**UTILISATION OF REMOTELY PILOTED AIRCRAFT SYSTEMS VERSUS CONVENTIONAL SURVEYING METHODS IN MINING OPERATIONS**

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# ABSTRACT

The most commonly used methods of obtaining geospatial data are terrestrial laser scanning and tacheometric surveys using Total Stations and Global Navigation Satellite Systems (GNSS). The accessibility of mining areas whilst collecting geospatial data sometimes poses a risk to mine surveyors and the actual collection of data may disrupt operations which may lead to downtime and thus having a negative impact on productivity. Geospatial data acquisition through surveying and mapping techniques that are safer, less time consuming and cost-effective is required. RPAS is now increasingly being used in the mining industry for geospatial data collection tasks in both underground and surface environments. The absence of RPAS-aided solutions in some areas of the mining industry can be attributed to the fear of deviating from the tried and tested techniques and the initial costs of acquiring RPAS equipment. There is limited documented information readily available on the effective use and the strengths and weaknesses of RPAS technology that can be used as a guide for users or potential users. This research develops a guideline framework for equipment selection based on the strengths, weaknesses, opportunities and threats of adopting RPAS in mining operations in comparison to existing geospatial data acquisition techniques. Furthermore, analysis of legislation governing the use of RPAS in South Africa, such as operator certification, is given in the research. The overall deduction from this research is that RPAS surveying is more cost-efficient, less time consuming, comparatively accurate and safer than conventional survey methods. However, the main recommendation is that RPAS should not always be considered as a substitute for conventional surveying and mapping methods, but as another valuable geospatial tool to augment existing methods.

I dedicate this research to the Lord Almighty, Jehovah Jireh (God my provider) and to everyone who believes in themselves.

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# CHAPTER 1. INTRODUCTION

Mining companies are continually looking to overcome the challenges related to hazardous mining conditions to ensure the health, safety and security of their workforce. In accordance with the South African Mine Health and Safety Act No. 29 of 1996, Section 23, “an employee has the right to leave any working place whenever circumstances arise at that working place which, with reasonable justification, appear to that employee to pose a serious danger to the health or safety of that employee; or the health and safety representative responsible for that working place directs that employee to leave that working place” (Department of Mineral Resources South Africa, 1996). It is, therefore, justified to deduce that hazardous mine working conditions have a direct impact on productivity and consequently mine revenue when operations are halted. Remotely Piloted Aircraft System (RPAS) technology is one solution that is increasingly being investigated to mitigate risk from such hazardous mining conditions by removing mine personnel from exposure to hazards (Shahmoradi, et al., 2020).

This research centres on digitilisation in the mining industry with a particular focus on the utilisation of RPAS in mining operations in comparison to conventional surveying techniques. “Digitalisation has become a key driver in mining to optimise processes and maximise the value of existing applications” (Wilson, 2019). Digitalisation is the utilisation of digital technologies to transform a business model and deliver additional revenue and value-creation opportunities (Gartner, 2021). Digitalisation in mining is the process by which mining companies reduce costs, increase productivity and transform their operations by adapting to computerised or digital devices or systems and digitised data (Barnewold & Lottermoser, 2020). According to a study conducted by the World Economic Forum, digitalisation in mining will decrease mining fatalities by 10% and mining injuries by 20% in the ten years from 2015 to 2025 (World Economic Forum, 2017). “Attention has shifted towards emerging technologies to optimise investments in equipment, improve safety at mines and reduce environmental impact” (Wilson, 2019). Some of the modern technologies associated with digital transformation in the mining industry include RPAS, automation, real-time data capture, artificial intelligence and digitalisation of geological data.

The increased focus by mining companies on utilising technological advancements paves the way for the growth of the company and greater returns on investment (Airobotics, 2018). A survey was conducted by Global Data across 179 mine sites in 2019 to investigate the extent of technological investments including RPAS by mining companies as shown in Figure 1.1.

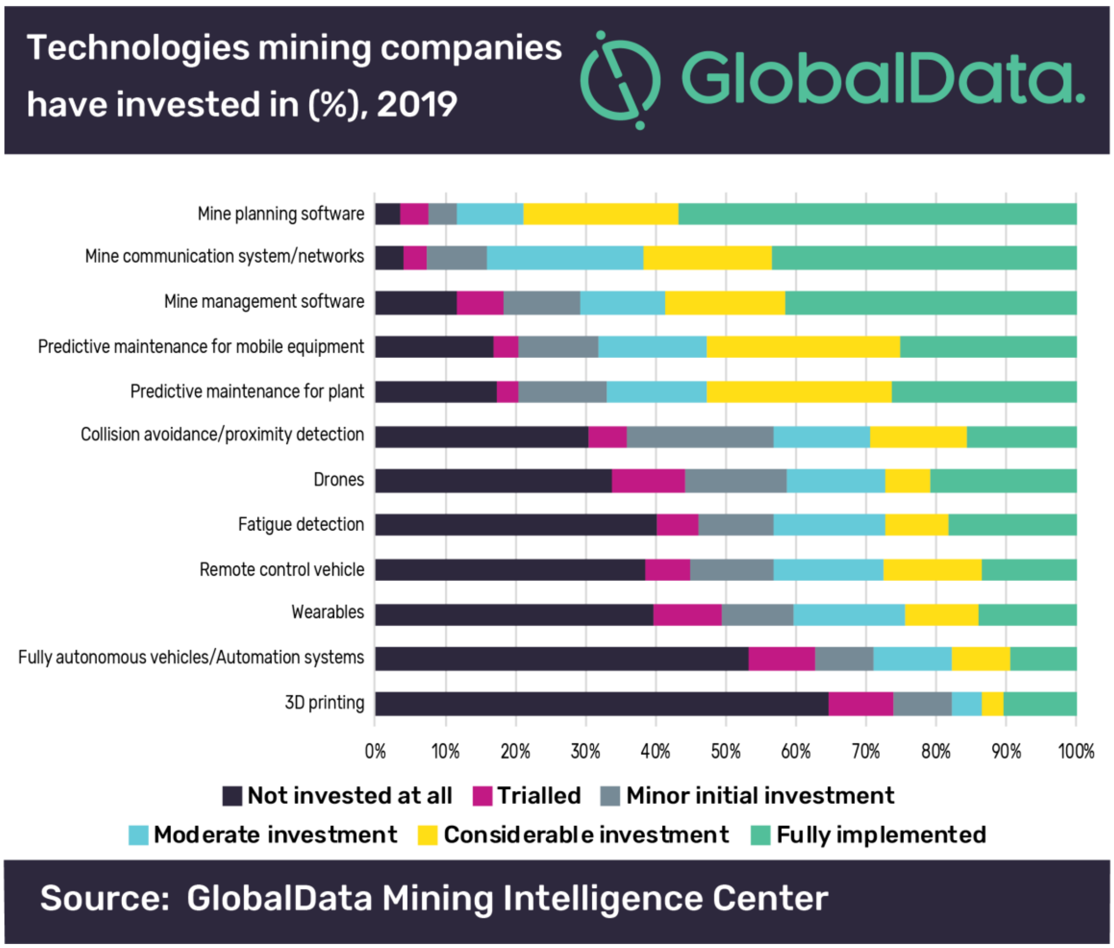


*Figure 1.1: Technologies mining companies have invested in percentage (%), 2019 (GlobalData, 2020)*

The survey shows that about 56% of mines have invested to some extent in RPAS (Drones) technology and 21% of mine sites surveyed at the end of 2019 had fully invested in RPAS, compared to just 9% in 2018 (GlobalData, 2020). Continuous improvement of RPAS technology and the gradual increase of its implementation into the mining sector is an indication that it is the long-term solution in improving the safety and productivity of mine survey and mapping operations (Nomthi, 2016).

## 1.1 Purpose of the Research

Through this research, the aim is to develop a guideline framework for equipment selection based on the strengths, weaknesses, opportunities and threats of adopting RPAS at mining operations compared to existing geospatial data acquisition techniques. The research will contribute to the pool of knowledge in promoting digital transformation in the 4$^{th}$ Industrial Revolution era. Since technology is constantly evolving, the results of this research will also stimulate further study on how RPAS can be further improved and utilised to maximise the efficiency of mining operations. The research investigates whether there is improved operational decision-making, increased employee re-skilling, health, safety and environmental impacts.

## 1.2 Research Background/Context

Mine surveyors, mining engineers and mine planners are in constant need of accurate, real-time and fit for purpose information to produce reliable reports concerning the productivity of the mine and other production-related data such as for stockpile volume management (Lautenschlager, 2015). This information is critical for planning purposes and decision-making on mining operations. The most commonly used methods of obtaining geospatial data are terrestrial laser scanning and tacheometric surveys using Total Stations and Global Navigation Satellite Systems (GNSS). The degree of accuracy of using tacheometric surveying techniques to obtain geospatial data can be disputed because they are unable to map the whole area of interest (Tucci, et al., 2019). The accessibility of mining areas whilst conducting these tasks sometimes poses a risk to mine surveyors and the actual collection of data may disrupt operations which may lead to downtime and thus having a negative impact on productivity (Tucci, et al., 2019). Mining companies have increased efforts in minimising the exposure of mine personnel to mining hazards, however, the emphasis on safety has seen an increase in manpower, time and cost required to carry out additional workplace inspections (Jones, et al., 2020). Routine examination of working areas such as open pit benches or high walls exposes mine personnel to risk despite risk assessments and risk mitigation measures that are implemented (Contreras, et al., 2006). Therefore, geospatial data acquisition through surveying and mapping techniques that are safer, less time consuming and cost-effective is required.

RPAS is now increasingly being used in the mining industry for geospatial data collection tasks in both underground and surface environments (Shahmoradi, et al., 2020). RPAS is mostly utilised for three-dimensional (3D) mapping with other uses in photogrammetric solutions, mining progress monitoring and disaster analysis (Tziavou, et al., 2018). The RPAS platform usually carries either a laser scanner or a high-resolution camera, which can be used to create 3D point clouds or ortho-rectified photo mosaics, to generate 3D geospatial models. The data acquired from the RPAS can be used to produce reports regarding mine development, production and mine planning forecasts (Lautenschlager, 2015). The use of RPAS technology introduces efficiency and reliability to the existing mine survey and mapping systems and thus benefits stakeholders such as geologists, mine planners and mining engineers (Bland, 2018).

## 1.3 Research Motivation

The absence of RPAS-aided solutions in some areas of the mining industry can be attributed to the fear of deviating from the tried and tested techniques and the initial costs of acquiring RPAS equipment (Dutta & Banerjee, 2018). There is limited documented information readily available on the effective use and the strengths and weaknesses of RPAS technology that can be used as a guide for users or potential users. Examples of such limited information include technical information concerning the quality of an orthomosaic obtained from RPAS. This includes the overlap between photos, flying height, lighting conditions, specifications of the lens, camera and weather conditions. When inexperienced RPAS operators produce a poor quality orthomosaic the usual consequence is the mistaken belief that the substandard results are always due to the restrictions of the RPAS technology (Tziavou, et al., 2018). There is a great need for an extensive investigation and documentation of the effective use of RPAS in mining operations and how it compares to the conventional methods of mine surveying and mapping. Mine surveying accuracy in South Africa is governed by the Mine Health and Safety Act in Chapter 17; “Regulations Relating to Surveying, Mapping and Mine Plans”.

## 1.4 Problem Statement

The conventional techniques of mine surveying and mapping of mining operations include the use of Total Stations, GNSS and terrestrial laser scanning (Tucci, et al., 2019). These techniques pose problems concerning:

- The accessibility of sites which exposes mine surveyors to mining hazards and risks (Tucci, et al., 2019);
- Collection of data may disrupt operations which may lead to downtime and thus affecting productivity (Tucci, et al., 2019); and
- Total Stations and terrestrial laser scanners; measurement of characteristic points is restricted due to the line of sight (LOS) which is sometimes obscured leading to incomplete datasets of geospatial information (Thomas, 2019).

Therefore, there is a need to apply techniques that are safe, less time consuming, cost-effective and give an all-encompassing view of the mining operation. RPAS is increasingly being adopted in the mining industry but limited broad knowledge about its strengths and weaknesses is apparent. A certain level of scepticism surrounding the adoption of RPAS on mining operations, which is compared to the tried and tested conventional survey methods, is evident. There are also instances where RPAS may be viewed as the “silver bullet” and deployed on a mine but the limitations of the system are not known and issues arise thereafter. Thus, an extensive investigation into the strengths, weaknesses, opportunities and threats associated with RPAS techniques is required to address and dismiss that scepticism.

## 1.5 Assumptions

Investigating the strengths and weaknesses of utilising RPAS in open pit mining operations is dependent on the following key assumptions which will be made in the research:

- The RPAS market is capable of delivering the services required to optimise mining operations;
- The input structures and cost structures of RPAS technology would remain constant, that is, the research may not be fully valid for new business models arising from advances in RPAS technology in the future as technology is always changing; and
- The researcher's findings will be a true representation of the impact of adopting RPAS technology on mining operations.

## 1.6 Research Methodology

This section highlights the methodology used for this research. This research aims to develop a guideline framework for equipment selection based on the strengths, weaknesses, opportunities and threats of adopting RPAS on mining operations in comparison to existing geospatial data acquisition techniques. This research was conducted using qualitative techniques for data collection with reference to the internet, RPAS related textbooks and journals, and consultation with mining industry professionals.

This research first reviews the common conventional methods of surveying and mapping used in the mining industry. Utilising the data compiled, a comprehensive SWOT analysis was conducted for these techniques. Analysis of existing literature and case studies were carried out to get a clear and comprehensive understanding of RPAS and its inclusion in the mining industry. Consultation with mine surveyors, aerial survey companies, mining engineers and other industry professionals was done to complement the background literature review of RPAS properties. Analysis of case studies and existing literature review aided in conducting a thorough performance evaluation on the adoption of RPAS for activities on mining operations. This research is of great benefit to mining companies to successfully utilise RPAS technology in mitigating risk and adding value to their operations.

To determine the most effective workflow, a comparison was then conducted between mine surveying using RPAS and mine surveying using conventional methods concerning safety, time, costs and accuracy. Furthermore, an analysis of legislation governing the use of RPAS in South Africa, such as operator certification, was conducted during the research.

## 1.7 Report Layout

This section highlights the outline of the chapters in the research report.

Chapter 1: Introduction

The research introduction comprises the research background, research motivation, research objectives, the scope of the study and the methodology used to conduct the research.

Chapter 2: Literature Review

This chapter details a comprehensive literature review of the different surveying methods currently being used in the mining industry before the introduction of RPAS. A SWOT analysis is presented for each surveying method. This chapter introduces the concept of RPAS in the research. The technical characteristics of the different types of RPAS are also outlined in this chapter.

Chapter 3: Remotely Piloted Aircraft Systems Photogrammetry and Remote Sensing

This chapter reviews RPAS photogrammetry and remote sensing, putting more emphasis on the workflow and principles of RPAS photogrammetry.

Chapter 4: Applications of Remotely Piloted Aircraft Systems in Mining

This chapter outlines a comprehensive study of the different applications of RPAS and how they can effectively improve mining operations.

Chapter 5: Legislation Governing the use of Remotely Piloted Aircraft Systems

This chapter outlines the current regulatory framework governing the use of RPAS. It also considers the legal and regulatory initiatives that need to be put in place in order to successfully adopt RPAS on mining operations.

Chapter 6: Strengths, Weaknesses, Opportunities and Threats Analysis of Remotely Piloted Aircraft Systems

This chapter consists of a SWOT analysis of utilising RPAS. A detailed comparison between RPAS and conventional surveying techniques with respect to safety, time, costs and accuracy is also detailed in this chapter.

Chapter 7: Conclusions and Recommendations

The chapter encompasses a discussion of the results of the research, with the conclusions and recommendations for future studies. Any limitations encountered during this research are stated in this chapter. The chapter also presents a geospatial systems matrix concerning the appropriate systems for specific tasks.

# CHAPTER 2. LITERATURE REVIEW

## 2.1 Review of Conventional Surveying Methods

This section provides an overview of the common conventional survey methods and systems currently being implemented on mine sites for various geospatial applications. For this research, the focus is on total stations, the Global Navigation Satellite System (GNSS) and terrestrial laser scanning (TLS). A SWOT analysis is also carried out after each reviewed survey method.

### 2.1.1 Total Stations

The total station is a surveying instrument that integrates the angle measuring capabilities of a theodolite with an electronic distance measurement (EDM) to electronically determine the horizontal angle, vertical angle and slope distance to a specific point (Chekole, 2014; Montana Department of Transportation, 2005). The electronic angle measurement system eradicates the horizontal-angle and vertical-angle errors that usually arise in conventional theodolites (Guyer, 2015). The angles and distances are surveyed electronically and then displayed digitally (Zeiske, 2004). Digital displays remove the ambiguity related to the interpretation and interpolating scale and micrometre data (Guyer, 2015). These instruments are also fitted with a dual-axis compensator, which automatically adjusts both horizontal and vertical angles for any deviation in the plumb line (Guyer, 2015). However, good survey practice allows for the surveyor to carry out horizontal and vertical collimation checks on the instrument. The horizontal distance, the height difference and the coordinates can be calculated automatically by the instrument and all measurements and additional information can be recorded (Zeiske, 2004). Measurements are centred on interpreting an integrated signal over the surface of the electronic instrument that produces an average angular value and eradicates the errors from eccentricity and circle graduation (Guyer, 2015). With the addition of a data collector, the total station interfaces directly with onboard microprocessors, external computer and software (Guyer, 2015). The operator's input into the total station comprises:

- Text (for example, date, job number and crew);
- Atmospheric corrections (for ambient temperature and atmospheric pressure for a parts per million adjustment to measured distances);
- Geodetic/grid definitions;
- Height of reflector above ground (HI) and height of total station above survey point (HR); and
- Descriptor/attribute of, for example, setup point, back-sight point, side-shot point, stakeout point. (Guyer, 2015)

Total stations are utilised where the positions and heights of points, or just their positions, need to be computed (Zeiske, 2004). Coordinates of an unknown point in relation to a known point can be determined using the total station on the condition that a direct LOS linking the two points is present (Chekole, 2014). Angles and distances are measured from the total station to survey points and the coordinates (X, Y and Z or northing, easting and elevation) of surveyed points in relation to the total station position are calculated using trigonometry from measured distances and directions (Chekole, 2014). Devices fitted with an automatic target recognition (ATR) (Leica Geosystems, 2016) sensor allows for the automatic tracking of a prism and subsequent angle and distance measurement (Chekole, 2014), without the user having to manually sight the prism (Reda & Bedada, 2012). ATR enables the instrument to lock on to and track a moving prism (Reda & Bedada, 2012). The prism is initially sighted using the telescope (Chekole, 2014). Vertical and horizontal angles and slope distance are measured to the centre of the prism and coordinates of the target calculated automatically (Chekole, 2014). Figure 2.1 shows the Trimble SX10 total station which is capable of collecting high accuracy total station data and a high-density 3D scan data.


*Figure 2.1: Trimble SX10 Scanning Total Station (Trimble Geospatial, 2021)*

Figure 2.2 shows the Leica Nova TS50 total station which is equipped with ATR and produces highly accurate scans.


*Figure 2.2: The Leica Nova TS50 Total Station (Leica Geosystems, 2013)*

To define an absolute location, a total station requires LOS observations and should be set up on a known point or with LOS to at least two points with known coordinates (Chekole, 2014). Total stations can be manually adjusted or be equipped with motors that drive their telescopes very accurately (Chekole, 2014). The most modern total stations can be operated remotely and continuously at specified levels of automation, that is, continuously or at defined time intervals (Chekole, 2014). The capability to operate remotely all measurements and to record the data with a single instrument has transformed and modernised surveying, especially concerning monitoring (Guyer, 2015).

**Measurement Accuracy**

Total station recordings are impacted by changes in ambient temperature, atmospheric pressure and relative humidity (Chekole, 2014). However, these changes can be adjusted for atmospheric effects by inputting the recorded ambient temperature, atmospheric pressure and relative humidity (Chekole, 2014). Any movement of the instrument, especially if it is set up on a tripod, will result in measurement inaccuracy (Chekole, 2014). EDM signal disturbances, severe heat shimmer and moving objects along the signal path can also cause deviations from the anticipated accuracy (Chekole, 2014; Reda & Bedada, 2012). Hence, it is essential to check and adjust the device before measurement (Chekole, 2014).

The accuracy with which the centre point of a prism can be established with ATR is subject to several aspects, for example, internal instrument ATR accuracy, instrument angle accuracy, prism type, particular EDM measuring program and the exterior measuring environment (Chekole, 2014). The ATR has a basic standard deviation level of ± 1 mm but beyond a certain distance, the total station angle accuracy predominates and takes over the standard deviation of the ATR (Chekole, 2014). Therefore, the measurement accuracy specifications of the total station are paramount. Utilising sub-standard prisms instead of the recommended manufacturers prisms may also result in reduced accuracy (Chekole, 2014). To acquire accurate and precise survey measurements, it is essential to:

- Regularly check and adjust the instrument, for example, horizontal and vertical collimation errors, ambient temperature and atmospheric pressure measurements, and after transportation;
- Take high precision measurements for the duration of the check and adjust procedures; and
- Measure targets in two faces. Instrument errors are eliminated by determining the mean of the angles (horizontal and vertical) from both face measurements. (Chekole, 2014)

**Mode of Distance Measurement**

There are three categories of total station distance measuring operational modes (Guyer, 2015). The categories are described in this section:

1) **Measuring with reflector -** an EDM device sends an infrared light wave to a reflective prism and by measuring the phase difference necessary in returning the reflected light wave to its origin, it determines the distance (Chekole, 2014; Reda & Bedada, 2012). The accuracy of standard measurements of prism distance is influenced by the type of reflector and the measuring method used (Chekole, 2014). Total stations require a solid reflector or retroreflector signal return from the distant point to determine digital angles and distances (Guyer, 2015). Prisms are fixed onto a pole sited above a particular feature (Guyer, 2015). It requires a two-man field team, that is, the operator and the survey assistant (Guyer, 2015).

2) **Reflectorless -** Distance measurement without a reflector is applicable when surveying difficult to access sites, for example, the top of a stockpile (Chekole, 2014). This technique makes it possible to survey areas from a distant location (Reda & Bedada, 2012). The accuracy is influenced by the distance between the total station and the target to be measured (Chekole, 2014). The distance is inversely proportional to the accuracy (Chekole, 2014). The reflectivity of the object being surveyed is directly proportional to the accuracy. Hence, a reflector-less EDM requires a high-energy laser pulse to enable it to reflect off any surface it is aimed

at. The total station resolves and coordinates signal returns off surface features (Guyer, 2015). Distances may be far more limited than those obtained from reflectors, usually not exceeding 300m (Guyer, 2015). This method does not require an additional crew member to hold the prism at the target point (Reda & Bedada, 2012), and allows for a more cost-effective one-man field crew operation (Guyer, 2015).

3) **Robotic** - The total station self-tracks a single operator or survey assistant at a distant target or stakeout points (Guyer, 2015). It is a one-man crew operation, with the operator typically positioned at the remote prism point (Guyer, 2015). The Leica Nova TS60 robotic total station is currently one of the most accurate total stations. It has an angular accuracy of 0.5" (sub-second) and distance accuracy of 0.6 mm + 1 ppm (sub-millimetre) (Leica Geosystems, 2020).

Both reflector and reflector-less mode measurements have their advantages and disadvantages (Chekole, 2014) and these are presented in Table 2.1.

*Table 2.1: Advantages and Disadvantages of Reflector and Reflectorless modes (Chekole, 2014)*

| | **Advantages** | **Disadvantages** |
|---|---|---|
| **Reflector** | • Can measure longer distances<br>• Faster than reflectorless mode<br>• Better precision than reflectorless mode | • A person is needed to hold the reflector/prism<br>• Inaccurate for internal corner measurements<br>• Measurements are difficult in some areas such as construction sites |
| **Reflectorless** | • No need for a person to hold reflector/prism<br>• Can measure inaccessible or difficult (hazardous) to access areas | • Good accuracy only for shorter distances<br>• Less accurate and slower |

**Strengths, Weaknesses, Opportunities and Threats: Analysis of Total Stations**

<u>Strengths</u>

The strengths associated with surveying using Total Stations are as follows:

- There is a high precision of setting-out singular points (in units of mm) (Patikova, 2004). The accuracy of measurements is much higher in comparison to other conventional surveying methods such as GNSS (Chekole, 2014; Civil Easy Learning, 2019; Constructionor, 2020; Falak, 2019). Both horizontal and vertical angles have comparable accuracies, which can be 0.5 or 1 second on highly accurate instruments, for example, the Leica TM50 (Leica Geosystems, 2013).

- A total station has an inbuilt processor which can record and compute the distances and, horizontal and vertical angles. Errors such as reading and manual recording can be eliminated since the functionality is computerised (Civil Easy Learning, 2019; Constructionor, 2020; Falak, 2019).
- With the help of data gathered from a total station, map-making and contour plotting can also be done quickly and efficiently which shows the graphical view of topography and plots for quick visualisation (Constructionor, 2020; Falak, 2019; Rajput, 2019).
- A total station is an all-in-one and multi-tasking instrument. A total station has a built-in database and data can be stored in the microprocessor of the instrument and transferred to a personal computer, for future use such as the compilation of maps using suitable software packages (Civil Easy Learning, 2019; Civil Knowledges, 2020;).
- Daily survey information can be quickly downloaded into CAD software which reduces the data manipulation time (Civil Easy Learning, 2019).
- Although some total stations are fitted with a GNSS attachment mount, a total station can accurately perform a positioning function without the use of satellites by using known set-out points to determine the position of the total station, that is, by resection (Chekole, 2014).
- Setting up of the instrument on a tripod can be done easily and quickly using a laser plummet (Falak, 2019; Online Civil, 2019; Rajput, 2019).
- A total station comprehends and supports several languages (Civil Easy Learning, 2019; Civil Knowledges, 2020; Constructionor, 2020).
- Multiple surveys can be performed at one set-up location (Civil Easy Learning, 2019). It is easy to perform distance and horizontal measurements with the simultaneous calculation of coordinates (Northings, Eastings, and Elevations) (Civil Easy Learning, 2019).
- A total station is compact and is easy to carry and transport (Chekole, 2014).

- Surveying is not negatively impacted by overhead obstacles (Chekole, 2014).

Weaknesses

The weaknesses associated with surveying using Total Stations are as follows:

- Surveying is limited to measurements between inter-visible points. Total stations function on the principle of signal reflection, therefore, there must be a LOS between the total station and the prism reflector or surveying target (Chekole, 2014).
- A total station performs indirect acquisitions of 3D coordinates (Chekole, 2014).
- It is too time-consuming to obtain very accurate terrestrial measurements. Data acquisition can take hours to days to get final results, subject to errors (Patikova, 2004). Usually, control points are situated at a distance to the survey area, and traversing with a total station to establish the control is a time-consuming task (Chekole, 2014).
- There are extensive manpower requirements to manually collect and process data. Terrestrial measurements normally require a minimum of two people (Patikova, 2004).
- Total stations are not robustly designed for extreme and harsh working conditions (Falak, 2019).
- Checking for errors or other issues during the operation is difficult and time consuming for the surveyor. To evaluate the survey completely, the surveyor has to get back to the office and produce the drawings with the relevant software (Constructionor, 2020; Rajput, 2019).
- Skilled personnel are required to handle a total station since it is a sophisticated instrument to operate (Civil Knowledges, 2020; Online Civil, 2019).
- Horizontal coordinates are calculated on a rectangular grid system (Civil Easy Learning, 2019). However, the real world is based on a spheroid and rectangular coordinates need to be transformed to geographic coordinates if projects are large scale (Civil Easy Learning, 2019).

Opportunities

In this research, there were no new opportunities of using a total station discovered besides those that are already being realised.

Threats

The threats associated with surveying using Total Stations are as follows:

- Overall mine costs are increased due to the manpower-requirements and skilled personnel.
- The survey crew is exposed to hazardous working conditions, for example, during the surveying of stockpiles or surveying of open pit highwalls.
- New surveying technology is quicker and does not necessarily need LOS, for example, GNSS.

### 2.1.2 Global Navigation Satellite System

GNSS surveys use the signals transmitted by satellites in orbit which make it possible to resolve any point on the Earth's surface at any time as long as the position dilution of precision (PDOP) is suitable (Zeiske, 2004). GNSS surveys are unaffected by weather conditions. The positioning accuracy is subject to the type of GNSS receiver and, the observation and post-processing methods applied (Zeiske, 2004). A GNSS receiver measures the received phase of the satellite signals to millimetre precision (Chekole, 2014). Figure 2.7 shows a typical GNSS receiver.

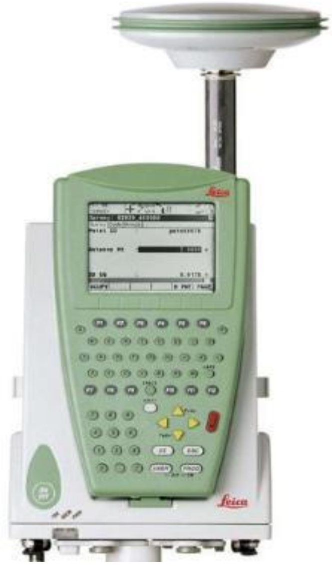

*Figure 2.3: Leica GNSS 1200 receiver (Chekole, 2014)*

As the satellite signals transmit from satellites to receivers they pass through and are influenced by the atmosphere (Chekole, 2014). The layers of the atmosphere that affect the inbound GNSS signal are the ionosphere and troposphere (Chekole, 2014). The free electrons in the ionosphere generate an electromagnetic wave that disturbs and causes a variable decrease in the velocity of GNSS signals from the satellite to the receiver, which ultimately affects positioning (Roy, 2017). The troposphere has an inhomogeneous refractive index which influences the accuracy of GNSS positioning, particularly concerning height (Dodo, et al., 2008). GNSS surveying is a differential technique, that is, a baseline is observed and defined between two receivers (Chekole, 2014). When the two receivers observe the same set of satellites concurrently, most of the atmospheric impacts are cancelled out (Chekole, 2014). These impacts decline as the baseline shortens because the probability that the atmosphere through which the GNSS signal passes to the two receivers will be identical increases (Chekole, 2014). Baseline accuracy is influenced by different aspects such as the number of satellites tracked, satellite geometry, observation time, ephemeris accuracy, ionospheric disturbance, multipath and resolved ambiguities (Chekole, 2014).

**Real-time Kinematic**

Real-time kinematic (RTK) survey techniques are widely used for engineering and construction surveys, as well as topographic site plan mapping, construction stake-out, construction equipment location and hydrographic surveying (Guyer, 2015). RTK data compilation utilises differential GNSS corrections broadcast by a base receiver to solve for coordinates at a rover receiver in real-time (Chekole, 2014). There are numerous means to pass on an adjustment signal from the base station to the mobile station (Chekole, 2014). The most common means to attain real-time transmission is radio communication (Chekole, 2014). The accuracy of the subsequent range measurement is influenced by factors such as the number of satellites visible, resolved uncertainties and satellite geometry (Chekole, 2014). The RTK approach for geodetic measurements is a quick technique for surveying and outcomes are accessible instantaneously (Kostov, 2011). There is no requisite for subsequent supplementary data processing as adjustments are made from the base station during the measurement through radio communication (Kostov, 2011). Figure 2.8 shows a typical static RTK base station.

*Figure 2.4: The Trimble SPS855 GNSS Modular Receiver RTK base station (Sitech, 2016)*

RTK survey systems function similarly as the robotic total station, except that a LOS between the reference point and remote data collection point is not requisite (Guyer, 2015). Both RTK and total stations use similar data collection procedures and techniques and can accomplish indistinguishable coordinate geometry (COGO) stake-out functions (Guyer, 2015). Kinematic surveying is a GNSS carrier phase surveying method that allows the operator to quickly and correctly measure baselines while moving from one point to the next, stopping only temporarily at the unknown points (Guyer, 2015). RTK can also be applied in dynamic motion such as a survey aircraft (Guyer, 2015). A reference receiver is set up at a known station and a remote, or rover receiver traverses to the unknown points to be coordinated (Guyer, 2015). The data is compiled and processed (either in real-time or post-time) to attain accurate locations to the centimetre level (Guyer, 2015). RTK survey methods involve initialisation to counter the carrier phase ambiguities (Guyer, 2015). This is conducted in real-time by utilising "On-the-Fly" (OTF) processing methods (Guyer, 2015). Sporadic loss of satellite lock can be acceptable and no static initialisation is necessary to recover geospatial position (Guyer, 2015). This varies from other GNSS methods that need static initialisation as the user is static which is the case with post-processing GNSS surveys (Guyer, 2015). A communication link between the reference and rover receivers is essential to preserve a real-time solution (Guyer, 2015).

**Post-processing Kinematic**

In post-processed kinematic (PPK) methods, the kinematic results are not achieved in real-time (Guyer, 2015). PPK systems do not necessitate a real-time data link with a fixed reference station, but they still guarantee sub-centimetre-level position accuracy (Geomatics World, 2017). This simplifies the whole set-up and reduces the requirements and power load of the GNSS receiver (Geomatics World, 2017). PPK systems minimise the risk of losing data as a result of unreliable radio links between the aircraft and the base station, which often affect aerial RTK operations (Geomatics World, 2017). The base station may be a receiver set up on a tripod at the site to record data during the flight or, for several countries, data downloaded from a national Continuous Operating Reference Station (CORS) can be used as an alternative (Geomatics World, 2017). With both RTK and PPK, when the receiver on the aircraft loses lock, a new integer ambiguity resolution procedure must be initiated (Geomatics World, 2017). The advantage with PPK is that the search can progress from previous and future data relative to that instant, whereas RTK solutions cannot use data that has not yet been recorded (Geomatics World, 2017).

**Strengths, Weaknesses, Opportunities and Threats: Analysis of Global Navigation Satellite System**

The strengths associated with surveying using GNSS are as follows:

Strengths

- GNSS can measure points without LOS (Chekole, 2014). It is not bound by constraints such as visibility between stations (Baseline Equipment, 2020; Wilson, 2019).
- GNSS achieves direct acquisition of 3D coordinates (Chekole, 2014).
- Data can be collected anytime, whether day or night (Chekole, 2014).
- GNSS provides data quickly and with a high degree of accuracy due to the multi-channel design (Baseline Equipment, 2020; Goodman, 2019; Wilson, 2019).
- A single surveyor can complete all the survey tasks in a relatively short period of time, for example, in one day, it is not labour intensive (Wilson, 2019).
- GNSS components can be carried and transported easily (Baseline Equipment, 2020; Wilson, 2019).
- GNSS provides wireless real-time data transmission (Baseline Equipment, 2020). This is helpful in different applications such as mapping and location (UK Essays, 2020; RF Wireless World, 2012).
- GNSS is enabled by satellite technology and can be accessed anywhere in the world. A reliable tracking system and a GNSS receiver are all that is needed (Bonheur, 2018; Goodman, 2019; RF Wireless World, 2012; UK Essays, 2020).
- There is a minimum need for highly trained personnel (Wilson, 2019). Navigation using GNSS is generally very easy and requires minimal skill or effort (Goodman, 2019).

- GNSS surveying is not affected by weather conditions such as snow, rain, high or low temperatures (Chekole, 2014; Wilson, 2019).
- GNSS allows for accurate work over long distances and there is no need to relocate the base unit to survey remote areas at the same level of accuracy (Wilson, 2019).
- The satellites behind the Global Positioning System (GPS) are paid for, maintained and upgraded by the United States Department of Defense (US DoD). That means that the system is essentially free without any subscription or license, although payment may be needed for the device and software to utilise it (Bonheur, 2018; Goodman, 2019; RF Wireless World, 2012).
- The GNSS system is regularly updated, by the US DoD, for example, to maintain a high level of accuracy. So, unlike a traditional printed map which goes out of date after a while, GNSS and related technology is current and accurate (Goodman, 2019).

