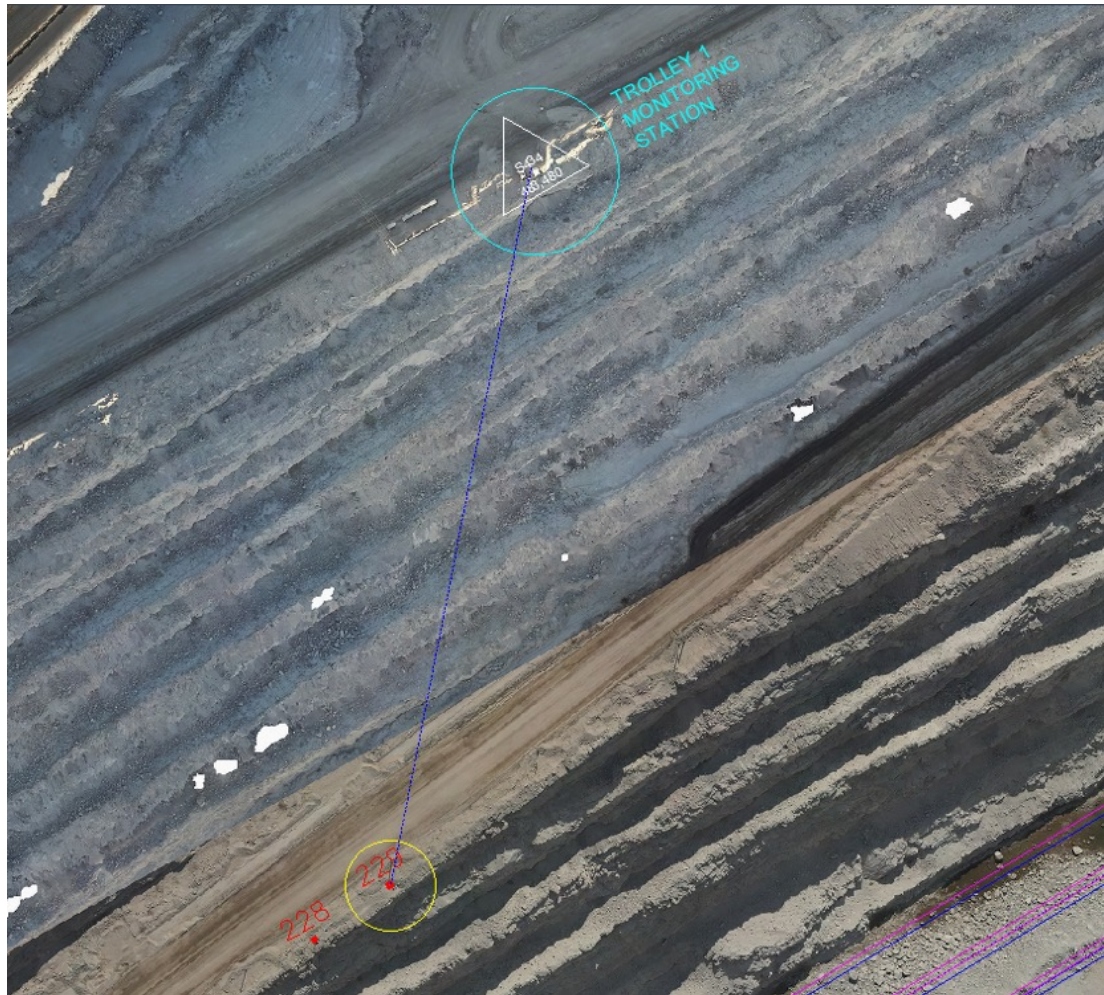


Figure 3-4: The location of Prism 229 in relation to the monitoring station Trolley 1 (Aero Vision Drone Services, 2022).



Figure 3-5: The location of Prism 229 in relation to Haul Road 11 (Aero Vision Drone Services, 2022).

The dust settlement study on prisms was undertaken by installing a new, clean prism on a beacon in the vicinity of Haul Road 11 in the open pit. An image of the prism was taken on the date of installation, as well as on the date it was observed fully covered in dust. The period between installation and full dust coverage of the prism was two months.

A test prism was installed on the prism pole where Prism 229 was recovered from on the 10th of August 2022. Figure 3-6 shows the absence of any dust on the prism surface at the time of installation.



Figure 3-6: A test prism on the Installation date: 10th of August 2022 (Aero Vision Drone Services, 2022).

The test prism was recovered on the 13th of October 2022 for analysis. This was after it was observed to be completely covered in dust just over two months post-installation on the beacon close to a haul road as shown in Figure 3-7.



Figure 3-7: The dust coverage on the test prism (Type: Leica GPR111) two months after installation (Aero Vision Drone Services, 2022).

3.3.4 The concept of UAV modification for prism-cleaning projects

The concept of UAV modification for prism-cleaning projects was developed with field experimentation data and information on UAVs from various manufacturing websites. Additional desktop studies were conducted for input, such as the NCAA regulations affecting the proposed solution. Discussions held with experts in the mine surveying, geotechnical and aviation disciplines were of key importance in the development of the concept.

The access loss for mine personnel to the prisms for cleaning and maintenance occurs either due to the open pit design, open crests, or hazardous high walls. This challenge presented an opportunity for additional adaptation of UAVs in the management of the SSM systems at RUL. A proposal for modifying and/or utilising UAVs for prism-cleaning projects has been considered and desktop studies and field experiments conducted to provide data for this concept are discussed in this section.

Table 3-II highlights key areas of consideration and research on the methodology for the modification or use of UAVs for prism-cleaning projects.

Table 3-II: Key Areas of consideration for the UAV modification for prism cleaning

KEY AREAS	KEY CONSIDERATIONS
Legal	Relevant regulations
	Licensing
	Patents
Safety and SSM integrity	Appropriate distance from UAV to prism without causing prism damage and backsplash
	Appropriate liquid pressure to avoid prism damage and position alteration
	Suitable cleaning solution and possible effects on the prism glass, such as hazing or scalling (Podmore, R., 2022)
UAV limitations and constraints (Wang, et al., 2020)	Battery life
	Payload Capacity
	Ideal tank capacity, location and effects on UAV performance
Hardware and Software	External attachment positioning
	Air pressure jet to avoid mudding effect
	Remote controlled or autonomous system
	Collision avoidance
	Flight plan scheduling and modification (Eyhorn, C., 2020)
Financial	Modification/ attachment costs
	Outsource/ inhouse
	Trade-off study: UAV versus abseiling
Operation	Cleaning intervals
	Practical scheduling
	Cleaning schedule alignment with short term planning schedule
	Live visual feed of operation to the operator's tablet

An experiment was conducted to answer questions regarding the practicality of the proposed prism-cleaning solution using UAVs. Due to financial constraints, a UAV could not be acquired at the time of the research, therefore a pressure washer was utilised for this experiment. The purpose of the experiment was to investigate the following:

1. The optimum distance of the spray nozzle from the prism;
2. The implications of the water pressure settings on the integrity of the prism position;
3. The cleaning effectiveness;
4. Any backslash onto the camera; and
5. The drying period of the prism surface.

A dust-covered, decommissioned Prism 229 was recovered and used in this experiment.

Prism-cleaning experiment methodology

A Kärcher Professional 1.170-902.0 HDS 6/14 CX hot water high-pressure washer as shown in Figure 3-8 was used for cleaning the prism in this experiment. The pressure washer was sourced from the RUL transport department for the experiment.



Figure 3-8: A Kärcher Professional 1.170-902.0 HDS 6/14 CX hot water High-Pressure washer.

The exact model used for the experiment could not be found online for additional images. Figure 3-9 is an example of a similar system currently available on the market, that could be utilised for any further research or experiment replication.



Figure 3-9: Pressure washer Kärcher 140 bar 3600 W (Allegro, 2023).

The methodology used in the prism cleaning experiment is discussed in this section and shown in Figures 4-32 to 4-34. The prism was mounted on a tripod and distances were measured at one-metre intervals from the prism. A high-pressure washer was used to clean the prism with a pressure of approximately 5MPa. The operation was closely monitored and video footage was captured for post-analysis of the experiment.

The experiment was carried out in stages one to three:

1. Installation of a prism on a tripod as shown in Figure 3-10;



Figure 3-10: Recovered Prism 229 mounted on a tripod for the cleaning experiment.

2. Measured and marked out distances at 1 m intervals (red tape markers) from the prism as shown in Figure 3-11;



Figure 3-11: Distances from the prism marked out at 1-metre intervals.

A test of the effects of the water pressure on a prism was conducted a few days before the cleaning of Prism 229, by setting up and spraying another prism from the different marked-out intervals. A judgement call based on the strength of the water pressure and its effects on the prism from the various distance intervals was made, to conduct the final cleaning experiment at 4 m to the prism.

During the final cleaning experiment, the outcome of the spraying at 4 m produced favourable results, therefore a decision was made to conclude the spraying experiment at 4 m.

Further experimentation at a 3 m distance was done on the same prism (229), to further observe and record the effect of the 5MPa water pressure on the prism. The findings are discussed in Chapter 5.

This experiment merely established the effects of the water pressure and the distance on the prism and provides a starting point for further research. Additional testing to ascertain the appropriate spraying distance of the UAV from the prism using a UAV is required as that is the platform from which the proposed prism-cleaning is to be conducted. The distance specifications will also differ depending on the UAV type and size, as well as wind speed and direction at the time of prism-cleaning.

3. Utilising a pressure washer at approximately 5 MPa pressure settings at the marked distance intervals to clean the prism as shown in Figure 3-12.



Figure 3-12: The cleaning process, with the nozzle at 4 m from the prism.
(Aero Vision Drone Services, 2022).

For the duration of the exercise, the prism was closely filmed to enable accurate post-analysis of the experiment. The effects of the water pressure on the prism such as prism tilting, the spraying period required to remove the dust, and the drying period of the prism post cleaning were deduced from the video footage. The data collected from the field research and the UAV specifications from the manufacturer websites were assessed and the results were used as input in the final recommended cleaning.

Dust composition analysis

A dust sample was collected before the cleaning of the prism as shown in Figure 3-13 and tested at the metallurgical laboratory onsite. The test was conducted to understand the composition of the dust in the RUL open pit. This information is beneficial for understanding the effects on the prism, of the potential reaction of the dust elements with the cleaning solutions that may be considered for prism cleaning.

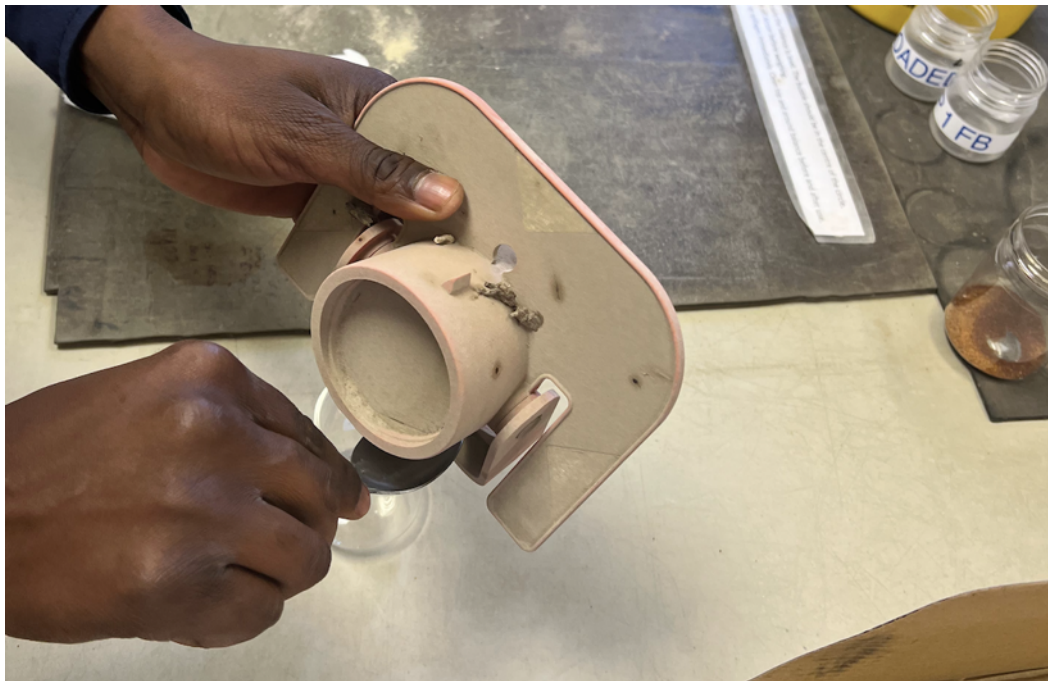


Figure 3-13: The collection of dust samples from Prism 229

The data validation for the UAV incorporation in the SSM system onsite has been validated through the ongoing successful replication and use of the data in the SSM processes onsite. Positive feedback on improved safety and efficiencies from the mine survey and geotechnical teams supported the validation of the effectiveness of the UAV data incorporation into the SSM system at RUL.

The desktop studies data of UAVs used in the proposed modification theory has been obtained from reputable manufacturers. In cases where information was uncertain, such areas are highlighted and recommended for further research in the next phase of development and implementation.

3.4 Data Analysis Approach

The contribution to the mine safety aspect was measured against compliance with company policies aimed at zero harm. This was achieved by analysing how the consistent substitution of mine personnel with UAVs has improved mine safety.

The prism inspection analysis was done by reviewing UAV images of the prisms to establish their status; whether they are clean, damaged, or facing in the right direction. The prism-cleaning experiment data was analysed by noting the outcomes during the exercise and taking photographs and video recordings of the process for post-analysis. This data was used to determine the prism behaviour under the washing conditions of the experiment, such as prism tilting, and the effectiveness of the cleaning. The data was also used to deduce periods for events, such as the washing or drying period.

3.5 Chapter Summary

The research was designed to take a flexible approach, merging data from field experiments and observations, with desktop studies to answer the research questions. The UAV data was obtained from the service provider onsite, and additional information was acquired from experts in the mine surveying, geotechnical, and aviation disciplines.

Information on UAVs on the market used in the development of the proposed prism-cleaning concept was acquired through web sources of UAV manufacturing companies.

4 DATA FOR THE RESEARCH

4.1 Introduction

The data used for the research is divided into the respective subheadings of the areas of UAV utilisation in the RUL SSM system. Datasets such as images for the prism inspection process, as well as the prism-cleaning experiment, were received directly from the UAV service provider onsite (AVDS). The data for geotechnical process inputs were received from the geotechnical team onsite, as well as from the company policies and procedures related to SSM.

4.2 The Use of Unmanned Aerial Vehicle data in Geotechnical Inspections

The UAV data in the form of 3D meshes and terrain models, video footage, and images are being utilised in the following four ways by the geotechnical team onsite:

1. Exporting break-lines for slope conformance measurements and waste dump settlement analysis;
2. Geotechnical mapping – remote mapping of structures on inaccessible walls;
3. Identification and monitoring of cracks; and
4. Blast analysis.

All the above are inputs for the overall wall condition assessments, to evaluate the drilling, blasting, and loading efficiency as shown in Figure 4-1.



Figure 4-1: An image of a damaged highwall (Aero Vision Drone Services, 2022).

4.2.1 Exporting break-lines for slope conformance measurements, and waste dump advancement monitoring

Using the Global Mapper or Riegl RiMINING software, break-lines are extracted from 3D meshes and point clouds to visualise the actual crest and toes in the field. The actual crests and toes were compared to the open pit design to evaluate mining conformance to design and highlight any recurring problems with over/undermining as shown in Figure 4-2.

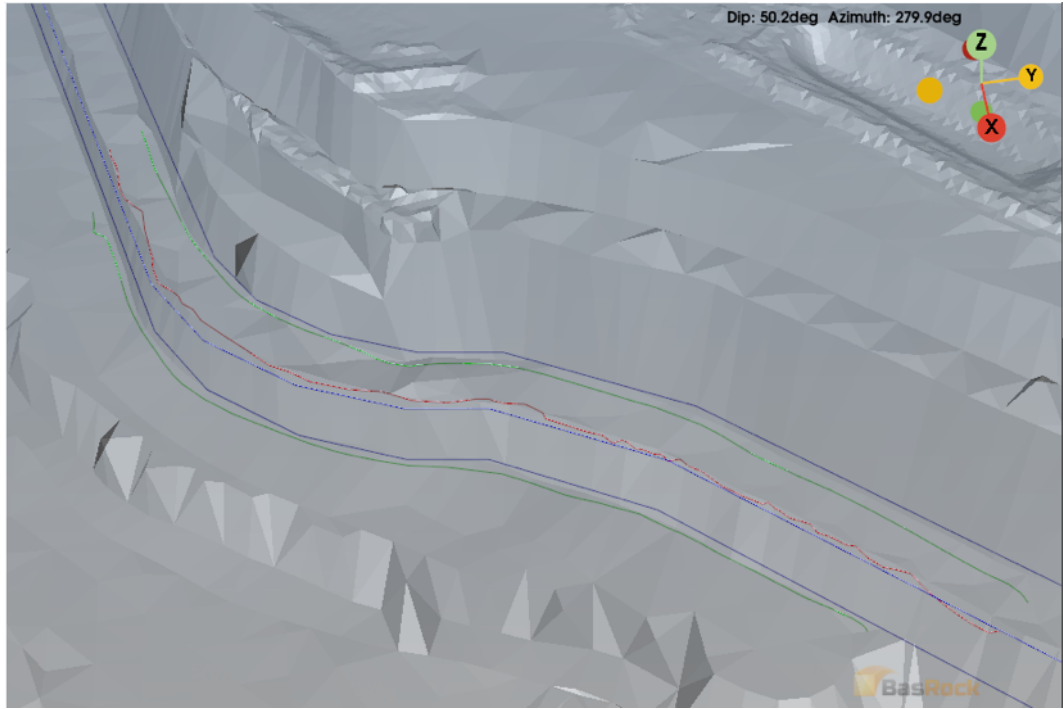


Figure 4-2: Actual crest (red) and toe (green) extracted from the UAV data (Pearce, 2022).

Figure 4-3 illustrates the use of waste dumps crest and toes for calculating dump advancement rates.

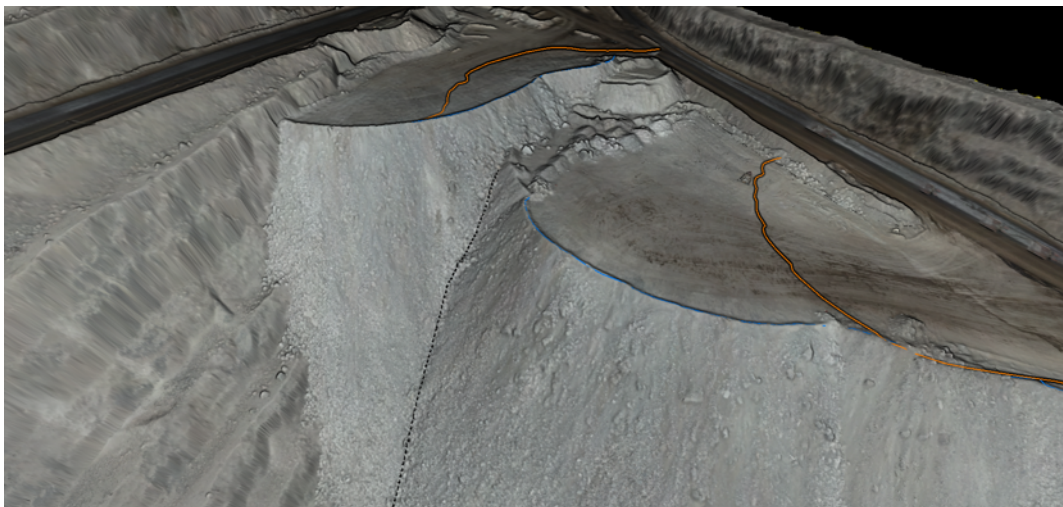


Figure 4-3: Waste Dump 5 advancement measurement using crest distances between a month apart (Pearce, 2022).

The advancement rate is dependent on the type of waste material, the type of foundation material, and the height of the dump. With data from the UAV surveys, safe advance rates can be calculated frequently, to monitor the waste dump advancement and prevent overloading the waste dump.

4.2.2 Geotechnical Mapping – remote mapping of structures on inaccessible walls

Figure 4-4 and Figure 4-5 are Illustrations of the mapped structures imported into Sirovision software for incorporation into structural, geological, and geotechnical models.

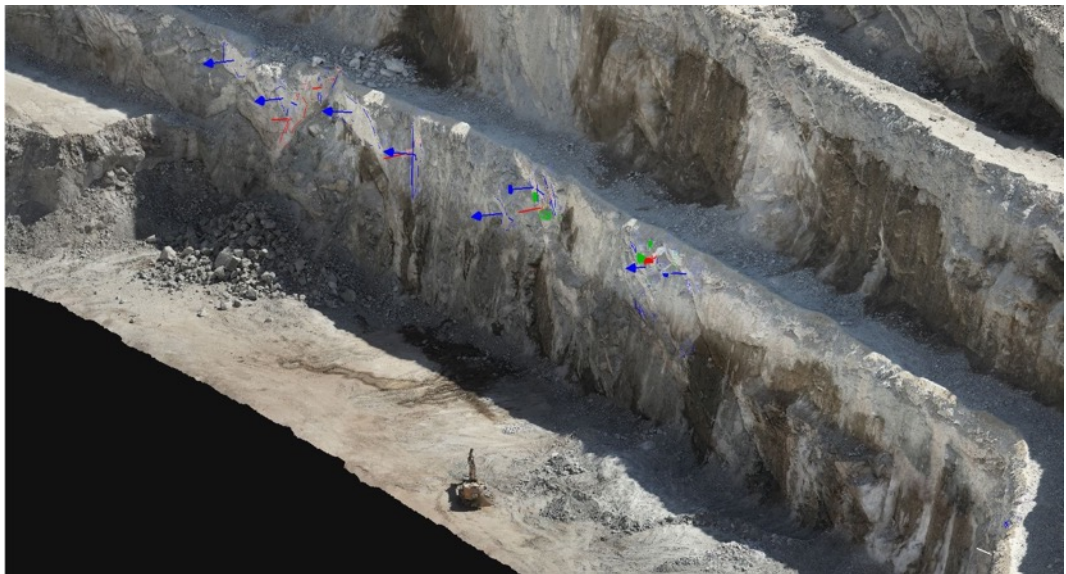


Figure 4-4: Mapping of a high wall using 3D mesh in Sirovision (Pearce, 2022).



Figure 4-5: An image from a high wall assessment flight (Aero Vision Drone Services, 2022).

Figure 4-6 is an example of the geo-referenced 3D model of the current highwall condition, utilised for the pre-meshing project analysis.

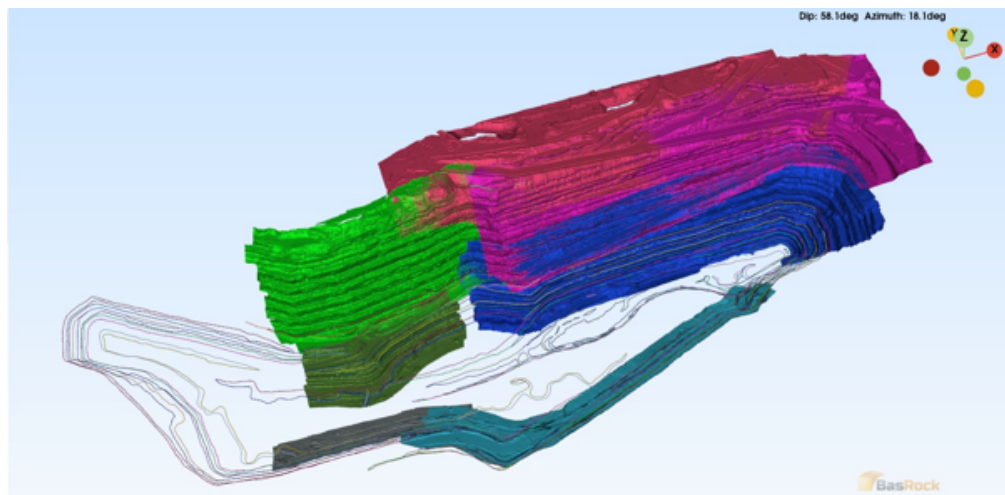


Figure 4-6: A geo-referenced 3D model for the reverse cut area (Aero Vision Drone Services, 2022).

4.2.3 Crack detection and monitoring

New cracks were observed on the tip head of the Waste Dump Five in-pit dump area. A UAV flight was conducted, and the data obtained was used to create 3D models as shown in Figure 4-7. This model was used as a base for periodic comparison and assessment of the area. Additional flights were scheduled for the area with intervals dependent upon the risk factors and were compared to the base to monitor the progression and/or development of new cracks in the area.



Figure 4-7: Cracks observed on Waste Dump Five (Aero Vision Drone Services, 2022).

There have been attempts to digitise the cracks and compare the previous lines to the new image after each flight, to improve the process of identifying new cracks and their development. The manual digitising method proved tedious at the time and is still under review and improvement.

In addition to the monitoring of the in-pit Waste Dump Five, cracks were observed post-blast on the open pit floor in Phase Three, close to a slip ramp in an area where staking and drilling of a pre-split was taking place as shown in Figure 4-8 and Figure 4-9.



Figure 4-8: Large cracks were observed in Phase Three (Aero Vision Drone Services, 2022).



Figure 4-9: A zoomed-in image of the cracks observed in Phase Three (Aero Vision Drone Services, 2022).

A quick flight of the area provided sufficient information for the geotechnical team. The data enabled them to perform visual observations in the field from a safe distance and still have enough information and images for prompt remedial action.

The safety measures put in place included temporary access restrictions to the area, ceasing all activities in the area, such as staking and drilling while continuously monitoring the area. Additionally, utilising the images in the hazard alert notice sent out to all employees eased orientation and ensured that mine personnel are aware of the area and location of the hazard. This hazard alert, coupled with field controls such as barricading, prevented the safety risk of inadvertent access to the area.