Weaknesses

The weaknesses associated with surveying using GNSS are as follows:

- GNSS surveying relies on receiving information from satellite signals (Chekole, 2014). The accuracy depends on the satellite availability, atmospheric effect, satellite geometry and multipathing (Chekole, 2014). If anything interferes with signal reception, the GNSS results can lose accuracy. Surveying with GNSS is negatively impacted by overhead obstacles. The ionosphere and the troposphere can slow down the rate of signal propagation (Bonheur, 2018). The accuracy of GNSS signals can be affected by solar flares. Solar flares produce an effect called ionospheric scintillation which degrades the quality of satellite signals (Natras, et al., 2019). Tree coverage, building and other tall structures, whether natural or manmade, may block satellite signals from reaching the GNSS receiver. Electromagnetic interference and even radio signal interference may also disrupt GNSS accuracy. Satellite signal reception also means that GNSS cannot be used when surveying underground areas or any property blocked from a direct view of the sky (Baseline Equipment, 2020; Chekole, 2014; Goodman, 2019; Lynch, 2020; RF Wireless World, 2012; UK Essays, 2020).

- The horizontal accuracy is better than vertical accuracy (Chekole, 2014). GNSS is incapable of directly measuring differences in elevation. Surveyors must instead use an accurate geoid model, which depicts the shape of the World's oceans under gravity alone, and at least four established elevation benchmarks to determine a point's elevation. The added effort may prove frustrating and time-consuming. In addition, errors in antenna height, baseline measurements and control point locations can further undermine elevation accuracy (Lynch, 2020).
- A device equipped with GNSS capabilities consumes battery power (Bonheur, 2018). The GNSS chip draws a lot of power and therefore GNSS survey equipment is subject to failure from dead batteries and system malfunction (Baseline Equipment, 2020). This requires replacement or recharging of the battery quite frequently (Bonheur, 2018; Goodman, 2019; RF Wireless World, 2012; UK Essays, 2020).
- Special equipment such as GNSS controllers, ultra-high frequency (UHF) radios and geographic information system (GIS) collectors may be required to support GNSS technology and the equipment can be costly (Baseline Equipment, 2020).
- GNSS surveying delivers full 3D representation, making it impossible to separate the horizontal from the vertical. In GNSS surveying, changing the horizontal measure changes the vertical and vice versa. Fixed-height antennas can help mitigate the problem, eliminating the need for height adjustments at each new location. However, errors in measuring antenna heights can plague many GNSS surveys (Lynch, 2020).

<u>Opportunities</u>

The opportunities associated with surveying using GNSS are as follows:

- Because the data collection process is faster, the time for getting final results and making mine planning decisions is understandably shorter (Wilson, 2019).
- GNSS surveying reduces both equipment and manpower requirements for completion of a surveying task, therefore the overall mine survey costs are reduced (Wilson, 2019).
- Combined with map technology, it becomes a powerful tool for tracking personnel and mobile equipment. GNSS can pinpoint the location with accuracy and by comparing coordinates, statistics can be used to calculate the equipment's direction of movement, distances travelled and speed. This information can be used for mine planning and production monitoring purposes (Goodman, 2019)
- GNSS can be used to prevent theft of mining equipment by attaching GNSS chips to mining tools and equipment where practicable (Goodman, 2019)
- GNSS can be used to help detect structural problems in haul roads and open pit high walls by measuring deformation (Goodman, 2019).
- GNSS can be used for weather surveillance in open pit mines by equipping a GNSS enabled device with different features such as barometric altimeters (Bonheur, 2018).

Threats

The threats associated with surveying using GNSS are as follows:

- GNSS can present some privacy concerns. GNSS devices can be used to track people without their consent which may affect employee attitude and consequently negatively impact production (Bonheur, 2018; Goodman, 2019).

### 2.1.3 Terrestrial Laser Scanning

Laser scanning is a technique that uses laser technology to sample or scan a surface (Chekole, 2014). It is similar to taking a snapshot comprising 3D depth information (Chekole, 2014). The benefit of laser scanning is that it can record several points with high accuracy in a relatively short duration (Chekole, 2014). Lasers radiate electromagnetic waves, which are coherent and monochromatic (Colombo & Marana, 2010). The emitted beams of radiation are highly directional, contain a lot of energy, can span hundreds of metres and are reflected from the surfaces of objects (Colombo & Marana, 2010). Hence laser scanning is increasingly being incorporated as the principal component in distance measurement instruments that can create 3D models of objects of a wide range of sizes and shapes (Colombo & Marana, 2010). Figure 2.9 shows a typical terrestrial laser scanner. Terrestrial laser scanning (TLS) is static and ground-based (Telling, et al., 2017).

*Figure 2.5: The Leica RTC360 3D Terrestrial Laser Scanner (ERG Engineering, 2019)*

Laser scanners are LOS devices, therefore, to ascertain widespread coverage of a structure, numerous scan points are needed (Quintero, et al., 2008). Laser scanning instruments demonstrate topographic features of landscapes and infrastructure with an exceptionally high density (Guyer, 2015). These tripod-mounted devices function in a similar way to a reflectorless total station (Guyer, 2015; Telling, et al., 2017). However, they can scan the complete field of view with centimetre-level pixel density (Guyer, 2015). The data from the scan can be used to create digital 2D illustrations or 3D models suitable for various uses (Chekole, 2014). This model then can be edited and feature attributes are added (Guyer, 2015). After processing, each point is given X, Y, Z coordinates, colour and reflectance value (Colombo & Marana, 2010). A laser scanner is a surveying tool that defines 3D coordinates of a particular view in the form of a point cloud (Chekole, 2014). The point clouds characterise the location of an item in 3D (Chekole, 2014). Figure 2.10 shows an RGB image and a rasterised TLS point intensity image of a rock outcrop from the same viewpoint and scale.

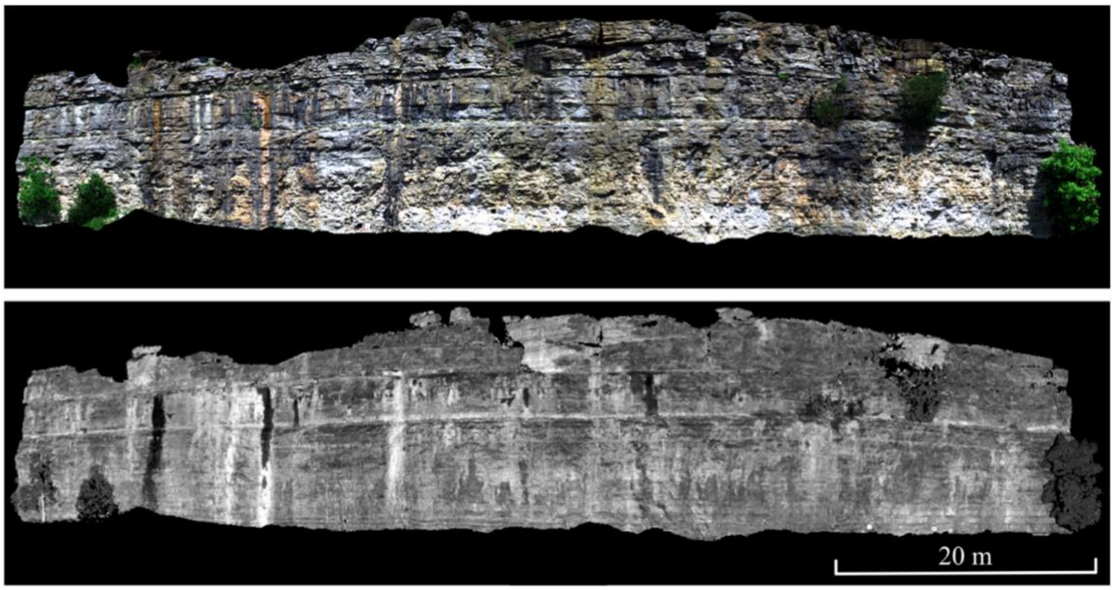


*Figure 2.6: Comparison of RGB (top) and rasterised TLS point intensity (bottom) images of a rock outcrop (Telling, et al., 2017)*

Laser scanners can measure the distance to a target by illuminating the target with light and using pulses from a laser (Adkins, 2012). By accurately measuring the return time of flight of the laser pulse, the distance can be computed using the speed of light (Adkins, 2012). The return energy detected by the receiver of the laser sensor is influenced by the reflective characteristics of the surface of an object, mathematically referred to as the reflection coefficient (Colombo & Marana, 2010). The reflection coefficient is the ratio between reflected energy and incident energy (Colombo & Marana, 2010). The reflection coefficient of smooth and bright surfaces ranges between 70% and 100% but drops to 20% when surfaces become rougher and darker (Colombo

& Marana, 2010). A measurement is only usable if the return energy is above a certain threshold (Colombo & Marana, 2010). The accuracy of a measurement is contingent on the distance between the laser sensor and object, beam divergence, shape and reflectivity of the object, and environmental conditions (Colombo & Marana, 2010).

Laser scanners such as the Leica RTC360 laser scanner can measure up to a rate of two million points per second (Leica Geosystems, 2020). Current applications of TLS include landslide and rock-fall dynamics (Abellan, et al., 2009; Abellan, et al., 2010; Teza, et al., 2007; Teza, et al., 2008; Wawrzyniec, et al., 2007). In this regard, showing the surface changes involves the comparison of two separate point clouds in 2D or 3D (Lague, et al., 2013). There are two types of measurements:

i. calculation of displacement based on the identification of corresponding features in successive point clouds (Aryal, et al., 2012; Monserrat & Crosetto, 2008; Teza, et al., 2007).
ii. measurement of the distance between two point clouds as used in change detection and volumetric calculation problems (Girardeau-Montaut, et al., 2005; Rosser, et al., 2005).

The second method of calculation does not take into consideration correspondence between point cloud features and measures a net surface (Milan, et al., 2007; Schurch, et al., 2011). This takes care of the 3D change detection problem where irregular complex topographies lack corresponding features among successive point clouds (Lague, et al., 2013).

**Strengths, Weaknesses, Opportunities and Threats Analysis of Terrestrial Laser Scanning**

<u>Strengths</u>

The strengths associated with surveying using TLS are as follows:

- TLS provides dense information along homogenous surfaces (Chekole, 2014). 3D laser scanning can measure up to two million data points per second as the laser is moved over the surface of the object or terrain (Leica Geosystems, 2020). This enables scans to be completed within hours or days depending on the scale of what is being scanned (Arayici, et al., 2006; Herring, 2019; Thornberry, 2020).
- Depending on the environment in which the scan is conducted and the specifications of the 3D laser scanner, a 3D point accuracy of 1.9 mm at a 10 m distance, 2.9 mm at a 20 m distance and 5.3 mm at a 40 m distance may be achieved (Leica Geosystems, 2020). This high level of accuracy helps ensure that measurements are correct the first time so that less work is needed to complete subsequent stages in design and production (Thornsberry, 2020).
- TLS enables direct acquisition of 3D coordinates (Chekole, 2014). 3D laser scanning provides a more thorough, detailed picture than can be achieved with traditional survey methods. All the required geospatial information can be collected at once (Arayici, et al., 2006; Herring, 2019; Thornberry, 2020; Torres, 2019).
- Visibility is not required and allows for day or night data collection (Chekole, 2014).
- Because 3D laser scanning is an optical-based technology, there is no need for the scanner to touch the object. This can be helpful when measuring small, intricate, or fragile features that may be distorted or damaged when touched (Thornsberry, 2020).
- With less time and manpower required for the measurement acquisition and design iteration steps, 3D laser scanning is substantially more cost-effective than most other measuring technologies (Thornsberry, 2020).
- The portable 3D laser scanners used for surveying can record accurate measurements from any distance up to several hundred metres. This allows operators to remain safe when the survey area is dangerous due to topography or hazardous conditions. The speed of this technology also reduces the time that

operators may be exposed to such hazardous conditions (Herring, 2019; Prevu3d, 2020; Thornsberry, 2020).

- TLS applies to all 2D and 3D surfaces (Arayici, et al., 2006).
- TLS allows the storing of point cloud data for later analysis. This reduces the need to revisit sites and lowers the probability of rework during operations (Prevu3d, 2020).
- The generally shorter measurement distances and static acquisition modality typical of TLS observations facilitate the development of 3D models that have both higher accuracy and resolution than airborne laser scanning outcomes (Telling, et al., 2017)

<u>Weaknesses</u>

The weaknesses associated with surveying using TLS are as follows:

- TLS projects require an expert who understands the workflow and details of each subsystem and can recognise consistent and accurate data (Torres, 2019).
- A ground-based sensor can only record information from a fixed geographic location continuously (Gallacher, 2016).
- Given the optical nature of 3D laser scanning, it is impossible to measure any surface that is out of the scanner's LOS (Herring, 2019; Thornsberry, 2020).
- Because 3D laser scanners read the light of a laser to record data, ambient light may blend with the laser and interfere with the scan's accuracy. Depending on the severity of this interference, the scan may be noisy or even unusable (Arayici, et al., 2006; Thornsberry, 2020).
- Acquisition of 3D laser scanning equipment is relatively expensive (Arayici, et al., 2006; Herring, 2019; Thornberry, 2020). Depending on their range, speed and features, industrial 3D laser scanners cost between USD $20,000 to USD $120,000 (Aniwaa, 2021). This does not include set-up accessories or operator training.

Opportunities

The opportunities associated with surveying using TLS are as follows:

- TLS affords the advantage of being able to model steep walls and rock outcrops that are difficult to observe with aerial laser scanning systems (Telling, et al., 2017; Young et al., 2010).
- TLS can be used for the design of infrastructure at a mine site (Greaves & Hohner, 2009). The models that are produced by the laser scanners may assist the health and safety personnel and other personnel to be able to understand the layout of the facility. Laser scanning also enables easy collaboration between the different professionals who might be working on the same project (Greaves & Hohner, 2009)
- 3D laser scanning can be easily outsourced to a company that specialises in 3D scanning services. This can reduce costs related to manpower and operator training (Thornsberry, 2020).
- 3D laser scanning may lead to employee upskilling and training to effectively utilise TLS.

Threats

The threats associated with surveying using TLS are as follows:

- TLS can significantly increase the overall mine costs due to the high acquisition costs of the equipment and skilled manpower requirements.
- Implementation of TLS surveying at mine operations may lead to loss of jobs for survey personnel who do not get the opportunity to be upskilled.

## 2.2 Remotely Piloted Aircraft Systems

The concept of RPAS was first introduced in 2011 by the International Civil Aviation Organisation (ICAO) in the ICAO Circular 328 (International Civil Aviation Organisation, 2011) after it was recommended by its Unmanned Aerial Systems Study

Group (UASSG) (Othman, 2016). ICAO agreed with the deduction that only unmanned aircraft that are remotely piloted could be incorporated into unsegregated airspace or at airstrips together with manned aircraft (Othman, 2016). ICAO subsequently narrowed its focus from all unmanned aerial systems to the types that are remotely piloted (Othman, 2016). If the wide-ranging benefits of utilising RPAS can be fully understood, it offers the greatly needed support to fully adopt RPAS into non-segregated airspace both nationally and globally (Othman, 2016). Therefore, RPAS terminology must correlate globally if there is to be international coordination (Othman, 2016). Consequently, ICAO established their Remotely Piloted Aircraft Systems Manual (RPASM) in 2015 (Othman, 2016) and the following standard ICAO terminology from that manual will be adopted in this research:

- Remotely piloted aircraft (RPA) – "an unmanned aircraft which is piloted from a remote pilot station" (International Civil Aviation Organisation, 2015, p. xviii); and
- Remotely piloted aircraft system (RPAS) – "a remotely piloted aircraft, its associated remote pilot station/s, the required communication data links and any other components as specified in the type design" (International Civil Aviation Organisation, 2015, p. xviii).

RPAS is also a constituent of the national or international aviation domain with its regulations, guidelines and disciplines (Austin, 2010). From the 2000s, the use of RPAS has increased significantly with reduced costs and weight, along with improved performance and capabilities of motors, batteries and electronics (Othman, 2016). An RPA possesses some level of autonomy and its capabilities include communicating with its pilot and returning payload data such as electro-optic or thermal images, together with its primary state information, that is, its location, airspeed, direction and altitude (Austin, 2010). An RPA will also communicate information regarding its condition, encompassing aspects such as the amount of fuel it has and temperatures of engines or electronics (Austin, 2010). If a fault arises in any of the sub-systems or components, the RPA may be designed to automatically take corrective action and/or alert its operator of the situation (Austin, 2010). If radio communication between the pilot and the RPA is disrupted, for instance, the RPA may be programmed to search for the radio signal and re-establish connection or to change to an alternative radio frequency band if the radio-link is twinned (Austin, 2010). An RPA with higher automatic intelligence may be programmed further to allow it to respond to different scenarios with specifically encoded actions (Austin, 2010).

The sizes of RPAs vary widely with wingspans ranging from 18 cm to 4 m (Abhishek & Kumar, 2013). One significant motivation for RPAS designers and manufacturers is the need to increase the payload capacity of the RPAS to the stages where they can carry any type of sensor (Mirza, et al., 2016). RPAS can carry different types of task-specific payloads such as cameras, infrared sensors and communications equipment (Odido & Madara, 2013). Potential applications of RPAS include monitoring mobile equipment, inspection of mine services pipelines or power-lines, surveillance of mine premises, mine surveying, inspection of mine infrastructure and monitoring concentrations in chemical spills (Abhishek & Kumar, 2013). In the past decade, commercial RPAS have experienced a significant increase in popularity, accessibility, diversity and competence (Jenzen-Jones & Smallwood, 2016). Basic technical knowledge must be readily accessible to aid policymakers and other important interested parties to properly classify and mitigate possible hazards associated with RPAS (Jenzen-Jones & Smallwood, 2016).

### 2.2.1 Components of Remotely Piloted Aircraft Systems

RPAS is an aerial vehicle equipped with several sub-systems that support it to fly without an onboard pilot (Boucher, 2015). According to Austin (2010), the sub-systems include:

a) The RPAS platform carrying the payload which can be of various forms;
b) The control station (CS) constitutes the system operators and the interfaces between the operators and the rest of the system;

c) The communication system between the CS and the RPAS platform; transmits control inputs from the CS to the RPAS platform and returns payload information and other data from the RPAS platform to the CS. This is usually achieved via radio transmission; and

d) Support equipment which may consist of maintenance and transport utilities.

These RPAS systems have different levels of automation and autonomy but typically include pilots that remotely navigate the aircraft from metres, kilometres or in some instances, continents away (Boucher, 2015). Other RPAS constituents considered essential include autopilots, navigation sensors, imaging sensors, mechanical servomotor and wireless systems (Colomina & Molina, 2014).

**Remotely Piloted Aircraft Systems platform**

The RPAS platform does not have a pilot onboard and flies under remote control or automated programming (Haider, 2014). The RPAS is remotely controlled by a pilot who has been trained and certified to similar standards as a manned aircraft pilot (Haider, 2014). RPAS is equipped with a receiver that receives commands from a transmitter by use of radio frequencies (Doumit, 2019). The type and performance of the RPAS are mainly influenced by the requirements of the mission (Austin, 2010). The main task of the RPAS is to carry the mission payload to the location of its use (Austin, 2010). Other important factors in the design of the RPAS configuration are the operational range, airspeed and endurance required by the mission parameters (Austin, 2010). The endurance and range constraints influence the amount of fuel or battery power to be loaded (Austin, 2010). Achieving a lightweight battery and maximised performance will necessitate an efficient propulsion system and optimal airframe aerodynamics (Austin, 2010). The speed requirements of the mission influence more importantly the type of RPAS used (Austin, 2010).

RPAS are comparatively robust and permit numerous flights before major maintenance is needed (Gutierrez & Searcy, 2016). RPAS do crash sometimes and propellers and rotors can be easily broken (Gutierrez & Searcy, 2016). However, the light weight of the small RPAS and their polymer expanded polyolefin (EPO) foam, or carbon fibre bodies prevent major damage, particularly if they plunge onto vegetation (Gutierrez & Searcy, 2016). These characteristics provide easy deployment and manoeuvrability in comparison to balloons, kites and gliders (Gutierrez & Searcy, 2016). The different types of RPAS platforms are discussed in this chapter.

**Ground Control Station**

A ground control station (GCS) is an immobile or portable system of hardware and software used to observe and direct the RPAS platform (Colomina & Molina, 2014). The operator uses it to control the RPAS, monitor its condition and may carry out pre-flight mission planning (Jenzen-Jones & Smallwood, 2016). It is normally, but not always, the main hub for pre-planning an RPAS mission. In such situations, it may be identified as the mission planning and control station (MPCS) (Austin, 2010). The mission may be planned from a central command centre and the mission data is transferred to the GCS for its implementation (Austin, 2010). From the GCS, the pilot commands the RPAS platform through the communications system uplink to guide its flight profile and to operate the different types of mission payload attached (Austin, 2010). Likewise, through the communications downlink, the RPAS platform sends feedback information and images to the operators, depending on the payload in use (Austin, 2010). The feedback may consist of data from the payloads, information on the condition of the RPAS platform's sub-systems and location information (Austin, 2010). Any variation in the route of the RPAS platform, any eventual error on the RPAS platform and/or any outcome of the payload sensors is sent to and perceived within the GCS (Colomina & Molina, 2014). The launching and recovery of the RPAS platform may be controlled from the central CS (Doumit, 2019) or a satellite (secondary) CS (Austin, 2010). The RPAS may be operated from the ground, sea or air (Colomina & Molina, 2014). The CS will typically also house the systems for communication with other external systems (Austin, 2010). These may include means of obtaining weather information, transfer of data to and from other systems in the network, instructions from higher authority and feedback reporting (Austin, 2010).

A GCS is operated by at least one person supplementary to a committed pilot who may have an additional spotter in some instances to ensure safety (Watts, et al., 2012). GCS are almost certainly as essential as the RPAS platforms themselves because they assist the interface with human intelligence (Colomina & Molina, 2014). GCS has progressed over the past years supported by the corresponding advances in computer science and telecommunications (Colomina & Molina, 2014). The setup of GCS differs broadly contingent on the platform and mission (Watts, et al., 2012). The requirements of RPAS-GCS communication, commanding devices, the number of monitors and the crew members needed to command an RPAS are essential factors to consider when configuring a specific GCS (Colomina & Molina, 2014). Figure 2.11 shows a typical GCS.

*Figure 2.7: Ground Control Station of an RPAS (Vasile, et al., 2019)*

Specific CS secured on board a vehicle may be allocated to large RPAS to maintain close proximity to the RPAS platform if restricted by distance or communication capabilities (Watts, et al., 2012). The smallest types of RPAS are usually complemented by a GCS comprising of a laptop computer and other mechanisms small enough to be transported easily together with the RPAS platform in small vehicles, aboard boats, or in backpacks (Watts, et al., 2012). A GCS can be in the form of a simple hand-held remote control with interfaces, for example, joysticks and switches (Jenzen-Jones & Smallwood, 2016). For more complex RPAS operations, the GCS typically comprises of custom software installed on a desktop or laptop computer where the RPAS is controlled via inputs from the keyboard and mouse (Jenzen-Jones & Smallwood, 2016). From a laptop, the operator may easily input waypoints onto a map base, for example, a Google map, and provide easy access to the key and frequently used features (Doumit, 2019). A laptop is not needed all the time in the field but it can provide some notable features such as mapping, missions, telemetry, spectrum analyser and disk video recorder (Doumit, 2019). It is not necessary to use computer hardware that is too sophisticated, just as long as it is capable of running 3D Earth representation software such as Google Earth at a minimum and the battery lasts for as long it is needed (Doumit, 2019). Ordinarily, manufacturers permit only one RPAS per pilot (Jenzen-Jones & Smallwood, 2016) and several countries require that the pilot maintains a visual line of sight (VLOS) with the RPAS platform (Austin, 2010). However, some of the RPAS control technology already in use does permit multiple RPAS platforms to be controlled by one pilot (Lazzaro, 2015). This technology could be used to an advantage as it would decrease the number of trained pilots required, in addition to reducing the cost of GCS equipment (Jenzen-Jones & Smallwood, 2016).

**RPAS Communication**

RPAS communication is essential to achieving mission objectives, that is, to command and control the RPAS and ultimately monitor the payload equipment (Colomina & Molina, 2014). It is also important with regards to safety, particularly RPAS integration with Air Traffic Control (ATC) in non-segregated airspace (Colomina & Molina, 2014). Even though RPAS has usually been used in isolated airspace where there is separation from other aircraft, organisations anticipate extensive deployment of RPAS in non-segregated airspace alongside manned aircraft (Colomina & Molina, 2014). The communications pathway between the RPAS and the ground is called a data link (Jenzen-Jones & Smallwood, 2016). The RPAS data links can be communicated through either LOS or beyond the line of sight (BLOS) (Haider, 2014). In BLOS, the data link connectivity is maintained via satellites and it provides far greater ranges than the LOS data links (Narang, 2016). The BLOS data links are a new development in aviation, which raises challenges concerning the responsibility for control of the RPAS and would need to be factored in RPAS regulations in the future (Narang, 2016). Currently, the South African aviation regulations require that the pilot must maintain a visual line of sight (VLOS) with the RPAS at all times. There are different types of data links and their design is influenced by the mission requirements, in addition to the competencies of the manufacturer and user (Jenzen-Jones & Smallwood, 2016). A communications system provides the data links between the GCS and the RPAS through radio frequencies (Doumit, 2019). The function of the data links are usually as follows:

(a) Uplink (from the GCS to the RPAS):

i) Transmit mission flight path which is then stored in the RPAS automatic flight control system (AFCS);
ii) Transmit real-time flight control commands to the AFCS when human interface flight is required;
iii) Transmit control commands to the RPAS-attached payloads and ancillaries; and
iv) Transmit real-time positional data to the RPAS inertial navigation system (INS) or AFCS where applicable. (Austin, 2010)

(b) Downlink (from the RPAS to the GCS):

i) Transmit RPAS positional information to the GCS where applicable;
ii) Transmit payload data to the GCS; and
iii) Transmit RPAS condition data such as fuel state and engine temperature to the GCS. (Austin, 2010)

RPAS communication infrastructure involves a combination of communication systems such as microwave links or radio frequency to constantly maintain the connection between the GCS and the RPAS (Jawhar, et al., 2017; Pokorny, et al., 2018; Sharma, 2019). A radio signal is needed to remotely operate and control an RPAS from a remote location (Othman, 2016). Radio control requires the following mechanisms (Othman, 2016):

- Transmitter - This can be as simple as a hand-held device or as complicated as a full mission control room, depending on the complexity of the RPAS (Othman, 2016). The transmitter is used to control the RPAS and generates an electric current that is fed into an oscillator circuit that produces an electro-magnetic wave, known as the radio signal (Othman, 2016). The transmitter then sends the radio signal via an antenna to the receiver (Othman, 2016).
- Receiver - This is a device inside the RPAS that has an antenna matched to the transmitting antenna and receives radio signals from the transmitter that it then converts to electric power to activate servo motors inside the RPAS as commanded by the transmitter (Othman, 2016).

Table 2.2 summarises the common types of data links used with RPAS. It is important to note, however, a data link is not essentially a requisite with an autopilot (Jenzen-Jones & Smallwood, 2016).

*Table 2.2: Data link Technologies (Jenzen-Jones & Smallwood, 2016)*

| Type | Purpose | Ground Equipment | Aircraft Equipment | Example |
|---|---|---|---|---|
| **Command Uplink** | Control the RPA and payload | Transmitter | Receiver | 72 MHz Remote Control |
| **Telemetry Downlink** | Transmit instrumentation data to the GCS | Receiver | Transmitter | 900 MHz Digital Radio |
| **Video Data link** | Transmit video files to the GCS | Receiver | Transmitter | 5800 MHz Analog Video |
| **Bi-directional Data link** | Transmit command and telemetry data and/or digital video files | Transceiver | Transmitter | 2400 or 5800 MHz Wi-Fi |

It is not unusual for a single aircraft to have separate command, telemetry and video data links (Jenzen-Jones & Smallwood, 2016). This is mainly a result of radio frequency interference issues and the absence of completely integrated bi-directional data links (Jenzen-Jones & Smallwood, 2016). However, manufacturers must use different frequencies when using as many data links to avoid interference (Jenzen-Jones & Smallwood, 2016). For instance, a command and telemetry link may exist in the 900 MHz band whilst the video data link operates in the 2400 MHz band (Jenzen-Jones & Smallwood, 2016). Ultimately, the safe operation of RPAS depends on communications, which signifies an important step in facilitating RPAS operations in non-segregated airspaces (International Telecommunication Union, 2009). To achieve safe operations of RPAS under LOS and BLOS situations, three types of radio communications between the RPAS platform and the GCS are required, which are as follows:

1) **Command and control communications (C2 data link) -** Command and control is the typical link between the GCS and the RPAS. The main function of the C2 data link is to send commands to adjust the movements of the RPAS and to receive data concerning the location and status of the RPAS (Othman, 2016). The C2 data link could experience interruptions lasting from a few seconds to a few minutes due to unreliability of the communications link and/or fading of radio signals (Adey, et al., 2014; Narang, 2016). However, the RPAS must be designed in such a way that the loss of the C2 data link does not cause a hazardous or disastrous event such as collision with another aircraft or uncontrolled collision with the ground or other structures (Othman, 2016). If the C2 data link is lost, there should exist a lost link procedure readily available and it should be activated as soon as the RPAS cannot be controlled using the C2 data link (Narang, 2016; Othman, 2016). Some programs that can be integrated into the design of the RPAS to safeguard against such events if the C2 data link is lost include:

- RPAS to return to the airfield or a pre-determined safe location;
- RPAS to complete its mission and land at a pre-determined safe location;
- RPAS to land instantaneously;
- RPAS to descend to a low altitude such that it cannot collide with another aircraft and then fly out to a pre-determined location with open waters and ditch; or
- RPAS to climb to altitude in an attempt to recover the C2 data link. (Adey, et al., 2014; Othman, 2016)

The mentioned scenarios and any other possible cases should undergo intense analysis with regards to the airspace the RPAS will be flying in and, the altitude and speed of the RPAS. The flight plan should be analysed for increased attentiveness on the section of flight at all points where the failure could occur (Othman, 2016). All these should be considered and programmed into the software that will deliver the commands to the on-board computer that takes-over flight control of the RPAS (Othman, 2016). The selected option should be sanctioned by ATC before the flight.

Furthermore, the remote pilot must inform ATC once the C2 data link fails (Othman, 2016).

2) **Air traffic control communications** - In non-segregated airspace, a link between ATC and the GCS passing through the RPAS is essential to relay ATC and air-to-air communications received and transmitted by the RPAS (International Telecommunication Union, 2009). The RPAS uses similar equipment as a manned aircraft for communicating with ATC (International Telecommunication Union, 2009). These communications include:

   - The downlink transmitting the ATC information from the RPAS to the GCS; and
   - The uplink from the GCS to the RPAS allowing the GCS to communicate with ATC. (International Telecommunication Union, 2009)

   These communications are essential for the safe management of controlled airspaces, particularly in the proximity of aerodromes with a high density of aircraft (International Telecommunication Union, 2009). ATC communications are different from the C2 data link communications (Othman, 2016). The communication requirements for RPAS are similar to those for manned aircraft flying in the same airspace (Othman, 2016). These could be either very high frequency (VHF) voice or Controller-Pilot-Data link-Communications (CPDLC) (Othman, 2016). They could also include telephone backup, provided that it is approved by ATC in advance (Othman, 2016). Communication between ATC and the remote pilot can either be via the RPAS or a broadcast, private or service provider network (Othman, 2016). Communication through the RPAS is probably the easiest as it is transparent to ATC and is well-suited with existing communications between ATC and manned aircraft pilots internationally (Othman, 2016). Its main limitation is that it may necessitate more bandwidth for the C2 data link to sustain the ATC voice and data relay between the RPAS and the remote pilot (Othman, 2016). Communications through a network are more complicated and may necessitate supplementary infrastructure or equipment in the ATC division (Othman, 2016).

3) **Communications for the Sense and Avoid function** - Sense and avoid (SAA) relates to the piloting principle "see and avoid" where the pilot is accountable for making sure the piloted aircraft evades nearby aircraft, landscape and obstacles (International Telecommunication Union, 2009). In these bi-directional communications between the GCS and the RPAS for the SAA function, two distinct data streams must be considered:

   - The SAA data uplink allows the GCS to control the operation of this function consistent with the flight surroundings. Similar to the Control uplink, the communication does not require high bit rates; and
   - The SAA data downlink from the RPAS to the GCS which communicates whether the SAA function works properly. Like the Control downlink requirement, the need to send video streams under this SAA function must be considered, but avoiding replication between the C2 downlink and the SAA video downlink. (International Telecommunication Union, 2009)

The C2 data link considerations and the SAA data radio frequency communication requirements must align with ICAO standards for the safe flight of the RPAS in areas under the jurisdiction of the aviation authorities (International Telecommunication Union, 2009). According to Austin (2010), the level of electrical power, the complexity of the processing and the antennae design, and therefore the complexity, weight and cost of the radio communications are influenced by:

i) "the range of operation of the RPAS from the transmitting station" (Austin, 2010, p. 13);
ii) "the sophistication demanded by transmission-down of the payload and housekeeping data" (Austin, 2010, p. 13); and
iii) "the need for security" (Austin, 2010, p. 13).

Figure 2.12 shows the communication system integrating the RPAS, CS and ATC in compliance with ICAO RPAS Manual.

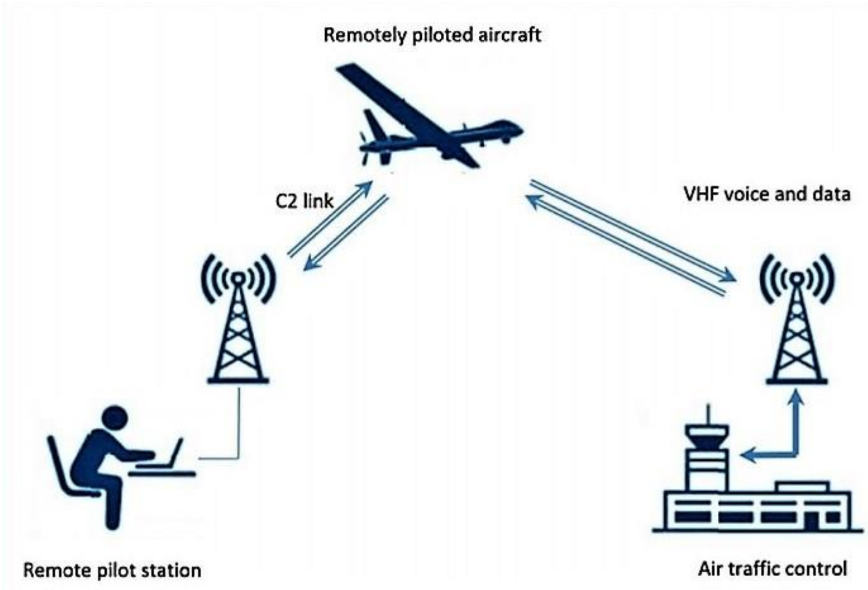


*Figure 2.8: RPAS, CS (labelled as a remote pilot station) and ATC interaction (Falkov, 2018)*

**Navigation Systems**

The remote pilot needs to have real-time information regarding the location of the RPAS (Austin, 2010). Reliable navigation and control systems are needed to safely pilot RPAS (Wang, et al., 2008). RPAS utilises various navigation systems to travel along a planned pathway (Elkaim, et al., 2015). More advanced navigation systems consist of more specific sensors such as:

- Accelerometer - measures linear acceleration in up to three axes (X, Y and Z). The units are normally in "gravity" (g) which is 9.81 metres per second. Accelerometers detect gravity and can sense a downward direction (Doumit, 2019).

- Gyroscope - measures the rate of angular change in up to three angular axes (alpha, beta, and gamma). The units are usually in degrees per second (Doumit, 2019).
- Inertial Measurement Unit (IMU) - these electronic devices are capable of providing 3D velocity and acceleration data of the RPAS they are installed on at high sampling rates. They consist of three accelerometers and three gyroscopes mounted in a set of three orthogonal axes (Edwards, 2017). The main challenge encountered with such developed low-cost IMUs is the need to perform the calibration process for the sensors (Dissanayake, et al., 2001).
- Global Navigation Satellite System (GNSS) - GNSS uses satellite signals to determine the specific geographic location of the RPAS and its registered coordinates of the take-off points to return to it in case of emergency during automated flights. A flight controller can have either an onboard GNSS or one which is connected to it via a cable. The accuracy of GNSS is not very high (Doumit, 2019), therefore it is complemented and further enhanced by the use of differential GNSS (Austin, 2010). The GNSS devices currently available provide real-time positional data and are light-weight, compact and relatively inexpensive (Austin, 2010).

Some of the most commonly used navigation technologies for RPAS include GNSS receivers and Inertial Navigation System (INS) devices (Klavins & Zagursky, 2017), used separately or in combination (Wang, et al., 2008). An INS may vary in design, size and level of accuracy (Ramdzan, n.d.). The INS, as input data, takes RPAS inertial sensor measurements, especially linear acceleration sensor (accelerometer) and angular rotation sensor (gyroscopes) measurements (Klavins & Zagursky, 2017). The combination of accelerometers and gyroscopes creates an IMU (Klavins & Zagursky, 2017). Using just the IMU readings and elapsed time (Ramdzan, n.d.), an INS provides a complete set of navigation parameters, including position, orientation, velocity, angular velocity and attitude, with a high data rate (Wang, et al., 2008). Usually, an initial established position is programmed on start-up to align the INS system

(Ramdzan, n.d.). A very simple navigation system will include only a three-axis gyroscope to be able to auto-level the RPAS (Doumit, 2019).

INS is a self-contained device that operates independently of any external signals or inputs (Wang, et al., 2008). However, one of the main disadvantages of INS, when used as a stand-alone device, is the rapid increase of systematic errors over time (Wang, et al., 2008). Generally, the smaller the INS, the greater the reduction in accuracy (Ramdzan, n.d.). In some instances, the INS has incorrect approximations of position which can be distant from an initial estimate (Ramdzan, n.d.). In contrast to INS's short-term positioning accuracy, satellite-based GNSS navigation techniques can offer relatively consistent accuracy if sufficient GNSS signals can be tracked during the entire RPAS mission (Wang, et al., 2008). However, GNSS cannot independently provide attitude measurements (Wang, et al., 2008). Integrated GNSS/INS navigation systems have been successfully implemented for various uses, but their performance is highly dependent on the availability and quality of GNSS signals (Wang, et al., 2008). Relying on GNSS alone to establish the INS drift is not an adequate solution, as GNSS signals are susceptible to jamming, spoofing, multipath, or blockage (Zahran, et al., 2019). GNSS signal interruptions can cause a significant deviation in the GNSS/INS navigation outcomes (Wang, et al., 2008). Other supporting sensors and methods of navigation must be utilised to replace the GNSS in periods when it is unavailable (Zahran, et al., 2019). Different sensors and methods can be used for navigation such as:

(a) Radio detection and ranging (RADAR) - The aircraft is equipped with a transponder that responds to a radar scanner emitting a signal from the GCS so that the aircraft position is observed on the GCS radar display in bearing and range (Fasano, et al., 2017; Mostafa, et al., 2018).
(b) Radio-tracking - The radio signal transmitting information from the aircraft to the GCS is tracked in bearing from the GCS, while its range is derived from the duration of a coded signal to travel between the aircraft and the GCS (Austin, 2010).

(c) Single or multiple cameras (Direct reckoning) - With the computer-integration of velocity vectors and time lapsed, the aircraft position may be computed (Austin, 2010). If the mission is above terrain and the aircraft has a camera attached surveying the ground, its position can be established by relating visible geographical landscapes with their known position on a map (Austin, 2010). However, to minimise complications of the operation, it is always favourable for the system to be as automatic, if not autonomous, as possible. (Chuanqi, et al., 2017; Urzua, et al., 2017; Zarandy, et al., 2016).

(d) Light Detection and Ranging (LiDAR) - LiDAR sensor allows the acquisition of 3D information consisting of latitude, longitude and altitude from the ground surface (Braga, et al., 2015). It also captures the intensity of the reflectance objects value in the terrain (Antonarakis, et al., 2008). Based on the combined information, with the analysis of LiDAR data, it is possible to identify objects of interest such as asphalt structures, transmission lines and water bodies (Hemman, et al., 2016; Kumar, et al., 2017; Mohamed, et al., 2017).

(e) Compass/Magnetometer - An electronic magnetic compass can measure the Earth's magnetic field, determine the true North and use it to determine the RPAS compass direction (Edwards, 2017). This sensor is installed in most systems, has GNSS input and is available in one to three axes (Doumit, 2019).

(f) Pressure/Barometer - Since atmospheric pressure changes the farther away you are from sea level, a pressure sensor can be used to provide fairly accurate measurements of the RPAS elevation. A barometer measures the air pressure to estimate the altitude of the RPAS (Edwards, 2017). Most flight controllers take input from both the pressure sensor and GNSS altitude to calculate a more accurate height above sea level (Doumit, 2019).

**Payloads (Sensor Types and Characteristics)**

The payload is the weight that an RPAS platform can carry (Ramdzan, n.d.). Sensors, especially cameras, are the most common types of payloads carried by small RPAS and they can gather data and transmit it to the GCS for further process (Jenzen-Jones &

Smallwood, 2016). The RPAS computer inside the RPAS is used to control the sensors which must coordinate with the RPAS mission flight plan (Ramdzan, n.d.). The payload can be carried either internally or externally by the RPAS (Haider, 2014). The types of cameras and other sensor payloads vary significantly (Edwards, 2017; Jenzen-Jones & Smallwood, 2016). The type and performance of the payloads are influenced by the requirements of the task (Austin, 2010; Edwards, 2017), RPAS size and the operator's budget (Jenzen-Jones & Smallwood, 2016). Most RPAS applications that have great potential involve the acquiring of data using remote sensing functions such as electromagnetic spectrum sensors, gamma ray sensors, biological sensors and chemical sensors (Doumit, 2019).

The majority of RPAS carry a camera on-board for piloting reasons or secondary objectives regardless that its main mission does not involve obtaining imagery (Jenzen-Jones & Smallwood, 2016). Setting up of the payload can differ considerably and is influenced by the type and model of RPAS, size and weight of the camera, operator's objectives and other aspects (Jenzen-Jones & Smallwood, 2016). Some sensors need gimbals to be mounted on the RPAS platform (Doumit, 2019). Gimbals are advanced mounting systems that reduce vibrations by stabilising the camera or sensor (Doumit, 2019). Connecting a sensor directly to the RPAS frame sometimes means it is always pointing in the same direction as the frame itself (Doumit, 2019). However, some gimbals provide a remote control for adjusting and rotating the camera to capture a different perspective (Doumit, 2019). Gimbals tend to reduce flight time due to their weight (LaFay, 2015).

Weight is the main practical limitation regarding sensors that can be attached to RPAS (Barbedo & Koenigkan, 2018). There have been improvements in the development of miniaturised sensors, specially designed or modified for RPAS payloads, such as hyperspectral cameras, LiDAR, synthetic aperture radar and thermal sensors (Klemas, 2015). Some manufacturers are now producing types of cameras suitable for small RPAS which are comparatively inexpensive and with few export restrictions (Jenzen-Jones & Smallwood, 2016). Consequently, it is now possible to deploy advanced instruments using light-weight, low-cost RPAS (Anderson & Gaston, 2013; Barbedo & Koenogkan, 2018). The development of small light-weight cameras has brought an important upgrade in imaging capabilities, in comparison to the integration problems of their heavier, larger predecessors (Jenzen-Jones & Smallwood, 2016). These cameras are very accessible, with a range of capabilities such as resolution, frame rate, camera modes and other features (Jenzen-Jones & Smallwood, 2016). However, the most noteworthy progress was probably the development of cameras that allow connection through an ad hoc Wi-Fi network, using a smartphone, tablet or similarly supported device (Jenzen-Jones & Smallwood, 2016). This approach presents two major challenges which are the characteristically short range of Wi-Fi and the radio frequency interference with RPAS controls (Jenzen-Jones & Smallwood, 2016). The increasing availability and accessibility of more advanced technologies, such as infrared (IR) cameras, is likely to continue (Jenzen-Jones & Smallwood, 2016). Some of the sensors that can deliver valuable information for equipment and personnel monitoring include:

1) **Visible light**: these are conventional cameras that capture images using three constituents of the visible spectrum (red, green and blue) and they are mostly used for the formation of true colour orthomosaics (Hogan, et al., 2017). An RGB camera is a sensing system that takes RGB (Red Green Blue) images, including a per-pixel depth report (Shahmoradi, et al., 2020). These sensors are usually inexpensive and the images produced are a near illustration of how humans would perceive the scene (Barbedo & Koenigkan, 2018). Repetitive sampling can be used to detect variations in landscape (Carvajal, et al., 2012; Niethammer, et al., 2011; Rau, et al., 2012) such as land subsidence (Gallacher, 2016). RPAS equipped with digital cameras provides geo-referenced images that can be processed using image-recognition algorithms to greatly increase the accuracy of population computations (Klemas, 2015). Some RPAS carry high-definition (HD) cameras with high power zoom for day-time operations and thermal imaging cameras for night time missions (Platt, 2013). RGB cameras can be used in surveying and mapping, stockpile volume calculations,

mobile equipment monitoring, surveillance and inspections (Shahmoradi, et al., 2020). RGB cameras work with one of two active stereos (Henry, et al., 2012; Konolige, 2010) or time-of-flight sensing to create depth evaluation with a large number of pixels (Henry, et al., 2012). Camera selection should be conducted cautiously, considering the RPAS payload carrying capability (Shahmoradi, et al., 2020).

2) **Infrared**: a thermographic camera or infrared (IR) camera is a device that creates an image using infrared radiation (Doumit, 2019). IR sensors, also called thermal sensors, are a kind of low-cost detector sensor (Shahmoradi, et al., 2020). They detect variations in heat using the long-wavelength IR band (Barbedo & Koenigkan, 2018; Shahmoradi, et al., 2020). IR radiation can be either detected or emitted by IR sensors (Shahmoradi, et al., 2020). Generally, all materials above absolute zero emit waves in the IR spectrum (Shahmoradi, et al., 2020). Regardless of the limited resolution, IR sensors can detect people (Bingham, et al., 2010; Cunha & Youcef-Toumi, 2018; Gageik, et al., 2015). The significant advantages of using thermal cameras are that they can efficiently operate during the hours of darkness (Linchant, et al., 2015), foggy conditions or through smoke (Shahmoradi, et al., 2020). However, they can be distorted by any objects emitting high temperatures (Shahmoradi, et al., 2020). Furthermore, IR sensors do not function properly through thick dust (Bingham, et al., 2010; Gageik, et al., 2015). In comparison to other types of sensors, IR sensors have a much lower spatial resolution (Chabot & Bird, 2015).

3) **Multispectral**: these cameras capture images at specific wavelengths, that is, in the visible band, in the near-infrared band or the thermal band (Barbedo & Koenigkan, 2018). Some features of the observed objects may be more noticeable in particular wavelengths, which can be explored to enhance the detection process (Barbedo & Koenigkan, 2018). Most of the multispectral imagers detect reflectance of the Earth’s surface material at several wide wavelength bands which are separated by spectral segments (Shahmoradi, et al., 2020). Sometimes bands may be integrated

to reveal other types of relevant information (Barbedo & Koenigkan, 2018). These sensors typically have a lower spatial resolution than visible light sensors (Chabot & Bird, 2015).

4) **Hyperspectral**: similar to the multispectral cameras, this type of sensor captures images at specific wavelengths, but with a significantly higher spectral resolution (hundreds of wavelengths) (Barbedo & Koenigkan, 2018). Hyperspectral sensors assess reflected radiation as a series of narrow and contiguous wavelength bands (Shahmoradi, et al., 2020). Typically, bands are measured at 10 to 20 nm intervals by hyperspectral sensors (Shippert, 2004). These sensors are usually very costly and the spectral resolution delivered is not necessary for personnel detection and counting (Barbedo & Koenigkan, 2018). Hyperspectral remote sensing, also known as imaging spectroscopy, is a relatively new technology that is being studied for the detection and identification of minerals, and land use (Doumit, 2019). Light-weight hyperspectral imaging (HSI) sensors are being developed for use on RPAS (Jakob, et al., 2017). These sensors can provide information that is not accessible by traditional methods (Shahmoradi, et al., 2020). Hyperspectral sensors are extensively used in geology, mineral mapping and exploration (Jakob, et al., 2016; Jakob, et al., 2017; Zimmermann, et al., 2016).

5) **RADAR**: most of the highly promising applications of RPAS radar-based sensing utilise synthetic aperture radar (SAR) (Doumit, 2019). SAR is a form of radar, which uses the relative motion between an antenna and a target region to provide distinctive long-term coherent-signal variations (Doumit, 2019). These signal variations are exploited to obtain a finer spatial resolution for the production of digital elevation models (DEM) (Doumit, 2019). SAR imaging can be used to remotely map the reflectivity of objects or environments with high spatial resolution, through the emission and reception of electromagnetic (EM) signals (Ferro-Famil & Pottier, 2017). Images acquired using this method can be used for various applications such as the detection of objects and their geographical localisation (Ferro-Famil & Pottier, 2017). They can also be used to estimate some

geophysical properties of complex environments, for example, moisture content, roughness, density and certain dimensions (Ferro-Famil & Pottier, 2017). The SAR system is not affected by daylight and is not especially impacted by weather conditions (Ferro-Famil & Pottier, 2017).

6) **LiDAR**: this is an optical remote sensing technology that can measure the distance to a target by illuminating the target with light, often using laser pulses (Doumit, 2019). This technology aids in 3D terrain modelling by producing 3D point clouds (Doumit, 2019). A LiDAR system typically comprises of the laser source, the synchronised system designed to detect the emitted waveform and the hybrid georeferencing system which makes it possible to locate the device and measure its attitude (Mallet, et al., 2017). The lasers which emit electromagnetic waves in a single direction are referred to as profilers (Mallet, et al., 2017). The measurement is spatialised using a vector displacement, often in conjunction with a beam deflection mechanism (Mallet, et al., 2017). LiDAR technology can be effectively applied in geomatics, archaeology, geography, geology, geomorphology, seismology, forestry, remote sensing and atmospheric physics (Wallace, et al., 2012).

7) **Air Quality Sensors**: these sensors are based on optical, ultrasound and electrochemical sensing elements (Molina, 2018). These sensors can be handheld, installed on a moving vehicle or set up from ground-based network systems (Shahmoradi, et al., 2020). Most of these sensors can be installed on an RPAS platform depending on the type of contamination, release time and measurement requirements (Shahmoradi, et al., 2020). Rotary-wing RPAS have previously been used to detect water vapour and carbon dioxide, methane (Khan, et al., 2012), ethanol and methane (Bennets, et al., 2012; Neumann, et al., 2013), nitrogen dioxide and ammonia (Alvarado, et al., 2015; Malaver, et al., 2012), carbon dioxide (Alvarado, et al., 2015; Watai, et al., 2006), sulphur dioxide (Brown & Taras, 2008). Furthermore, different types of this platform were used to identify sewage discharges along the coastline of Italy by detecting gases such as carbon monoxide,

benzene, nitrogen dioxide, ozone, sulphur dioxide, nitrous fumes, fine particulate matter, for example, $PM_{10}$ dust, and thermal images (Alvarado, et al., 2015; Lega, et al., 2012).

Some advanced RPAS carry a combination of different types of sensors, within a payload module (Castelvecchi, 2010; Marris, 2013) or a series of modules (Austin, 2010). The information from these various sensors may be processed and integrated to deliver improved data or information that could not be acquired using only one of the sensors (Austin, 2010). The information obtained using these sensors is processed into a format that can be transmitted through the downlink to the GCS or other applicable destination (Austin, 2010).

**Autopilots**

An autopilot is the component of the RPAS control system onboard the RPAS (Jenzen-Jones & Smallwood, 2016). Autopilots are systems of servomechanisms that guide the aircraft along a planned flight path, altitude, ground speed and landing profile (Nickols & Lin, 2019). An autopilot operates without assistance from operators and it consists of both hardware and its supporting software (Doumit, 2019). Autopilot and stability augmentation systems typically fitted on RPAS use sensors such as magnetometers, accelerometers and gyroscopes to provide information regarding the movements of the aircraft (Grauer & Hubbard Jr, 2013). For small RPAS, the autopilot is typically a single assembly needed for the following functions:

- Stabilising the RPAS;
- Controlling the RPAS orientation, position, speed and course; and
- Controlling sub-systems onboard the RPAS including the payload and communications. (Jenzen-Jones & Smallwood, 2016)

Autopilots need at least one microprocessor and the capability to compute the flight parameters as well as the aircraft's health parameters such as battery voltages or fuel reserves (Jenzen-Jones & Smallwood, 2016). The autopilot needs to maintain communication with the GCS for control mode switch, to receive the transmission from GNSS satellite for position updates and to send commands to RPAS motors (Doumit, 2019). The level of autonomy of an RPAS autopilot system is determined by the type of RPAS operation, that is, semi-autonomous or fully autonomous (Huang, et al., 2005). Autonomy is a system's ability to complete a mission without human interference (Jenzen-Jones & Smallwood, 2016). The concept of autonomy was introduced as a means to reduce the workload of human operators by transferring some tasks to a machine process, for example, an aircraft's autopilot mode (Grant, 2014). ICAO defines autonomous aircraft as "an unmanned aircraft that does not allow pilot intervention in the management of the flight" (International Civil Organisation, 2015, p. xiv).

Semi-autonomous autopilots automatically control some functions constantly throughout the mission, and other controls when instructed by the operator (Jenzen-Jones & Smallwood, 2016). When an RPAS is equipped with a fully autonomous autopilot, then operator interference reduces even further (Jenzen-Jones & Smallwood, 2016). The operator inputs constraints, such as flight destination and time of arrival or finding and tracking targets, and the autopilot controls the RPAS to complete the planned mission (Jenzen-Jones & Smallwood, 2016). Taking this definition into consideration, very few operational autopilots are fully autonomous (Huang, et al., 2005). The terms "fully autonomous flight" usually mean that mission data is pre-programmed for the autopilot to complete on a time or event basis (Jenzen-Jones & Smallwood, 2016). The aircraft is then permitted to fly along a pre-planned flight path before receiving additional commands (Grant, 2014). Many autopilots have a manual control mode which allows the operator to bypass the autopilot and directly control the aircraft with joysticks or another input device (Jenzen-Jones & Smallwood, 2016). With regards to RPAS, automating some phases of the operation can improve the safety of the overall operation (Grant, 2014).

### 2.2.2 Types of Remotely Piloted Aircraft Systems

Different types of RPAS are efficient for different tasks therefore it is essential to understand their characteristics to determine the correct type of RPAS for the task intended (Culus, et al., 2018). Their functions are supported by key technologies such as autopilots, communications, GCS and different propulsion technologies which allow the attachment and use of different payloads (Jenzen-Jones & Smallwood, 2016). These RPAS are specially designed to carry small payloads and integrated flight control systems (Klemas, 2015). RPAS can be classified in terms of the configuration of the aerial platform, the degree of autonomy, the size and weight of the RPAS and the power source (Vergouw, et al., 2016). The degree of autonomy of RPAS can vary from full autonomous operation to full remote control by a pilot (Vergouw, et al., 2016). The size of RPAS can vary from a few centimetres in length and breadth to RPAS the size of a commercial aeroplane (Vergouw, et al., 2016). The weight of an RPAS can vary from several grams to hundreds of kilograms (Vergouw, et al., 2016). Examples of RPAS power sources include battery cells, solar cells and traditional aviation fuel (Vergouw, et al., 2016). These criteria are all important as they determine the RPAS cruising range, the maximum flight duration and the payload capacity (Vergouw, et al., 2016). RPAS can also be classified using parameters such as range, endurance, altitude, speed and payload (Jenzen-Jones & Smallwood, 2016). The most common basis of the classification of RPAS is the configuration of the aerial platform of the RPAS (Jojo, 2017). There are four major types of RPAS based on these criteria, namely:

- Fixed-wing RPAS;
- Fixed-wing Hybrid VTOL (Vertical take-off and landing) RPAS;
- Single-rotor RPAS (Helicopter); and
- Multi-rotor RPAS. (Chapman, 2016)

The industry mostly recognises the multi-rotor RPAS but they also have limitations that are complemented by other types of RPAS (Chapman, 2016). For a case in point, fixed-wing RPAS is the best option for aerial mapping because it is more energy-efficient than rotary RPAS (Chapman, 2016). This section gives an overview of the four main types of RPAS platforms focusing on their strengths and weaknesses.

**Fixed-wing Remotely Piloted Aircraft Systems**

Fixed-wing is a term used in the aviation industry to define aircraft that use fixed, static wings in combination with forward airspeed to generate the lift to ascend the aircraft into the air (Vergouw, et al., 2016). Fixed-wing RPAS use wings which are similar to a normal aeroplane instead of vertical-lift rotors (Chapman, 2016). The aerodynamic profile of the wings enables the RPAS, once in flight, to generate lift that compensates for the weight of the aircraft (Doumit, 2019). This makes it a relatively more effective technique of generating vertical lift (Das, 2019). Fixed-wing RPAS are therefore considered to be more energy-efficient than rotary RPAS (Chapman, 2016). Energy is only required to move the RPAS forward on the set course as long as the energy permits, while the aerodynamic forces lift the aircraft into the air (Chapman, 2016). Like an aeroplane, fixed-wing RPAS have ailerons that enable the aircraft to steer (Doumit, 2019). Some RPAS also feature a rudder and elevators, sometimes even flaps (Doumit, 2019).

Fixed-wing RPAS are capable of flying for a few kilometres from the take-off site, although regulations usually require that a VLOS from the pilot be constantly maintained (Anderson & Gaston, 2013). They can cover large aerial mapping areas, travel longer distances, can fly at high speeds and can fly for longer times whilst covering the targeted areas (Chapman, 2016; Das, 2019). Most fixed-wing RPAS are battery powered and can stay in the air for two hours but combustion engine powered RPAS can stay in the air for 16 hours or more due to the greater energy efficiency of fuel (Das, 2019; Jojo, 2017). Fixed-wing RPAS, however, cannot hover in one position which makes it difficult for static observation and inspection (Chapman, 2016; Das, 2019). This characteristic also negatively affects the processes of launching and landing of the RPAS (Chapman, 2016). Figure 2.13 shows a typical fixed-wing RPAS in flight.

*Figure 2.9: Fixed-wing RPAS in flight (Jojo, 2017)*

Launching and landing fixed-wing RPAS can be challenging (Das, 2019), but it can be done in several different ways (Gundlach, 2014). Small fixed-wing RPAS, usually with gross take-off weights (GTOW) of not more than 10 kg, can be hand-launched into the air and can belly land in an open space (Chapman, 2016; Das, 2019; Jenzen-Jones & Smallwood, 2016). This consequently minimises equipment needed for the launch and recovery of RPAS of that size (Linchant, et al., 2015). Heavier RPAS usually launch from a long paved runway to reach the high lift-off speed required by the high wing-loading needed for low aerodynamic drag (Austin, 2010; Das, 2019) or use a specially-assembled catapult launcher (Chapman, 2016; Jenzen-Jones & Smallwood, 2016). Safe recovery of the fixed-wing RPAS is typically achieved using a runway, parachute, guided flight into a catchment net (Chapman, 2016; Das, 2019), deep stall landing or skid landing (Jenzen-Jones & Smallwood, 2016). Guiding flight into the net is usually accompanied by disastrous outcomes as in most cases the RPAS is damaged or completely wrecked (Doumit, 2019). Deep stall landing happens when the aircraft is flown in at low altitude and the nose is pulled up to below stall speed (Jenzen-Jones & Smallwood, 2016). The RPAS loses aerodynamic lift and falls to the ground (Jenzen-Jones & Smallwood, 2016). A skid landing is similar to a conventional landing (Jenzen-Jones & Smallwood, 2016).

It is more difficult to learn how to pilot a fixed-wing RPAS and also relatively more expensive to buy a fixed-wing RPAS compared to the multi-rotor RPAS (Chapman, 2016; Das, 2019). A fixed-wing RPAS is constantly in a forward motion once it has taken off and it moves faster than a multi-rotor RPAS (Chapman, 2016). Therefore, a fixed-wing RPAS requires much attention and concentration as there is no room to hover in one place whilst the pilot orientates himself or herself (Chapman, 2016). A fixed-wing RPAS is best suited for extended flight times over a long distance (Niethammer, et al., 2012). Long endurance and long-range surveillance or aerial mapping tasks are well suited for a high aspect-ratio fixed-wing RPAS flying at high altitude (Austin, 2010). Fixed-wing RPAS typically have greater speed, use less power and can carry more payload than the rotary RPAS (Miller, et al., 2017), but are less manoeuvrable (Barbedo & Koenigkan, 2018). Images captured by a fixed-wing RPAS usually show stronger smearing effects because of the aircraft speed and associated vibrations (Barbedo & Koenigkan, 2018). Generally, a compact camera is preferred for fixed-wing RPAS because they cannot carry heavy devices (Lee & Choi, 2016).

**Fixed-wing Hybrid Remotely Piloted Aircraft Systems**

The hybrid VTOL (vertical take-off and landing) RPAS integrates the advantages of fixed-wing RPAS with the ability to hover and, take-off and land vertically (Chapman, 2016; Das, 2019). VTOL RPAS can generate downward thrust and take-off within a very limited space which is an essential characteristic best suited for missions where limitations of terrain require this capability (Watts, et al., 2012). These missions include operations where run-way facilities are unavailable, such as in forest or bush areas, or launching and recovering from non-carrier vehicles (Arjomandi, 2007). There are different types of VTOL RPAS available or under development (Chapman, 2016). Some have the current fixed-wing designs but with vertical lift motors attached to them (Chapman, 2016; Das, 2019). This configuration reduces the thrust needed from the rotor and equips the aircraft with higher speeds (Austin, 2010). However, the increase in speed is a trade-off with payload capacity and endurance (Austin, 2010). There are tail-sitter type RPAS that look like regular aeroplanes but rest on their tails on the ground pointing directly upwards for take-off before tilting forward to fly normally in a horizontal plane (Chapman, 2016; Das, 2019). Others are called tilt-rotor types where the rotors or the whole wing, with propellers attached, can rotate from pointing upwards for take-off to pointing horizontally for forward motion (Chapman, 2016), with the aircraft weight being carried by the wings (Austin, 2010). Figure 2.14 shows a typical VTOL hybrid RPAS in its take-off position.

*Figure 2.10: Hybrid VTOL RPAS in take-off position (Ridden, 2019)*

VTOL RPAS provide a compromise between the need to take-off and land vertically and have long flight endurance (Austin, 2010). Additionally, these configurations have a lower payload capacity compared to rotary-wing or fixed-wing RPAS (Austin, 2010). VTOL RPAS operate at different altitudes depending on the mission plan but mostly operate at low altitudes (Watts, et al., 2012). High power requirements for hovering limit the flight durations for VTOL RPAS (Watts, et al., 2012). However, with larger VTOL RPAS the increased lifting capabilities provide greater fuel capacity (Watts, et al., 2012). In the 1950s and 1960s, some of the hybrid VTOL designs were tried for manned aircraft but they posed some complications and difficulties in flying (Chapman, 2016). The introduction of new generation sensors, such as gyroscopes and accelerometers, have made these configurations feasible (Jojo, 2017). Gyroscopes and accelerometers function in automated mode (autopilot) to maintain the stability of the

RPAS in the air whilst the pilot remains with the easier manual control of guiding the RPAS along the desired route (Jojo, 2017).

**Single-rotor Remotely Piloted Aircraft Systems (Helicopter)**

A single-rotor RPAS has a large single rotor overhead to generate vertical lift and a smaller anti-torque tail rotor to control its heading perpendicular to the main rotor (Chapman, 2016; Das, 2019; Edwards, 2017). The rotation of the main rotor creates a torque reaction which must be stabilised, usually by the tail rotor in vertical rotation (Jenzen-Jones & Smallwood, 2016). Other methods of neutralising the torque include tandem rotors with rotations that counteract each other, although, such RPAS are not common (Jenzen-Jones & Smallwood, 2016). The pilot can control the pitch and roll of a single-rotor RPAS by tilting the individual blades of the main rotor, consequently altering the thrust vector (Edwards, 2017). The pilot can adjust the yaw of the aircraft by changing the pitch of the tail rotor (Edwards, 2017). The single-rotor RPAS can be powered by an internal combustion engine for a longer flight duration and it has a greater flight efficiency compared to a multi-rotor RPAS (Chapman, 2016; Das, 2019). The general rule of aerodynamics states that the larger the rotor blade, the slower it spins and hence the more efficient it is (Chapman, 2016; Das, 2019). A single-rotor RPAS uses very long blades which gives it greater efficiency (Chapman, 2016; Das, 2019). Figure 2.15 shows a typical single-rotor RPAS in its take-off position.

*Figure 2.11: Single-rotor RPAS in take-off position (Jojo, 2017)*

Single-rotor RPAS are mostly suited for tasks that require hovering with heavy payloads such as an aerial LiDAR laser scanner or tasks that require the integration of hovering with long endurance or fast forward flight (Chapman, 2016; Das, 2019). The disadvantages associated with single-rotor RPAS include their complexity, high costs, vibration and operational risks posed by the large spinning blades (Chapman, 2016; Das, 2019). Precautions need to be taken to avoid any injury caused by the spinning rotor (Das, 2019). With regards to difficulty, single-rotor RPAS lie between multi-rotor RPAS and fixed-wing RPAS (Chapman, 2016; Das, 2019). The single-rotor RPAS can hover in one position, therefore the pilot can get accustomed to it as it rises into the air (Chapman, 2016). However, a single-rotor RPAS is not as stable and it can be hazardous in the event of a bad landing (Chapman, 2016). Single-rotor RPAS require special training to operate them (Jojo, 2017) and also demand high maintenance due to their mechanical complexity (Chapman, 2016; Gundlach, 2014).

Single-rotor RPAS can hover above a target location, descend for closer inspection and change altitude to provide imagery for mapping at preferred spatial resolutions (Klemas, 2015; Jenzen-Jones & Smallwood, 2016). A single-rotor RPAS offers the most efficient hover and low-speed performance (Austin, 2010). Within its speed range, it is the least sensitive to air turbulence due to its high rotor-blade loading (Austin, 2010). The rotors of small rotary-wing RPAS can be powered by either electric motors or internal combustion engines (Jenzen-Jones & Smallwood, 2016).

**Multi-rotor Remotely Piloted Aircraft Systems**

Multi-rotor systems are derived from rotorcrafts which is a term used in aviation to describe aircraft that use rotary wings to generate the thrust that lifts them into the air (Vergouw, et al., 2016). Multi-rotor RPAS have sets of propellers installed either around a central platform or along two opposing arms (Anderson & Gaston, 2013). Multiple rotors are necessary for the stability of the aircraft (Vergouw, et al., 2016). However, a certain level of symmetry is necessary to sustain the RPAS stability, with the most common configurations having four, six or eight rotors (Jenzen-Jones &

Smallwood, 2016). Each rotor is powered by a separate motor or engine (Jenzen-Jones & Smallwood, 2016). Most multi-rotor RPAS have a similar design standard where the motors are fitted on the outside of the RPAS and a little tilted, to help counteract torques and provide stability and control (Mansson & Stenberg, 2014). The number of rotors is influenced largely by the weight of the RPAS, with a larger number of rotors permitting more GTOW (Jenzen-Jones & Smallwood, 2016). Multi-rotors can further be classified according to the number of rotors on the RPAS platform and these include:

- Tricopter (3 rotors);
- Quadcopter (4 rotors);
- Hexacopter (6 rotors); and
- Octocopter (8 rotors). (Jojo, 2017)

The most appropriate RPAS to deploy depends on the required application (Lautenschlager, 2015). Quadcopters are the most commonly used type of multi-rotors (Arango & Morales, 2015; Siebert & Teizer, 2014). Figure 2.16 shows a typical quadcopter RPAS in flight (Jojo, 2017).

*Figure 2.12: A quadcopter RPAS in flight (Jojo, 2017)*

Most multi-rotor RPAS are powered by electric motors due to their relatively lightweight construction (Jenzen-Jones & Smallwood, 2016) and the need for fast and high-precision throttle changes which are essential for stability (Chapman, 2016).

However, some designs use internal combustion engines which provide better endurance, power and payload capacity (Jenzen-Jones & Smallwood, 2016). Multi-rotor RPAS are more complex systems than fixed-wing RPAS (Doumit, 2019). A rotary system moves through the air by varying the power supplied to the different propellers (Doumit, 2019). This determines their revolutions per minute and therefore the thrust these generate (Doumit, 2019). Multi-rotor RPAS can be fitted with guards that shield the rotors, which decreases the likelihood of harm (Othman, 2016). On the other hand, the guards can cause a drop in the performance of the multi-rotor (Othman, 2016).

Multi-rotor RPAS are the most common RPAS configuration (Othman, 2016) because they are easier to obtain and easier to learn how to operate (Das, 2019). Multi-rotor RPAS are the easiest and cheapest option for conducting aerial photography work (Chapman, 2016) and they are also relatively the cheapest and easiest to manufacture (Jojo, 2017). Multi-rotor RPAS can hover above fixed positions, can stay in-flight if one of the rotors fails, demonstrate fewer vibrations than fixed-wing RPAS, are easier to operate and are relatively inexpensive (Barbedo & Koenigkan, 2018). Relative to other types of RPAS, the multi-rotor RPAS possesses some advantages which include its ease of operation, high flexibility and stability (Arango & Morales, 2015), and it makes less noise than fixed-wing RPAS (Vergouw, et al., 2016). They are used mainly for aerial photography and video surveillance as they provide great control over positioning and framing (Das, 2019; Jojo, 2017).

Multi-rotor RPAS are suitable for missions that require constant recording of information from a fixed position or the capture of data at very low altitudes and slow speed (Gutierrez & Searcy, 2016). Small multi-rotor RPAS move at speeds of up to 15 m/sec (54 km/hr) (Gutierrez & Searcy, 2016). A multi-rotor RPAS is also suitable for inspecting large, difficult-to-reach equipment or plants, such as processing plants at mine sites, with minimal use of mine personnel (Lautenschlager, 2015). This deployment of multi-rotor RPAS also removes mine personnel from risk (Lautenschlager, 2015). Multi-rotor RPAS are also convenient in areas of uneven landscape as they do not need a landing strip (Niethammer, et al., 2012; Vergouw, et al., 2016). These RPAS are easy to manage attributable to an integrated GNSS that controls its position in real-time and a digital compass that allows them to hover over a fixed position and rotate on its axis (Gutierrez & Searcy, 2016).