4.2.4 Blast monitoring

The data obtained from post-blast flights was used to investigate the presence of wall damage, and/or degree of impact of the blasting activity, especially in areas with existing slope instabilities. Figure 4-10 is an example of an image from a blast video recording that was used for post-blast analysis.



Figure 4-10: A screenshot from a blast video recording (Aero Vision Drone Services, 2022).

4.3 Prism Inspections

4.3.1 Phase one

Figure 4-11 illustrates the plotted prism locations, imported into Global Mapper software from a .csv file, and appended to an open pit model and image. The prisms are colour coded based on their functional status, with red prisms such as 520, 507, 506, and 518 being prisms of concern and the green-coloured prisms being in normal functionality. The location and proximity of the red prisms is used to determine the inspection flight area zoning and scheduling.

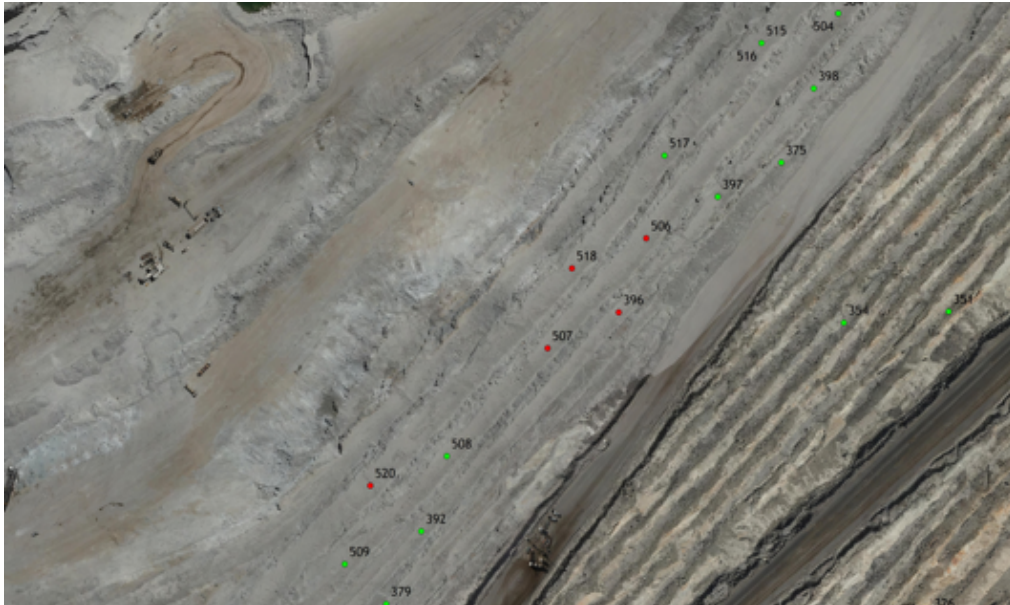


Figure 4-11: Prism locations on an open pit image in Global Mapper software (Aero Vision Drone Services, 2022).

4.3.2 Phase two

Figure 4-12 to Figure 4-15 are images from phase two of the prism inspection process, during which a wide-range flight of the area of the prisms of interest is conducted. This flight aimed to determine the general presence or lack of prisms in the area. In each image, the left side illustrates the locations (blue points) of the prisms on the geo-referenced open pit model. The light blue point on the model is the highlighted prism location, with its corresponding image on the right side of the figure.

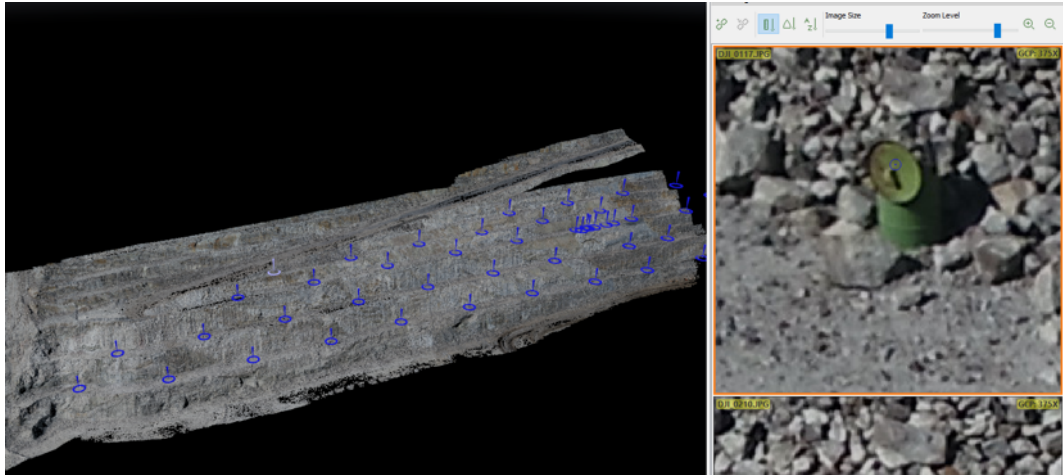


Figure 4-12: Prism location on the open pit model and general status preview
(RUL Internal Data, 2022).

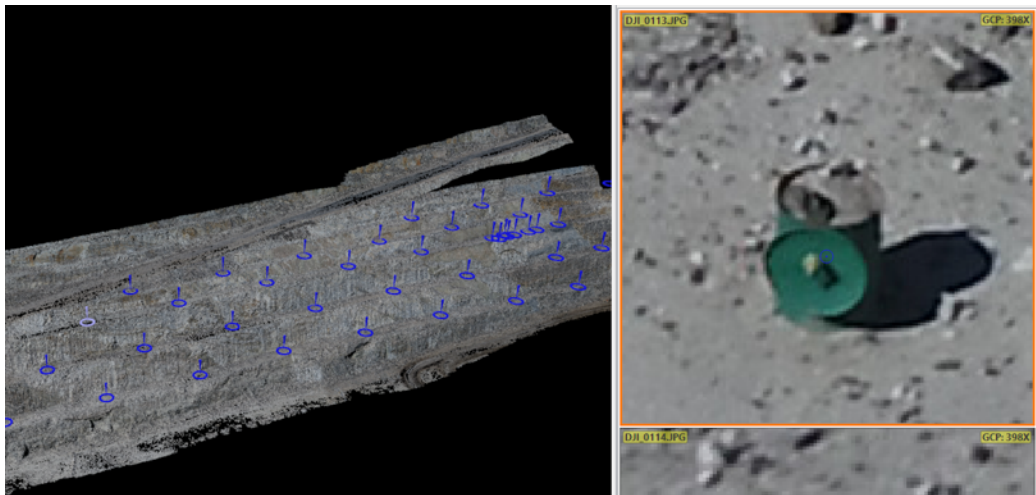


Figure 4-13: Prism location on the open pit model and general status preview
(RUL Internal Data, 2022).

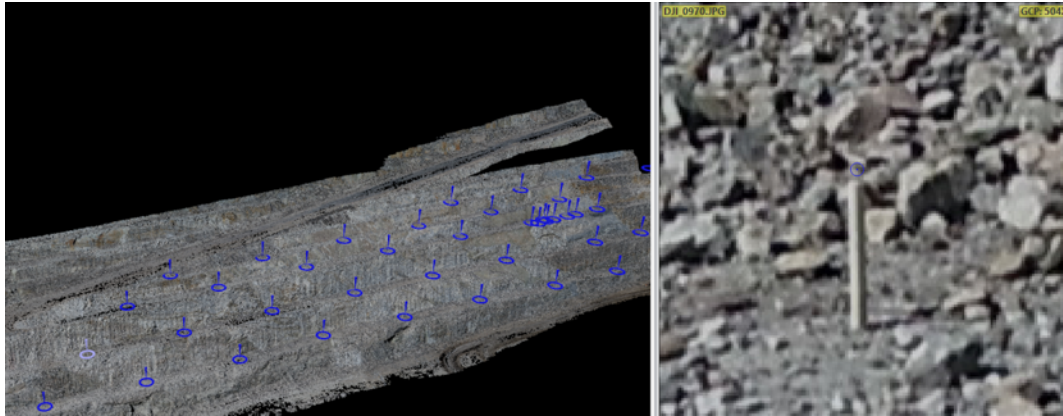


Figure 4-14: Prism location on the open pit model and general status preview
(RUL Internal Data, 2022).

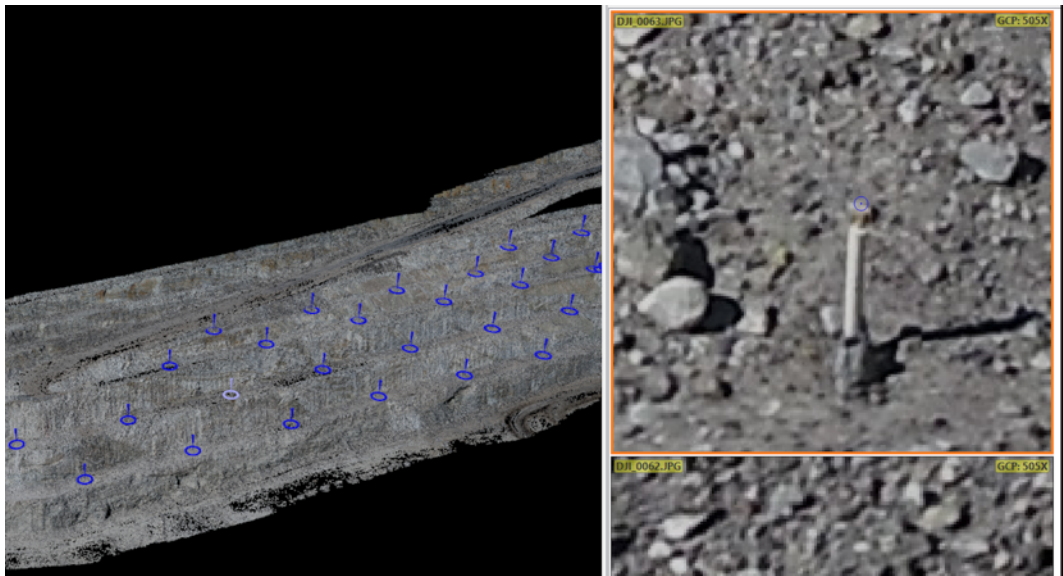


Figure 4-15: Prism location on the open pit model and general status preview
(RUL Internal Data, 2022).

4.3.3 Phase three

A targeted flight of the prisms identified for detailed prism inspection was done in phase three. The findings utilised in the assessment for determining the final prism status. Figure 4-16 and Figure 4-17 are close-up images of a prism, taken during the prism inspection flight, clearly depicting damage to that prism. Figure 4-16 shows the prism glass surface is missing.



Figure 4-16: A close-up image of a prism with a missing glass surface (RUL Internal Data, 2022).

Figure 4-17 shows the deformed structure of the prism. This deformation was suspected to have resulted from fly-rock during a blast, destroying the prism surface and disorientating the prism from facing towards the direction of the monitoring station. Even without damage to the glass surface, this prism would be untraceable and unmeasurable by the RTS due to the wrong orientation it is currently facing.



Figure 4-17: A damaged prism and deformed prism structure (RUL Internal Data, 2022).

The images in Figure 4-18 and Figure 4-19 were taken at different angles during the inspection, clearly showing the extent and type of the prism damage. The red circle in Figure 4-18 illustrates the distance travelled by a broken piece from the prism.



Figure 4-18: An image of a damaged prism (RUL Internal Data, 2022).



Figure 4-19: A prism with a missing glass surface (RUL Internal Data, 2022).

Figure 4-20 illustrates an image of a damaged prism. The prism is near an open edge (highwall), exposing anyone that attempts to replace it to a fall from height risk. The proximity of the prism to the open edge (highwall) may have resulted from excessive back-break of the material during the blast, over-mining and or excessive weathering of the material in the area.



Figure 4-20: A damaged prism near an open edge (highwall) (RUL Internal Data 2022).

4.4 The Concept of UAV Modification for Prism-Cleaning Projects

4.4.1 Dust settlement study

Figure 4-21 and Figure 4-22 are images of Prism 229 fully covered in dust after it was recovered from the beacon next to the in-pit Haul Road 11; the prism was last measured in July 2018.



Figure 4-21: Prism 229 fully covered in dust on the date of recovery (Aero Vision Drone Services, 2022).



Figure 4-22: The dust accumulation on Prism 229.

Figure 4-23 shows the last graphical measurements from T4D software for Prism 229. The last readings of the prism as indicated on the graph were in 2018. The prism was recovered undamaged, still facing in the right direction, but fully covered in dust. The loss of data from the prism is therefore attributed to the covering of dust.