Multi-rotor RPAS are however not suited for large-scale aerial mapping, long-endurance monitoring or long-distance inspections due to their limited flying time and speed (Chapman, 2016). Multi-rotor RPAS typically have shorter flight durations but offer greater manoeuvrability (Jokotola, 2013). They are slow, have a limited payload capacity, can cover only relatively small areas (Anderson & Gaston, 2013) and are unstable with winds above 25 km/h (Miller, et al., 2017). Multi-rotor RPAS require a lot of energy to overcome gravity and maintain stability in the air, thus they are regarded as relatively inefficient (Chapman, 2016). When carrying a light-weight camera payload, multi-rotor RPAS are expected to remain in the air for about 20 to 30 minutes with current battery technology (Chapman, 2016). There are some multi-rotor RPAS that are capable of carrying heavy-weight payload but it is a trade-off with much shorter flight times (Chapman, 2016).

Multi-rotor RPAS have similar advantages to single-rotor RPAS with regards to VTOL and hovering capabilities (Jenzen-Jones & Smallwood, 2016). However, there are some significant differences which include their inability to auto-rotate, so mid-flight power failures can be disastrous, particularly for quadcopters (Jenzen-Jones & Smallwood, 2016). Multi-rotor RPAS typically have less endurance and speed relative to single-rotor RPAS (Gundlach, 2014).

## 2.3 Conclusion

In this chapter, a review was conducted on some of the different types of conventional surveying methods. These methods include total station, GNSS and TLS. The benefits of introducing RPAS technology into mining operations can be significant, however, it is imperative to take into account that there exist other technologies that could offer similar or more favourable solutions for mining companies and their operations. The implementation of each surveying method was assessed in this section for their associated strengths, weaknesses, opportunities and threats.

This chapter also gave an overview of the common characteristics and classifications of RPAS. The most common method of classifying RPAS is by the configuration of an aerial platform. There are four main types of RPAS, namely, fixed-wing, fixed-wing hybrid, single-rotor and multi-rotor RPAS. Each type of RPAS has unique characteristics and potential applications in the mining industry.

# CHAPTER 3. REMOTELY PILOTED AIRCRAFT SYSTEMS PHOTOGRAMMETRY AND REMOTE SENSING

## 3.1 Introduction

The science of remote sensing is constantly progressing to cater to the increasing need for information regarding the condition of the environment (Whitehead & Hugenholtz, 2014). When considering the potential sources of remote sensing data for a certain task, the requirements of spatial, spectral and temporal resolution should be taken into account (Milas, et al., 2018). RPAS mainly takes care of the issues of spatial and temporal resolution in the acquisition of data (Milas, et al., 2018). Using RPAS, data can be acquired where and when it is required at a reasonably low cost (Milas, et al., 2018). A remote sensing system largely comprises five components, that is, carrier platform, remote sensor, control and positioning system, data transmission and data preprocessing (Yin, et al., 2019). RPAS remote sensing includes electromagnetic spectrum sensors, biological sensors, gamma-ray sensors and chemical sensors (Ramdzan, n.d.). This chapter will focus mainly on RPAS photogrammetry, which is a constituent of the electromagnetic sensors, specifically the visual spectrum.

Photogrammetry is “the art, science, and technology of obtaining reliable information about physical objects and the environment, through processes of recording, measuring, and interpreting images and patterns of electromagnetic radiant energy and other phenomena” (Doumit, 2019, p. 5). Photogrammetry is a commonly used method for generating digital elevation models (DEMs) and orthorectified image mosaics from aerial (stereo) photographs (Lillesand, et al., 2015). RPAS photogrammetry uses near-vertical photographic images that are captured at a distance by a flying RPAS platform (Falkner & Morgan, 2002). Many high-resolution photos are captured over an area and these images overlap such that a single point on the ground is observable in several photos and from different angles (Torres, 2019). Photogrammetry merges images that cover the same point on the ground from multiple viewpoints to generate detailed 2D and 3D maps (Torres, 2019). The outcome comprises a high-resolution 3D model that has elevation data, texture, shape and colour for every point on the map which enables easier interpretation of the resulting 3D point cloud (Torres, 2019).

RPAS used in photogrammetry are cost-effective and provide outstanding flexibility concerning where, when and how the 2D and 3D data is captured (Torres, 2019). In the field of aerial photography, the last couple of decades has witnessed the advancement of high-resolution digital imagery and the development of on-board navigational systems that provide accurate data regarding position and altitude (Gutierrez & Searcy, 2016). This has prompted the corresponding development of automated photogrammetric processing software packages which deliver a semi-automated workflow, allowing for the production of DEMs and orthophoto mosaics with limited operator interference (Gutierrez & Searcy, 2016). The log-file from the RPAS autopilot is used to provide initial estimations for the position and orientation of each image (Gutierrez & Searcy, 2016). There are certain things to avoid to produce good imagery and these include:

- "Very dark surfaces" (Doumit, 2019, p. 36);
- "Reflective surfaces" (Doumit, 2019, p. 36);
- "Transparent surfaces (including water)" (Doumit, 2019, p. 36);
- "Uniform textures and solid colour surfaces" (Doumit, 2019, p. 36); and
- "Moving light sources/shadows" (Doumit, 2019, p. 36).

A blue sky with bright sunlight or shadows is not an ideal weather condition for conducting aerial photography in open pit mining (Patikova, 2004). There are very deep areas characterised by almost vertical walls in an open pit (Patikova, 2004). The sharp and dark shadows complicate the processing (especially the evaluation of heights) in such areas (Patikova, 2004). Hence, it is more desirable to have soft light passing through high clouds (Patikova, 2004).

RPAS is merely an airborne platform and data acquisition should be executed by remote sensors, in this case by digital photographic cameras (Gutierrez & Searcy, 2016). Sometimes the weight of the camera can limit what can be completed and the quality of the topographic modelling, unless the RPAS is capable of carrying heavy payloads (Gutierrez & Searcy, 2016). The most suitable camera for a commercial RPAS should be small, lightweight, have a large capacity solid-state memory, durable lithium batteries, but above all, a large camera sensor (Gutierrez & Searcy, 2016). Octocopters can carry 35 mm full-frame Digital Single Lens Reflex (DSLR) cameras that provide detailed and high-quality images (Gutierrez & Searcy, 2016). Small RPAS have less payload capacity and can carry compact cameras with smaller sensors (Gutierrez & Searcy, 2016). These cameras capture high-resolution images, but they can be as costly as full-size DSLR cameras and some may need an external interval meter or electronic adjustments for operating remotely (Gutierrez & Searcy, 2016). Applications of RPAS photogrammetry in mining include monitoring of mining activities, stockpile volumetric computations, decision-making and planning and proposals of reclamation (Patikova, 2004). An advanced high-resolution full-frame sensor camera such as WingtraOne’s Sony RX1R II, shown in Figure 3.1 with the RPAS camera mount, can produce results with horizontal accuracies in the range of one centimetre and elevation accuracies in the range of two to three centimetres over hard surfaces (Torres, 2019). This enables precise volumetric interpretation (Torres, 2019).


*Figure 3.1: WingtraOne's Sony RX1R II with the RPAS camera mount (Ghostysky, 2021)*

## 3.2 Project Preparation

The mission planning and management subsystem is a crucial element of RPAS for spatial data collection (Colomina & Molina, 2014). RPAS surveys typically start with flight planning (Hugenholtz, et al., 2013). The flight planning is conducted following the location and extent of the area to be mapped and the objectives of the mission (Combrink, 2011; Patikova, 2004). This step is supported by specialised flight-planning software (Whitehead & Hugenholtz, 2014). A background map or satellite image is used to outline the survey area (Whitehead & Hugenholtz, 2014). Various flight planning software tools exist and these aid in defining the type of camera (focal length), overlaps between photos in the strip and between strips, photo scale and scanning resolution (Patikova, 2004). Further information that can be added includes the preferred flying altitude, the orientation of the camera and the preferred flightpath (Whitehead & Hugenholtz, 2014). The optimal flight planning approach encompasses a built-in elevation dataset comprising the altitude of each flight line and allows the operator's elevation data to be imported (Doumit, 2019). Most professional RPAS employ waypoint navigation to define their flightpath (Doumit, 2019). Modern flight planning software handles this automatically, incorporating the three pillars of aerial mapping which are the mission area, overlap and ground resolution (Doumit, 2019).

When defining the aircraft’s take-off trajectory, the software allows the operator to outline the exact direction the aircraft will follow after being launched (Doumit, 2019). When landing, the operator indicates the landing spot (Doumit, 2019). During this process, the different mission factors can be adjusted until the operator is satisfied with the flight plan (Whitehead & Hugenholtz, 2014). The flight plan is subsequently uploaded to the RPAS autopilot (Whitehead & Hugenholtz, 2014). The commands incorporated in the flight plan are utilised by the autopilot to calculate the required rate of altitude increase and positional adjustments that allow the aircraft to align with the planned flight path as much as possible (Whitehead & Hugenholtz, 2014). Figure 3.2 shows a flight planning example showing image waypoints and flight lines.

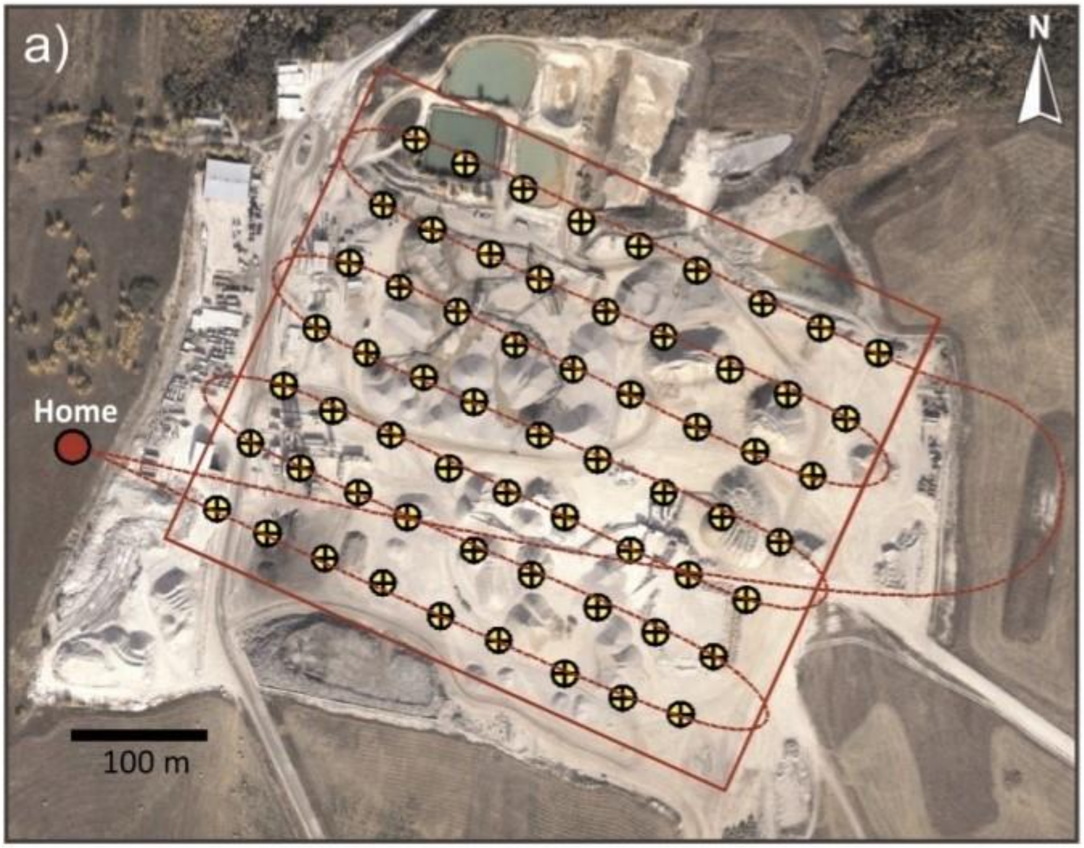


*Figure 3.2: Flight planning example (a) showing image waypoints and flight lines (Whitehead & Hugenholtz, 2014)*

Figure 3.3 shows the image footprints with overlap with reference to Figure 3.2 (Whitehead & Hugenholtz, 2014)

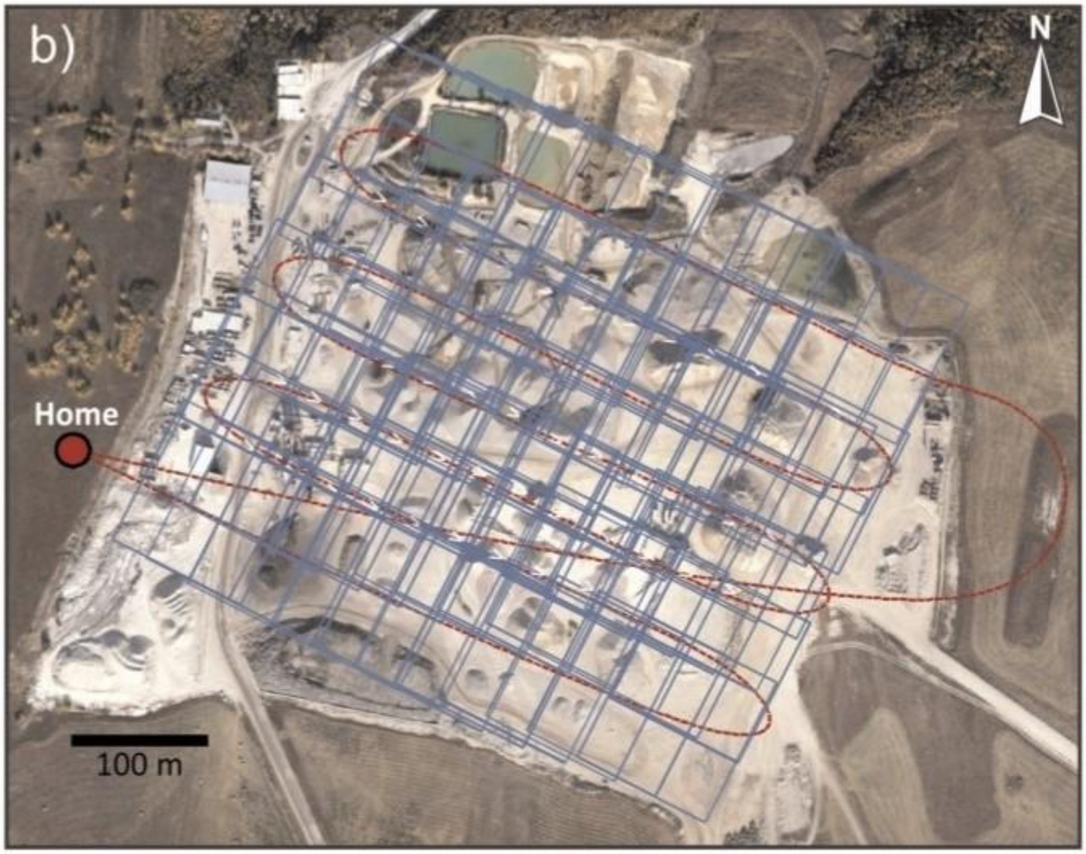


*Figure 3.3: Flight planning example (b) showing image footprints with overlap (Whitehead & Hugenholtz, 2014)*

The home point indicates the location of the GCS and the location used for take-off and landing (Whitehead & Hugenholtz, 2014). Unfavourable weather conditions sometimes result in long waiting periods before a flight mission commences (Patikova, 2004). Ground control points (GCPs) may be covered with snow or leaves or destroyed, therefore, they need to be frequently checked for visibility and stabilisation (Patikova, 2004). A meticulous plan of the RPAS flight path and a flexible real-time mission management capability is essential in accomplishing productive and safe acquisition operations (Mayr, 2011). A characteristic feature, for example, of mission plans for RPAS photogrammetry is the large forward (80%) and cross (60–80%) overlap to counter aircraft unsteadiness (Colomina & Molina, 2014). A standard RPAS system with professional mission planning and post-processing workflow assists in ensuring the acquisition of quality data that produces accurate results (Torres, 2019).

### 3.3 Flight Execution

Even with intelligent, automated RPAS mapping systems, it is crucial to carefully monitor every flight via LOS and using the RPAS ground station software (Doumit, 2019). The aircraft's position and other important factors such as its battery's remaining charge, and therefore flight time, should always be visible on the screen display (OSD) (Doumit, 2019).

RPAS are typically launched in one of the three ways, that is, by hand, via a runway, or using a launching system such as a catapult (Doumit, 2019). After take-off, the RPAS will quickly gain altitude and travel, either on autopilot or on real-time command, to cover its mapping area and to begin the aerial imaging mission (Doumit, 2019). RPAS operations can be completed in either VLOS or BVLOS of the remote pilot or RPAS observer (Othman, 2016). VLOS is when the remote pilot must keep up direct unaided visual contact with the RPAS constantly during the flight mission (Othman, 2016). In BVLOS operations, neither the remote pilot nor the RPAS observer can maintain direct unaided visual contact with the RPAS (Othman, 2016). As the range and difficulty of BVLOS missions increase, so does the minimum equipment requirements to support the operations and the costs incurred in ascertaining the strength of the communications data link (Othman, 2016).

Typically, a remote pilot will ensure the safety of an operation by maintaining VLOS with the RPAS as is required by the South African regulations (Doumit, 2019). The RPAS aids this human monitoring by continually transmitting status information displayed on the screen (Doumit, 2019). It is also important to be able to detect and avoid other traffic or obstacles throughout the flight (Othman, 2016). After the mapping task is completed, for landing, the pilot should indicate the point and the position of landing (Doumit, 2019). The aircraft should be inspected immediately after the landing for any evidence of overheating of the motors or electronics (Doumit, 2019). The aerial images should also be inspected for quality after the first flight and any necessary adjustments to be made to the camera settings before additional flights are carried out (Doumit, 2019).

A basic commercial quadcopter without modifications is capable of capturing data for approximately 25 ha per flight (500 m x 500 m) (Gutierrez & Searcy, 2016). Hence, GCPs can be prepared on the first day, aircraft flown on the second day and the preliminary results available at the end of the third day (Gutierrez & Searcy, 2016). Subject to the quality of the cameras used and the altitude of the RPAS, photogrammetry can provide imagery of small areas with a resolution of 0.5 cm/pixel (Ancin-Murguzur, et al., 2019). This is a pixel size that commercial satellites are not yet capable of delivering (Gutierrez & Searcy, 2016).

### 3.3.1 Ground Sampling Distance

The spatial resolution of digital maps is usually referred to as the ground sampling distance (GSD) (Barnes, et al., 2014). GSD is the distance between the centre points of each sample taken of the ground (Propeller Aero, 2018). In the case of photogrammetry, the sample is called a pixel (Propeller Aero, 2018). Therefore, the GSD is the distance, measured on the ground, between the centres of two adjacent pixels in a digital image (Delair Aerial Intelligence, 2020; Humboldt State University, 2019). The higher the flight altitude the larger the GSD value, and therefore the lower the spatial resolution of the image and the less visible details (Anders, et at., 2020; Delair Aerial Intelligence, 2020; Humboldt State University, 2019).

GSD is usually expressed in metric units, often centimetres (Humboldt State University, 2019). For instance, an image with 5cm/pixel GSD means the locations of two consecutive pixels are 5cm apart on the ground (Delair Aerial Intelligence, 2020). GSD is also an indicator for the dimension of a square on the ground covered by one pixel such that a 5cm/pixel GSD means a pixel accounts for a ground area of 2 cm by 2 cm, which is 4 $cm^2$ (Delair Aerial Intelligence, 2020). GSD "is a function of the resolution of the camera sensor, the focal length (f) of the camera and the flying height (H = the distance between camera and ground)" (Barnes, et al., 2014, p. 10). The formula for calculating GSD is (Barnes, et al., 2014):

$$\frac{GSD}{p} = \frac{H}{f}$$ ***Equation 3-1***

The pixel size (p) is found in the camera's technical specifications (Barnes, et al., 2014). The dimensions of the image are indicated in linear units (for example, 17.3 x 13.0 mm) as well as in a number of pixels (4000 x 3000 pixels) (Barnes, et al., 2014). Pixel size is calculated by dividing the linear units by the number of pixels (Barnes, et al., 2014). In photogrammetry, to generate 3D models, images should be captured in stereo mode and with sufficient overlap (Barnes, et al., 2014). When a flying height has been determined it is essential to calculate the distance between each exposure position, the spacing between flight lines and the image overlap as shown in Figure 3.4 (Barnes, et al., 2014).

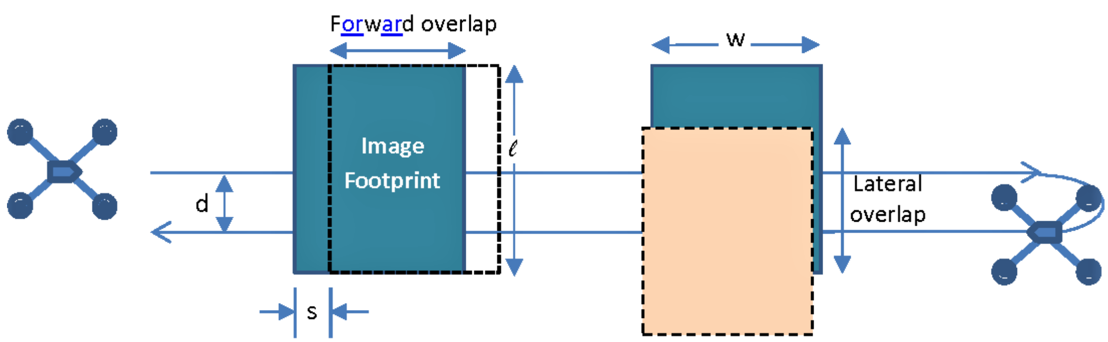


*Figure 3.4: Image footprints and overlaps (Barnes et al., 2014)*

The exposure distance intervals (s) and the spacing between the flight lines (d) are subject to the preferred forward and lateral overlaps respectively (Barnes, et al., 2014). For RPAS mapping projects, a forward overlap of 80% and a lateral overlap of 70% has proved to produce good results (Barnes, et al., 2014). Figure 3.5 shows the orientation of the aircraft and the image overlap during the aerial photography process.

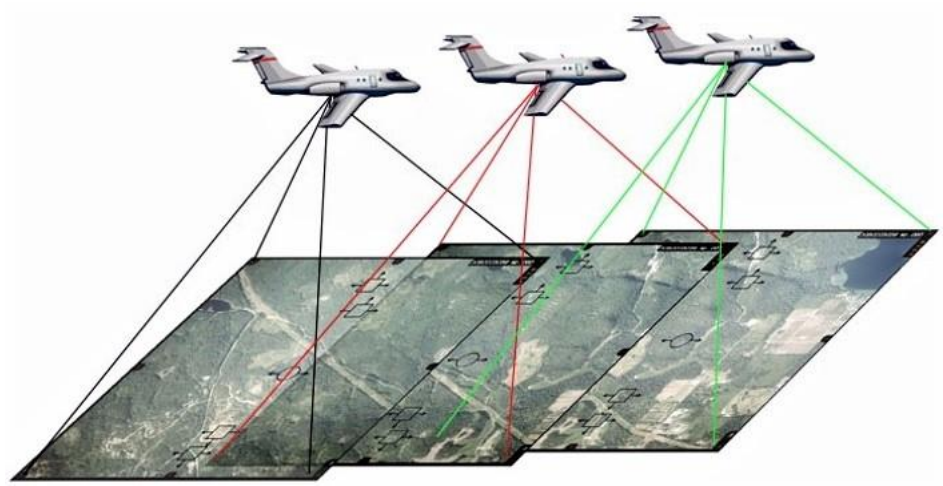

*Figure 3.5: Image overlap (Seedat, et al., 2012)*

Some RPAS cameras cannot capture images at specified distance intervals and in such instances, the camera is programmed to expose at a fixed time interval (Barnes, et al., 2014). Small GSD values usually necessitate lower flying heights and slower ground speeds (Barnes, et al., 2014). For high-resolution projects (GSD 1 to 2cm) multi-rotor RPAS are considered to be the most suitable platform (Barnes, et al., 2014).

## 3.4 Processing

The processing of the data and measurements gathered in an RPAS mission is a fundamental stage of RPAS photogrammetry (Colomina & Molina, 2014). RPAS acquisition equipment, such as platforms and sensors, are now lighter, smaller and simpler (Colomina & Molina, 2014). However, this does not essentially mean simpler processing software systems are used (Colomina & Molina, 2014). More advanced processing is generally necessary to make up for the unavoidably limited performance of small, lightweight platforms and acquisition systems (Qin, et al., 2012). It is also key to note that lighter, smaller and simpler does not ultimately mean substandard outcomes because the conditions of RPAS photogrammetry missions vary (Colomina & Molina, 2014).

After the conclusion of the flight, a log file is normally downloaded from the RPAS autopilot (Hugenholtz, et al., 2013). This file comprises detailed information about the aircraft position and altitude during the flight, in addition to information about when the camera was activated (Jokotola, 2013). This log file is normally used to provide initial estimates for image centre positions and camera orientations, which are then used as inputs to the photogrammetric process (Jokotola, 2013). These initial estimates indicate the accuracy of onboard equipment (Jokotola, 2013). Errors occur if there is uncertainty in the timing of the camera shutter release (Jokotola, 2013). These errors can be significant, with a one-second delay possibly causing an error of 30 m to 50 m in the flight direction for a fast-flying fixed-wing RPAS (Jokotola, 2013).

The foundation of the work consists of fast computers and essential photogrammetric software in conjunction with other supplementary programs, for example, programs for digital terrain modelling (DTM), computer-aided design (CAD) and converters (Patikova, 2004). The calibration protocol should be produced in a format in line with the software requirements (Patikova, 2004). Photogrammetric processing of RPAS imagery has been made simpler by the availability of commercial software such as Agisoft PhotoScan, Autodesk 123D Catch, ARC 3D, Leica Photogrammetry Suite, Photo Modeler Scanner and Recap Photo (Gutierrez & Searcy, 2016). Agisoft PhotoScan has become the standard photogrammetric software package (Gutierrez & Searcy, 2016). PhotoScan operates on powerful "Structure from Motion" (SfM) algorithms to align digital photography, which allows the generation of point clouds and polygonal meshes through multi-view stereo-matching algorithms (Verhoeven, 2011). Polygonal meshes are required to create Digital Surface Models (DSMs) that capture whole landscapes and their associated topography, vegetation, geomorphology and anthropogenic elements, as well as for Digital Elevation Models (DEMs) (Gutierrez & Searcy, 2016).

### 3.4.1 Image Processing

The RPAS non-metric cameras are lighter and less expensive, therefore usually favoured over conventional metric cameras (Doumit, 2019). Nonetheless, non-metric cameras are not geometrically stable, which is a basic constraint for classic photogrammetric mapping (Doumit, 2019). To mitigate this problem, most RPAS image processing software use a blend of classic photogrammetry and computer vision techniques, known as Motion Vision Stereopsis (MVS) (Doumit, 2019). Figure 3.6 shows a typical MVS workflow.

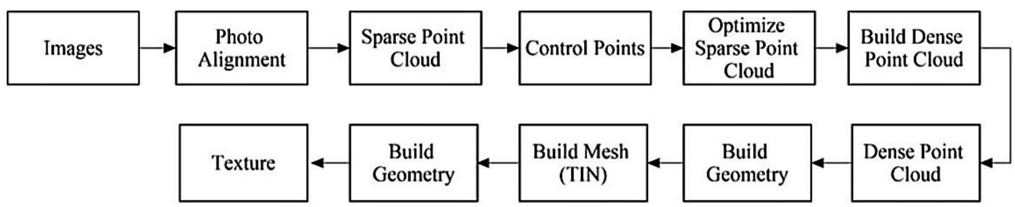


*Figure 3.6: MVS workflow (Doumit, 2019)*

Normally RPAS processing software will try to determine the approximate camera geometry, that is, focal length and sensor size (Doumit, 2019). In an MVS approach, the camera geometry for each image is calculated independently, thus the camera exposure coordinates are calculated in some arbitrary local spatial reference system (Doumit, 2019). Therefore, if the final product is not required to be referenced to some spatial reference frame, the images are all that is needed to generate a model (Doumit, 2019). However, the process of determining the relative camera exposure positions is significantly speeded up if the relative camera exposure positions are integrated with the coordinates established in the after-flight image geo-referencing process (Doumit, 2019). Ground control is vital to rectify (geo-reference) the images to their exact geographical position on the Earth’s surface (Doumit, 2019).

The differential rectification method is a phased procedure that uses several XYZ GCPs to geo-reference an aerial photograph to its true place on the earth (Doumit, 2019). The exact location and number of ground points required are based upon the scale and accuracy of the final orthophoto (Doumit, 2019). Selecting the GCPs should be decided by the photogrammetric technician planning the project depending on their experience and equipment (Falkner & Morgan, 2002). Geo-referencing is essential since the photogrammetry software generates its coordinate system when the models are produced (Doumit, 2019). The selected GCPs are marked in the processing software by putting markers in the photos comprising each point (Doumit, 2019). The reason for marking the points in multiple photos is to allow the software to triangulate the locations of the point using the camera locations that have already been processed and gives a new georeferenced sparse point cloud (Newsome, 2016). The software uses the optimised sparse point cloud and improved camera positions to produce a dense point cloud (Doumit, 2019). Several accuracies and depth filtering settings are provided in this process (Doumit, 2019).

The generation of the dense point cloud is typically more time-consuming than the other processing steps (Doumit, 2019). The dense point cloud is used to generate a surface model in the form of a triangulated irregular network (TIN), a texture is built and applied to the surface features of the model (Doumit, 2019). Various spatial products, such as DSMs and orthophotos, can be generated using the export options offered by the image processing software (Colomina & Molina, 2014; Doumit, 2019). Digital surface models can be prepared either in a vector format as triangulated irregular networks (TIN), used extensively in CAD software for engineering applications, or in a raster format for GIS uses (Doumit, 2019). A suitable DSM must be obtained to provide a vertical datum for an orthophoto; DSM for orthophoto rectification does not have to be as dense or as detailed as a terrain model for contour generation (Falkner & Morgan, 2002).

Currently, various applications of geospatial mapping products require current planimetric feature data (Doumit, 2019). Analysis and design from geospatial data sets usually necessitate a known positional accuracy of features (Doumit, 2019). The compilation and updating of planimetric features in a data set can be costly (Doumit, 2019). Various end-users are also not used to viewing and analysing vector-based mapping data sets (Doumit, 2019). They prefer viewing planimetric features such as a photo image (Doumit, 2019). The last phase of the orthophoto process is the integration of the digital image and the DSM together with corrections in pixel intensity throughout the image (Doumit, 2019). Software, used to combine the digital raster image with the DSM, makes adjustments in the horizontal location of pixels depending on their proximity to DSM points (Doumit, 2019). This process eliminates the errors due to displacement and produces an orthogonally accurate image (Falkner & Morgan, 2002).

Suitable imagery and ground control are the basic fundamental data that determine the final orthophoto reliability which comprises the accuracy of distances between points within the orthophoto and the accuracy of features concerning their true location on the Earth (Doumit, 2019). Distance and area accuracy is based on the pixel size (Doumit, 2019). Relative feature precision is based on the accuracy of the DSM used in the rectification process (Doumit, 2019). The relative accuracy cannot be more precise than the reliability of the DSM (Falkner & Morgan, 2002). For most operations, 3D results attainable with photogrammetry are similar to those obtained with LiDAR, but with greater versatility, due to the high-resolution visual data (Torres, 2019).

### 3.5 Conclusion

This chapter gave an overview of remote sensing using RPAS with a particular focus on RPAS photogrammetry. This encompasses the stages undertaken by an RPAS crew when conducting photogrammetry missions, that is, from the planning stage to the processing of raw data.

# CHAPTER 4. APPLICATIONS OF REMOTELY PILOTED AIRCRAFT SYSTEMS IN MINING

## 4.1 Introduction

An essential characteristic in the use of RPAS is the distinction between the aircraft platform and the equipment attached to it, that is, the payload. RPAS comprises a flying platform that can be used for different tasks which can be accomplished in combination with the specific payload applicable to that task (Vergouw, et al., 2016). The most appropriate RPAS to deploy depends on the required application (Lautenschlager, 2015). RPAS utilisation increases the productivity of certain mine operations by improving the efficiencies of conventional mine surveying processes (New Zealand Ministry of Transport, 2019). RPAS can carry various types of sensors with equally varying applications, to areas that were previously costly, or difficult, to access (Gallacher, 2016). Miniature cameras and sensors that can be attached to different types of RPAS platforms are being manufactured, thus increasing the prospect of carrying various types of equipment into the air (Gutierrez & Searcy, 2016). RPAS technology is currently being implemented in new applications, substituting current applications and expanding a new dimension to current applications (Odido & Madara, 2013). Some potential applications for RPAS can be implemented more safely through developing Internet of Things (IoT) networks, whereby a large volume of data is captured from several fixed points and vehicles, centralised through the internet and analysed in real-time (Gallacher, 2016).

The benefits of RPAS in the mining industry are gradually becoming self-evident (Micklethwaite, 2018). The technology offers significant improvements with regards to safety, cost-effectiveness and, more importantly, the ability to do far more work within a limited time (Micklethwaite, 2018). RPAS can also be utilised in almost all stages of the mining value chain, from exploration through to production, ore processing, transport and rehabilitation (Micklethwaite, 2018). The utilisation of RPAS for commercial purposes is still in its primary stages in most countries (New Zealand

Ministry of Transport, 2019). In the Gartner Hype Cycle, there are trends related to emerging technology that comprise of a period of inflated expectations, often followed by a lack of expectation (Micklethwaite, 2018). The Gartner Hype Cycle is a graphical illustration of a common pattern associated with the relative market promotion and perceived value of new technologies (Blosch & Fenn, 2018). Figure 4.1 shows the Gartner Hype Cycle for emerging technologies as of July 2020.

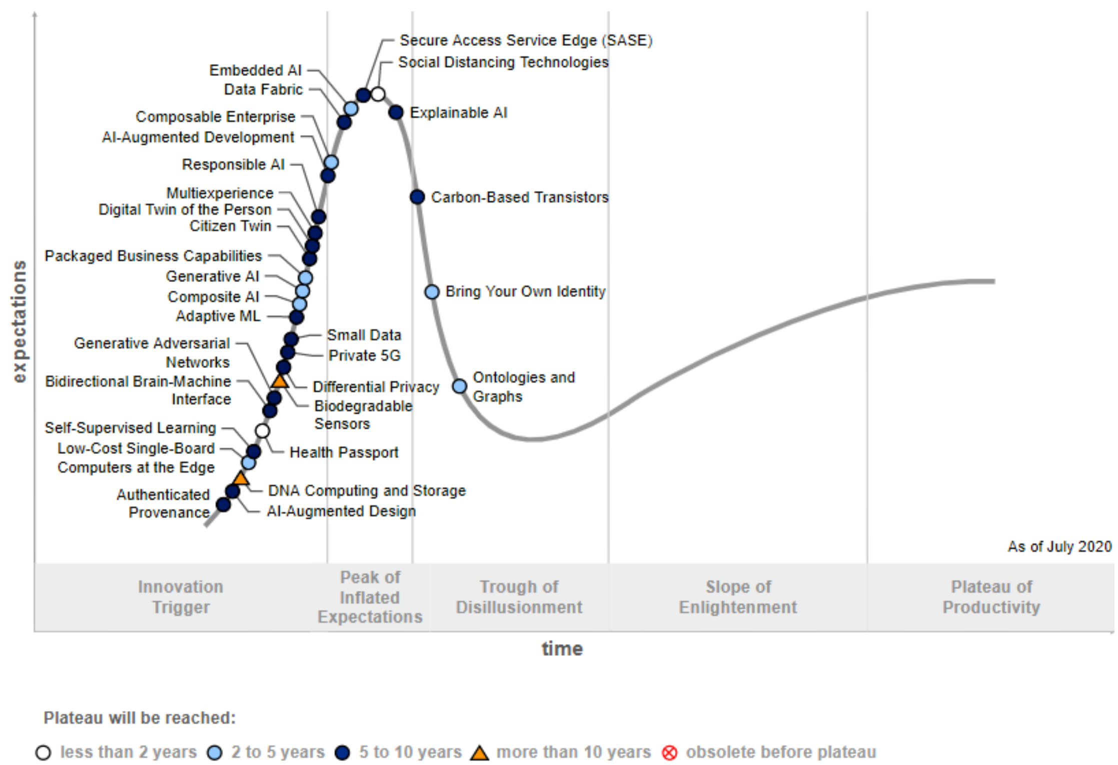


*Figure 4.1: The Gartner Hype Cycle for Emerging Technologies, 2020 (Gartner, 2020)*

For some companies in the mining industry, there may already exist a certain level of scepticism towards adopting RPAS technology in their respective operations (Micklethwaite, 2018). Therefore, it is problematic but equally imperative to appreciate the possible opportunities associated with RPAS and the requirements to realise those opportunities (New Zealand Ministry of Transport, 2019). Characteristic of new innovative technology, the major challenge is that there is minimal documented evidence to prove the industrial worth of RPAS (New Zealand Ministry of Transport, 2019). Factors that will affect the adoption of RPAS include:

- Affordability of RPAS based resolutions in comparison to other technologies;
- The extent to which RPAS will increase the efficiency of operations or solve existing problems;
- Societal reception; and
- The regulatory environment. (New Zealand Ministry of Transport, 2019)

Acceptance of RPAS into the mining industry will be affected in areas where there are alternative innovative technologies and the RPAS is not seen to add value (New Zealand Ministry of Transport, 2019). Mining operations can either adopt RPAS fully as part of their equipment inventory or contract RPAS services as the need arises (New Zealand Ministry of Transport, 2019).

During engagements with players in the RPAS sector, it was cited that in most operations RPAS technology would be incorporated and integrated with or in parallel to conventional methods (New Zealand Ministry of Transport, 2019). It is not perceived as a replacement for current techniques where human presence is necessary (New Zealand Ministry of Transport, 2019). An example is, in certain instances, immediate medical first aid intervention and assistance would be needed to stabilise an individual before evacuation (New Zealand Ministry of Transport, 2019). Therefore, RPAS would complement existing systems, delivering better outcomes and increasing the availability of resources for alternative utilisation (New Zealand Ministry of Transport, 2019). This means that it is challenging to separate and account for RPAS-specific benefits because the technology would form part of the broader service (New Zealand Ministry of Transport, 2019). This chapter outlines some of the applications of RPAS in the mining industry.

## 4.2 Topographical Mapping of Open Pit Mines

One of the most common industrial applications of RPAS is for large-scale photogrammetric mapping (Hugenholtz, et al., 2013; Whitehead, et al., 2013). RPAS photogrammetry can easily collect aerial images and generate 3D models of mine sites, pits and infrastructure (Micklethwaite, 2018). The 3D maps produced during aerial surveying can be used for providing management with a near-real-time overview of the mine operation, including the location of mining personnel and equipment (Edwards, 2017). 3D modelling can display actual views of the open pit, views from different aspects and show the effects of mining on the environment. Up-to-date vector mapping data from aerial photos, DTM and orthophotos in mosaics can be used for the analysis of open pit mining development, animations (fly-throughs), simulations and archiving (Patikova, 2004). The size and aerodynamics of an RPAS allow them to fly at lower altitudes, collecting more accurate data than manned aircraft or satellites (Jokotola, 2013). A typical RPAS can capture images at about 0.7 cm/px spatial resolution with a low-cost camera when flying at an altitude of 25 m above ground (Seifert, et al., 2019).

Surveyors and GIS professionals can utilise RPAS mapping to reduce the time normally required to collect accurate data using conventional terrestrial survey methods (Lautenschlager, 2015; Mitka & Mouroutsos, 2017; Shahmoradi, et al., 2020). The relatively short time frame spent in the field ensures the safety of surveyors by reducing the amount of time they are exposed to potentially hazardous working conditions (Micklethwaite, 2018; Mitka & Mouroutsos, 2017). Utilising RPAS as a substitute for a manned aircraft can reduce survey costs and provide more accurate geo-referenced data by capturing high-resolution orthoimages and producing repeatable 3D point clouds (Mining Technology, 2020; Mitka & Mouroutsos, 2017). Colomina and Molina (2014) and Nex and Remondino (2013) give some important reviews on RPAS and their utilisation in topographical mapping. Most research related to the utilisation of RPAS in mining has focused on mapping open pit mines and stockpile geometry (Raeva, et al., 2016; Rossi, et al., 2017). The information from an RPAS survey is wide-ranging and can be processed in several different ways (Lautenschlager, 2015).

In May 2018, the Erdenet Mine, one of Asia's and the World's largest copper mines, in the north of Mongolia was mapped in just three days. The dimensions of the open pit mine are 5km by 2km with an elevation difference of 200 metres (Karas, 2018). The dusty and complex circumstances necessitated the use of RPAS (Karas, 2018). Even though there were strong winds and fluctuating weather conditions, a single fixed-wing RPAS (MaVinci Sirius) was used to capture the required geospatial data of the mine (Karas, 2018). The task was completed in nine mapping flights for a three day duration, usually with two flights in the morning and two in the evening dependent on the weather conditions (Karas, 2018). Each flight did not extend beyond 30 minutes due to the increasing strength of the wind (Karas, 2018). The vast amount of data collected and processed provided a comprehensive overview of the extensive area and showed the exact status of the mine explorations, thus allowing 3D modelling of the complex site (Karas, 2018). This was the first time an RPAS had been used at this mine, but the results were so satisfactory that the RPAS method was fully adopted at the mine (Karas, 2018). This allows the management to construct an overview of the mine in 4D which includes the time dimension. By merging the initial results with future flights, they can easily compare data series over time to plan and capture mine development and create a digital 4D archive (Karas, 2018).

## 4.3 Oil and Mineral Exploration

RPAS can assist in exploration by helping in the building of 3D models of the terrain (Odido & Madara, 2013). This may be synchronised with data acquired from other sources (Odido & Madara, 2013). RPAS can be a beneficial means for collecting geological data and mapping the engineering geology of both accessible and inaccessible areas (Katuruza & Birch, 2019; Shahmoradi, et al., 2020). Engineering geology encompasses mapping outcrops, strikes, dips and feature notation that result in the characterisation of the site (Shahmoradi, et al., 2020). New algorithms in image processing assist in identifying the type of rocks, strike, faults, and dips which significantly reduces the manual labour and time in the field workload (Shahmoradi, et al., 2020).

RPAS can be used to carry out geophysical surveys, especially geomagnetic surveys where the processed measurements of the Earth's differential magnetic field strength are used to estimate the characteristics of the underlying magnetic rock structure

(Deepika & Lavanya, 2015). Information on the underlying rock structure assists geophysicists to predict the location of mineral deposits (Deepika & Lavanya, 2015). Oil and gas exploration and production entails the monitoring of the integrity of oil and gas pipelines and associated installations (Deepika & Lavanya, 2015). For above-ground pipelines, this monitoring task can be carried out using digital cameras attached to one or more RPAS (Deepika & Lavanya, 2015).

### 4.4 Inspection of Mine Workings

Mines are usually located in extensive and remote rugged areas (Shahmoradi, et al., 2020). As a result, the monitoring of mines and related infrastructures is a challenging task which demands extensive manpower (Xiang, et al., 2019). Considering their excellent manoeuvrability and low cost and maintenance (Ranjan, et al., 2018), RPAS can be used to provide visual and other different types of sensing data for inspections at mine sites (Shahmoradi, et al., 2020). In technical projects, it is critically important to be able to have an overall overview of the mine site and it can also be beneficial to see objects from different viewpoints (Othman, 2016). Similarly, it is very important not to disturb or influence the environment in which one is working so RPAS are well suited to aid in projects without disturbing the environment (Othman, 2016).

Mining is one of the most unsafe industries for workers, particularly in deep underground mines (Mining Technology, 2020). RPAS in underground mines has several potential applications in health and safety (Shahmoradi, et al., 2020). Some of the applications are surface roughness mapping, rock mass stability analysis, ventilation modelling, hazardous gas detection and leakage monitoring (Hennage, et al., 2019; Mirzaeinia, et al., 2019; Russell, 2018). Ensuring employees’ safety is of utmost importance, but it is one of the main challenges faced by the mining industry (Geomatics World, 2019). Inspecting dangerous worksites and monitoring difficult-to-access areas from a safe distance can potentially save lives (Geomatics World, 2019). RPAS can also be used to evaluate safety compliance on a work site (Irizarry, et al., 2012). Work-related accidents continue to be a serious concern in the mining industry because mine personnel can be exposed to hazards such as rock-falls, extreme heat and humid conditions, harmful gas leaks, dust explosions or floods (Mining Technology, 2020). The risks posed by such hazards can be minimised by introducing unmanned inspections in mine workings. Therefore, mining companies can employ RPAS at their mining operations to monitor and inspect hazardous and difficult to access working areas and equipment (Deepika & Lavanya, 2015; Mining Technology, 2020).

### 4.4.1 Production Monitoring

RPAS can be used to provide aerial surveys of mining activities and equipment without the difficulties of having to work around obstacles on the ground or disrupting operations (Xiang, et al., 2019). An aerial viewpoint provides a comprehensive view of areas and positions that can be easily missed or cannot be seen at ground level (Rowan, et al., 2015). The geospatial data provided by RPAS gives credibility to reports presented to any stakeholder as it can be provided in real-time, even during mine meetings such as mine production meetings. This facilitates mine personnel in making real-time sound decisions related to operational planning or business strategy (Mining Technology, 2018). Figure 4.2 shows a wide aerial view of an open pit mine taken using RPAS.

*Figure 4.2: A wide aerial view of an open pit mine (Thomas, 2020)*

RPAS can be used to monitor the movements of mobile equipment such as in loading and hauling operations. This provides mine supervisors and planners with real-time observations of activities that are happening on the ground and assists in making decisions on how to improve the efficiency of those activities. Figure 4.3 and Figure 4.4 show aerial views of the loading and hauling fleet in an open pit mine.

*Figure 4.3: Aerial view of the loading and hauling fleet positioning during loading (Thomas, 2020)*

*Figure 4.4: An aerial view of a shovel loading blasted ore into a dump truck (Thomas, 2020)*

### 4.4.2 Inspection of Equipment and Infrastructure

Globally, RPAS are starting to be utilised in construction works to assist during maintenance, progress monitoring and infrastructure inspection (New Zealand Ministry of Transport, 2019). In mining, RPAS can be utilised for inspection of mining equipment, which is normally a costly and time-consuming process and it necessitates a highly skilled workforce when conducted manually (Mining Technology, 2020). Industrial inspections usually entail the use of ladders, ropes and rigs to access large equipment, oversee processes and detect bottlenecks (Airobotics, 2018). In addition to this being potentially hazardous for the inspection personnel, the procedure usually requires machinery to be shut down, which directly impacts business finances (Airobotics, 2018). As an example, visual inspections of ore processing facilities are usually carried out during a planned plant shut-down (Micklethwaite, 2018). The quality of data collected manually during the shut-down may be affected by the limited time allocated for the inspection (Mining Technology, 2020). RPAS allow inspections to be carried out while the plant continues to operate which minimises production down-time (Micklethwaite, 2018). Utilising RPAS for equipment inspections means that this task can be completed more efficiently and safely (Airobotics, 2018; Mining Technology, 2020). Figure 4.5 shows an aerial viewpoint of the steelwork of a processing plant.

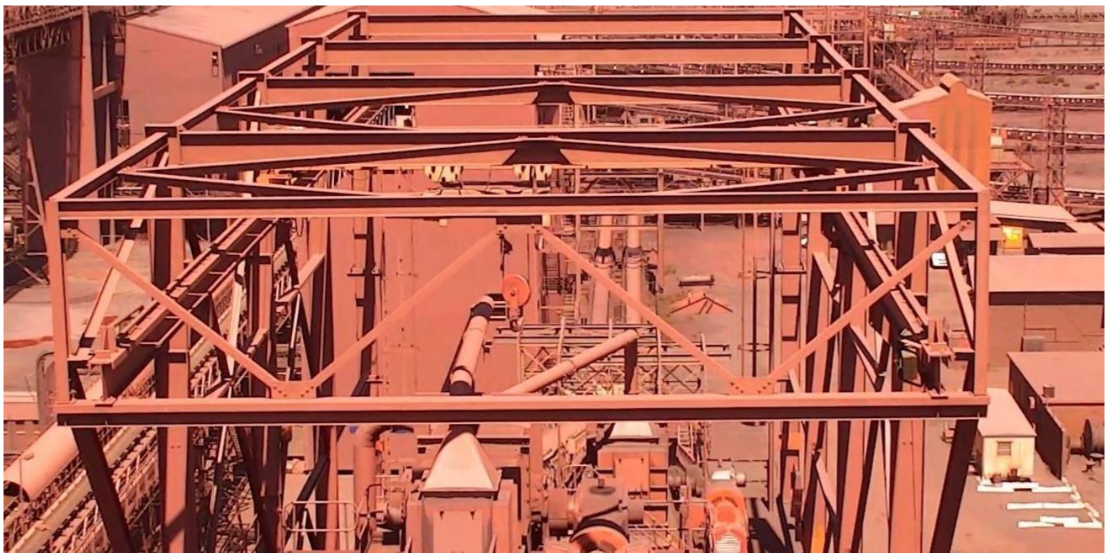

*Figure 4.5: An aerial view of the steelwork of a processing plant (Thomas, 2020)*

The advantageous aerial viewpoint that RPAS provides is the main motivation for using the system in any engineering scenario requiring infrastructure monitoring (Colomina & Molina, 2014). Figure 4.6 shows a closer inspection of the bolts and fittings of a processing plant.

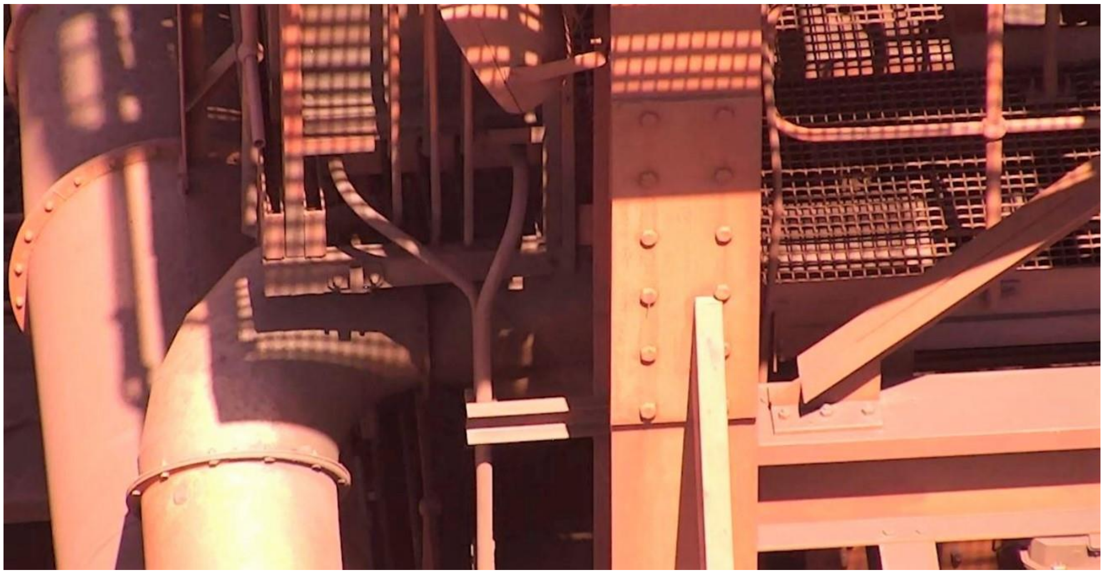

*Figure 4.6: A closer aerial inspection of the bolts and fittings of a processing plant (Thomas, 2020)*

Merz and Chapman (2011) presented the design of a single-rotor helicopter RPAS which targets infrastructure inspections using an RGB camera and suitable filters. Shi, et al. (2011) introduced a technique for object-change detection dealing with large rotations in pairs of RPAS-based images, aiming at infrastructure monitoring applications. Rupprecht and Pieters (2018) recommended flying an RPAS over the area of interest for reopening an old abandoned mine in South Africa. The RPAS captured images of the whole targeted mine including images of damage to plant and infrastructure (Rupprecht & Pieters, 2018).

RPAS technology can be utilised to improve reliability in services supply to mining operations, by enhancing condition assessments and minimising unplanned stoppages (New Zealand Ministry of Transport, 2019). Furthermore, RPAS can reduce the costs related to inspections of service delivery equipment and infrastructure such as power transmission lines and water pipelines (Odido & Madara, 2013). The clear advantages of utilising RPAS technology are realised through a combination of the following:

- Less reactive maintenance - Improved data quality helps in better planning and better directed proactive maintenance so less reactive is required;
- Better response times and reduced breakdown times - The RPAS can detect the locality of the breakdown so that maintenance crews can travel directly to the respective location; and
- Reduction in planned maintenance - The less costly RPAS technology in comparison to manned aircraft allows inspections to be done more often, thus, planned maintenance can be conducted in a more targeted approach. (New Zealand Ministry of Transport, 2019)

### 4.4.3 Gas Testing in Mine Workings

The application of RPAS to monitor air pollution in China progressed from experimental to large scale in late 2013 (Xuefeng, 2015), but progress in the rest of the world has been much slower (Gallacher, 2016). Modern innovations in sensor technology have led to the development of advanced miniature sensors (Snaddon, et al., 2013) that can detect different types of particulate matter in the air and the presence of hazardous gases (Gallacher, 2016). In 2015, the IoT supplier Libelum already had sensors that could detect temperature, humidity, air pressure, carbon monoxide, carbon dioxide, oxygen, nitrogen dioxide, methane and other combustible gases (Gallacher, 2016). Potential RPAS gas testing applications in mining operations include:

- Testing air quality over a wide-ranging area on the surface, such as haul roads and pathways, in a short duration, using a fixed-wing RPAS; and
- Testing pollution point sources underground, for example, blasted ends, using a multi-rotor RPAS. (Gallacher, 2016)

Samples of air can be collected for laboratory analysis or assessed in-situ using onboard sensors (Gallacher, 2016). At the University of Queensland, RPAS technology was used to investigate the characterisation of blasting plumes (Shahmoradi, et al., 2020). RPAS was shown to measure blasting plumes with a concentration of 1 $mg/m^3$

accuracy (Shahmoradi, et al., 2020). The air quality sensor and autopilot data were merged to create an airborne particulates characterisation in time and space, which had not been accessed without using RPAS (Shahmoradi, et al., 2020). The complex part of the investigation was choosing a suitable RPAS-based sensor for dust monitoring (Shahmoradi, et al., 2020). Alvarado, et al. (2017) developed a methodology to monitor $PM_{10}$ (particles with a diameter of 10 micrometres or less) dust particles produced from mining activities by using a small RPAS. Flight tests were carried out to show that a modular sensor provided data that could be used to calculate the rate of dust emission of a source.

RPAS can be utilised for hazardous gas detection in underground mines by making use of a combination of sensors that can continuously measure atmospheric parameters and gas concentration (Shahmoradi, et al., 2020). Dunnington and Nakagawa (2017) presented the use of RPAS for gas detection in underground coal mines. A gas sensor was installed on a DJI S1000 octocopter RPAS and utilised to measure coal fire gases for assessing characteristics of underground coal fires. With the combination of this RPAS and sensor, they could achieve 10 to 15 minutes flight-time (Dunnington & Nakagawa, 2017). Automated gas testing can also be a significant safety addition to other mine site operations such as ore processing plants and refineries (Airobotics, 2018).

### 4.4.4 Ground Monitoring

One of the major challenges in the mining industry is collecting geotechnical data from areas that are difficult to access (Shahmoradi, et al., 2020). RPAS and remote sensing technology can be used for ground deformation monitoring in mines (Colomina & Molina, 2014). Modern laser scanners have a millimetre or even sub-millimetre accuracy, which is suitable for detecting gradual changes to the ground structure of a mine which may point toward a potential collapse (Edwards, 2017). Although mapping discontinuity for slope stability can be completed using terrestrial LiDAR methodology, gaps in data constantly arise as a result of the limited scan angle of

LiDAR technology (Shahmoradi, et al., 2020). Imagery techniques such as photogrammetry and forward-looking infrared (FLIR) also enable the characterisation of rock masses (Shahmoradi, et al., 2020). RPAS fitted with a hyperspectral camera can be utilised to capture images and make measurements by using the analysis of overlapping photographs (Shahmoradi, et al., 2020). RPAS can provide necessary data where there are potential hazards such as in slopes or unstable mine excavations, thus making mines a safer workplace (Shahmoradi, et al., 2020; Xiang, et al., 2019). Also, FLIR imagery can be used to recognise areas of loose rock, which usually stay undetected until the situation becomes a hazard (Turner, et al., 2018).

In open-pit mines, optimisation of the slope angle has a significant role in the reduction of mine production costs and efficiency of mining activities (Shahmoradi, et al., 2020). Figure 4.7 shows an aerial view taken from an RPAS of highwall benches for the inspection of toes and crests.

*Figure 4.7: An aerial view of highwall benches of an open pit mine (Thomas, 2020)*

Figure 4.8 shows cracks forming on the crest of an open pit highwall.

*Figure 4.8: Cracks forming on the crest of an open pit highwall (Thomas, 2020)*

McLeod et al. (2013) investigated an open-pit mine to determine the direction of discontinuity on the surface of rock slope by using an RPAS topographical survey. An Aerial Scout multi-rotor RPAS carrying a 100-gram camera captured images of the fractures and 3D point clouds were generated by using SfM software. SfM photogrammetry software makes use of overlapping images captured from multiple viewpoints from a moving sensor to produce 3D data, hence the name "Structure from Motion" (Micheletti, et al., 2015). An image processing algorithm was then generated to estimate fracture orientation in the open-pit mine (Shahmoradi, et al., 2020). RPAS-SfM has in recent times been used to map surface displacement in different fields, for example, glaciology and landslide monitoring (Bhardwaj, et al., 2016; Cook, 2017; Fernandez, et al., 2016).

In underground excavations, rock mass data collections typically involve the rock engineer physically surveying the rock mass (Shahmoradi, et al., 2020). The exposure of the mine personnel to unsupported areas such as open stopes and newly blasted faces puts at risk the safety of the mine personnel (Turner, et al., 2018). The small size and manoeuvrability of RPAS enable them to access difficult-to-access areas in underground mines without threatening the safety of the mine personnel (Hrabar, 2019;

Shahmoradi, et al., 2020). 3D maps generated from RPAS can be used for hazard identification, for example, potentially dangerous structural changes to the mine shaft (Edwards, 2017; Geomatics World, 2019). RPAS have demonstrated capabilities operating in the dark, fog and difficult visibility conditions (Mitka & Mouroutsos, 2017).

### 4.4.5 Inspection of Abandoned Mines

According to the Council for Geoscience, one of the National Science Councils of South Africa, there are about 6,000 abandoned and derelict mines across the country (Council for Geoscience, 2021). Abandoned mine lands (AMLs) worldwide give rise to environmental, health and safety risks to persons (Shahmoradi, et al., 2020). An example is the case of the nine underground miners at Quecreek Mine in Somerset County, Pennsylvania in the United States of America, who accidentally breached a flooded abandoned mine in 2002 (Erdley, 2002). The abandoned mine was not completely mapped and the latest available map of the mine was compiled in 1964. The nine miners were trapped underground for over 77 hours at 73 m below the surface (Thrun, et al., 2004). Another case in point is the presence of the abandoned underground mines in Newcastle and Ipswich in Australia which are located underneath residential areas. This increases the risk of ground subsidence (Bell, et al., 2000). In a similar situation, subsidence is being monitored for the abandoned gold mines in Nova Scotia and Ontario, Canada and coal mines in Illinois and Ohio, USA (O'Connor & Murphy, 1997).

Furthermore, when a coal mine is abandoned, methane emissions are reduced but do not completely stop (Shahmoradi, et al., 2020). Abandoned mines can release methane at a near-steady rate for a prolonged duration (Shahmoradi, et al., 2020). Hence, monitoring and mapping abandoned mines is essential to reduce the risk of environmental hazards (Shahmoradi, et al., 2020). However, monitoring such extensive areas with conventional, labour-intensive, costly monitoring methods is challenging.

RPAS technology is an alternative cost-effective solution. The application of RPAS in abandoned mines includes:

- Ground subsidence mapping - Generating a ground subsidence map indicating the locations and details of previous subsidence incidents (Lee & Choi, 2016; Suh & Choi, 2017);
- Rehabilitation - Generating a high-quality 3D DEM to calculate the amount of material required for the rehabilitation of a closed mine (Shen, et al., 2017; Yucel & Turan, 2016);
- Mineshaft and pillar mapping - Shaft examination and mapping of pillars in abandoned underground mines when there is a risk of deploying personnel (Cawood, 2015; Zhou, et al., 2019);
- Detection of gas pockets - Generating a 3D virtual mine map from 3D point cloud data of optical sensors to calculate the volume capacity for gas storage in abandoned mines (Neumann, et al., 2013); and
- Monitoring acid mine drainage (AMD) - Investigation and monitoring of AMD from abandoned mines and tailings to the groundwater system (Matthews, 2018).

## 4.5 Stockpile Management

Effective management of stockpiles can produce major benefits for mining companies, for example, grade optimisation by blending of ore, buffer ore supply during production disruptions and financial reporting (Mining Technology, 2020). A detailed stockpile management programme enables mining engineers to account for stockpiles and archive ore grades accurately and efficiently throughout the life of a stockpile (Airobotics, 2018). Traditionally, ground-based techniques and technologies are used in stockpile management programmes to achieve operational efficiency (Airobotics, 2018). However, these conventional methods can be time-consuming, labour-intensive and costly (Airobotics, 2018). The height and area of stockpiles are challenges encountered while managing them because stockpile dimensions tend to change frequently (Mining Technology, 2020). The simplicity, speed and agility offered by

RPAS for stockpile management differentiate them from manned aircraft and other conventional terrestrial data collection methods (Airobotics, 2018; Shahmoradi, et al., 2020).

RPAS provides accurate measurements through aerial data capture using photogrammetry or LiDAR (Airobotics, 2018) and can aid mining companies in generating high-quality DTMs of the stockpile inventories (Mining Technology, 2020; Patikova, 2004). RPAS photogrammetry with a suitable GSD can comprehensively outline the irregular shapes of stockpiles in detail for volumetric calculations (Pix4d, 2017). Volumes can be computed as the difference between an old and a new model or the difference between a new model and a defined plane (Patikova, 2004). The outcome consists of information on cut and fill volume as well as cut and fill area (Patikova, 2004). The delivered format can be a DTM, a string file, a file with 3D triangles, 3D drawing exchange format (DXF), or just a text file with point co-ordinates and information about features such as edges (Patikova, 2004). This data is transferred directly into a mining or GIS software program for further analysis and evaluation (Airobotics, 2018).

Automated RPAS can be incorporated into stockpile management programs including blending efforts by assisting in the calculation of blended piles by tracking the quantities of ore grades mixed (Airobotics, 2018). Additionally, RPAS stockpile management programs can provide value in archiving layered stockpiles by profiling historical stockpile grades and archiving ore grades across the life of the stockpile to minimise misclassification (Airobotics, 2018). Furthermore, deploying RPAS frequently can ensure companies continuously monitor stockpile movement (Mining Technology, 2020). Tucci, et al. (2019) investigated the monitoring and computing of stockpile volumes using RPAS photogrammetric survey and the generation of 3D models starting from point clouds. The test was conducted using two RPAS flight sessions, with vertical and oblique camera arrangements, and using a terrestrial laser scanner for measuring the GCPs and as ground truth for testing the two survey configurations (Tucci, et al., 2019).

The Portuguese surveying and engineering company Geotrilho tested the suitability of RPAS for the measurement of stockpile volumes. A rotary Airbot X6 RPAS was used to quickly map a wide-ranging area of the mine and measure stockpile volumes. The hexacopter methodically flew along the preset grid at a height of 96 metres, capturing images of the ground below. The RPAS captured the stockpile area with a flight speed of 4 m/s. Four strategically selected points were used for take-off and landing. The Airbot X6 effectively endured the high wind speeds of up to 10 m/s it was exposed to on the day. On completing the flight, the data was uploaded onto the photogrammetry software Agisoft for further processing to generate a textured 3D model. A 3D model of a coal stockpile was generated using the same technique but without control points. In contrast to surveying the ground, the surveyors were spared the potentially hazardous activity of climbing on the coal pile. The complete process, including data generation, was completed in one hour (Lautenschlager, 2015).

### 4.6 Blast Optimisation

RPAS can be effectively used for blast analysis (Shahmoradi, et al., 2020) which normally involves some significant safety risks (Hoffmann & McAllister, 2018). RPAS can, after pre-blast and post-blast analysis, provide mining engineers with better reconciliations and a greater understanding of their blast practices to minimise dilution and improve the cost efficiency (Hrabar, 2019). However, RPAS may not fly close during a blast therefore aerial surveillance is conducted at a safe distance (Thomas, 2019). RPAS can aid in the control of the key factors in blasting design, which includes the rock type, geology, topography, geometry and borehole location (Shahmoradi, et al., 2020). RPAS can be used to analyse the block size before and fragmentation after blasting (Shahmoradi, et al., 2020). In one case, RPAS and sensor were used to monitor dust particles after blasting operation in an open-pit mine (Shahmoradi, et al., 2020). Using RPAS in blasting operations has several benefits including:

- Improved operational safety, as there is no need to deploy mine personnel to the active and hazardous part of the mine to acquire specific data;

- Enhanced quality results, since the sensors fitted on the RPAS provide very exact, high-quality data and images from angles that are not accessible from the ground; and
- Productivity improvements, by reducing the time and personnel needed to capture data and images. (MAXAM Foundation, 2018)

"Blasting involves controlling a large amount of information to ensure the optimal design of the explosive's energy distribution. This requires a series of checks before and during the charging process and after blasting, which is where RPAS can be useful" (MAXAM Foundation, 2018). RPAS technology can provide the acquisition of high-resolution data which can be beneficial in blast design, mill operations and other mine-to-mill process optimisation operations (Bamford, et al., 2017). Furthermore, RPAS can provide data acquisition fast and often, which improves the statistical reliability of measurements (Bamford, et al., 2017).

### 4.6.1 Pre-blast Planning and Analysis

One of the many functions of RPAS technology can be found in planning, designing, charging and assessing blasting operations (MAXAM Foundation, 2018). The combination of RPAS and 3D photogrammetry allows high-precision profiling of the blasting area, to make accurate assessments of critical characteristics, for example, safety (MAXAM Foundation, 2018). Pre-blast planning using RPAS includes:

- Topographical mapping - Generating an orthomosaic and DTMs of areas that are unstable or difficult to access;
- Bench geometry - Acquire high-precision 3D geometric models of the blast bench profile. The models obtained enable a geomechanical analysis of the bench, which is compatible with blasting software in use, thus ensuring an optimal blast design based on actual conditions;
- Positioning blast holes - Actual positions can be determined accurately without the need for conventional topography as shown in Figure 4.9. The information

obtained by the RPAS is used to update the 3D blast model and optimise the blast design while allowing improved prediction of both results and any possible collateral effects such as vibrations and projected blast material (flyrock); and

- Safety inspections - Reduces the time and risk of safety zone inspections carried out before and after blasting, inspecting a large area without the deployment of personnel. Figure 4.9 shows an aerial viewpoint of a blast pattern being drilled that allows for better recognition of the terrain, avoiding blind spots. (MAXAM Foundation, 2018)

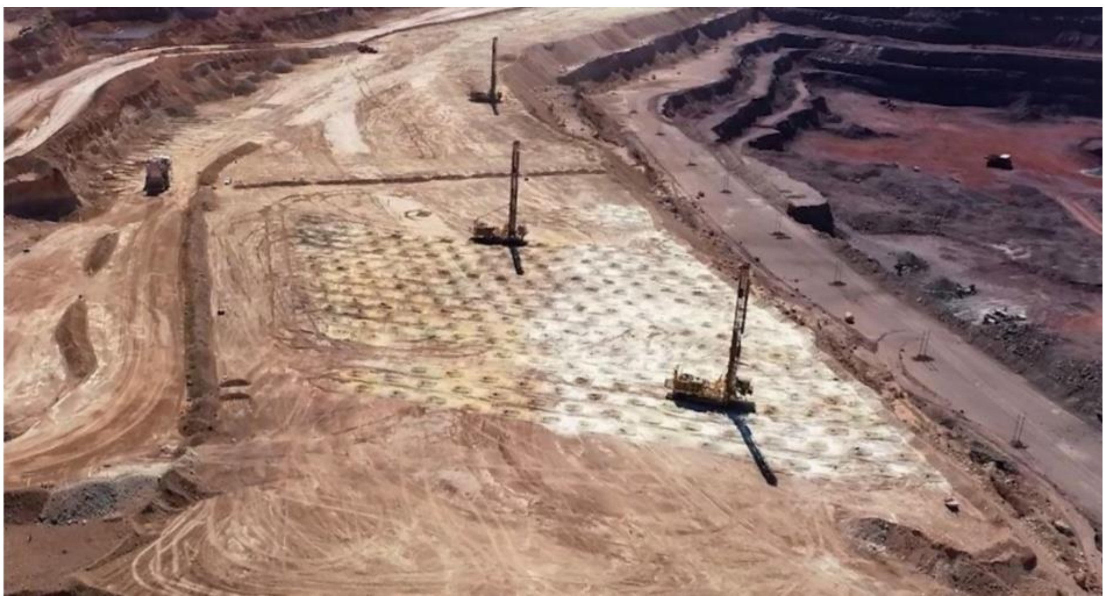

*Figure 4.9: An aerial view of a designed blast pattern being drilled (Thomas, 2020)*

### 4.6.2 During Blasting Analysis

RPAS allow for capturing high-resolution images and high-speed video from angles that would be impossible from a terrestrial view, with the additional benefit of having the operator located in a remote safe location. Hence, it is possible to analyse blast behaviour and material flow, along with any incidents during detonation (MAXAM Foundation, 2018). Real-time measurement of the gases emitted can also be generated during the blast to help assess the safety conditions on the bench and a faster return to work. It means there is no need to send mine personnel to control the blasted area (MAXAM Foundation, 2018). It is proposed that real-time fragmentation measurement should be carried out to improve blast design over time to produce an optimal rock size distribution for downstream processes (Esen, et al., 2007).

### 4.6.3 Post-blast Analysis

Some of the key applications of RPAS for post-blast analysis include:

- Bench volume measurement - Measuring bench volumes before and after blasting provides quick, direct information to measure the in situ volume from pre-blast and cleared bench profiles;
- Blasted material pile volume measurement - Accurate calculation of blasted material pile. The work can be carried out without interrupting the loading process and without the need to send mine personnel to the area; and
- Fragmentation analysis - The images obtained with RPAS are optimal for semi-automatic analysis of the fragmentation obtained in the different blasting areas, without the need for scale references. Accurate results can be achieved more quickly and without the need to deploy mine personnel to the blasted area. (MAXAM Foundation, 2018)

Measuring post-blast rock fragmentation is essential in the optimisation of a mining operation (Bamford, et al., 2017). Rock fragmentation can impact the volumetric and bulking properties of the rock, for example, fill factor and bulk volume (Mosher, 2011). As a result, the efficiency of succeeding production stages, that is, loading and hauling are also affected (Bamford, et al., 2017; Kanchibotla, et al., 1999; Mosher, 2011). There are several techniques used for analysis of rock size distribution, for example, a visual observation by an expert, sieve analysis and image processing (Bamford, et al., 2017; Shahmoradi, et al., 2020).