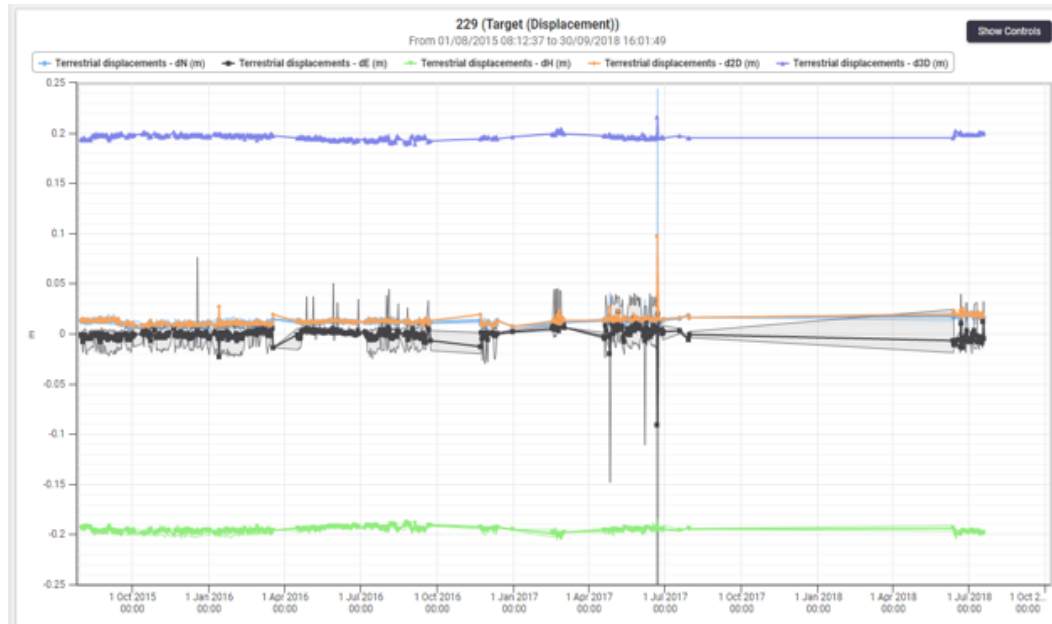


Figure 4-23: An illustration of the last graphical measurements on Prism 229 from T4D software.

Dust Composition Study

A dust sample collected from a dirty Prism 229 shown in Figure 4-24 was analysed to identify the elemental composition of the dust. Dust composition varies for different mine sites, and understanding the composition of site-specific dust is a vital input in the selection of the appropriate cleaning solution. This will prevent utilising solutions that may react with the dust elements in a manner that causes hazing of the prism surface or accelerate dust calcification on the prism.



Figure 4-24: The dust sample collected from Prism 229.

4.4.2 Legal considerations for the use of UAVs for prism cleaning

The methodology for prism-cleaning with UAVs will require dispensing of a cleaning liquid from a UAV towards a fixed prism. According to the NCAA, an additional regulation applies to UAV operations that dispense substances using a UAV (NCAA, 2020).

This regulation is directly applicable to the research aspect of using UAVs for cleaning prisms, as it requires dispensing of a cleaning solution from the UAV to the prism. It is critical to ensure that the required licensing and approval are granted before commencement of the project.

Namibian Civil Aviation Regulations (NAMCAR) part 101.04.1(2) with regards to importing, manufacturing, assembly, and testing of UAVs or RPA and Remotely Piloted Aircraft Systems (RPAS), state that *“Any person intending to manufacture, assemble, modify or test an RPA or RPA system or a component of it, must ensure compliance with requirements of the State of Design, State of Manufacture, State of Import or State of Registration to the extent required by the Executive Director and in compliance with the requirements, where relevant, set out in Namibian Civil Aviation Technical Standards relating to Remote Piloted Aircraft and Remote Piloted Aircraft systems.”* (NCAA, 2020).

This regulation is relevant to the modification theory of UAVs for prism-cleaning projects. To comply with this regulation, all modifications on the UAV unit(s) should be discussed and implemented by the manufacturer before import or registration with the NCAA.

4.4.3 Patents and Utility Models

The definition of a patent according to the Business and Intellectual Property Authority (BIPA) in Namibia is *“an exclusive right granted for an invention of a process providing a novel approach to doing something, or offering a new technical solution to an existing problem”* (Business and Intellectual Property Authority of Namibia, 2022)

A patent is further described as a legal document, that protects the invention of the owner, giving them rights to halt any manufacturing, duplication, use, and or selling of that invention, without the inventor’s consent. Patents may only be provided for innovations not known or in current use by others, as well as those not already patented or described in any printed publications (BIPA, n.d.).

As part of the research, a telephonic inquiry to BIPA, on the requirements and guidelines for registration of a patent for the concept of UAV modification for use in prism-cleaning projects.

The advice obtained from BIPA was that patents may only be applied for upon the creation of an invention. The modification concept is an alteration of an existing idea and therefore does not qualify to be registered as a new patent. The guidance given was to apply for a Utility Model Certification.

According to the World Intellectual Property Organization (WIPO, n.d), a utility model system functions similarly to the patent system and offers protection for minor improvements of existing products, which do not meet the patentability requirements but play a significant role in a local innovation system. Utility models grant an exclusive right that enables the right holder to prevent commercial use of the protected invention, without authorisation, for a finite period (World Intellectual Property Organization, n.d.).

An important note concerning the registration of patents for individuals is to be aware of any legally binding agreements with institutions or employers. This understanding is key in ensuring the appropriate legal approach is taken, to prevent any breach of contract. At the time of the research completion, no intellectual property application had been filed.

4.4.4 Effects of the water spray on the prism

Analysis from the experiment conducted indicates that at a nozzle distance of 4 m away from the prism and stream pressure of approximately 5Mpa:

- There was no water backslash;
- No prism damage; or
- No prism tilt compromises the safety and position of the prism. This may be attributed to the light pressure of the stream by the time it reaches the prism from 4 m away.

The ingress protection (IP) rating of the Leica prisms is IP54 (Podmore, 2022). The first digit in the IP Code denotes the level of protection the enclosure offers against solid objects. The degree of protection against water is indicated by the second number.

The protection of the prism against water (4) is satisfactory for the prism-cleaning research and the outcome of the tests. Only genuine manufacturer prisms must be used, to ensure that the prism function is not affected by water. Non-genuine prisms may not have the same waterproofing protection as genuine manufactured prisms.

4.4.5 UAVs available on the market considered for the proposed prism-cleaning concept

A desktop study comparing four UAVs that are currently on the market was carried out to determine the best UAV option to adopt or partially modify for the prism-cleaning function. The main features of interest in this study were:

- The tank capacity;
- Nozzle type (horizontal or vertical) and flexibility;
- Hovering duration/ battery capacity;
- Safety functions;
- Modification requirements; and
- The cost of the unit.

These UAVs have not been physically tested for this research. A comparative assessment of their specifications was carried out to arrive at a recommendation for the best option to adopt for follow-up research on the prism-cleaning concept. The UAVs compared were:

- XAG P100 Agricultural Drone (Figure 4-25 and Figure 4-26);
- XAG V40 Agricultural Drone equipped with a RevoSpraying System (Figure 4-27, Figure 4-28 and Figure 4-29);
- DJI T40 Agricultural Drone (Figure 4-30 and Figure 4-31); and
- Weifang Little Stone Craft's M50S Agricultural Sprayer Drone (Figure 4-32, Figure 4-33, Figure 4-34 and Figure 4-35).

XAG P100



Figure 4-25: An XAG P100 Agricultural Drone fitted with a sprayer tank. (XAG, 2022a).



Figure 4-26: An XAG P100 Agricultural Drone fitted with a sprayer tank (2) (XAG, 2022a).

XAG V40 Agricultural Drone



Figure 4-27: An XAG V40 Agricultural Drone Agricultural Drone equipped with a RevoSpraying System (XAG, 2022b).

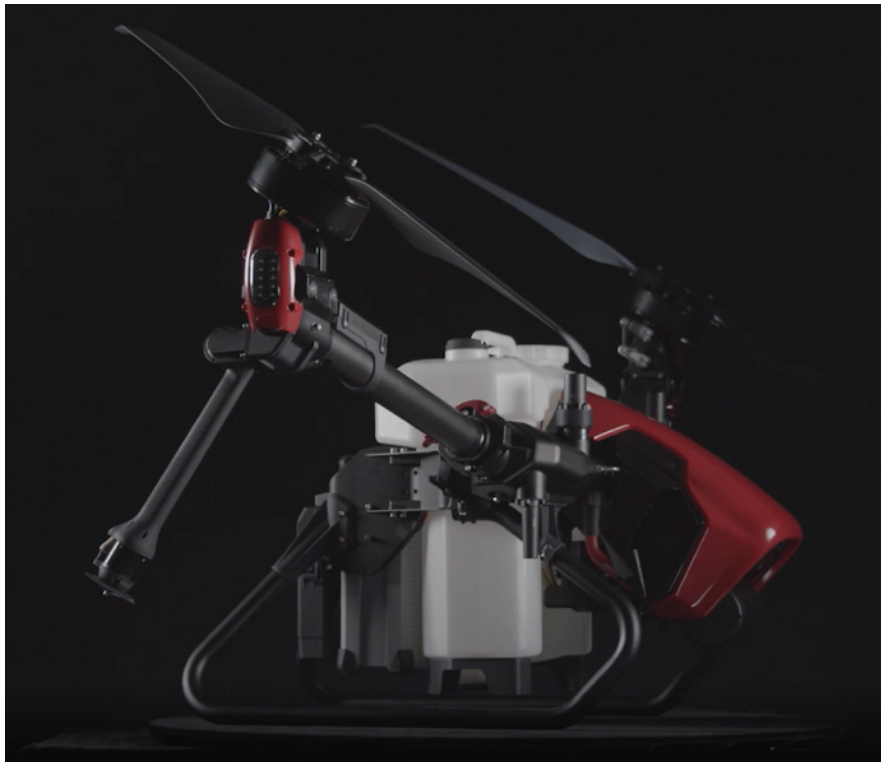


Figure 4-28: An XAG V40 Agricultural Drone equipped with a RevoSpraying System (2) (XAG, 2022b).



Figure 4-29: An XAG V40 Agricultural Drone with an activated RevoSpraying System (XAG, 2022b).

DJI AGRAS T40 Agricultural Drone



Figure 4-30: A DJI AGRAS T40 Agricultural Drone. (DJI Official Website, 2022b).



Figure 4-31: DJI AGRAS T40 Agricultural Drone (2) (DJI Official Website, 2022b).

Weifang Little Stone Craft M50S Agricultural Sprayer Drone



Figure 4-32: Weifang Little Stone Craft M50S Agricultural Sprayer Drone (Weifang Little Stone Craft Co., 2022).



Figure 4-33: Weifang Little Stone Craft M50S Agricultural Sprayer Drone with a horizontal nozzle (Weifang Little Stone Craft Co., 2022).



Figure 4-34: Weifang Little Stone Craft M50S Agricultural Sprayer Drone (Weifang Little Stone Craft Co., 2022).



Figure 4-35: Weifang Little Stone Craft M50S Agricultural Sprayer Drone with an activated horizontal sprayer (Weifang Little Stone Craft Co., 2022).

The results of the research are shown in Table 4-I. The anticipated modifications required are to change the front nozzles from vertical to horizontal or incorporate a 90-degree tilt function on the front nozzles, to enable both horizontal and vertical spray functions. These modifications as required for each model are shown in Table 4-I.

Table 4-I: A comparison of four UAVs on the market for prism-cleaning projects.

				
	XAG P100 Agricultural Drone	XAG V40 Agricultural Drone	DJI T40 Agricultural Drone	Weifang Little Stone Craft M50S Agricultural Sprayer Drone
ATTRIBUTE				
Tank Capacity	40L	16L	40L	60L
Nozzle Type	Vertical	Vertical	Vertical	Horizontal, flexible motion.
Hovering Duration at full tank capacity (battery power fell from 100% to 0%)	6 minutes	7 minutes	7 minutes	Unspecified.
Sprayer Modification Requirements	Change the nozzles from vertical to horizontal, or incorporate a 90-degree tilt function on the nozzle, and install an independent nozzle disabling function.	Change the nozzles from vertical to horizontal, or incorporate a 90-degree tilt function on the nozzle, and install an independent nozzle disabling function.	Change the nozzles from vertical to horizontal, or incorporate a 90-degree tilt function on the nozzle, and install an independent nozzle disabling function.	No modification required identified.
Safety Functions	Terrain radar, obstacle avoidance capability.	Dynamic radar, intelligent obstacle avoidance	360-degree obstacle sensing capability.	Unspecified.
Navigation System Enabled	Yes.	Yes.	Yes.	Unspecified.
Camera Fitted	Yes.	Yes.	Yes.	Unspecified.
Approximate Unit Cost	USD 39 900 (HSE-UAV.com, 2022)	USD 25 000 (HSE-UAV.com, 2022)	USD 26 520.00 (Drone Nerds, 2022)	USD 8000 – USD 10 000.00 (Alibaba, 2022)

The data utilised in the comparison of the UAVs was extracted from the specification sheets of the units on their respective websites. The cost for XAG P100 and the XAG V40 was obtained from HSE-UAV (2022), a XAG approved distributor, for the DJI AGRAS T40 from Drone Nerds, (2022), and the Weifang Little Stone Craft M50S was obtained from Alibaba (n.d.).

The battery capacity and hovering period are identified as one of the main constraints for using UAVs for prism cleaning. The average hovering period at full capacity of the assessed UAVs is seven minutes. This is concerning due to the time required to carefully position the UAV before the prism cleaning can commence, as well as the time required to move from one prism to another.

The Weifang MS50 agricultural drone is the preferred unit for modification for prism cleaning. This preference is based on the unit's horizontal nozzle type, and low cost, rendering it suitable for trial as it is available on the market and does not require major adjustments. Inquiries on the nozzle modification and the related costs required for the other UAVs have not been received at the time of concluding the research. The key concern concerning the Weifang MS50 is the unspecified hovering duration, as well as confirmation of the positioning system and camera fitting. UAVs that are not equipped with accurate positioning systems, as well as front camera functionality also present a challenge of a prolonged period of locating prisms.

Accurate global navigation systems and front camera functionality will enable prompt positioning of the drone, at the desired distance away from the prism. This will reduce the time spent trying to navigate to the prism, as well as reduce the potential accidental damage and shifting of prisms by the UAV colliding with the prism. The mounted camera will not only present live visuals of the cleaning process to assess effectiveness but will also provide data for prism inspections and assessment. The data can also be utilised for ongoing learning for further process improvement by post-analysis of the footage. It is therefore imperative that thorough research and installation of all required systems are done before procuring the UAV for further research.

4.4.6 Economic considerations and operation

A UAV prism-cleaning solution sourcing evaluation was done, assessing the cost, legal requirement responsibilities, as well as operational considerations. These factors were evaluated against the insourcing and outsourcing options as shown in Table 4-II on pages 90 to 91.

Table 4-II: UAV Prism-cleaning Sourcing Evaluation.

	<u>UAV Prism Cleaning Project Sourcing Evaluation.</u>		
		IN-SOURCING	OUT-SOURCING
COST	UAV Acquisition and Shipping fees	Cost borne directly by the company.	Indirect cost, through a contract variation to include the new task in the current UAV service contract or through a new service provider for the UAV prism-cleaning project.
	UAV Modification	Modification cost and arrangements borne by company.	Direct modification cost and arrangements borne by the UAV company, (which specialises in UAV technology). Company invoiced for this service as per variation or new contract agreement.
	Insurance	Cost and arrangements borne directly by company	Cost and arrangements borne directly by UAV contractor company.
	Staffing and Training	Staffing and training cost responsibility borne by the company. Possibility of additional hire to take up the new task and manage the UAV cleaning project. New hire annual package will be inclusive of all benefits, such as pension and bonuses. An additional hire on a fixed contract is also an alternative, however skill retention post training, licensing and exposure is will be a threat.	Staffing and Training are the direct responsibility of the contractor, and recovered from the mining company through a contract fee.

	<u>UAV Prism Cleaning Project Sourcing Evaluation.</u>		
		IN-SOURCING	OUT-SOURCING
LICENSING AND LEGAL REQUIREMENTS	UAV Registration with NCAA	Compliance to NCAA registrations, renewals, applications and all requirements will be the responsibility of the current staff. This will likely end up neglected, as the primary focus and core business values are mining production, leading to potential repercussions with NCAA.	Compliance to NCAA registrations, renewals, applications and all requirements will be the responsibility of the contractor. The contractor is audited on the status of their licences on a monthly basis through the RUL contractor score card process.
	Pilot Licesing and license renewals	Pilot Licesing is the responsibility of the company, and skill retention post training, licensing and exposure is will be a threat.	Pilot Licesing and renewals are the responsibility of the contractor, and they are audited on the status of their licences on a monthly basis through the RUL contractor score card process.
	Relevant Operational permissions from NCAA	Ensuring compliance to NCAA applications and all requirements will be the responsibility of the current staff. This will likely end up neglected, as the primary focus and core business values are mining production, leading to potential repercussions with NCAA.	Compliance to NCAA registrations, renewals, applications and all requirements will be the responsibility of the contractor, and they are audited on the status of their licences on a monthly basis through the RUL contractor score card process.
OPERATION	Task absorption into current workflow	Difficult - the current man power plan will not be able to accommodate additional responsibility of this mangnitude. Alternatively, a new hire should be added to the team and training and licensing provided for all team members. This will able a multi-functional team that can rotate and step in as required, without compromising production duties.	Possible - the contractor can hire additional pilot to assist with the cleaning project either full time, or periodically.

5 RESEARCH ANALYSIS AND FINDINGS

5.1 Introduction

This chapter summarises the analysis and observations of the research, in all the areas of the SSM system at RUL in which the utilisation of UAVs has been adopted.

5.2 Analysis and Findings

5.2.1 Exporting break-lines for slope conformance measurements

Using BasRock GEM4D software, the distance by which as-built crests and toes differ from the design can be easily represented, both visually and statistically are shown in Figure 5-1 and Figure 5-2. The most common file types are usually .dxf / .dwg and csv. Other software can do this in varying degrees of detail, however, GEM4D is the current preference for the geotechnical team on-site (Pearce, 2022).

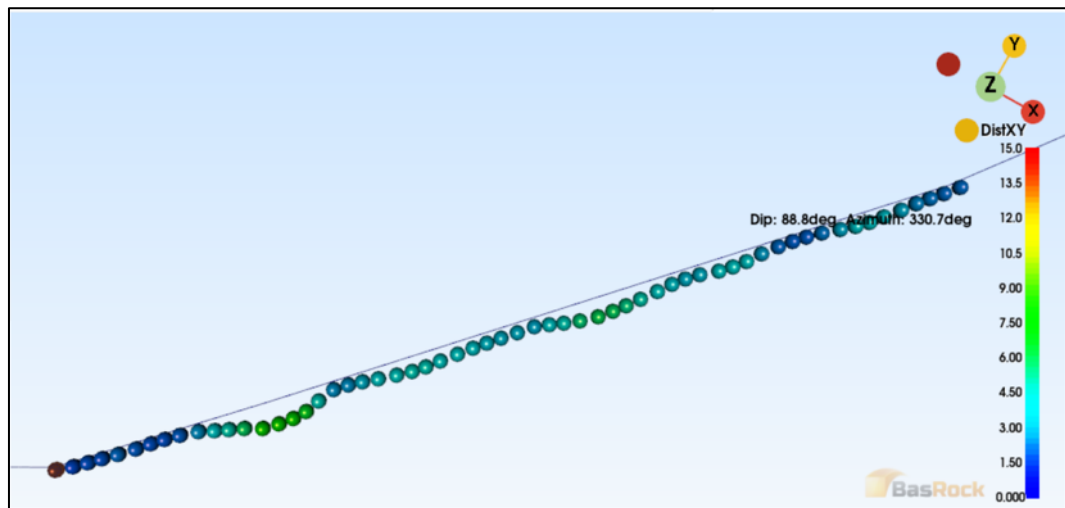


Figure 5-1: Using BasRock GEM4D software to display actual toe deviation from the open pit design (Pearce, 2022).

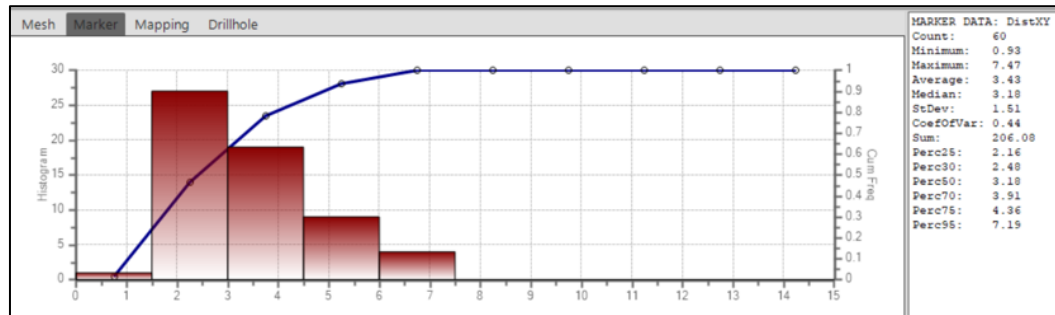


Figure 5-2: A display of results in GEM4D software of the mining and open pit design compliance analysis (Pearce, 2022).

In the process of dump establishment, it is crucial that frequent and continuous monitoring of the dumping activities is conducted to ensure that the appropriate advancement rate is followed. This is for the prevention of dump failures resulting from overloading the dump foundation, or not allowing sufficient time for the dump material to settle and compact (Pearce, 2022).

The ability of UAVs to capture and provide data over large areas frequently and timeously has enabled the geotechnical team at RUL to conduct slope conformance analysis. This includes monitoring the dumping activities at the appropriate frequency, and proactively providing continuous guidance to the mining operation team, hence increasing the safety of the operation.

5.2.2 Geotechnical mapping – remote mapping of structures on inaccessible walls

The use of UAVs reduces the exposure of mine personnel to dangerous open pit environments, which alleviates many of the safety concerns related to geological structural mapping and fragmentation analysis. The structural mapping near the highwall can thus be avoided and maintain the safety of mine personnel.

A crucial advantage of 3D meshes in mapping is the ability to zoom and rotate the image of the high wall for viewing at different angles as shown in

Figure 5-3. This allows for improved ease and accuracy of interpretation and identification of multi-bench structural trends (Pearce, 2022).



Figure 5-3: A 3D model of the highwall (Aero Vision Drone Services, 2022).

5.2.3 Crack monitoring

3D meshes and images obtained from UAV flights are further used to identify, measure and monitor cracks on crests or high walls. These are often inaccessible or in areas that are not safe for mine personnel to approach to conduct visual observations. The ability to visualise the dataset from different viewpoints, such as from an eagle-eye view as shown in Figure 5-4 provides invaluable information on the extent and progression of the cracks while keeping mine personnel out of hazardous areas.



Figure 5-4 A UAV image of a large crack in the highwall (Aero Vision Drone Services, 2022).

5.2.4 Dust settlement research: RUL Haul Road 11

Haul roads and main in-pit access ways are critical monitoring areas, as failure to predict instabilities that can potentially disrupt access to the open pit have high safety risk and economic impacts. The potential safety impact is fatalities and/or injuries due to being struck or buried by rock or delayed medical intervention for any mine personnel trapped and/or injured in the open pit.

Economic impacts may include a prolonged stoppage of operations due to inaccessibility and prioritising the budget for clean-ups to create accessways into the open pit. Whereas failures elsewhere in the open pit could have slightly more flexible clean-up schedules, and increased cycle times, in cases where there are other open roads for access.

5.2.5 Prism inspection

The images obtained during the prism inspection process are an invaluable input into the management of the prism monitoring system. Analysis of these images provides a clear indication of the prism status, in areas that would otherwise be inaccessible. This information is crucial in understanding the reason behind the loss of prism measurements and identifying the relevant remedial actions timeously. The factors affecting accessibility to prisms include open pit design or unsafe conditions for personnel to access, such as poor highwall conditions and fall-from-height risks due to open crests.

The results of the inspection are presented in a form of a colour-coded report, indicating the name of the prism, its status, as well as an image for prisms with concerning outcomes. This report as shown in Figure 5-5 and 5-6 is distributed to the geotechnical and mine survey teams for further action.

Preliminary Prism Condition Report

No Concern	Not Being Read/Requires Inspection	At Risk	Damaged
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Area: Bottom Haul Road 15b

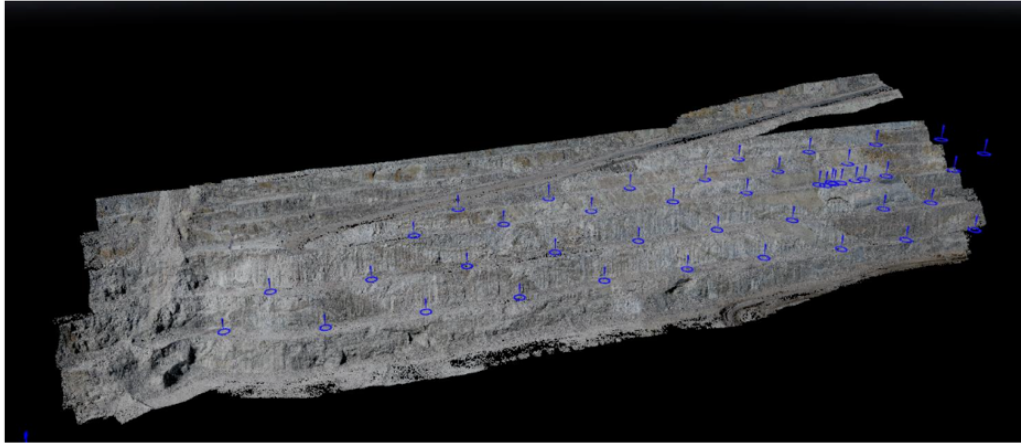


Figure 5-5: A Preliminary Prism Condition Report from a prism inspection
(Aero Vision Drone Services, 2022).

Prism	Condition	Images
368		
369	Comment: Very close to crest	
370		
371	No Drone Data	
375	Not being read	Inspection Pending
376		
377	No evidence found	
378	Boulder Strike	

Figure 5-6: Preliminary Prism Condition report continued (Aero Vision Drone Services, 2022).

5.2.6 Dust settlement on prisms: RUL Haul Road 11

A decommissioned dirty prism was recovered from prism pole 229 near Haul Road 11, presenting an opportunity to assess the dust settlement rate on prisms near a haul road. A new prism was installed on this pole to be used for the dust settlement rate assessment. Figure 5-7 shows the location of prism pole 229 in the open pit in relation to Haul Road 11. The location of the prism is indicated by the yellow circle around the red prism number.