Visual observation entails inspecting the muck pile and subjectively judging the quality of the blast (Bamford, et al., 2017). This subjective technique can lead to inaccurate results (Bamford, et al., 2017). Sieve analysis involves passing a sample of the muck pile being analysed through a series sieve trays of different sizes (Bamford, et al., 2017). This method is more expensive, time-consuming and in some instances impractical to carry out as the sample rock size distribution may not be statistically representative of the whole muck pile (Bamford, et al., 2017). Conducting image analysis involves taking 2D photos, stereo images or 3D laser scans of the muck pile and processing these images to determine particle sizes (Onederra, et al., 2014; Sanchidrian, et al., 2009). Image analysis techniques are quick and comparatively accurate for rock fragmentation measurements (Bamford, et al., 2017; Villaescusa, 2014). RPAS can be effectively utilised for aerial image capture and data analysis of blasted rock fragmentation.

### 4.7 Haul Road Optimisation

The haul road system has a major influence on the efficiency of mining activities (Mining Technology, 2020). Haul road quality requires continuous monitoring due to daily wear and tear from heavy machinery and weather conditions, which may damage the road (Airobotics, 2018). To achieve safe and even movement, the haul road conditions must be continuously monitored (Mining Technology, 2020). RPAS can aid this process by collecting a large amount of aerial data, covering extensive areas more accurately, which can then be used by engineers for planning, designing, construction, inspection and maintenance of haul roads (Airobotics, 2018; Mining Technology, 2020). RPAS can also be used to improve onsite road safety by monitoring mobile equipment, berms, road degradation and hazards (Micklethwaite, 2018; Propeller Aero, 2017). Irrespective of the mining environment, or type of task, RPAS are not prone to tiredness or contentment and function as a valuable industrial multi-tool (Airobotics, 2018).

Automated RPAS can assist with the designing of haul roads through high-quality imagery and videos to be processed into digital 3D models, which help and guide mining professionals with the planning and construction of roads (Airobotics, 2018).

Automated RPAS can also assist with slope inspection, by calculating vertical and horizontal slopes of haul roads, so preventing the temporary stoppage of haul trucks resulting in optimal productivity (Airobotics, 2018). Furthermore, incorporating automated RPAS for haul road inspection missions is a safer in comparison to a manned inspection of dangerous areas, reducing risks of accidents and injury to mine personnel as well as daily routine inspections (Airobotics, 2018). Data acquired using RPAS can then be analysed, shared and logged digitally for real-time and future reference by the relevant mining personnel (Airobotics, 2018). Mine planners can utilise RPAS data to monitor haul road width at several locations, by digitally measuring the ground distance between opposite road edges (Airobotics, 2018). Additional applications of automated RPAS include measuring side barriers to identify areas that require maintenance and water drainage simulations to simulate flow and accumulation of water (Airobotics, 2018).

## 4.8 Mine Residue Deposits Management

Mining operations produce large amounts of waste materials, and the volume of waste products is expected to increase in the future as lower grades of ores are extracted and processed in mining (Garbarino, et al., 2020; Wang, et al., 2014). One of the types of waste produced is tailings, which consist of solid particles from mineral extraction and a mixture of water and other constituents such as coagulants and flocculants (Rauhala, et al., 2017). Tailings impoundments give rise to one of the major environmental risks in mining areas (Airobotics, 2018; Rico, et al., 2008; Wang, et al., 2014). Particularly, conventional storage of tailings in the form of a slurry can present high environmental risks due to potentially hazardous contaminants seepage, spills and dam collapse (Airobotics, 2018; Rauhala, et al., 2017). In addition to the safety risks, complications in tailings dams can also have huge failure costs implications (Jackson, 2020). Rico et al. (2008) reviewed mine dam failures and revealed that one of the most common causes of tailings dam failure was poor management.

The behaviour of tailings is very complex and can be impacted by process adjustments, flocculation, sedimentation, consolidation, segregation, deposition, freeze-thawing and desiccation (Ahmed & Siddiqua, 2014). Therefore, the use of modern remote sensing techniques to support conventional geotechnical measurements in the impoundment-scale monitoring of tailings could improve the management of tailings and expand existing information on tailings behaviour (Rauhala, et al., 2017). RPAS can be utilised to effectively monitor seepages, leaks and the structural integrity of tailings dams (Jackson, 2020). Currently, personnel are physically deployed to carry out tailings dam inspections on foot (Jackson, 2020). “These inspections are labour intensive, involve a moisture meter, trial pits and geotechnical equipment to physically measure saturation levels in the soil” (Jackson, 2020). These physical methods are also time-consuming, costly, challenging and restricted to safely accessible areas of the dam (Jackson, 2020).

RPAS can collect high-quality data for informed risk management and control of tailings dams without exposing mine personnel to hazards (Airobotics, 2018; Mining Technology, 2020). RPAS can enable cost-effective and work-efficient surveillance of mine residue deposits (MRD) facilities (Colomina & Molina, 2014; Gasperini, et al., 2014; Nex & Remondino, 2013; Pajares, 2015). The use of RPAS for tailings dams enables routine data-collection to assist in evaluations, which can assist in early detection and prevention (Airobotics, 2018). The potential impacts of tailings on the neighbouring environment can be minimised by monitoring and controlling the moisture of the mine tailings (Xiang, et al., 2019). Thermal sensors can be fitted on RPAS to detect changes in the spatial and temporal surface moisture content in mine tailings (Shahmoradi, et al., 2020). RPAS thermal leak detection solution involves the detection of temperature variations within tailings dam-walls, enabling mines to detect moisture leakage and surface movements in tailings dams (Jackson, 2020).

Additionally, RPAS with standard RGB cameras can be deployed which enables identifying the existence of any structural defects such as bulging or pressure in the wall which could result in a disastrous blow out of a section of the tailings dam (Jackson, 2020). Instead of changing the whole dam wall, the thermal RPAS imagery helps in targeting the exact areas necessitating repair, improving tailings dam management, increasing productivity and saving time and money (Jackson, 2020). Imagery acquired from RPAS inspections is then submitted to mine engineers for accurate analysis (Jackson, 2020). Furthermore, RPAS imagery and thermal data can be collected from multiple flights and superimposed to produce a trend analysis (Jackson, 2020). This will help to detect changes in the shape and size of the dam, pick up issues that were not previously identified and determine the rate of progression of these issues, which would usually go undetected (Jackson, 2020). Consequently, this will help to accurately predict tailings dam failures and effectively plan mitigation measures (Jackson, 2020).

Rauhala, et al. (2017) utilised RPAS and SfM-generated DEMs to monitor a tailings impoundment and movement of the tailings surface. RPAS and SfM photogrammetry is regarded as a quick and flexible data acquisition system that can be used to generate orthomosaics and 3D models (Colomina & Molina, 2014; Nex & Remondino, 2013; Pajares, 2015). The accuracy obtained for the DEMs and DEMs of Difference (DoDs) indicated that RPAS-aided monitoring of tailings impoundments is sufficiently accurate for management operations such as volume calculations and tracking surface movement in the decimetre range (Rauhala, et al., 2017). Analyses of the compiled data on a digital platform helps mining companies to maintain the structural integrity of the tailings dam, design expansion and avoid failure (Mining Technology, 2020). The RPAS covers the entire dam area, helping in quickly and safely pinpointing the exact, geo-referenced areas where leakage has occurred (Jackson, 2020). This aids in planning more effectively and attend to urgent issues immediately (Jackson, 2020). This helps to precisely detect potential issues before the occurrence, prevent disastrous events, keep mine personnel and the public safe, remain legally compliant and save on failure costs (Jackson, 2020).

## 4.9 Emergency Response and Search and Rescue Missions

When an accident occurs at a mining operation, RPAS can be quickly deployed to assess affected areas and improve situational awareness, assisting first responders in determining the most effective allocation of resources and delivery of life-saving equipment and supplies (Deepika & Lavanya, 2015; me consulting, 2019; Othman, 2016). Quick, easy deployment and the ability to enter hazardous areas make RPAS a beneficial tool for collecting real-time support information for effective decision-making process and disaster management operations (Deepika & Lavanya, 2015; Jokotola, 2013; Odido & Madara, 2013). Emergency response personnel may use RPAS equipped with thermal imagery for mapping the affected area for the search and rescue of injured mine personnel potentially trapped in mine working areas (Deepika & Lavanya, 2015; Edwards, 2017; Mitka & Mouroutsos, 2017; Rudol & Doherty, 2008). RPAS can provide information to emergency response planners by monitoring the evacuation, identifying where conditions are worsening and contribute to rescue efforts (Jokotola, 2013). This information can be incorporated into current and future early warning systems at a mining operation (Jokotola, 2013).

RPAS can deliver first aid assistance, medicines and vaccines, and retrieve medical samples, into and out of remote or otherwise inaccessible areas (Deepika & Lavanya, 2015; Odido & Madara, 2013). Figure 4.10 shows an ambulance RPAS designed by Alec Momont for the delivery of an automated external defibrillator in emergency response circumstances (Mitka & Mouroutsos, 2017).

*Figure 4.10: An ambulance RPAS designed for medical emergency response (TurboSquid, 2020)*

RPAS can also be utilised for fire mapping applications (Watts, et al., 2012). Firefighting services make use of RPAS equipped with thermal imaging equipment to provide advanced intelligence in respect of the detection of fire in mines (Othman, 2016) and detection of any trapped personnel (Ambrosia, et al., 2003; Casbeer, et al., 2006; Mitka & Mouroutsos, 2017; Odido & Madara, 2013). RPAS can assist firefighters in safely accessing the location of the fire and perform navigation to coordinate a non-dangerous traceable flight path through the fire (Mitka & Mouroutsos, 2017). At a coal mine, the thermal imaging camera of the RPAS detects heat emanating from the facilities in the dressing plant, such as the conveyor belt system, to prepare for hazardous issues due to the overheating of the facilities (Shahmoradi, et al., 2020). It can also quickly detect the self-ignition point of coal to monitor accidents (Shahmoradi, et al., 2020).

Many mines are in remote areas where reliable communication systems may not be available (Shahmoradi, et al., 2020). RPAS provide quick solutions in support of communications coverage of rescue operations (Hayat, et al., 2016) (Shakhatreh, et al., 2019). RPAS can provide disaster warnings and assist with accelerating rescue and recovery operations when the communications networks are not reliable (Shahmoradi, et al., 2020). RPAS also can carry medical supplies to difficult-to-access areas (Shahmoradi, et al., 2020). In certain situations, for example, poisonous gas infiltration and searching for missing persons, RPAS can support these operations (Silvagni, et al., 2017).

Molina, et al. (2012) reported on the use of a rotary-wing RPAS fitted with video and thermal cameras to detect lost personnel in difficult-to-access sites, that is, to aid in the search component of search-and-rescue. A similar development was described by Van Persie, et al. (2011), using a rotary-wing RPAS equipped with a video camera to assist fire brigades in real-time crisis management. Choi & Lee (2011) presented another rotary-wing development for rapid disaster management, carrying two optical cameras and a LiDAR, and producing results which include a geo-referenced LiDAR point cloud. RPAS have been used previously and demonstrated to be beneficial after the occurence of a natural disaster, for example, the Asian Tsunami and Hurricane Katrina where they were used in damage assessment and the search for survivors (Frost and Sullivan, 2007).

Ranjan, et al. (2018) proposed a multihop emergency communication system to assist the miners and rescue team in emergencies and improve mining productivity. The design involved the use of an RPAS named SkyHelp as a wireless communication framework to monitor mining activities and support search and rescue operations in deep open-pit mines. A simulation was done by using MATLAB to assess the concept (Shahmoradi, et al., 2020). Hoffman and McAllister, in 2018, recommended using the F450 quadcopter RPAS to locate trapped workers (Hoffman, 2017). The RPAS would assess the collapsed area and identify any opening through the pile of rock or soil (Shahmoradi, et al., 2020).

## 4.10 Conclusion

In this chapter, different applications of RPAS in the mining industry were discussed. It was shown that RPAS technology can improve the safety and reliability of mining operations. Despite significant advancement in RPAS technology, the applications of

RPAS in underground mines are still limited. This is due to challenges such as GNSS-denied environments, lack of wireless signal, confined spaces, the concentration of dust and gases, and generally harsh environments.

# CHAPTER 5. LEGISLATION GOVERNING THE USE OF REMOTELY PILOTED AIRCRAFT SYSTEMS

## 5.1 Introduction

Regulations are essential for the safe use of RPAS by licensed pilots concerning the RPAS, the pilot and the surrounding environment (Stark, et al., 2015). RPAS is evolving into a very significant element in civilian and industrial operations but regulations surrounding such use have been lagging on a global scale (Stark, et al., 2015). There are questions regarding the safety of RPAS operations and their integration with human activities (Stark, et al., 2015). RPAS sits within the national and international legal framework and different countries have different legislation regarding safe practices (Mining Technology, 2019). As the use of RPAS becomes extensive, national aviation authorities globally are advocating for the modernisation of legislation to promote commercial use (Mining Technology, 2019).

As the use of RPAS technology increases, there is potential for problems regarding interference in the aviation system and airspace control (Klemas, 2015; New Zealand Ministry of Transport, 2019). These concerns necessitate the incorporation of technological and regulatory mediations to overcome any issues regarding RPAS use (New Zealand Ministry of Transport, 2019). The technological challenges can be overcome by developing enabling technologies and the regulatory challenges can be mitigated by amending the existing rules and regulations as well as formulating new ones to facilitate operations of RPAS in the non-segregated air space (Narang, 2016). Regulatory requirements ultimately define the operational boundaries of RPAS certification, flight operations, and operator certification (DeGarmo, 2004). Most countries have adopted the use of RPAS, particularly for recreational purposes, as an industry that only needs to be monitored for safety rather than be strictly regulated (Drone Genuity, 2020).

Even though RPAS technology is being incorporated at an exponential rate in the civilian sector, many countries are finding it difficult to regulate the commercial usage of RPAS (Othman, 2016). The utilisation of RPAS in industrial or commercial operations often raises concerns of safety, privacy and ethics (Othman, 2016). Although supervisory boards may use regulations to limit the use of RPAS for commercial and civil purposes from a safety standpoint, the main public concerns are with regards to the privacy significances of their adoption (Othman, 2016). Legislators, public interest groups and certain sectors of society are opposed to the integration of RPAS technology because they fear intrusions into their daily lives and privacy violations (Othman, 2016). As a result, some countries completely prohibit the use of RPAS, for example, Barbados, Cuba, Morocco and Uzbekistan (Ghosh, 2021).

RPAS can be an important tool but when incorrectly used it can pose a great danger (Stark, et al., 2015). According to Stark et al. (2015), the success of RPAS in civil aviation requires finding solutions to the following questions:

1. Who should be permitted to use RPAS and in what role or function?
2. What can be implemented to make certain that RPAS is being utilised appropriately?
3. How can regulations be employed to promote air safety?
4. Can standardised training be introduced for commercial operations?
5. Is strict regulation necessarily the proper solution?
6. How can RPAS be utilised efficiently and cost-effectively in the presence of regulation? (Stark, et al., 2015)

Stark et al. (2015) proposed that outlining an operational model is the primary stage in addressing these concerns and understanding how RPAS can be effectively and safely utilised by all stakeholders. Safety must always be a key priority but sometimes legislation restricts the potential that RPAS can contribute to the industry, for example, flying within the VLOS (Mining Technology, 2019). The greater potential of RPAS capabilities lies in autonomous operation (Mining Technology, 2019). Some of the areas of interest include prohibited flying of RPAS in certain areas such as airports, night-time flying limits, regular inspections and flying height boundaries (Mining Technology, 2019). However, if there is a great demand for a product or service within society, laws and regulations become unproductive and can have conflicting implications for the intended purpose (Othman, 2016).

The rapid rate of development of RPAS technology, its unique characteristics, capabilities and diversity of RPAS applications necessitates a recalibration of approach as to how to regulate its adoption (Othman, 2016). RPAS technology is developing quicker than governments comprehend how to legally and ethically control it (Othman, 2016). Nonetheless, if society cannot effectively control RPAS then, besides the harm, hazards and hindrance they may cause, any benefits associated with the technology cannot be fully realised (Othman, 2016). This chapter gives an overview of the regulations governing the use of RPAS and how they affect the integration of RPAS in the mining industry.

## 5.2 Remotely Piloted Aircraft Systems International Regulatory Framework

The employment of a consistent regulatory landscape has been called for by RPAS participants to eliminate the obstructions for RPAS certification and commercialisation all over the world (Colomina & Molina, 2014). When it comes to flying professional RPAS within the law, the respective rules around the globe are varied and until now there are no unique regulations for all countries (Doumit, 2019). Aviation authorities are integrating RPAS into civilian airspace, and each jurisdiction has its own rules and regulations (Doumit, 2019). The safety of humans and aviation assets is paramount in flying, with all else being secondary (Bahadur, 2017). If there is ever uncertainty in the interpretation of a regulation, the rule of thumb is, “flight safety is of the utmost importance”, and all activities are to be adjusted on that account (Bahadur, 2017).

The RPAS regulatory framework within individual countries is established by the Convention on International Civil Aviation, also known as the Chicago Convention (Clarke & Moses, 2014). The International Civil Aviation Organisation (ICAO) is a specialised agency of the United Nations (UN) which is responsible for providing the international regulatory framework for RPAS integration into the non-segregated air space in consultation with member states (Clarke & Moses, 2014; Narang, 2016). It accomplishes this by publishing numerous Standards and Recommended Practices (SARPs) (Clarke & Moses, 2014; Narang, 2016). Almost all countries are signatories to the Convention, and operational air safety concerns are dependent on regulations within national constitutions (Clarke & Moses, 2014; Narang, 2016). Individual countries may employ regulations that are different from the SARPs, however, they are obligated to file such regulations with the ICAO (Clarke & Moses, 2014; Narang, 2016).

The ICAO has made slow progress in formulating regulations since the setting up of the Unmanned Aircraft Systems Study Group (UASSG) in 2007 and the RPAS Panel (RPASP) in 2014 (Narang, 2016). The UASSG was tasked, among other things, with developing a regulatory concept and associated guidance material to support and guide the regulatory process for unmanned aircraft (Othman, 2016). The Manual on RPAS (MRPAS) was a major piece of work produced by the UASSG (Othman, 2016). The purpose of the manual is to provide guidance on the technical and operational matters applicable to the integration of RPAS in non-segregated airspace and at airfields (Othman, 2016). The UASSG concentrated its efforts on unmanned aircraft that are remotely piloted, that is, RPAS (Othman, 2016). The decision was also taken that military aircraft, autonomous unmanned aircraft, which includes unmanned free balloons or other types of aircraft which cannot be controlled in real-time during flight, and model aircraft would be excluded from the Work Program (Othman, 2016). The UASSG expanded the previous definitions recorded in Circular 328 and established a new set of terms that are unique to this new technology that includes:

- "Remotely Piloted Aircraft Systems (RPAS) – A remotely piloted aircraft, its associated remote pilot station(s), the required C2 links and any other components as specified in the type design" (International Civil Aviation Organisation, 2015, p. xviii);

- “Remotely Piloted Aircraft (RPA) - An unmanned aircraft that is piloted from a remote pilot station” (International Civil Aviation Organisation, 2015, p. xviii);
- “Remote Pilot Station (RPS) - The component of the RPAS containing the equipment used to pilot the RPA” (International Civil Aviation Organisation, 2015, p. xviii);
- “Remote crew-member - A crew-member charged with duties essential to the operation of an RPAS during a flight duty period” (International Civil Aviation Organisation, 2015, p. xviii);
- “Remote pilot - A person charged by the operator with duties essential to the operation of an RPA and who manipulates the flight controls, as appropriate, during flight time” (International Civil Aviation Organisation, 2015, p. xviii); and
- “RPAS operator certificate (ROC) - A certificate authorising an operator to carry out specified RPAS operations” (International Civil Aviation Organisation, 2015, p. xviii).

The publication of Circular 328 in 2011, MRPAS in 2015 and amendment of three out of 18 Annexures indicates the slow pace of formulation of the regulatory framework (Narang, 2016). The setting up of working groups to address issues related to airworthiness, telecommunication for C2 and ATC, Detect and Avoid (DAA), personnel licensing, RPAS operations and air traffic management indicate unresolved critical areas needing further research and deliberations (Narang, 2016). All the SARPs have to be completed to facilitate the integration of RPAS into the non-segregated air space (Narang, 2016).

## 5.3 Operational Regulations

Regulators have mostly managed to mitigate risks associated with RPAS by introducing limitations concerning where and when RPAS operations can be conducted which is the operational regulatory domain (Clothier, et al., 2015). Operational regulations are passed mainly to ensure the safety of everyone in the surrounding areas of RPAS operations, their privacy and the safety of their property. For case in point, in South Africa, the South African Civil Aviation Authority (SACAA) prohibits flying an RPAS 50 m or closer from:

- Any property without consent from the owner of the property; and
- Any person or group of persons such as a sports field, road races, schools or social events. (Western Cape Government, 2019)

The SACAA is the RPAS regulatory agency (Goitom, 2016). The laws introduced by SACAA for RPAS extend beyond the few mentioned including rules around licensing of RPAS pilots as well (Goitom, 2016). Its influence includes the authority to sanction aviation regulations, establish safety and security standards, issue all mandatory licenses and permits and develop enforcement tools to ensure compliance with all pertinent laws and standards (Goitom, 2016).

## 5.4 Airworthiness Regulatory Framework

Airworthiness is a wide-ranging concept that can be defined as comprising the essential principles for safe and controlled flight (De Florio, 2016). It combines the vital components of an airworthy system, that is:

a) Proper aircraft standards - Aircraft standards are used to outline the essentials in promoting an understanding of suitable means of compliance with air safety requirements. One key area that current regulations lack is the standards concerning the use of autonomous control and how it affects safety standards. (Stark, et al., 2015)

b) Ground control criteria - The Ground Control Station (GCS) plays an essential part in the airworthiness of an RPAS. The GCS comprises of two main components which are the utilisation of the GSC to assist RPAS operations and the employment of a communication standard. The GSC presents a means of communication between the RPAS operator and the RPAS which is essential in sustaining safe operations. The GSC is used in addition to the onboard autopilot to provide the operator with adequate information to make well-versed safe decisions. Most RPAS operations are restricted to LOS for safety reasons as well as the use of communal civilian frequencies. (Stark, et al., 2015)

c) Air safety - Air safety contributes a substantial part in defining airworthiness. This is conducted through risk assessments and analysis to cover the most complex part of the incorporation of RPAS into civil aviation airspace (Stark, et al., 2015). A typical procedure would consist of an initial system safety examination by analysing the separate operational stages, that is, planning, staging, launching, flying and landing. The functions of the individual active components are identified at each stage and potential fault conditions recorded. The impact and likelihood of the individual fault conditions can be computed by making use of common cause analysis metrics (STANAG 4671, 2010). RPAS are likely to encounter two types of airborne traffic while flying in the non-segregated air space, that is, cooperative and non-cooperative traffic (Narang, 2016). Cooperative traffic is capable of broadcasting its position through a transponder or by any other means, while non-cooperative traffic does not broadcast its position (Narang, 2016). RPAS would have to be equipped with suitable sensing and safety equipment while flying through air space with dense air traffic (Narang, 2016). This helps to identify non-cooperative traffic, maintain separation and take appropriate evasive actions if the traffic is detected to be closing in dangerously (Narang, 2016). Furthermore, regulatory provisions for licensing, certification and operations are needed to integrate RPAS with manned aircraft (Narang, 2016).

The current lack of extensive standard RPAS airworthiness regulations impacts the development of RPAS and their incorporation into non-segregated airspaces (Maneschijn, et al., 2011). The main hazards affecting RPAS flights can be categorised into:

- The collision between aircraft whether airborne or grounded; and

- The controlled or uncontrolled impact of the RPAS with landscape or objects on the ground. (Clothier, et al., 2015; Gimenes, et al., 2013; Smith, 2015)

Airworthiness regulations are largely affected by the second-mentioned hazard (Clothier, et al., 2015).

### 5.4.1 Regulatory Forms Related to Air Safety

This section outlines the four forms of regulation associated with air safety, that is, formal regulation, co-regulation, industry self-regulation and organisational self-regulation:

a) Formal Regulation - Formal regulations encompass statutes and delegated legislation. In some countries, they also include common law provisions, supplemented by enforcement tools such as civil lawsuits and measures taken by an authorised and resourced government organisation (Clarke & Moses, 2014).

b) Co-Regulation - Co-regulation means a regulatory framework in which the industry has a major contribution to the setting up of enforceable legal requirements (Hepburn, 2006). Such tools are usually known as statutory codes, which helps to differentiate them from ordinary industry codes (Clarke & Moses, 2014). When the requirements are broken down into narrower detail, such as in conventional aviation, the term “Statutory Standards” is more suitable for detailed specifications (Clarke & Moses, 2014). Co-regulation can provide a formal regulatory framework, guided by an organisation that is sufficiently authoritative and well-resourced, to ensure that public needs are fulfilled (Clarke & Moses, 2014). Furthermore, co-regulation can ensure that the Codes and Standards are relevant to the persons and companies bound by them. These include industry participants that are knowledgeable about the technological environment that will be guided by the regulation, and that have significant influence over the contents of the documents (Clarke & Moses, 2014).

However, the process and outcome are potentially compromised, possibly to the level where the regulator is controlled by the parties supposedly bound by that regulator (Clarke & Moses, 2014). In theory, some equilibrium between the two extremes can be reached where stakeholders, excluding the industry, are also involved, and the relevant government lawfully exercises its authority to discard the co-regulatory approach and enforce formal regulation (Clarke & Moses, 2014). Such circumstances can only be satisfied if other stakeholders, mainly the public, are incorporated in negotiations, and both empowered and resourced (Clarke & Moses, 2014). In reality, the concerns of industry participants usually dictate the process and the outcomes (Clarke & Moses, 2014).

c) Industry Self-Regulation - The industry self-regulatory approach comes about when cooperatives of companies impose restrictions on all companies in an industry, or specifically on member companies (Clarke & Moses, 2014). Generally, the motivation behind industry self-regulation is that the key players in the industry anticipate events and opinions that would restrict their business potential. Then a cooperative can develop and execute proactive or reactive courses of action that address the apparent concerns (Clarke & Moses, 2014).

d) Organisational Self-Regulation - There are several motivations for companies to enforce restrictions on their activities (Clarke & Moses, 2014). Some companies may consider actively taking accountability on the perception of business ethics and Corporate Social Responsibility (Clarke & Moses, 2014). Others may acknowledge the strategic importance of dispelling concerns in government, among stakeholders, and among the general public, to avoid damage to reputation, barriers to acceptance and the imposition of regulatory measures (Clarke & Moses, 2014). Several other companies may be affected by such concerns and attempt to address them in a delayed strategic response (Clarke & Moses, 2014). A survey of the major participants in the RPAS industry shows that self-control is not a key control on unrestrained conduct (Clarke & Moses, 2014).

## 5.5 Challenges in the Development of an Airworthiness Regulatory Framework for Remotely Piloted Aircraft Systems

Clothier, et al. (2015) proposed that the development of an effective airworthiness regulatory framework for RPAS should be based on a systematic and risk-based process of:

- "Stipulating the safety strategy and the safety objectives" (Clothier, et al., 2015, p. 1);
- "Developing an airworthiness classification framework" (Clothier, et al., 2015, p. 1); and
- "Identifying a regulatory approach suitable for each airworthiness classification" (Clothier, et al., 2015, p. 1).

This process should be carried out before the development of low-level airworthiness standards and procedures (Clothier, et al., 2015). This section presents some of the challenges associated with the development of an airworthiness regulatory framework for RPAS (Clothier, et al., 2015).

### 5.5.1 The Problem of Diversity

RPAS differ considerably in size, type, complexity, autonomy and capability, and the operations conducted by these systems also vary significantly (Palmer & Clothier, 2013). Consequently, the risks associated with the operations and the efficiency of mitigation measures implemented vary as well. This means that a singular regulatory framework is not suitable for application on all RPAS. A process of adapting airworthiness regulations can be implemented which defines a hazard capacity for a specific RPAS, mission and environment. The variety of RPAS operational models need to be divided into a determinate number of separate airworthiness regulatory classifications and suitable regulations for each category can then be outlined (Clothier, et al., 2015).

### 5.5.2 The Pace of Technology Development

The efficiencies of technological components such as inertial sensors, batteries, computer processors, and communication and propulsion systems are increasing. However, the costs of constituent technologies are consistently declining which leads to smaller RPAS of increasing proficiency and efficiency. The continual progression poses difficulties in the development of airworthiness regulations for the RPAS industry. The need for configuration control contradicts with RPAS manufacturers' objectives to supply competitive products that align with the prevailing technological development (Clothier, et al., 2015).

### 5.5.3 Non-Traditional Participants

Different types of non-conventional participants such as hobbyists, modelling and remote-control enthusiasts and roboticists have access to opportunities that allow them to enter the aerospace field due to the nature of the technology. These participants are involved in all phases of the design, manufacture, maintenance and operation of RPAS but most of them are inexperienced in the engineering, operational techniques and regulations adopted in aviation. Therefore, their approach to RPAS cannot be anticipated to be similar to that of members of the aviation profession. This group regularly challenges the prevailing state of things in the RPAS industry, which is good for flexibility, but it also tends to reduce the stride towards the meeting of minds and settlement (Clothier, et al., 2015).

### 5.5.4 From Aircraft Certification to System Certification

According to the ICAO, the RPAS constitutes an RPA, a C2 Link and RPS. The allocation of safety performance needs to be conducted across all components of the RPAS relative to the level of autonomy of the RPAS of which there is no specific regulatory outline currently available (Clothier, et al., 2013). The process of applying current aircraft performance properties to RPAS poses some challenges to regulators. Different regulations relating specifically to RPAS need to be established.

### 5.5.5 Regulatory Surveillance and Enforcement

There are several factors that pose challenges in enforcing regulations for RPAS, for example, sometimes it is impossible to brand a visible identification number on an RPAS because of its small size. It is also a difficult task for regulators to identify which person is responsible for operating a particular RPAS because the remote piloting of the aircraft is restricted only by the radio frequency range of the communication link being used which can be global coverage if satellite links are in use. The designing, building or purchasing of an RPAS is more stress-free than doing the same for a Commercial Piloted Aircraft (CPA). The barriers of entry into the RPAS industry are not as high as in CPA. The technology of RPAS is easier to access, and so any proposed limitations towards the importation and distribution of RPAS cannot be as effective in the industry. Although the pilot is accountable for the safe operation of their RPAS, verifying the details of any RPAS accident can be challenging.

### 5.5.6 Human System Interaction

The interaction of humans with RPAS can be significantly influenced by various physical, cognitive, social and environmental factors. The term human includes the operational crew, other airspace users, air traffic controllers and maintenance personnel (Fothergill, et al., 2013). So far research into RPAS human system interactions (HSI) has concentrated on the physical and cognitive components, mostly involving the operational roles of the remote crew (Fothergill, et al., 2013). Presently, the social and mental factors specific to RPAS such as detachment, risk-taking behaviour, trust in autonomy and crew interactions are mostly uncharted. The degree of ignorance is even greater with regards to interaction with other airspace users and non-operational personnel such as air traffic controllers. Conventionally airworthiness regulations have focused mainly on the human-machine interface (HMI) and ergonomics aspects in aircraft design which means that flight crewing, training and licensing and organisational factors of HSI are addressed by operational regulations. There is a need to impose an integrated method to the regulation of HSI factors in RPAS by using modern concepts such as human-centred design (Endsley & Jones, 2011).

## 5.6 Remote Operator Certification and Licensing

In most countries, pilots of RPAS can technically start flying by treating their aircraft as a model aircraft, with no training in operation, emergency procedures, proximity rules or even safety (Othman, 2016). Aside from this, most situations require an operator certification or a license (Doumit, 2019). Some RPAS are small and designed to be very easy to operate, especially some of the very small hand-launched RPAS (DeGarmo, 2004). These may require only a minimum of training (DeGarmo, 2004).

Training is usually conducted with the new aircraft itself, so skills are aircraft, controller and software specific (Othman, 2016). An operator certificate is ordinarily issued by intermediaries such as authorised training centres or RPAS manufacturers (Doumit, 2019). It necessitates a basic practical and theoretical training of the pilot (Doumit, 2019). On the contrary, the procedure and requirements to acquire an RPAS pilot license typically involves advanced aeronautical background knowledge and is accorded by national aviation authorities (Doumit, 2019). Differentiating between who should or should not require a license, or what licensing levels might apply, will continue to be a challenge for standards developers and regulators (DeGarmo, 2004). There are two principal requirements for an RPAS operator. The RPAS pilot must be fully competent to control the aircraft and must be able to integrate safely into non-segregated airspace with other aircraft (DeGarmo, 2004). Training is one area of RPAS operations that will continuously improve due to aviation's tradition of sharing bad experiences and lessons learnt to support research and education (Othman, 2016).

## 5.7 Remotely Piloted Aircraft Systems Regulations in South Africa

As stated in previous sections, SACAA is the country's RPAS regulatory agency. Its objectives include management and control of the operations and development of the civil aviation industry, and issuing regulations mandated by the Civil Aviation Act (Library of Congress, 2019). With that goal, the CAA has several roles, such as:

- Establishing and upholding applicable, comprehensible and concise regulatory requirements and technical aviation safety and security standards;
- Establishing effective enforcement policies to ensure compliance with aviation safety and security standards;
- Issuing certificates, licences, registrations and permits; and
- Developing and sanctioning supporting regulations and technical standards through a consultative process with the aviation industry. (Library of Congress, 2019)

The standards, technical guidance material and circulars concerning RPAS used in South Africa were all issued by the CAA on the basis of this authority (Library of Congress, 2019). The 2009 Civil Aviation Act shapes the foundation for regulating RPAS (Library of Congress, 2019). The Ministry of Transportation issued regulations and technical standards on RPAS known as the South Africa Civil Aviation Technical Standards (SA-CATS), and both came into effect on the 1st of July 2015 (Library of Congress, 2019). Furthermore, several aeronautical information circulars (AICs) applicable to RPAS have also been issued. The technical guidance material known as the Technical Guidance Material for RPAS−Part 101 was issued by SACAA in September 2015 (Library of Congress, 2019).

### 5.7.1 Operational Restrictions for Remotely Piloted Aircraft Systems

There are several restrictions concerning commercial, corporate and non-profit operations of RPAS (Library of Congress, 2019). These restrictions include:

1) Public Roads - “Use of public roads as a take-off and landing ground is not permitted unless the operator is a holder of a Remote Operator Certificate (ROC) and such use has been approved by the Director of Civil Aviation and the relevant local authority.” (Library of Congress, 2019)

2) Controlled Airspace - “RPAS may only be piloted in controlled airspace by a holder of a ROC and when approved the Director of Civil Aviation. The Director may issue such approval only in a visual meteorological condition (VMC) in an airfield traffic zone (ATZ) and control traffic region (CTR) below 400 ft (121.92 m)” (Library of Congress, 2019). Also, for an RPAS to be used in an operation within an ATZ or CTR, it must:

   - “Be equipped with a Mode C or S transponder capable of displaying the unique squawk code issued to them, unless otherwise exempted by the Director of Civil Aviation and/or the applicable Air Traffic Service Unit (ATSU) or Central Airspace Management Unit (CAMU) upon lodging an application for a Flexible Use of Airspace (FUA)” (Library of Congress, 2019);
   - “Be equipped with an altimeter, corrected for ambient pressure (QNH), capable of displaying the RPAS platform’s altitude above ground level to the operator on the GCS” (Library of Congress, 2019);
   - “Be equipped with a functioning strobe light or lights, fitted in such a way that the strobe lights are visible from both below and above the RPAS platform, at all azimuth angles” (Library of Congress, 2019); and
   - “In the case of an aeroplane, be equipped with functioning navigation lights” (Library of Congress, 2019).

   “All of the stated components must be serviceable and functioning for the duration of the operation and the failure of one of them would result in the immediate stoppage of the operation. In addition to the listed technical requirements imposed on the RPAS, operation in an ATZ or CTR entails a ROC holder to satisfy specific operational requirements.” (Library of Congress, 2019)

3) Objects or Substances - “The Civil Aviation Regulations prohibit the use of an RPAS for releasing, dispensing, dropping, delivering, or deploying any object or substance unless it is carried out by a ROC holder and with the approval of the Director of Civil Aviation.” (Library of Congress, 2019)

4) General Restrictions - This category comprises various restrictions. For case in point, operators are restricted from using RPAS to tow other aircraft, perform aerial or aerobatic displays, or for the purpose of flying them in formation or swarm. Furthermore, unless executed by a ROC holder and with the approval of the Director of Civil Aviation, an RPAS operator is barred from flying an RPAS:

   - Beyond 400 feet (121.92 m) above ground;
   - Within a 10 kilometre radius of an airfield;
   - Within restricted or prohibited airspace; or
   - Near or above sensitive areas, including a nuclear power plant, prison, police station, crime scene, or court. (Library of Congress, 2019; Stopforth, 2017).

5) Beyond Visual Line of Sight (BVLOS) - “A BVLOS operation is permitted only for ROC holders approved for such operations by the Director of Civil Aviation. The Director may approve such operations only if the operator meets specific requirements, which vary depending on whether the operation is within or outside of controlled airspace.” If the proposed operation is outside controlled airspace, the operator must demonstrate compliance with the following technical requirements:

   - The RPAS will only be operated using command inputs;
   - The operator has met the requirements prescribed in Technical Standard 101.02.2 concerning the approval and registration of commercial, corporate and non-profit RPAS operations;

- That the RPAS can stay clear from obstacles and any other hazards and can take appropriate action to execute collision avoidance from such obstacles or other aircraft where necessary. This ability shall be applicable for normal and lost/degraded C2 links unless:

  ~ "The area is void of other air traffic" (Library of Congress, 2019); or

  ~ "The operation occurs in specifically delimited or segregated airspace" (Library of Congress, 2019); or

  ~ "Any other mitigation is in place to avoid other aircraft, obstacles or any hazards" (Library of Congress, 2019).

- The C2 data link frequency to be used for data link is considered suitable by the Director of Civil Aviation; and
- The C2 performance requirements as specified in Technical Standard 101.05.8 (C2 link operational requirements) are acceptable to the Director of Civil Aviation; and
- The operator must demonstrate operational capabilities, including the ability to command the RPA to follow a planned pathway or collection of way-point inputs.

For operations within a restricted airspace, the operator must satisfy additional technical requirements. (Library of Congress, 2019)

6) Operation in Vicinity of People, Property, or Public Roads - Only a ROC holder, with the approval of the Director of Civil Aviation, is permitted to operate an RPAS directly above or a lateral distance of 50 m from any person and. The same regulation relates to the operation of an RPAS in the vicinity of structures or buildings. Nonetheless, in this case, it is also possible to operate an RPAS by just obtaining the permission of the owner of the structure or building at issue. Operating an RPAS along the length of a public road or at a distance of less

than 50 m from a public road in use is only permitted for a ROC holder when approved by the Director of Civil Aviation. (Library of Congress, 2019)

7) Radio Communication Requirements - All operations of RPAS (VLOS, restricted VLOS, extended VLOS and beyond VLOS) must be conducted within a radio line of sight (RLOS). An RLOS is a direct, electronic, point-to-point contact between a transmitter and receiver. The regulations require that "the air-band radio shall have the required output and be configured in such a way that the range, strength of transmission and quality of communication extends beyond the furthest likely position of the RPA from the pilot" (Library of Congress, 2019). Further requirements may be imposed contingent on the specific operation under consideration. (Library of Congress, 2019)

### 5.7.2 Remote Pilot Licensing

South Africa was the first country in the world to establish regulations for the training and issuing of Remote Pilot Licenses (RPL) which are accredited by ICAO, on the 1st of July 2015 (Stopforth, 2017). A valid RPL is required for commercial, corporate and non-profit operations of an RPAS (Library of Congress, 2019). There are three classes of an RPL which are:

- RPL (Aeroplane);
- RPL (Helicopter); and
- RPL (Multi-rotor). (Library of Congress, 2019)

An RPL is issued for a two-year term and can be renewed for another term after the holder undertakes a "revalidation check" (Library of Congress, 2019). Several requirements should be met to obtain an RPL and they include the following:

- "An applicant should at least 18 years of age" (Library of Congress, 2019);
- "Applicants must have valid medical assessments" (Library of Congress, 2019);

- “An aviation training organisation (ATO) for training must be identified” (Library of Congress, 2019);
- “Foreign theoretical training will be approved and validated” (Library of Congress, 2019);
- “Only successful completion will be accepted” (Library of Congress, 2019);
- “Applicants must pass the RPL practical assessment” (Library of Congress, 2019);
- “Applicants must also pass Radiotelephony Examination” (Library of Congress, 2019);
- “Applicants must attain English Language Proficiency (ELP) level 4 or higher” (Library of Congress, 2019); and
- “All applications must be put forward to the CAA” (Library of Congress, 2019).

There are five main classes of RPAS considered when rating RPLs for commercial purposes, as listed in Table 5.1 (Stopforth, 2017). Each class is determined by the LOS, the amount of energy at impact (Impact Velocity) should a collision occur, the height above ground that the RPAS operates best and the maximum take-off mass (MTOM) (Stopforth, 2017). The different types of LOS categories include VLOS, restricted VLOS (RVLOS), extended VLOS (EVLOS) and beyond VLOS (BVLOS) (Stopforth, 2017).

*Table 5.1: Different RPAS Classifications (Stopforth, 2017)*

<table>
<tr><th>Class</th><th colspan="4">RPAS Classification</th></tr>
<tr><td></td><td>Line-of-sight</td><td>Energy (kJ) at impact</td><td>Height (ft) above the surface</td><td>MTOM (kg)</td></tr>
<tr><td>1A</td><td>RVLOS/VLOS</td><td>E < 15</td><td rowspan="4">h < 400</td><td>m < 1.5</td></tr>
<tr><td>1B</td><td>RVLOS/VLOS/EVLOS</td><td>E < 15</td><td>m < 7</td></tr>
<tr><td>1C</td><td>VLOS/EVLOS</td><td>E < 34</td><td rowspan="2">m < 20</td></tr>
<tr><td>2A</td><td>VLOS/EVLOS</td><td>E > 34</td></tr>
<tr><td>2B</td><td colspan="4">Experimental/Research</td></tr>
<tr><td>3A</td><td>BVLOS</td><td>E > 34</td><td>h < 400</td><td rowspan="3">m < 150</td></tr>
<tr><td>3B</td><td>VLOS/EVLOS</td><td>Any</td><td rowspan="2">h > 400</td></tr>
<tr><td>4A</td><td>BVLOS</td><td>Any</td></tr>
<tr><td>4B</td><td colspan="4">Any</td></tr>
<tr><td>5</td><td colspan="4">Reserved</td></tr>
</table>

Rated pilots are allowed to fly Class 1 and Class 2 category aircraft under the South African Civil Aviation Regulations (CARs) and Civil Aviation Technical Standards (CATS) of Part 101 of the aviation law (Stopforth, 2017). Other classes of RPAS and any flying that is not VLOS, can be done only after permission has been obtained from the Director of Civil Aviation by letter of exemption (Stopforth, 2017). These letters of exemption need to be justified by a safety case and inspection of the RPAS and supporting equipment. A demonstration is usually required of the applicant to prove that their safety case and standards are met completely (Stopforth, 2017). A stated before, there are currently three types of RPAS aircraft ratings available, that is, aeroplane, multi-rotor and helicopter (Stopforth, 2017). The latter is not popular at the moment due to the dangers of much larger and heavier spinning rotor blades as well as a high level of skill required to fly a helicopter (Stopforth, 2017). To date, all these ratings consider the same theoretical training (Stopforth, 2017).

### 5.7.3 Remote Pilot Operator Certificate

An RPAS operator certificate (ROC) is also required for commercial, corporate and non-profit operations of an RPA (Library of Congress, 2019). For a commercial operator, obtaining an air service license under the relevant law is one of the conditions of getting a ROC (Library of Congress, 2019). The ROC application procedure follows the ICAO five-step process, that is, pre-application, formal application, document evaluation, demonstration and inspection, and certification (Library of Congress, 2019). A ROC is issued for a one-year term at the end of which the holder of the certificate must apply for renewal (Library of Congress, 2019).

A ROC holder has various responsibilities (Library of Congress, 2019). The ROC holder is required to develop an operation manual to be approved by the Director of Civil Aviation (Library of Congress, 2019). The manual must include the "type and scope of operations, including the manner in which each type of RPAS and operation will be safely conducted," (Library of Congress, 2019) and any change to the type or scope of operations requires the prior approval of the Director (Library of Congress, 2019). The holder must also "establish a safety management system commensurate with the size of the organisation or entity and the complexity of its operations" (Library of Congress, 2019). This must include:

- A process to identify actual and potential safety hazards and assess the associated risks;
- A process to develop and implement mitigation measures to maintain a suitable degree of safety; and
- Provision for continuous and periodic evaluation of the suitability and effectiveness of safety management activities. (Library of Congress, 2019)

Additionally, the ROC holder is required to employ various security measures, including conducting background checks and regular criminal record checks on personnel that work with RPAS (Library of Congress, 2019). The holder must also always have sufficient third-party liability insurance (Library of Congress, 2019).

## 5.8 Conclusion

This chapter detailed the regulatory framework for the effective adoption of RPAS in mining operations, particularly in South Africa. The guidelines consider both operational regulations and airworthiness regulations.

# CHAPTER 6. RESEARCH FINDINGS AND ANALYSIS

## 6.1 Introduction

This chapter details the analysis of the results extracted from various field research activities comprising surveying with RPAS technology and at least one other alternative conventional surveying method. The surveying activities covered volumetric calculations and topographical mapping in different applications. The analysis of the data is with regards to costs incurred, the time taken to complete each survey and the relative accuracy of RPAS in comparison to conventional surveying methods. A SWOT analysis of surveying using RPAS, total station, RTK GNSS and TLS is also presented in this chapter.

## 6.2 Comparison of RPAS versus Conventional Surveying Methods

### 6.2.1 Comparison of Costs

The costs comparison analysis is based on data from field experiments as detailed in Appendix A. The specific sources are stated for each comparison. There are various currencies (Euros, US Dollars, Swiss Francs) which are used in this analysis but the importance is on the percentage figures. Equation 7-1 is used to calculate the survey costs reduction.

$$Survey\ Costs\ Reduction\ (\%) =$$

$$\frac{Conventional\ \ Method\ Survey\ Costs - RPAS\ Survey\ Costs}{Conventional\ Method\ Survey\ Costs} \times 100$$

***Equation 6-1***

The data and consequently the analysis of RPAS survey costs versus surveying using a total station in this research only encompasses topographic mapping. The topographic mapping data was extracted from El Meouche, et al. (2016).

RPAS versus Total Station: Topographic Mapping Data

From El Meouche, et al. (2016);

| | | |
|---|---|---|
| Total Station Survey Costs | = | €2 000 |
| RPAS Survey Costs | = | €1 200 |

$$\mathit{Survey\ Costs\ Reduction}\ (\%) = \frac{€2\ 000 - €1\ 200}{€2\ 000} \times 100 = 40\%$$

Figure 6.1 shows the costs comparison between the RPAS survey and conventional surveying using a total station.

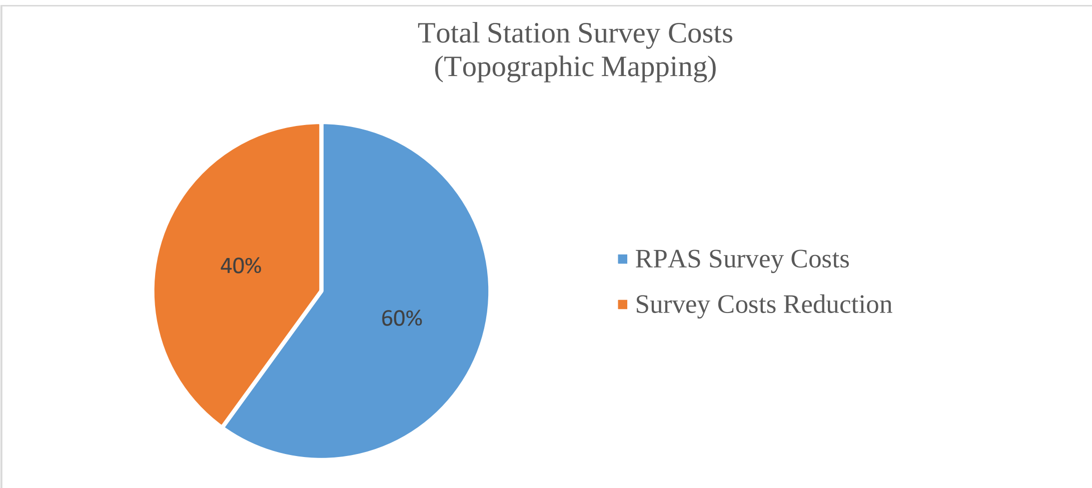


*Figure 6.1: RPAS Survey Costs versus Total Station Survey Costs (El Meouche, et al., 2016)*

There was a 40% cost reduction when total station topographic mapping was substituted with RPAS topographic mapping. The data and the analysis of RPAS survey costs versus surveying using RTK GNSS in this research encompasses topographic mapping and volumetric calculations. The topographic mapping data was extracted from Fitzpatrick (2016) and Volkmann (2017). The volumetric calculation data was extracted from Fitzpatrick (2016).

RPAS versus RTK GNSS: Topographic Mapping Data

1) From Fitzpatrick (2016);

RTK GNSS Survey Costs = US$3 200

RPAS Survey Costs = US$1 944

$$Survey\ Costs\ Reduction\ (\%) = \frac{\$3\ 200 - \$1\ 944}{\$3\ 200} \times 100 = 39\%$$

2) From Volkmann (2017);

RTK GNSS Survey Costs = US$9 984 + US$960 = US$10 944

RPAS Survey Costs = US$1 440 + US$2 520 = US$3 960

$$Survey\ Costs\ Reduction\ (\%) = \frac{\$10\ 944 - \$3\ 960}{\$10\ 944} \times 100 = 64\%$$

3) From Volkmann (2017);

RTK GNSS Survey Costs = US$3 120 + US$90 = US$3 210

RPAS Survey Costs = US$277.20 + US$216 = US$493.20

$$Survey\ Costs\ Reduction\ (\%) = \frac{\$3\ 210 - \$493.20}{\$3\ 210} \times 100 = 85\%$$

Therefore;

$$Average\ Survey\ Costs\ Reduction\ (\%) = \frac{39\% + 64\% + 85\%}{3} = 63\%$$

RPAS versus RTK GNSS: Volumetric Calculation Data

From Fitzpatrick (2016);

RTK GNSS Survey Costs = US$2 235

RPAS Survey Costs = US$1 316.50

$$Survey\ Costs\ Reduction\ (\%) = \frac{\$2\ 235 - \$1\ 316.50}{\$2\ 235} \times 100 = 41\%$$

Figure 6.2 shows the costs comparison between an RPAS survey and surveying using RTK GNSS for topographic mapping and volumetric calculation.

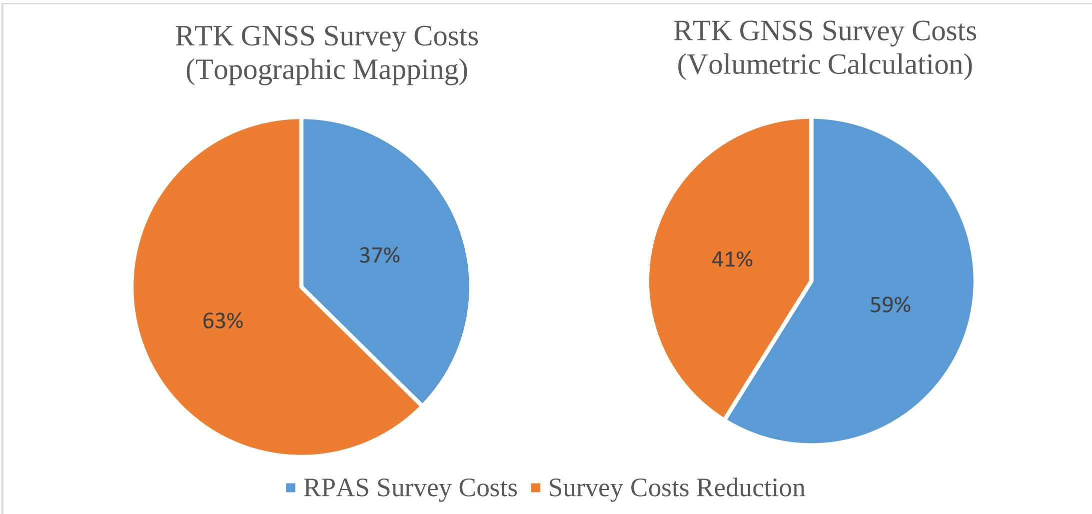


*Figure 6.2: RPAS Survey Costs versus RTK GNSS Survey Costs (Fitzpatrick, 2016; Volkmann, 2017).*

There was a 63% cost reduction when RTK GNSS topographic mapping was substituted with RPAS topographic mapping. There was a 41% cost reduction when RTK GNSS was substituted with RPAS for volumetric calculations. The data and the analysis of RPAS survey costs versus surveying using TLS in this research encompasses topographic mapping and volumetric calculations. The topographic mapping data was extracted from Fitzpatrick (2016). The volumetric calculation data was extracted from Weber and Lerch (2018).

<u>RPAS versus TLS: Topographic Mapping Data</u>

From Fitzpatrick (2016);

| | | |
|---|---|---|
| TLS Survey Costs | = | US$4 600 |
| RPAS Survey Costs | = | US$2 450 |

$$Survey\ Costs\ Reduction\ (\%) = \frac{\$4\ 600 - \$2\ 450}{\$4\ 600} \times 100 = 47\%$$

RPAS versus TLS: Volumetric Calculation Data

From Weber and Lerch (2018);

| | | |
|---|---|---|
| TLS Survey Costs | = | 80 000 CHF |
| RPAS Survey Costs | = | 30 000 CHF |

$$\mathit{Survey\ Costs\ Reduction}\ (\%) = \frac{80\ 000\ CHF - 30\ 000\ CHF}{80\ 000\ CHF} \times 100 = 63\%$$

Figure 6.3 shows the costs comparison between the RPAS survey and surveying using TLS for topographic mapping and volumetric calculation.

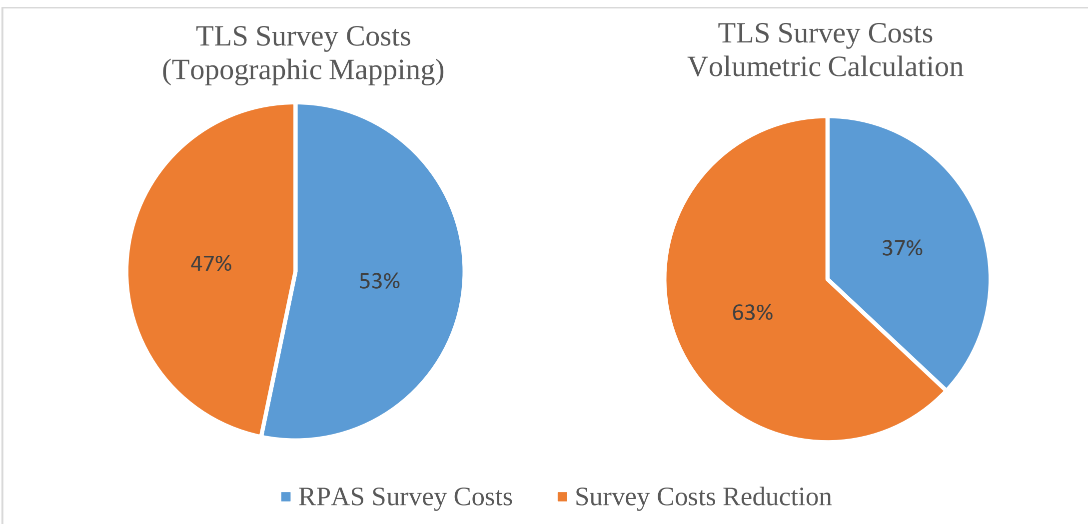


*Figure 6.3: RPAS Survey Costs versus TLS Survey Costs (Fitzpatrick, 2016; Weber & Lerch; 2018)*

There was a 47% cost reduction when TLS topographic mapping was substituted with RPAS topographic mapping. There was a 63% cost reduction when TLS was substituted with RPAS for volumetric calculations. The data and the analysis of RPAS survey costs versus surveying using manned aircraft in this research only encompasses topographic mapping. The topographic mapping data was extracted from Fitzpatrick (2016) and Matese, et al. (2015).

RPAS versus Manned Aircraft: Topographic Mapping Data

1) From Fitzpatrick (2016);

| | | |
|---|---|---|
| Manned Aircraft Survey Costs | = | US$5 000 |
| RPAS Survey Costs | = | US$1 960 |

$$Survey\ Costs\ Reduction\ (\%) = \frac{\$5\ 000 - \$1\ 960}{\$5\ 000} \times 100 = 61\%$$

2) From Matese, et al. (2015);

| | | | | |
|---|---|---|---|---|
| Manned Aircraft Survey Costs | = | €2 200 + €100 + €150 | = | €2 450 |
| RPAS Survey Costs | = | €1 500 + €500 + €200 | = | €2 200 |

$$Survey\ Costs\ Reduction\ (\%) = \frac{€2\ 450 - €2\ 200}{€2\ 450} \times 100 = 10\%$$

3) From Matese, et al. (2015);

| | | | | |
|---|---|---|---|---|
| Manned Aircraft Survey Costs | = | €3 000 + €500 + €300 | = | €3 800 |
| RPAS Survey Costs | = | €4 000 + €1 000 + €300 | = | €5 300 |

$$Survey\ Costs\ Reduction\ (\%) = \frac{€3\ 800 - €5\ 300}{€3\ 800} \times 100 = -39\%$$

Therefore;

$$Average\ Survey\ Costs\ Reduction\ (\%) = \frac{61\% + 10\% + (-39\%)}{3} = 11\%$$

Figure 6.4 shows the costs comparison between the RPAS survey and surveying using manned aircraft for topographic mapping.

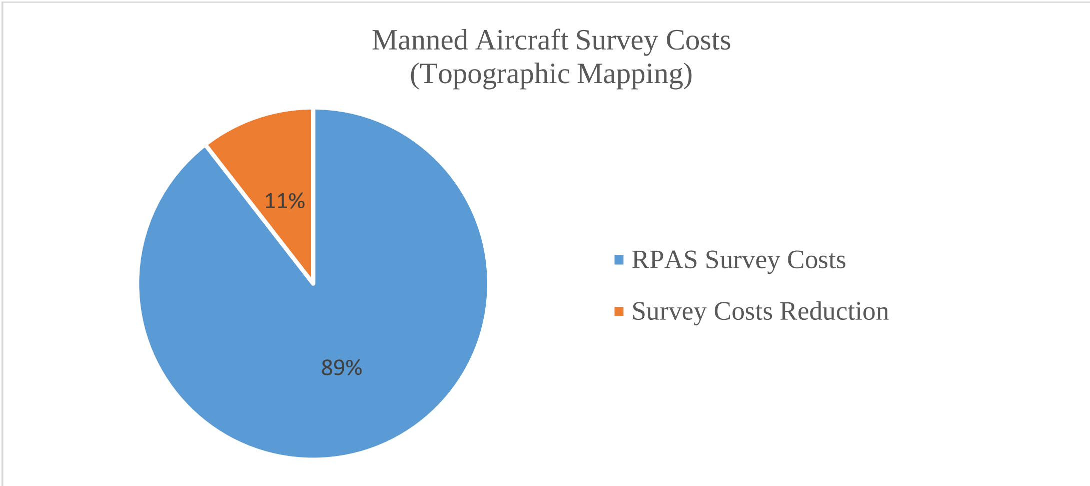


*Figure 6.4: RPAS Survey Costs versus Manned Aircraft Survey Costs (Fitzpatrick, 2016; Matese, et al., 2015)*

There was an 11% cost reduction when Manned Aircraft was substituted with RPAS for topographic mapping. The cost/benefit analysis for this comparison was calculated based on a service that is offered by a third party, thus not including the investment cost of purchasing an aerial platform or an RPAS, instrumentation, or maintenance.

### 6.2.2 Comparison of Time Taken

The time comparison analysis is based on data from field experiments as detailed in Appendix B. The specific sources are stated for each comparison. Equation 7-2 is used to calculate survey time reduction.

$$Survey\ Time\ Reduction\ (\%) =$$

$$\frac{Conventional\ \ Method\ Survey\ Time - RPAS\ Survey\ Time}{Conventional\ Method\ Survey\ Time} \times 100$$

***Equation 6-2***

The data and consequently the analysis of tie taken to complete an RPAS survey versus time taken to survey using a total station in this research only encompasses topographic mapping. The topographic mapping data was extracted from Carrera-Hernandez, et al. (2020), El-Ashmawy (2015), El Meouche, et al. (2016), Eyoh, et al. (2019), Peterman (n.d.) and Yeh, et al. (2018).

RPAS versus Total Station: Topographic Mapping Data

1) From Carrera-Hernandez, et al. (2020);

Total Station Survey Time Taken = 7 days × 24 hrs = 168 hrs

RPAS Survey Time Taken = 4 hrs

$$Survey\ Time\ Reduction\ (\%) = \frac{168\ hrs - 4\ hrs}{168\ hrs} \times 100 = 98\%$$

2) From El-Ashmawy (2015);

Total Station Survey Time Taken = 1 day × 24 hrs × 60 mins = 1 440 mins

RPAS Survey Time Taken = 40 mins

$$Survey\ Time\ Reduction\ (\%) = \frac{1\ 440\ mins - 40\ mins}{1\ 440\ mins} \times 100 = 97\%$$

3) From El Meouche, et al. (2016);

Total Station Survey Time Taken = 7 hrs

RPAS Survey Time Taken = 4 hrs

$$Survey\ Time\ Reduction\ (\%) = \frac{7\ hrs - 4\ hrs}{7\ hrs} \times 100 = 43\%$$

4) From Eyoh, et al. (2019);

Total Station Survey Time Taken = 12 hrs × 60 mins = 720 mins

RPAS Survey Time Taken = 30 mins

$$Survey\ Time\ Reduction\ (\%) = \frac{720\ mins - 30\ mins}{720\ mins} \times 100 = 96\%$$

5) From Peterman (n.d.);

Total Station Survey Time Taken = 4 hrs + 2 hrs = 6 hrs

RPAS Survey Time Taken = 2 hrs

$$Survey\ Time\ Reduction\ (\%) = \frac{6\ hrs - 2\ hrs}{6\ hrs} \times 100 = 67\%$$

6) From Yeh, et al. (2018);

Total Station Survey Time Taken = 3 hrs × 60 mins = 180 mins

RPAS Survey Time Taken = 20 mins

$$Survey\ Time\ Reduction\ (\%) = \frac{180\ mins - 20\ mins}{180\ mins} \times 100 = 89\%$$

Therefore;

$$Average\ Survey\ Time\ Reduction\ (\%) = \frac{98\% + 97\% + 43\% + 96\% + 67\% + 89\%}{6}$$

$$= 82\%$$

Figure 6.5 shows the comparison between the time taken to complete an RPAS survey and time taken to survey using a total station for topographic mapping.

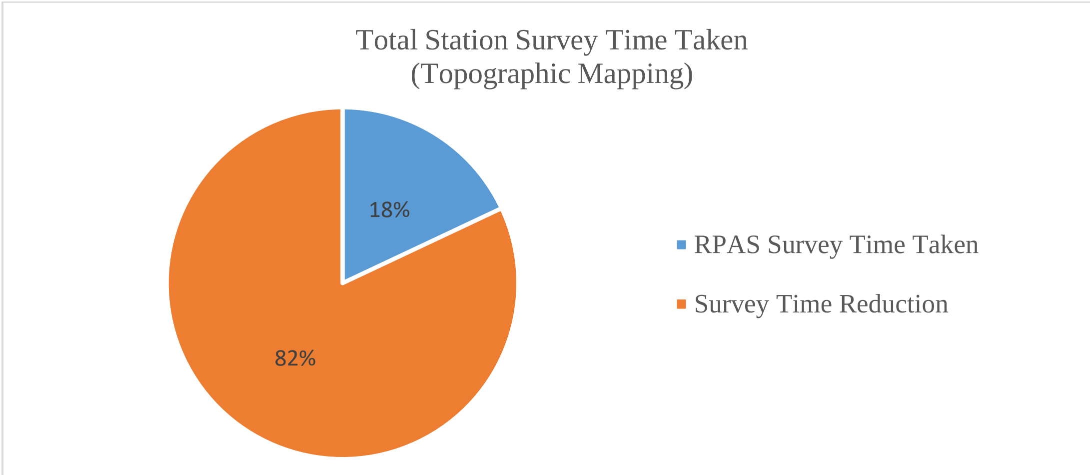


*Figure 6.5: RPAS Survey Time Taken versus Total Station Survey Time Taken (Carrera-Hernandez, et al., 2020; El-Ashmawy, 2015; El Meouche, et al., 2016; Eyoh, et al., 2019; Peterman, n.d.; Yeh, et al., 2018)*

The RPAS topographic mapping method completed the project in 18% of the turn-around time attained when using a total station. The data and the analysis of time taken to complete an RPAS survey versus time taken to survey using RTK GNSS in this research encompasses topographic mapping and volumetric calculations. The topographic mapping data was extracted from Albright (2019), El-Ashmawy (2015), Fitzpatrick (2016), Mora, et al. (2019) and Volkmann (2017). The volumetric calculation data was extracted from Fitzpatrick (2016).

<u>RPAS versus RTK GNSS: Topographic Mapping Data</u>

1) From Albright (2019);

| | | | | |
|---|---|---|---|---|
| RTK GNSS Survey Time Taken | = | 10 hrs + 11 hrs | = | 21 hrs |
| RPAS Survey Time Taken | = | 5 hrs + 11 hrs + 15 hrs | = | 31 hrs |

$$Survey\ Time\ Reduction\ (\%) = \frac{21\ hrs - 31\ hrs}{21\ hrs} \times 100 = -48\%$$

2) From El-Ashmawy (2015);

RTK GNSS Survey Time Taken = 40 mins

RPAS Survey Time Taken = 40 mins

$$Survey\ Time\ Reduction\ (\%) = \frac{40\ mins - 40\ mins}{40\ mins} \times 100 = 0\%$$

3) From Fitzpatrick (2016);

RTK GNSS Survey Time Taken = 16 hrs

RPAS Survey Time Taken = 8 hrs

$$Survey\ Time\ Reduction\ (\%) = \frac{16\ hrs - 8\ hrs}{16\ hrs} \times 100 = 50\%$$

4) From Mora, et al. (2019);

RTK GNSS Survey Time Taken = 2 hrs × 60 mins × 60 sec = 7 200 sec

RPAS Survey Time Taken = (5 mins × 60 sec) + 46 sec = 346 sec

$$Survey\ Time\ Reduction\ (\%) = \frac{7\ 200\ sec - 346\ sec}{7\ 200\ sec} \times 100 = 95\%$$

5) From Volkmann (2017);

RTK GNSS Survey Time Taken = 20.8 days + 4 days = 24.8 days

RPAS Survey Time Taken = 3 days + 10.5 days = 13.5 days

$$Survey\ Time\ Reduction\ (\%) = \frac{24.8\ days - 13.5\ days}{24.8\ days} \times 100 = 46\%$$

6) From Volkmann (2017);

RTK GNSS Survey Time Taken = (52 hrs + 3 hrs) × 60 mins = 3 300 mins

RPAS Survey Time Taken = [(4 hrs + 7 hrs + 12 hrs) × 60 mins] + 37 mins + 12 mins = 1 429 mins

$$Survey\ Time\ Reduction\ (\%) = \frac{3\ 300\ mins - 1\ 429\ mins}{3\ 300\ mins} \times 100 = 57\%$$

Therefore;

$$\text{Average Survey Time Reduction (\%)} = \frac{(-48\%) + 0\% + 50\% + 95\% + 46\% + 57\%}{6}$$

= 33%

<u>RPAS versus RTK GNSS: Volumetric Calculation Data</u>

From Fitzpatrick (2016);

RTK GNSS Survey Time Taken = 11 hrs

RPAS Survey Time Taken = 6 hrs

$$\text{Survey Time Reduction (\%)} = \frac{11\ hrs - 6\ hrs}{11\ hrs} \times 100 = 45\%$$

Figure 6.6 shows the comparison between the time taken to complete an RPAS survey and the time taken to survey using RTK GNSS for topographic mapping and volumetric calculation.

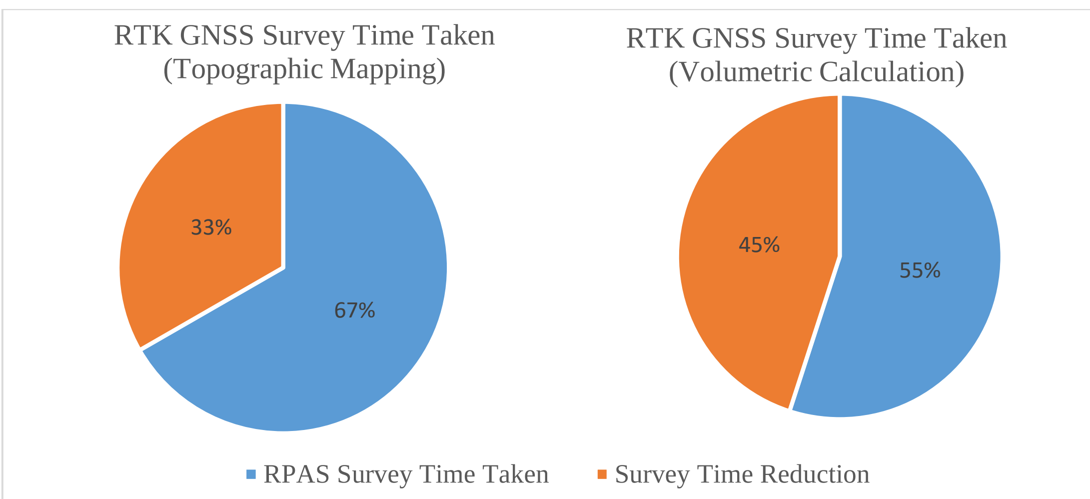


*Figure 6.6: Time required to complete an RPAS Survey versus RTK GNSS Survey (Albright, 2019; El-Ashmawy, 2015; Fitzpatrick, 2016; Mora, et al., 2019; Volkmann, 2017)*

The RPAS topographic mapping method completed the project in 67% of the turn-around time when compared to using RTK GNSS. The RPAS survey method completes volumetric calculations in 55% of the turn-around time when compared to using RTK GNSS. The data and the analysis of time taken to complete an RPAS survey versus time taken to survey using TLS in this research encompasses topographic mapping and volumetric calculations. The topographic mapping data was extracted from El-Ashmawy (2015) and Fitzpatrick (2016). The volumetric calculation data was extracted from Arango and Morales (2015), Tucci, et al. (2019) and Weber and Lerch (2018).