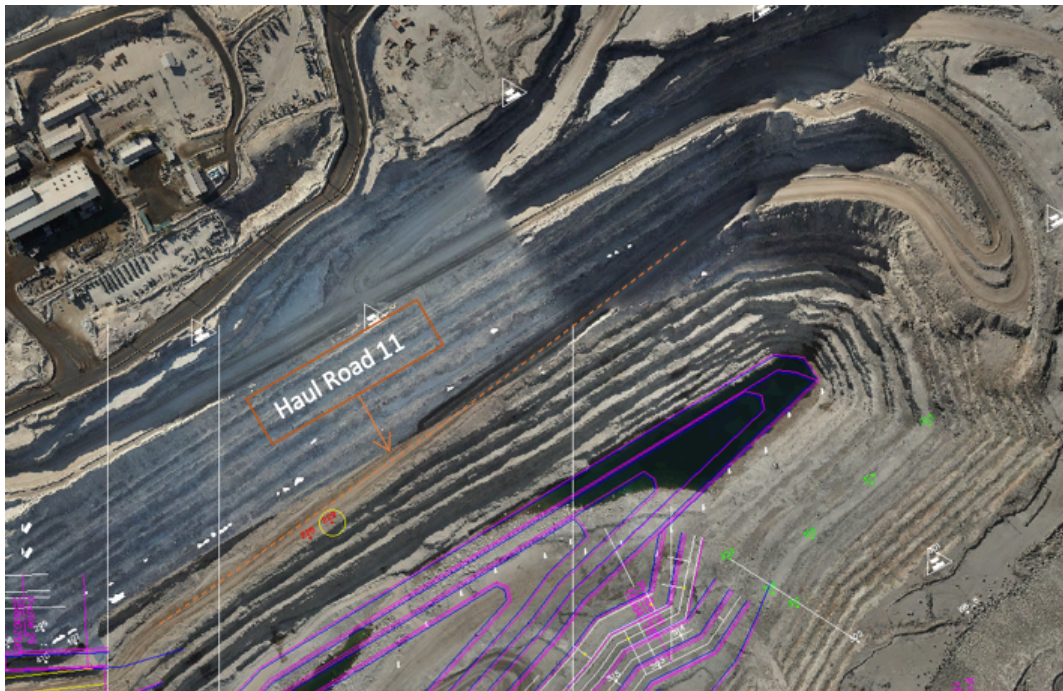


Figure 5-7: The location of prism pole 229 in relation to Haul Road 11 (Aero Vision Drone Services, 2022).

The prism was found fully covered in dust after two months and three days. The dust coverage indicated a high potential of not being locatable by an RTS as shown in Figure 5-8, therefore the prism was removed, ending the field data collection aspect of the study.



Figure 5-8: Dust accumulation on the newly installed prism.

The reason for the rapid dust accumulation rate can be linked mainly to the traffic movement, as well as drilling and blasting activities on the benches below in the area, as the prism was installed facing the closest Monitoring Station, Trolley One, which is across from Haul Road 11.

5.2.7 The concept of UAV modification for prism-cleaning projects

At a 4 m distance from the prism, the dust accumulation is cleaned up in approximately four seconds. The nozzle aimed at the centre of the prism cleans off the dust significantly and a minor amount of mud accumulation is observed at the bottom of the prism housing as shown in Figure 5-9.



Figure 5-9: Initial outcomes of the spray cleaning experiment (Type: Leica GPR111).

Aiming the spray stream slightly below the prism centre significantly reduces the residual mud settling on the prism base. This will not obstruct any future signal reflection from the prism, however, ongoing accumulation may be an area of concern and requires improvement. A recommendation is to drill a small hole at the bottom of the prism housing that allows for water and mud drainage, with great care to prevent damaging the prism.

Figure 5-10 shows a significant reduction in the mud accumulation at the bottom of the prism achieved. There was no tilting of the prism observed during the experiment at a 4 m distance from the nozzle to the prism.

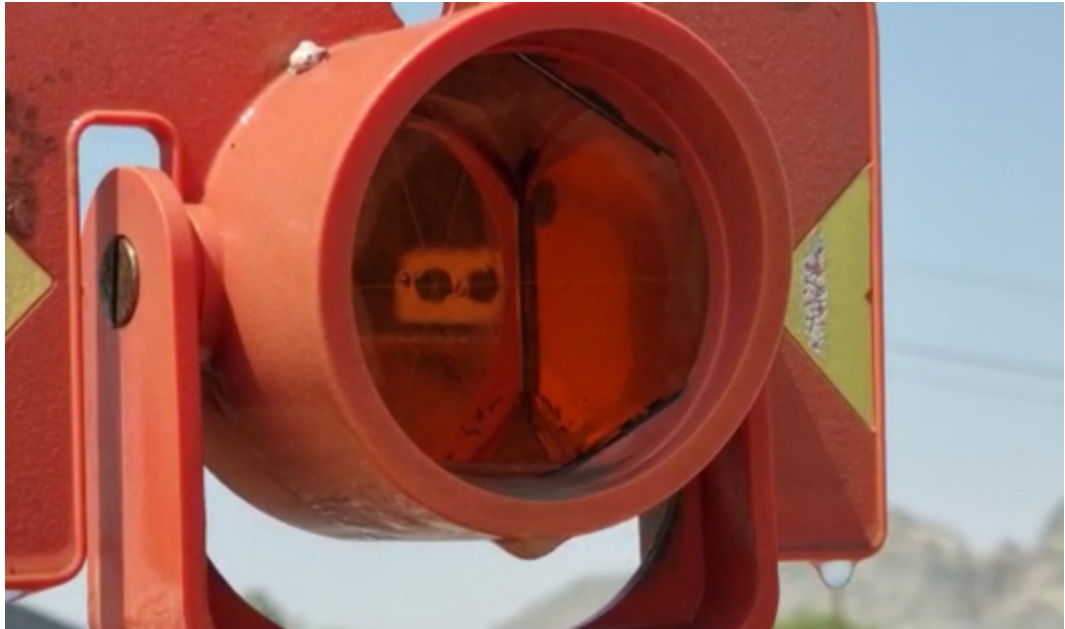


Figure 5-10: Spray cleaning outcome.

It took approximately 80 seconds for the prism surface to dry out after the washdown, this reduces the concern of more dust settling and calcifying on the prism if the water stands on the prism surface for too long. The drying period was deduced by closely filming the prism between wash down and drying and calculating the drying period. Figure 5-11 displays a partially dry prism after being washed down.



Figure 5-11: An image of a partially dry prism

No backslash of water was observed during the experiment at 4 m, this can be attributed to the lightness of the spray stream, as well as the distance from the prism. A slight backward tilt of the prism section labelled “A” was observed when sprayed with the same water pressure at a 3 m distance. However, no movement of the section labelled “B” was observed. The position integrity of section “B” of the prism is crucial and should be tightly screwed onto the grouted pipe during prims installation to ensure accurate readings.

It is the author’s understanding that a slight tilt of section “A”, although not ideal, would not change the accuracy of the measurement. The Trimble S9 RTS used for monitoring projects is equipped with Trimble FineLock technology, which enables the RTS to lock on the centre of the prism (Trimble, 2023).

The measured position of the prism centre is expected to remain unchanged, as it is dependent on the movement of section “B”. The main concern with a higher tilt magnitude is the prism swivelling too far up or down that it faces away from the RTS line of sight, rendering it untraceable by the RTS, and increasing data gaps. For the UAV modification trial, the appropriate nozzle distance from the prism, and its positioning on the UAV is an important aspect to ascertain through further research with a UAV.

The wind direction and locality of the prisms should be considered during the cleaning schedule, to prevent redirection of the water, or tail winds effects on the UAV. The experiment needs to be replicated for the UAV to verify the suitable distance (4 m) with a 5MPa pressure.

5.2.8 Dust composition study

The results from the dust composition study as shown in Table 5-I indicate that approximately 91% of the dust deposited on the prism is silicon dioxide (SiO₂) and approximately 2% is iron (Fe), with the remainder of the composition, are traces (Elago, 2022).

Table 5-I: The results from the composition study of the dust sample collected from Prism 229 (Elago, 2022)

	Sample Id	R	Acquisition Time	QC Status	Dataset File	Method File	Mn 403.075	Fe 259.939	Mg 285.213	Cu 213.597	Mo 202.031	U 424,167	Cr 267.716	P 177,434	
60	Calibration Curves		2022/08/16 14:23:08												
	Sample Id	R	Acquisition Time	QC Status	Dataset File	Method File	Mn 403.075	Fe(%)	Mg (%)	Cu (%)	Mo (%)	U (%)	Cr (%)	P (%)	SiO ₂ (%)
61	BLANK		2022/08/16 14:24:41	Passed	DAVE ORGANICS	SOLUTE BALANCE MULTI	-2,044	-9,305	-0,017	-0,007	-0,007	-0,004	-0,008	-0,004	
62	100PPM		2022/08/16 14:26:14	Passed	DAVE ORGANICS	SOLUTE BALANCE MULTI	99,149	104,500	103,200	99,560	110,000	103,000	106,000	105,000	XRF confirmation required
65	Prism 229 (1)		2022/08/16 14:31:01		DAVE ORGANICS	SOLUTE BALANCE MULTI	-0,507	1,880	-0,004	-0,008	-0,008	-0,004	-0,008	-0,003	90,700
66	Prism 229 (2)		2022/08/16 14:32:35		DAVE ORGANICS	SOLUTE BALANCE MULTI	-1,810	1,830	-0,003	-0,008	-0,008	-0,004	-0,008	-0,003	91,200

The advice from the laboratory was that it is safe to use normal tap water, or iodised water for cleaning purposes, as none of the compounds or elements will react with the water which may result in hazing or damage of the prism surface (Elago, 2022). Operations must use genuine manufactured prisms, instead of cheaper substitutes, as amongst other benefits, there is no expected corrosion for genuine manufactured prisms.

5.2.9 A comparison of prism-cleaning and inspection methods

A comparison of the different prism-cleaning and inspection methods, including the proposed concept of adopting UAV technology to the prism-cleaning projects, has been done. The methods of prism cleaning include:

- Manual cleaning by mine personnel;
- Abseiling services; and
- Utilising a UAV.

These methods have been analysed against safety, prism accessibility, cost as well as overall effectiveness and the outcomes are shown in Table 5-II.

Table 5-II: A comparison of prism-cleaning and inspection methods.

Prism Cleaning and Inspection Methods			
	Manual cleaning by Employees	Abseiling Services	Proposed UAV Solution
Safety Risk	High risk - personnel exposure to open crests, proximity to highwall with limited bench step out, and limited emergency exit options.	High risk - personnel exposure to potential rope tangling trauma, slope failures, rock falls, as well as fall from height.	Safe - remotely operated , personnel are not indirect contact with hazardous areas. Most UAVs are equipped with collision avoidance technology, protecting them against coliding into objects.
Prism Accessibility	Poor - limited to no safe access to prisms on upper benches, or in active work areas. Access to upper benches will require a crane and man cage, which by recent experience onsite has proven difficult to secure. The challenges experienced with the crane and man cage option included manpower constraints. Difficulty to secure crane operators, surveyors, and protection services personell at the same time, due to production priority and/ weather constraints. Weather, such as strong and dusty wind made it unsafe to operate the crane and man cage.	Good - abseilers are able to reach most areas, provided the highwall conditions allow for safe anchor installation and abseiling. Operations are however halted during windy conditions, to prevent rope tangling trauma, when it is raining, due to increased slope failure risk, as well as when it is too hot so as to manage fatigue.	Very good - with the tank attachment to the UAV, there is minimal to no compromise in the ability to access and manuevre inaccessible upper benches. The pilot is required to assess and identify the closest accessible areas, such as the pit floor or permanent ramps to fly from for the operation.
Cost	No direct cost implications, as employees are providing the services, both for cleaning, and operating the cranes and man cage. Indirect costs in a form of crane maintainance can be assumed minimal, as the cranes already have planned/scheduled maintainance plans.	The cost is dependent on the number of prisms to be cleaned, and the distance (vertically from anchor points). The average costs reviewed rages from R1700.00 (0 m - 20 m) to R3500.00 (80.1 m to 100 m) per prism. Example, on avarege, the cleaning of 60 prims once off, will cost a minimum of R170 000.00. Approximatly R2800.00 per prism.	The cost of acquiring a UAV alone ranges between R180 000.00 - R780 000.00. Additional costs include modification fees, once offshipping costs, additional spares , service fees and maintenance fees, as well as pilot costs.
Overall Effectiveness	Ineffective option, due to the high safety risk, little to no access to upper bench prisms, as well as challenging logistics.	More effective than utilising employees, however it is a very high safety risk task, and time consuming. The time and effort required to clean depends on the conditions of the highwall, the vertical distance to abseil, the horizontal distance from the anchor point, as well as the setting up of various anchor points.	High potential of being highly effective once modification is successfully implimented. The method has not been fully tested yet, therefor there is a range of potential unkonwn expectations.