RPAS versus TLS: Topographic Mapping Data

1) From El-Ashmawy (2015);

   TLS Survey Time Taken = 50 mins

   RPAS Survey Time Taken = 40 mins

$$Survey\ Time\ Reduction\ (\%) = \frac{50\ mins - 40\ mins}{50\ mins} \times 100 = 20\%$$

2) From Fitzpatrick (2016);

   TLS Survey Time Taken = 10 hrs

   RPAS Survey Time Taken = 7 hrs

$$Survey\ Time\ Reduction\ (\%) = \frac{10\ hrs - 7\ hrs}{10\ hrs} \times 100 = 30\%$$

Therefore;

$$Average\ Survey\ Time\ Reduction\ (\%) = \frac{20\% + 30\%}{2} = 25\%$$

RPAS versus TLS: Volumetric Calculation Data

1) From Arango and Morales (2015);

   TLS Survey Time Taken = (3 hrs × 60 mins) + 5 mins = 185 mins

   RPAS Survey Time Taken = 35 mins

$$Survey\ Time\ Reduction\ (\%) = \frac{185\ mins - 35\ mins}{185\ mins} \times 100 = 81\%$$

2) From Tucci, et al. (2019);

TLS Survey Time Taken = 3 hrs

RPAS Survey Time Taken = 2 hrs

$$Survey\ Time\ Reduction\ (\%) = \frac{3\ hrs - 2\ hrs}{3\ hrs} \times 100 = 33\%$$

3) From Weber and Lerch (2018);

TLS Survey Time Taken = (3 hrs × 60 mins) + 55 mins = 235 mins

RPAS Survey Time Taken = 20 mins

$$Survey\ Time\ Reduction\ (\%) = \frac{235\ mins - 20 mins}{235\ mins} \times 100 = 91\%$$

Therefore;

$$Average\ Survey\ Time\ Reduction\ (\%) = \frac{81\% + 33\% + 91\%}{3} = 68\%$$

Figure 6.7 shows the comparison between the time taken to complete an RPAS survey and time taken to survey using TLS for topographic mapping and volumetric calculation.

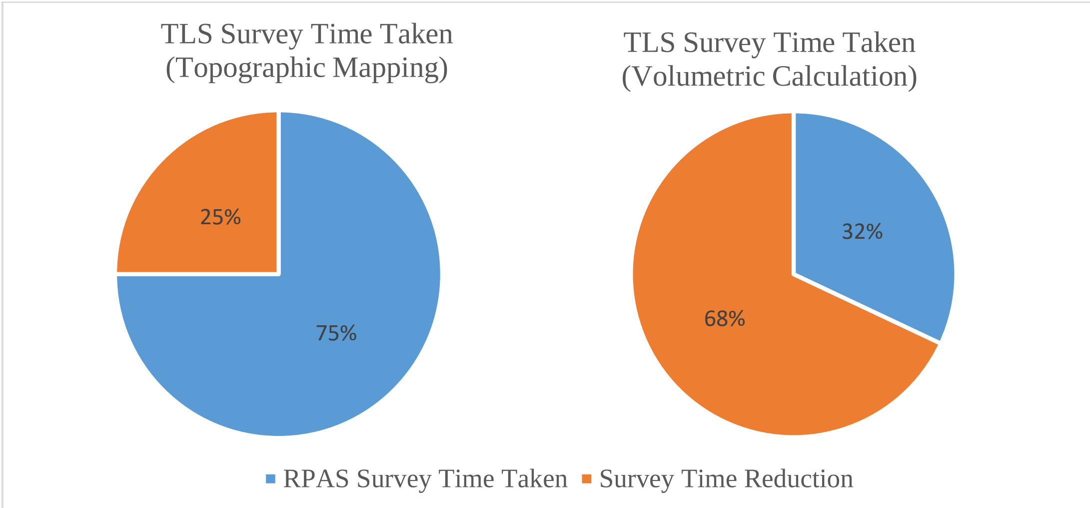


*Figure 6.7: RPAS Survey Time Taken versus TLS Survey Time Taken (Arango & Morales, 2015; El-Ashmawy, 2015; Fitzpatrick, 2016; Tucci, et al., 2019; Weber & Lerch, 2018)*

The RPAS topographic mapping method completed the project in 75% of the turn-around time compared to when using TLS. The RPAS survey method completes volumetric calculations in 32% of the turn-around time attained when using RTK GNSS.

### 6.2.3 Comparison of Accuracy

The accuracy comparison analysis is based on data from field experiments as detailed in Appendix C. For best results, there needs to be a set of reference coordinates that are used for comparison with geospatial coordinates obtained from RPAS and conventional surveying methods. Such data could only be obtained for comparison of:

- RPAS survey versus surveying using a total station for volumetric calculations;
- RPAS survey versus surveying using a total station for topographic mapping; and
- RPAS survey versus surveying using TLS for topographic mapping.

Some field studies listed in Appendix D do not have independent reference control points, that is, for comparison of RPAS survey accuracy versus RTK GNSS and manned aircraft. Therefore, analysis in such circumstances is made from how RPAS survey results deviate from those obtained from conventional surveying methods.

Appendix C shows that RPAS is more accurate than using a total station for volumetric calculations. This can be attributed to a point cloud having a large number of points as compared to a typical total station survey. RPAS has a variance of -0.6% and the total station has a variance of 2.88% from the actual reference volume. For topographic mapping, results show that RPAS has a lower horizontal accuracy but greater 3D accuracy than a total station, using RTK GNSS reference control points. In a 1.1km route survey, RPAS had 0.25 m horizontal accuracy and 0.30 m 3D accuracy, whereas the total station had 0.24 m horizontal accuracy and 0.33 m 3D accuracy. RPAS topographic mapping results had a 0.03 m difference between contour lines with manned aircraft. Therefore, topographic mapping using RPAS is as accurate as using manned aircraft.

Volumetric calculations using RPAS have slight variations from results obtained from RTK GNSS. In one field test, RPAS had a volume variance of 0.09% from RTK GNSS results and in another independent field test, the volume difference was -0.6%. Therefore, it can be deduced that volumetric calculation using RPAS was as accurate as using RTK GNSS. In topographic mapping, results in Appendix D show small variances between RPAS results and RTK GNSS with a mean 3D error of not more than 0.075 m in survey areas ranging from 17 000 $m^2$ to 93 077.7 $m^2$. RPAS volumetric calculations show a small offset from the results obtained from a TLS survey. The RPAS results had a standard deviation of 0.052 m at a 100 m altitude and 0.059 m at a 150 m altitude. In topographic mapping, compiled data shows that RPAS produces more accurate results than results obtained using TLS. RPAS had an average error of not more than 0.075 m from independent reference control points whereas TLS had an average error of 0.647 m.

## 6.3 Strengths, Weaknesses, Opportunities and Threats Analysis of Remotely Piloted Aircraft Systems

The deployment of RPAS technology on mining operations can be beneficial, however, it is imperative to consider that there exist other technologies that could offer similar or more favourable solutions. The implementation of each surveying method is compared in this section concerning their associated strengths, weaknesses, opportunities and threats. The benefits of RPAS should be greater than the risks and should also be competitive with conventional surveying methods to help dispel the scepticism around the deployment and integration of RPAS on mining operations. It is also important to note that the utilisation of RPAS technology in mining operations is not free from risk. A fair evaluation can only be reached when the disadvantages of RPAS have also been comprehensively investigated and documented.

<u>Strengths</u>

The strengths associated with utilising RPAS on mining operations are as follows:

- *Extensive spatial coverage* - RPAS can fly over and allow for the surveying of extensive areas (Klemas, 2015; New Zealand Ministry of Transport, 2019, Patikova, 2004). A ground-based sensor can record information from a fixed geographic location continuously, whereas RPAS provides a more favourable vantage point of aerial remote sensing with varying position and orientation (Doumit, 2019; Gallacher, 2016; Klemas, 2015).
- *Less time consuming* - RPAS have the capability for fast data acquisition while transmitting the image, video and orientation data in real-time to the GCS (Doumit, 2019; New Zealand Ministry of Transport, 2019). RPAS allows for the quick availability of raw data (Hardin & Hardin, 2010; Niethammer, et al., 2012; Rango & Laliberte, 2010) and timeous processing of the data (Patikova, 2004). The short turn-around times and real-time telemetry capabilities make RPAS the favourable option for 3D mapping rather than using ground-based conventional

survey methods (Deepika & Lavanya, 2015; Gutierrez & Searcy, 2016; Micklethwaite, 2018).

- *More cost-effective* - Utilisation of RPAS is more cost-effective than conventional survey methods (New Zealand Ministry of Transport, 2019; Micklethwaite, 2018). RPAS offer a viable alternative to conventional platforms for acquiring high-resolution remote-sensing data at a lower cost (Klemas, 2015). RPAS have lower acquisition costs (Patikova, 2004) and operating costs than manned aircraft due to their reduced scale, complexity and lesser infrastructure requirements, for example, runways and refuelling stations (Doumit, 2019; New Zealand Ministry of Transport, 2019; Micklethwaite, 2018; Odido & Madara, 2013). The direct cost savings and benefits of RPAS technology over manned aircraft extend to the environment through reduced aircraft emissions (Othman, 2016).
- *Not labour intensive* - Terrestrial measurements normally require a minimum of two people whereas one person can successfully carry out survey tasks using RPAS and data processing (Patikova, 2004). A modern RPAS can be operated by just one person taking the roles of a pilot and a spotter to keep track of the aircraft position (Gutierrez & Searcy, 2016).
- *Portability* - RPAS are lightweight and easy to transport (Hardin & Hardin, 2010; Klemas, 2015; Niethammer, et al., 2012; Rango & Laliberte, 2010)
- *Operational flexibility* - RPAS allow for rapid and flexible deployment predominantly due to their reduced scale which also allows an increased range of uses (Klemas, 2015; New Zealand Ministry of Transport, 2019). RPAS have little need for space and infrastructure (Odido & Madara, 2013). An RPAS has real-time capability and can be launched on-demand (Doumit, 2019). RPAS can fly at a variety of altitudes depending on data collection needs (Deepika & Lavanya, 2015). They can fly at a low altitude close to the target area where manned aircraft systems cannot be flown (Doumit, 2019). One of the main advantages of RPAS is that they come in such a wide variety of configurations and capabilities (Hogan, et al., 2017) that technical requirements attached to any

given application are likely to be met by some available system (Barbedo & Koenigkan, 2018).

- *High spatial and temporal resolution* - Due to the low operation altitude, RPAS achieve a very high resolution in terms of GSD and can, therefore, compete with airborne large format digital cameras carried by manned aircraft (Irschara, et al., 2010). Depending on the quality of the cameras used and the altitude of the RPAS, photogrammetry provides imagery of small areas with resolutions of 0.5 cm to 7 cm (Oczipka, et al., 2009). This is a pixel size that commercial satellites cannot yet deliver (Gutierrez & Searcy, 2016). RPAS can also provide high-resolution images and precise positioning/orientation data from the onboard GNSS and INS navigation sensors (Deepika & Lavanya, 2015; Torres, 2019).
- *High accuracy* - Both photogrammetry and LiDAR can provide suitable levels of 3D model accuracy, especially compared with terrestrial sampling methods (Torres, 2019). Photogrammetry has better DTM accuracy than terrestrial measurement because of a larger quantity of points that can comprehensively illustrate terrain (Patikova, 2004).
- *Adaptable to weather conditions* - RPAS remote sensing is unaffected by cloud cover. In cloudy and poor weather conditions, data acquisition with RPAS is possible (Doumit, 2019). Such weather conditions typically do not allow survey operations using manned aircraft (Doumit, 2019).
- *Less interference with the surrounding environment* - Discrete RPAS do not disturb operations on the ground when carrying out surveying tasks (Doumit, 2019).

Weaknesses

The weaknesses associated with utilising RPAS on mining operations are as follows:

- *Limited accuracy of a singular point* - The accuracy of a single point is slightly less (tens of cm) but it is appropriate for open pit mining (Patikova, 2004). Because of the low flying heights used, RPAS imagery is particularly prone to the effects of relief displacement (Eisenbeiss, 2009; Niethammer, et al., 2012). "Relief displacement occurs when images of ground features, for example, hilltops, are displaced from the central projection of an aerial photograph due to terrain relief. The further objects are away from the centre of the image, the more relief displacement occurs for a feature" (GIS Geography, 2020). The low operating altitude and relatively low accuracy of onboard navigational sensors can result in major variances between the image footprints estimated during flight planning and the actual ground coverage of each image, particularly in uneven terrain (Gutierrez & Searcy, 2016).

- *Payload limitations* - Often lightweight sensors such as small or medium format amateur cameras are mounted on RPAS, in comparison to large format cameras on manned aircraft (Doumit, 2019). Most RPAS are small, which means a limited payload capacity for critical components such as cameras and sensors. The RPAS payload limitations require the use of lightweight navigation units, which implies potentially less accurate results for the orientation of the sensors (Doumit, 2019).
- *Limited spatial coverage* - RPAS have a small image footprint and have to acquire a higher number of images to obtain the same image coverage and comparable image resolution as manned aircraft (Doumit, 2019; Hardin & Hardin, 2010; Niethammer, et al., 2012; Rango & Laliberte, 2010).
- *Limited flight time* - Commercial or civilian RPAS have lower battery/fuel capacity in comparison to manned aircraft (Doumit, 2019). Consequently, most commercial RPAS cover less ground than a manned aircraft. This limitation is primarily due to the use of battery-powered engines. As battery technology improves in the future, so too will RPAS flight time.
- *Reliance on GNSS technology* - GNSS is susceptible to interference from various wireless sources, which may affect the positional accuracy of acquired data. There is also a possibility that the RPAS would have a communication failure and lose control due to insufficient broadcast signal from satellites (Ramdzan, n.d.).

- *Specialised skills required* - RPAS may be challenging to pilot, even if GNSS-enabled navigation is utilised (Anderson & Gaston, 2013). Take-off and landing, in particular, would require some proficiency to avoid incidents (Barbedo & Koenigkan, 2018). Integration of RPAS on mining operations would require the upskilling of mine surveyors or employing suitably skilled personnel.
- *Affected by certain weather conditions* - In surface mines, weather conditions present a challenge by inducing deviations in RPAS planned paths (Shahmoradi, et al., 2020). RPAS can be limited by wind speed and gusts. In some cases, weather conditions can be damaging to the RPAS, leading to failure in their missions (Jordan, 2015; Shakhatreh, et al., 2019). Image footprints can also differ from expectation due to changes in the roll, pitch and yaw of the aircraft caused by wind and navigation corrections (Gutierrez & Searcy, 2016).
- *Set-out of survey points* - An RPAS cannot be used to set-out survey points.
- *LOS requirements* - According to South African regulations, the operation of RPAS requires operator line of sight (visibility of RPAS) at all times.

Opportunities

The opportunities associated with utilising RPAS on mining operations are as follows:

- *Improved ease of access to data* - RPAS can access areas that are difficult or impossible to access by air, land-based vehicles or physically by mine personnel (New Zealand Ministry of Transport, 2019). RPAS can be safely and effectively utilised in potentially hazardous tasks without endangering mine personnel (Deepika & Lavanya, 2015; Doumit, 2019; Micklethwaite, 2018; Odido & Madara, 2013; Ramadzan, n.d.). RPAS are nimble, manoeuvrable and capable of hovering which enables observation and recording in previously inaccessible areas with an on-demand schedule (Hardin & Hardin, 2010; Niethammer, et al., 2012; Rango & Laliberte, 2010).
- *Improved data quality* - The low flying heights typically make it possible to capture imagery with sub-decimetre spatial resolution (Gutierrez & Searcy,

2016). This improves data quality that is used as input for project management, improving the efficiency of the process (New Zealand Ministry of Transport, 2019).

- *Training and upskilling* - The introduction of RPAS on mining operations provide an opportunity for current employees to be upskilled which may translate to better remunerations on their part.
- *Inspections and monitoring* - RPAS can be used in intelligence work and information gathering on critical mine site operations, for example, blast optimisation, ore stockpile management and MRD management (Ramdzan, n.d.).

Threats

The threats associated with utilising RPAS on mining operations are as follows:

- *Dynamic legislation* - Flight regulations for commercial RPAS operations are not globally standardised, vary from region to region and are subject to frequent change (Geomatics World, 2019). Extrinsic factors such as government regulations may discourage RPAS use (Watts, et al., 2012).
- *Expertise acquisition* - Mining companies have to acquire mine survey personnel with the suitable skills required for RPAS (Geomatics World, 2019). This means that they either upskill current employees or employ new expertise altogether. Upskilling may impact on the overall costs of the operations whilst finding new employees may be a lengthy process.
- *Loss of jobs* - Mine surveying tasks that were previously carried out by at least two people would be reduced to only one person who can acquire and process the data, resulting in redundant mine survey personnel.

# CHAPTER 7. CONCLUSION AND RECOMMENDATIONS

## 7.1 Discussion and Conclusion

The main aim of this research was to develop a guideline that provides a knowledge base surrounding the utilisation of RPAS on mining operations. This research serves to promote digital transformation in the 4$^{th}$ Industrial Revolution era. The objectives of the research included a comparison of RPAS with other conventional surveying techniques concerning costs, time, accuracy and safety. The research has shown that there are significant quantitative and qualitative advantages of utilising RPAS over conventional survey methods. The benefits of RPAS can be summarised as reduced survey costs implications, less time is taken for survey activities, greater survey accuracy in some instances and safer survey operations. The overall conclusion from this research is that surveying with RPAS is more cost-efficient, less time consuming, more accurate in some cases and safer for specific survey functions than conventional surveying methods. However, the following data could not be gathered during this research due to the lack of availability of sources:

- Costs and time associated with volumetric calculations using a total station;
- Costs and time associated with volumetric calculations using manned aircraft; and
- The time required for topographic mapping using manned aircraft.

Therefore, the comparison of RPAS methods with conventional survey methods which lie in the above-mentioned categories remains inconclusive. Based on the data gathered, surveying using a total station required more time and hence higher survey costs for topographic mapping than the RPAS method. RTK GNSS survey required more time and higher survey costs for topographic mapping and volumetric calculations than the RPAS method. Surveying using TLS required more time and higher survey costs for topographic mapping and volumetric calculation than the RPAS method. Manned aircraft topographic mapping incurred more costs than RPAS topographic mapping. The data gathered shows that RPAS has a greater 3D accuracy than using a total station for topographic mapping and volumetric analysis. This can be attributed to a point cloud having a large number of points as compared to a typical total station survey. Comparison of the RPAS method and RTK GNSS shows that results from both methods had minor variances for volumetric calculations and topographic mapping. Surveying using RPAS produces more accurate results than TLS for topographic mapping but results for volumetric calculations show slight differences. The RPAS results had a standard deviation of 0.052 m at a 100 m altitude and 0.059 m at a 150 m altitude. The data gathered also demonstrates that RPAS survey and manned aircraft have similar accuracies for topographic mapping but the comparison of volumetric calculation was inconclusive.

A SWOT analysis was conducted of surveying using RPAS and surveying using conventional surveying methods. Although there are advantages of using each surveying methods, there are also limitations that accompany them. From the analysis made in this research, it shows that the strengths and opportunities of adopting RPAS technology in mining operations outweigh the corresponding weaknesses and threats. RPAS can be more cost-effective and less time consuming than conventional survey methods, but it may not necessarily be the best tool for every aspect of surveying and mapping. For case in point, the limited flight time and the requirement to maintain LOS with the aircraft requiring multiple launches and recoveries, and subsequent repositioning of the operator, make the mapping of extensive areas less effective than with manned aircraft. This research was not able to determine at what point an area is too large for RPAS to be cost-effective when compared to manned aircraft. This would be a suitable topic for future research. In conclusion, in some cases, RPAS should not be considered as a substitute for conventional surveying and mapping methods, but rather viewed as another valuable tool in the toolbox, to be utilised when the circumstances arise.

## 7.2 Limitations of the Research

When conducting this research, certain limitations were encountered that could not be mitigated within the scope of the research. The limitations include:

- This research was conducted during the COVID-19 pandemic which had major implications on the collection of data. Mine site visits had been arranged but had to be cancelled due to the national lockdown and mine-specific measures which were implemented to prevent the spread of the COVID-19 virus;
- There is minimal information about RPAS applications in the mining industry and their associated costs, accuracies and survey completion time. Most of the available literature encompasses the utilisation of RPAS in military applications; military applications are beyond the scope of this research;
- Accessing business-specific data is often challenging with confidentiality constraints. The research relied on published information as far as possible. This implies that the sample space was relatively small and so the constraints of those sources are integrated within this research;
- There are several unknowns and uncertainties around the direct ongoing expenses associated with the utilisation of RPAS in mining operations. This research does not perform an all-inclusive cost-benefit analysis of RPAS. Aspects such as the cost to repair or renewing RPAS are not included. Similarly, the environmental costs and risks of RPAS are beyond the scope of this work; and
- This research does not include an analysis of the durability of RPAS and the average useful life of fit-for-purpose RPAS in the mining industry, that is, how many flying hours could be expected from RPAS.

## 7.3 Recommendations

This research provided a guideline for the successful integration of RPAS into mining operations to promote digital transformation in the $4^{th}$ Industrial Revolution era. However, there is much room for improvement for that to be realised efficiently and this section provides the recommended actions to be taken. These recommendations are intended to motivate cooperation among the various stakeholders in the RPAS industry, particularly mining companies. The recommendations are as follows:

- *Research and development (R&D)* - R&D should be supported to pursue the development of smaller lightweight sensors and RPAS that are more easily manoeuvrable. Another essential area of technological advancement is the autonomy of RPAS operations. There is a need for RPAS manufacturers to produce user-defined RPAS designs that are fit-for-purpose and readily applicable to mining operations. There is a need to develop effective technologies and procedures to prevent collisions of RPAS with other aircraft, the ground, or other obstacles. The development of an aeronautical data exchange, processing, and synchronisation network that uniquely accounts for RPAS requirements is also essential. Most RPAS, particularly those that will be permited to operate autonomously, will rely on accurate and timely information for navigational guidance and flight path optimisation.
- *Industry engagement* - There is a need to continuously assess the adoption rate of RPAS technology in the mining industry to obtain an accurate forecast of the size of the RPAS industry. This will influence the required level of investment by mining companies. Communicating RPAS developments and inventions to all stakeholders will be vital to acceptance in the mining industry. Manufacturers, operators, airspace users and regulators need to arrive at a consensus on how RPAS will operate on mining operations, including specific terms and conditions related to the different RPAS types. Most operational models seek to integrate RPAS within the existing framework for manned aircraft operations. However, this may not be practical for the small RPAS systems and those having unique capabilities and performance characteristics.
- *RPAS classification* - There is a need to develop a classification scheme and definitions for RPAS based more on the airspace intended for use instead of on aircraft size, endurance levels and mission types, as is currently practised. Other factors that should also be considered, for example, are communication

capabilities and range, navigational accuracy, levels of autonomous control, kinetic energy values and an ability to be detected by ATC and other aircraft. A common understanding of RPAS classifications and definitions is an essential initial stage to the development of global standards, regulations and certification requirements.

- *RPAS legislation* - There is a need to consider GCSs, communications links, flight control systems and software in the RPAS system certification process. The existence of government/industry consensus standards and classification scheme for RPAS is a prerequisite to defining these requirements. Beyond the technical systems, air traffic regulations and operating procedures should also be structured in a way to safely accommodate the unique properties, equipage, environments and trajectories flown by more advanced RPAS that are yet to be developed. Such regulations and procedures need to address the human element, for example, health checks and fitness for duty, as well as ground and airborne components of the air traffic system. Standards and regulations should clearly outline the requirements for a safe and effective collision avoidance system, but should not specify a given technology or procedure. This would consequently pave the way for the regulation introduction of RPAS operations that are beyond the visual LOS in countries such as South Africa.
- *Global harmonisation* - There is a need to harmonise RPAS regulations, certification standards and operational procedures. RPAS will continue to operate in a global context, for example, an RPAS can be designed and manufactured in one country but then utilised on mining operations in several other countries. Without a common set of approaches to manufacture, operating and maintaining RPAS systems, the market for RPAS will suffer and acquisition and operating costs will be unnecessarily inflated. If there exist complications in, for example, the acquisition of the appropriate maintenance equipment for RPAS, mining companies will opt for the tried and tested conventional surveying equipment and practices. Further, civil aviation authorities will find the cost and complexity of achieving interoperable systems among ground and airborne elements to be

difficult and oversight and enforcement of RPAS operations and systems more challenging. Harmonising various national and international approaches is vital to the development of the RPAS market and will help in controlling the manipulation of costs by some suppliers taking advantage of the relatively relaxed RPAS regulations in their respective countries. Policies must be established, workable classifications created, regulations codified, frequencies allocated, technologies developed, systems tested and certified, and resource made available to effectively enact change. These actions fall collectively on the different RPAS industry stakeholders such as governments, manufacturers and users.

## 7.4 Geospatial Systems Strengths and Weaknesses Comparison Matrix

This section provides a matrix comparing the strengths and weaknesses of the various geospatial systems investigated in this research. Table 8.1 shows the respective comparison with a particular focus on the suitable application of the geospatial systems.

*Table 7.1: Comparison of the strengths and weaknesses of different geospatial systems*

| | **Strengths** | **Weaknesses** |
|---|---|---|
| **Total Station** | • Surveying tasks<br>• Setting-out points | • Mapping large areas<br>• Extreme and harsh weather conditions |
| **GNSS** | • Surveying tasks<br>• Setting-out points<br>• Daylight or darkness<br>• Any weather conditions, for example, snow, rain, high or low temperatures<br>• Mapping large areas | • Surveying in areas without satellite visibility, for example, in buildings or underground<br>• Measuring elevation differences without a suitable elevation model |
| **TLS** | • Mapping<br>• Mapping large areas<br>• Cloudy and poor weather conditions<br>• Daylight or darkness<br>• Ground monitoring | • Setting-out points |
| **Manned Aircraft** | • Mapping large areas | • Cloudy and poor weather conditions<br>• Setting-out points |
| **RPAS** | • Mapping<br>• Mapping large areas<br>• Site inspections on the surface and in some underground environments | • Setting-out points |

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## Appendix A: Comparison of Costs

| Reference | Survey Type | Survey Area | Total Station | RTK GNSS | TLS | Manned Aircraft | RPAS |
|---|---|---|---|---|---|---|---|
| Fitzpatrick (2016) | Volumetric Calculation | 32 374.9 $m^2$ (8 acres) | - | US$2 235 (total) | - | - | US$1 316.50 (total) |
| Weber and Lerch (2018) | Volumetric Calculation | 0.04 $km^2$ | - | - | ≈ 80 000 CHF (US$88 481.52) (total) | - | ≈ 30 000 CHF (US$33 180.57) (total) |
| El Meouche, et al. (2016) | Topographic Mapping | unknown | ≈ €2 000 (US$2 372.50) (total) | - | - | - | ≈ €1 200 (US$1 423.50) (total) |
| Fitzpatrick (2016) | Topographic Mapping | 40 468.6 $m^2$ (10 acres) | - | - | US$4 600 (total) | - | US$2 450 (total) |
| Fitzpatrick (2016) | Topographic Mapping | 93 077.7 $m^2$ (23 acres) | - | US$3 200 (total) | - | - | US$1 944 (total) |
| Fitzpatrick (2016) | Topographic Mapping | 56 656 $m^2$ (14 acres) | - | - | - | US$5 000 (total) | US$1 960 (total) |
| Matese, et al. (2015) | Topographic Mapping | 0.05 $km^2$ | - | - | - | €2 200 (US$2 609.75) (acquisition) €100 | €1 500 (US$1 779.38) (acquisition) €500 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | (US$118.63) (georeferencing & orthorectifying) €150 (US$177.94) (image processing) | (US$593.13) (georeferencing & orthorectifying) €200 (US$237.25) (image processing) |
| Matese, et al. (2015) | Topographic Mapping | 0.5 km$^2$ | - | - | - | €3 000 (US$3 558.75) (acquisition) €500 (US$593.13) (georeferencing & orthorectifying) €300 (US$355.88) (image processing) | €4 000 (US$4 745) (acquisition) €1 000 (US$1 186.25) (georeferencing & orthorectifying) €300 (US$355.88) (image processing) |
| Volkmann (2017) | Topographic Mapping | 7.95 km$^2$ | - | US$9 984 (field labour) | - | - | US$1 440 (field labour) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | US$960 (office labour) | | | US$2 520 (office labour) |
| Volkmann (2017) | Topographic Mapping | 0.09 km² | - | US$3 120 (field labour) US$90 (office labour) | - | - | US$277.20 (field labour) US$216 (office labour) |

## Appendix B: Comparison of Time taken for data collection

| Reference | Survey Type | Survey Area | Total Station | RTK GNSS | TLS | Manned Aircraft | RPAS |
|---|---|---|---|---|---|---|---|
| Arango and Morales (2015) | Volumetric Calculation | - | - | - | 3 hrs 5 mins (fieldwork) | - | 35 mins (fieldwork) |
| Fitzpatrick (2016) | Volumetric Calculation | 32 374.9 $m^2$ (8 acres) | - | 11 hrs (total) | - | - | 6 hrs (total) |
| Tucci, et al. (2019) | Volumetric Calculation | 0.01 $km^2$ | - | - | ≈ 3 hrs (fieldwork) | - | ≈ 2 hrs (fieldwork) |
| Weber and Lerch (2018) | Volumetric Calculation | 0.04 $km^2$ | - | - | 3 hrs 55 mins (fieldwork + processing) | - | 20 mins (fieldwork + processing) |
| Albright (2019) | Topographic Mapping | 80 937.1 $m^2$ (20 acres) | - | 10 hrs (fieldwork) 11 hrs (office work) | - | - | 5 hrs (fieldwork) 11 hrs (office work) 15 hrs (data processing) |
| Carrera-Hernandez, et al. (2020) | Topographic Mapping | 0.327 $km^2$ (32.767 ha) | 7 days (fieldwork) | - | - | - | ≈ 4 hrs (fieldwork) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| El-Ashmawy (2015) | Topographic Mapping | 0.82 $km^2$ | ≈ 1 day (fieldwork) | ≈ 40 mins (fieldwork) | ≈ 50 mins (fieldwork) | - | ≈ 40 mins (fieldwork) |
| El Meouche, et al. (2016) | Topographic Mapping | unknown | 7 hrs (fieldwork) | - | - | - | 4 hrs (fieldwork) |
| Eyoh, et al. (2019) | Topographic Mapping | 1.1 km (Route survey) | > 12 hrs (fieldwork) | - | - | - | < 30 mins (fieldwork) |
| Fitzpatrick (2016) | Topographic Mapping | 40 468.6 $m^2$ (10 acres) | - | - | 10 hrs (total) | - | 7 hrs (total) |
| Fitzpatrick (2016) | Topographic Mapping | 93 077.7 $m^2$ (23 acres) | - | 16 hrs (total) | - | - | 8 hrs (total) |
| Fitzpatrick (2016) | Topographic Mapping | 56 656 $m^2$ (14 acres) | - | - | - | unknown | 4 hrs (total) |
| Mora, et al. (2019) | Topographic Mapping | 0.017 $km^2$ | - | 2 hrs (fieldwork) | - | - | 5 mins 46 sec (fieldwork) |
| Peterman (n.d.) | Topographic Mapping | 0.3 $km^2$ | 4 hrs (fieldwork) 2 hrs (office work) | - | - | - | 2 hrs (fieldwork + office work) |
| Volkmann (2017) | Topographic Mapping | 7.95 $km^2$ | - | 20.8 days (fieldwork) 4 days (office work) | - | - | 3 days (fieldwork) 10.5 days (office work) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Volkmann (2017) | Topographic Mapping | 0.09 $km^2$ | - | 52 hrs (fieldwork) 3 hrs (office work) | - | - | 4 hrs 37 mins (fieldwork) 7 hrs 12 mins (office work) 12 hrs (data processing) |
| Yeh, et al. (2018) | Topographic Mapping | 0.0029 $km^2$ | 3 hrs (fieldwork) | - | - | - | 20 mins (fieldwork) |

## Appendix C: Comparison of Accuracy

| Reference | Survey Type | Survey Area | Total Station | RTK GNSS | TLS | Manned Aircraft | RPAS |
|---|---|---|---|---|---|---|---|
| Arango and Morales (2015) | Volumetric Calculation | unknown | 2.88% Difference from actual volume | - | - | - | -0.67% Difference from the actual volume |
| Fitzpatrick (2016) | Volumetric Calculation | 32 374.9 $m^2$ (8 acres) | - | Reference volume | - | - | 0.09% Volume difference |
| Martin (2018) | Volumetric Calculation | - | - | Reference volume | - | - | -0.6% Volume difference |
| Weber and Lerch (2018) | Volumetric Calculation | 0.04 $km^2$ | - | - | Reference point cloud | - | 0.052 m Standard deviation (100 m flight height) 0.059 m Standard deviation (150 m flight height) |
| Barry and Coakley (2015) | Topographic Mapping | 0.02 $km^2$ | - | Reference control points | - | - | 0.021 m Mean error (XY-coordinates) |

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|---|---|---|---|---|---|---|---|
| | | | | | | | 0.031 m Mean error (Z-coordinates) |
| Beretta, et al. (2018) | Topographic Mapping | ≈ 0.059 $km^2$ | - | Reference control points | 0.647 m Average error | - | 0.007 m Average error (Vertical images) 0.061 m Average error (70° images) |
| Beretta, et al. (2018) | Topographic Mapping | ≈ 0.059 $km^2$ | - | Reference control points | 0.647 m Average error | - | 0.075 m Average error (Vertical images) 0.075 m Average error (70° images) |
| Chi, et al. (2016) | Topographic Mapping | unknown | Reference control points | - | - | - | 0.008% Absolute error (X-component) 0.020% Absolute error (Y-component) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Erenoglu, et al. (2018) | Topographic Mapping | 0.2 $km^2$ | Reference control points | - | - | - | 0.0325m Mean error (Y-component) 0.0537m Mean error (X-component) 0.0695m Mean error (height component) |
| Eyoh, et al. (2019) | Topographic Mapping | 1.1 km (Route survey) | 0.23633874 m Horizontal accuracy 0.32819415 m 3D accuracy | - | Reference control points | - | 0.250468326 m Horizontal accuracy 0.302205824 m 3D accuracy |
| Fitzpatrick (2016) | Topographic Mapping | 40 468.6 $m^2$ (10 acres) | - | - | 41% of points within 0.1 ft of RPAS points | - | 41% of points within 0.1 ft of TLS points |
| Fitzpatrick (2016) | Topographic Mapping | 93 077.7 $m^2$ (23 acres) | - | < 0.03048 m Difference between contour lines with RPAS | - | - | < 0.03048 m Difference between contour lines with RTK GPS |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Fitzpatrick (2016) | Topographic Mapping | 56 656 $m^2$ (14 acres) | - | - | - | < 0.03048 m Difference between contour lines with RPAS | < 0.03048 m Difference between contour lines with Manned Aircraft |
| Karki and Karki (2014) | Topographic Mapping | unknown | Reference control points | - | - | - | 0.0013 m Mean 3D error |
| Mora, et al. (2019) | Topographic Mapping | 0.017 $km^2$ | - | Reference point cloud | - | - | 0.033 m Mean 3D error |
| Mora, et al. (2019) | Topographic Mapping | 0.017 $km^2$ | - | - | Reference point cloud | - | 0.002 m Mean error (Vertical component) |
| Peterman (n.d.) | Topographic Mapping | 0.3 $km^2$ | Reference control points | - | - | - | 0.02667 m Mean 3D error |
| Yeh, et al. (2018) | Topographic Mapping | 0.0029 $km^2$ | Reference control points | - | - | - | 0.008 m Minimum error 0.151 m Maximum error |