The analysis of the comparison of prism-cleaning and inspection methods indicates that abseiling contractors as shown in Figure 5-12 is a more effective option than utilising mine employees to clean prisms. However, it is still an extremely high-risk exercise and exposes abseiling personnel to hazardous conditions. The potential risks associated with abseiling include rope tangling trauma, falling from a height, slope failures, as well as rock fall incidents (Mulenga, 2022).



Figure 5-12: An image of abseilers working against a highwall. (Marshal Geotechnical Services, 2018)

The proposed modification and/or use of UAVs for the prism-cleaning task remove mine and abseiling personnel from hazardous environments. In the long run, UAV utilisation for prism-cleaning has the potential of being the best option of the three, in terms of safety, cost, as well as implementational effectiveness. While untested, it is estimated to be an operational low-risk, high-reward venture as UAVs have proven themselves in various industrial processes and continue to become more flexible in functionality at affordable costs.

6 CONCLUSION AND RECOMMENDATIONS

6.1 Introduction

The objective of this research was to identify areas in the RUL SSM processes, where the incorporation of UAV technology has improved the SSM systems and procedures. The research also aimed to identify the potential benefits of such incorporation by answering the following questions:

- Can the utilisation of UAV data for highwall inspections and crack detection provide reliable results of the condition of the slopes?
- Can a UAV be successfully modified to meet the design parameters required for the effective cleaning and inspection of prisms in open pit environments?
- Will the incorporation of UAV technology in the TARPs as a visual aid for the evacuation and rescue of mine personnel and equipment improve safety?
- Do the benefits warrant the economic investment to incorporate UAVs in the SSM system?

The key findings and recommendations of the case study and the results of the experiments and evaluations conducted are discussed in this chapter.

6.2 Summary of Chapters

This report has presented six chapters, the content of which is briefly discussed in the paragraphs below. Chapter 1 introduced the incorporation of UAVs in the SSM system at RUL operation as the key focus. The loss of access to certain in-pit areas and its effects on prism maintenance, and geotechnical functions such as physical visual observations, and mapping have been identified as key problems in the system. The loss of access can be attributed to the open pit design or unsafe slope conditions for personnel access. The safety improvement gained by incorporating UAVs was highlighted as a justification for the research. Additionally, this chapter

covered the hybrid of quantitative and qualitative research methodology used for the research;

Chapter 2 reviewed relevant literature in the SSM and UAV fields highlights the key aspects of SSM and the benefits of the adoption of UAV systems in slope management processes. The different schools of thought regarding reflectorless monitoring as an equal or alternative substitute for prism monitoring were also discussed in this section;

Chapter 3 was an in-depth discussion of the research approach presented in chapter three. This discussion reviewed the following aspects:

- The design of the research;
- The UAV data acquisition process from AVDS;
- The geotechnical team processes;
- Desktop studies of various UAVs in the market; and
- As well as the data validation processes.

Chapter 4 was a combination of all the data and inputs utilised in the study to answer the research questions. These inputs included the geotechnical data acquired, the field experimentation for the prism inspections and prism washing proposal and evaluations of the available prism-cleaning methods.

Chapter 5 discussed the analysis conducted on the research data collected from the field observations and the experimental and desktop studies conducted. The resultant findings were also discussed in this chapter.

Chapter 6 was the conclusion and recommendations that resulted from the analysis and evaluations to answer the research questions. Particularly the overall safety improvements gained by incorporating UAVs in the SSM system.

6.3 Research Observations

6.3.1 Initial and complimentary studies

The complementary studies carried out for this research include the in-pit dust settlement study, as well as the prism washing experiment. The results of both have been used as inputs in the development of the concept of utilising UAVs for prism-cleaning projects.

6.3.2 Key findings and observations

The use of unmanned aerial vehicle data in geotechnical inspections

The following characteristics of UAV technology have been observed to render the technology's incorporation into the geotechnical and mine survey processes at RUL invaluable for safety and process improvement and compliance with the SDMP:

- UAVs are capable of timeously collecting large datasets over wide areas, creating an inventory of historical data for conformance analysis, and post-failure back analysis;
- Prompt deployment, minimum notice on flight requests required, as well as short data turn-around time in various formats, and different coordinate systems. These factors enable quick assessments, and seamless data transfer between stakeholders, facilitating prompt decision-making in varying degrees of urgency;
- The ability to access and manoeuvre in areas that could be unsafe for mine personnel to enter, eliminates the safety risk exposure, without compromising the monitoring processes; and
- The data obtained from pre, during, and post-blast flights aid in the investigation of the presence and/or degree of impact of the blasting activity. This data also enables the proactive implementation of geotechnical controls, as well as ongoing guidance for safe mining operations along the slopes.

By utilising images and geo-referenced 3D models, the extraction of crest and toes enable ongoing safe evaluation of mining conformance to design and highlights recurring problems with over/undermining. Continuous dump advancement rate monitoring, as well as crack identification and progression monitoring, is also achieved by utilising UAV data.

Additionally, the use of geo-referenced 3D meshes and images, using specialised software such as Sirovision enables safe and accurate mapping of structures and geological contacts that are inaccessible or out of reach. An example of this is shown in Figure 6-1 (Pearce, 2022).

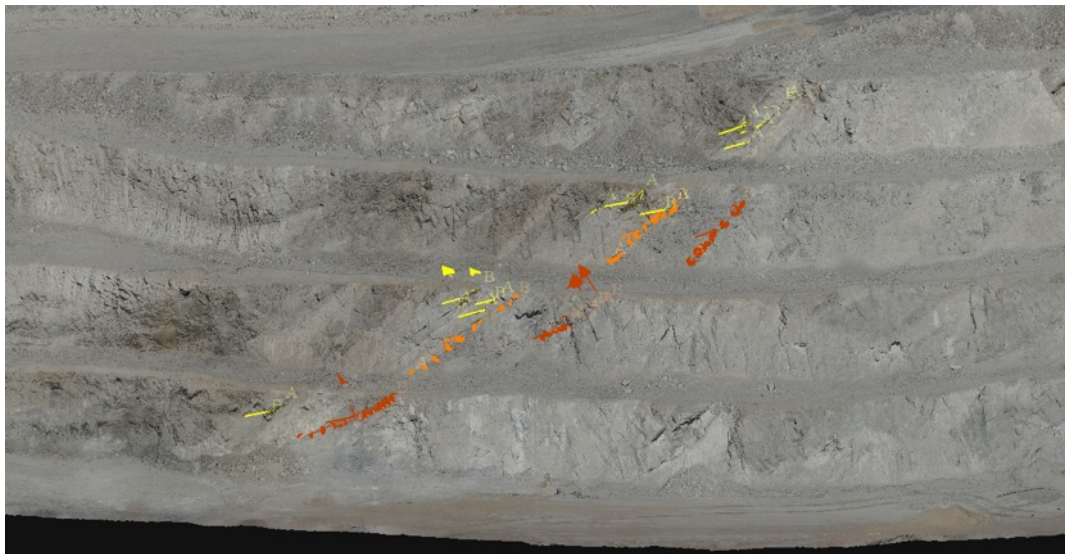


Figure 6-1: Mapped structures on an inaccessible highwall (Pearce, 2022).

All of the various applications of UAV data in the geotechnical processes are ultimately utilised to assess the overall condition of the final highwall as shown in Figures 6-2 and 6-3. This considers different factors such as the rock mass properties, the impact of geotechnical structures, blasting efficiency/damage, drilling accuracy, and wall cleaning/loading practices.

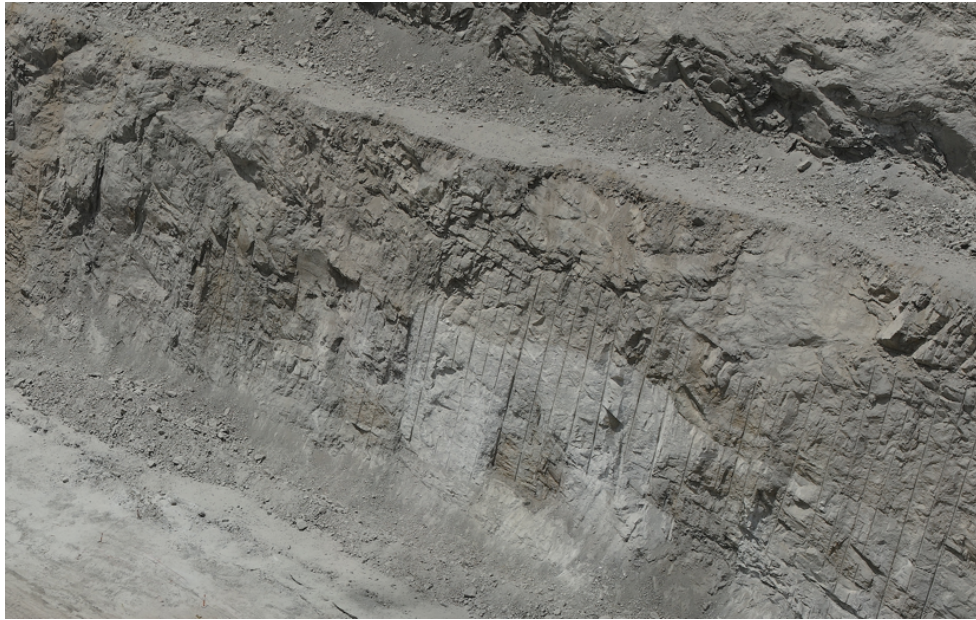


Figure 6-2: Final highwall condition image.(Aero Vision Drone Services, 2022).



Figure 6-3: An image from a final highwall assessment (Pearce, 2022).

3D meshes make these observations easier, as it allows for accurate assessment of the safety of the high walls to indicate walls that are not safe to approach, areas of excessive slope angle, or are no longer accessible (Pearce, 2022).

Overall wall assessment rating

Overall wall assessment rating is an indication of the final wall condition, in percentages, aimed at indicating the condition of the highwall, performed by the geotechnical team. A higher final wall assessment rating indicates a favourable wall condition. The process also highlights areas of improvement in operational activities as a proactive measure towards the prevention of failures due to negligence. These activities include drilling and blasting activities, as well as toe clean-ups. The final rating is based on the assessment of the following aspects:

- Rock properties;
- Structures;
- The effects of blasting activities in the area;
- The drilling effects; and
- The final wall cleaning.

The assessment is done by field observations and UAV data analysis. Stronger rock properties get a higher rating and weaker brittle structures get a lower rating. Areas with visible pre-split barrels get a higher rating than those left with frozen toes and overhangs. Material left on the toe or poor highwall scaling gets a lower percentage towards the overall wall rating (Pearce, 2022). Figure 6-4 is a representation of the overall wall assessment.

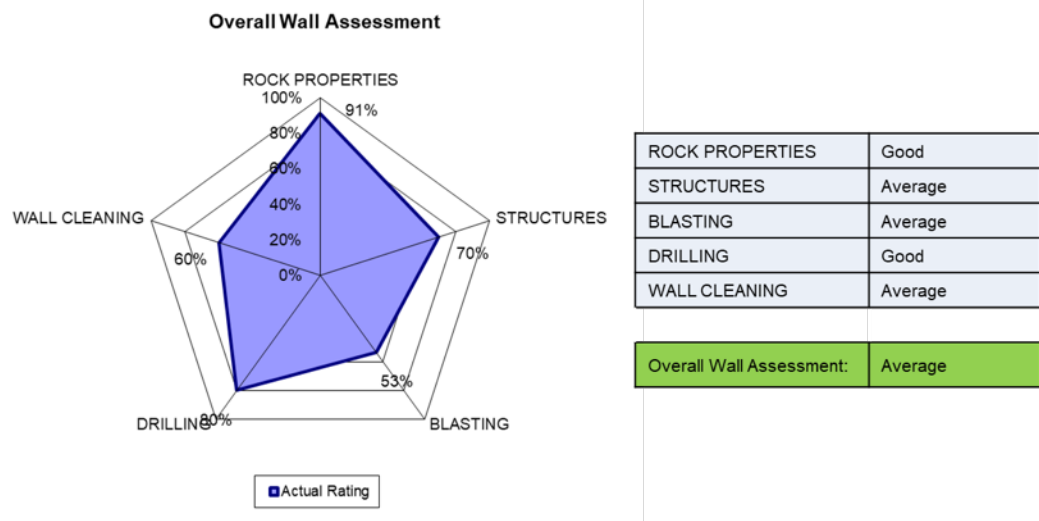


Figure 6-4. A presentation of the outcome of the overall wall assessment process (Pearce, 2022).

The criteria for the rating are shown below:

- Poor/ unfavourable 0% - 50%
- Average 51% - 70%
- Good 71% - 100%

Dust settlement study: RUL Haul Road 11

The findings of the dust settlement experiment indicated that in approximately two months, a prism in the vicinity of a haul road can be fully covered by dust. This highlights that in-pit access roads, which are critical monitoring areas, are at a higher risk of becoming monitoring blind spots due to dust accumulation on the prisms.

This is a key input in prism-cleaning planning and scheduling, as it indicates a need to clean the prisms on access roads at least once a month to ensure sufficient prism measurement availability. An additional recommendation is regular or increased dust suppression on the main haul roads, to reduce dust generation from the continuous hauling activities in the area.

Haul roads and main in-pit access ways are critical monitoring areas, as failure to predict instabilities that can potentially disrupt access to the open pit have high safety risk and economic impacts. The potential safety risk impact is fatalities due to being struck or buried by rock or delayed medical intervention for any mine personnel trapped and/or injured in the open pit.

The potential economic impacts may include a prolonged suspension of operations and reputational damage. Additionally, slope failures can sterilise an orebody due to the amount of failure rock covering it. The prohibitive cost to rehabilitate the mine to resume production may result in premature closure of the mine.

It is recommended that further dust settlement trials are undertaken, to test dust settlement in different areas of the open pit, and in different seasons. The method for prism inspections using UAVs can be used to conduct these trials. The results can be a valuable input into optimising prism cleaning frequencies and scheduling.

Prism inspection

The utilisation of UAVs for the prism inspection process has proven to be instrumental in the management of the prism monitoring system. The images acquired from UAVs provide a clear indication of the prism status, in areas that would otherwise be inaccessible to mine personnel. Understanding the prism status in the open pit accelerates the identification and implementation of the appropriate remedial actions, thus improving the data integrity and defensibility of the system.

The concept of UAV modification and/or adoption in prism-cleaning projects

The experiments and trials discussed below were conducted to develop the concept of modifying or adopting a UAV for cleaning prisms, especially in inaccessible areas. The key findings and observations have been used to develop this concept:

- An analysis of dust settlement on prisms near a haul road was done to serve as input for the proposed cleaning frequency. The results indicated complete coverage of the prisms by dust within two months of installation, suggesting that a cleaning frequency of at least once a month is adopted.
- A laboratory test of the dust sample was requested to determine the composition of the dust on the prisms. The results were important in identifying a cleaning solution that preserves the prism's reflective characteristics for measurement. The test indicated that none of the identified dust components poses a risk of reacting with water or iodised water in a manner that will result in scaling or hazing the prism surface.
- The prism-cleaning trial was done utilising a pressure washer, tap water, and a dust-covered prism recovered from the open pit. The purpose of the trial was to identify the optimum cleaning parameters that promote the effectiveness of the cleaning process while honouring the safety and positional integrity of the prism.

The outcomes of the trial allude to the following parameters for effectively cleaning one prism, without significant backlash and no tilting of the prism:

- Water pressure: approximately 5Mpa;
- Distance of nozzle from the prism: 4 m;
- Nozzle aims to prevent mud accumulation at the prism bottom: slightly below the prism centre;
- Spraying period: four seconds; and

- Prism drying period: 80 seconds.

The Leica GPR 111 (as shown in Figure 3-7 and Figure 5-9) and the GPR121 (circular prism with holder) or the GPH1P (Precision prism), are predominantly used on Reference beacons which are located on stable ground and usually at a safe distance back from highwalls. These prisms within the SSM beacon network system can be cleaned relatively safely due to safe accessibility. In comparison, prisms installed as monitoring points in hazardous areas such as on the edge of highwalls or bench faces are inaccessible due to safety issues. The prisms at the highest risk of inaccessibility and would be cleaned frequently with a UAV are the Leica GPR112 Monitoring prism (shown in Figure 2-1) utilised on the edge of highwalls or bench faces. These prism types are of a rigid construction configuration and are therefore not prone to prism tilting.

A comparison of four UAVs on the market was carried out aimed at identifying the best unit to adopt or partially modify for the prism-cleaning function. The units assessed were the XAG P100 Agricultural Drone, XAG V40 Agricultural Drone, DJI AGRAS T40, and the Weifang MS50 Agricultural Drone.

The Weifang MS50 Agricultural Drone is the preferred unit for modification for prism cleaning. This preference is based on the unit's horizontal nozzle type and low cost, meaning that it is almost ready for trial as it is on the market without further major adjustments. The outcomes of the comparison of different prism-cleaning options highlighted the use of UAVs as the option that strikes the best balance in terms of safety, functionality, and cost.

A sourcing evaluation for the UAV prism-cleaning service was conducted to evaluate the best sourcing option between insourcing and outsourcing, using RUL as a case study. The results favoured the outsourcing option mainly due to constraints of the current manpower plan, the cost, as well as the NCAA compliance requirements.

Table 6-I illustrates the attributes for trialling the UAV modification for prism-cleaning projects. The data included in the table is the outcome of all the trials conducted for the development of this concept to date and whether this can be replicated using the preferred choice of UAV.

The UAVs have not been physically trialled for this research and further trials must be undertaken to utilise a UAV for further development of this concept. The trials are aimed to either replicate the experiments already completed or identify new approaches to ascertain the appropriate cleaning parameters utilising a UAV. Further discussion on the trial aspects and areas of clarification are discussed in section 6.6.1.

Table 6-1 The attributes for the concept of UAV modification for prism cleaning.

Attributes for the concept of UAV modification and/or adopting in prism cleaning projects

ATTRIBUTE	PROPOSED TRIAL DETAILS
UAV unit to trial	Weifang MS50 Agricultural Drone
Cleaning solution	Tap water/ iodised water
Water pressure	Approximately 5 Mpa
Distance of nozzle from the prism	4 m
Spray nozzle aim to prevent mud accumulation at the prism bottom	Slightly below the prism centre
Spraying period	four seconds
Prism drying period	80 seconds
Minimum cleaning frequency for prism in Haul Road proximity	Once a month

6.4 Research Contributions

This research has the potential to improve safety by removing mine personnel from working in hazardous areas. Thus, aiding with prompt decision-making in emergencies, as well as by improving data integrity and the overall effectiveness of an SSM system.

The research will contribute to the body of knowledge in the form of additional literature on the incorporation of UAVs in SSM in open pit environments. Furthermore, the studies done on the proposed concept of utilising UAVs for cleaning inaccessible prisms will serve as a starting point for further research into utilising UAVs for prism-cleaning projects.

6.5 Research Limitations

Financial constraints prevented the procurement and modification of a UAV for prism-cleaning for the research process as initially planned. Although multiple attempts to secure research funding and or partnerships with UAV manufacturing companies were done.

This has limited the research to just developing a theoretical concept of the cleaning project, using desktop studies and experimental work with a water jet spray. Modifying and trialling an actual prototype would have been of great value add to mining and SSM. The author plans on further research of the concept once funding for further research and development of the prototype becomes available.

6.6 Recommendations for Future Research Work

6.6.1 UAV modification for prism-cleaning projects

The author recommends the actual trialling of a UAV modification for use in prism-cleaning projects, with attention paid to:

- Higher order surveying of prisms to be undertaken during the test phase of utilising a UAV for prism cleaning, to ascertain the position integrity of the prisms after spraying;
- Determining the optimal hovering distance from the prism that enables suitable cleaning with the water pressure that the UAV cleaning system can supply;
- The effects of the cleaning fluid pressure from the UAV and its distance from the prism, on the safety, and positional integrity of the prism;
- The effective cleaning scheduling, against the location of the prism such as the prism's proximity to haul roads and the mining activities in the area;
- Undertake further dust settlement analysis trials to evaluate dust settlement in different areas of the open pit, and in different seasons. The method for prism inspections using UAVs can be used to conduct these trials. The results can be a valuable input into optimising prism cleaning frequencies and scheduling;
- The number of prisms washed down in each flight, using one full tank of cleaning fluid and against the hovering time before battery recharging is required;
- Considering that the IP rating of the prisms is 54, it is crucial to monitor the physical implications that direct stream washing could have on the prism. This is important for prompt identification and remedial actions for any damage that may result from the new cleaning method; and
- An investigation into utilising autonomous swarm operations for prism-cleaning and inspection projects.

6.6.2 Proposal: Incorporating UAVs into TARP at RUL

Barbeau *et al.* (2022) discuss how UAV agility enables them to manoeuvre and complete tasks in a variety of indoor and outdoor locations. Examples of applications include shipping and delivering necessary goods to remote or inaccessible locations, gathering information for disaster management or safe contactless delivery, mapping inaccessible terrain, and assisting with thermal scanning during search and rescue operations (Barbeau *et al.*, 2022).

The incorporation of UAV technology in the TARP has the potential to drastically improve safety in the event of an imminent failure. This potential is realised through the provision of visual aids to assess access ways and fast-tracking the decision-making processes for evacuation and rescue of mine personnel and equipment.

The historical registry of data created provides an opportunity for sufficient data for post-failure assessments, audits, to improve evacuation processes, as well as accurate volumetric calculations of the failure material. The tonnage figure is vital in determining the magnitude of the failure and is a crucial input in evaluating the resultant economic impacts, as well as determining the optimal post-failure recovery plan.

The ability of certain UAVs to carry payloads is used in various sectors as a delivery service and for deploying medical packages to remote areas. This process can be adopted in the mining industry, for the fast and efficient delivery of first aid and key survival packages to mine personnel trapped in the open pit in case of closure of accessways into the open pit.

Figure 6-5 is a proposal for incorporating UAVs into the current TARP at RUL as proposed by the author.

PROPOSED UAV INCORPORATION INTO TARP

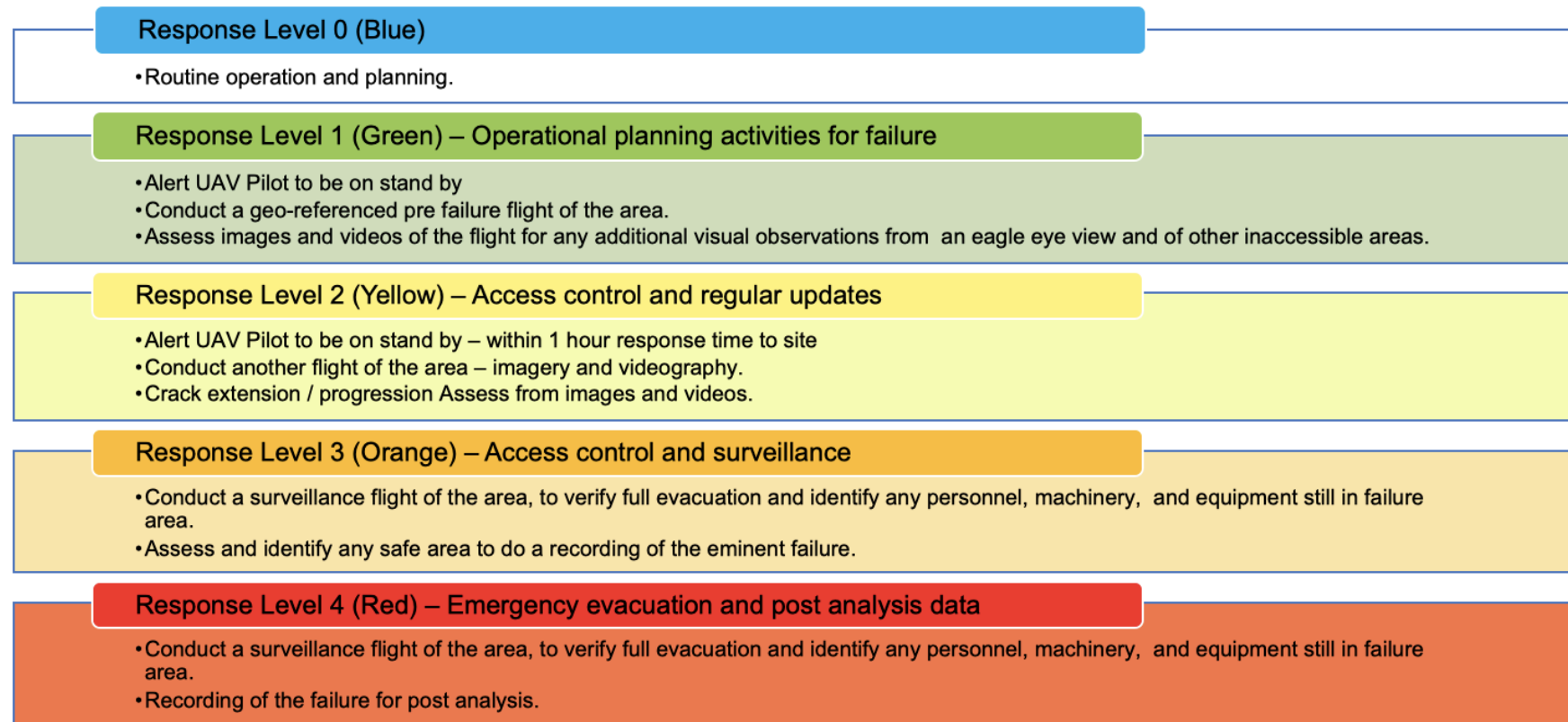


Figure 6-5 The proposed incorporation of UAVs into the RUL TARP.

In the UAV incorporation into TARPs proposal above, the UAV tasks in response Level 1, will be actioned as part of the operational planning activities for failure, collecting status data for area observations in an area that may be dangerous for physical observations. Level 2 and Level 3 tasks will be absorbed into access control, surveillance and regular update activities. Level 4 final surveillance of the area and recording of the failure will be conducted as part of the emergency evacuation strategy. All data recorded will be archived and used for post-analysis, possible investigations, and future learnings.

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