# Autonomous 3D Mapping and Surveillance of Mines with MAVs

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**Abstract**

The mapping of mines, both operational and abandoned, is a long, difficult and occasionally dangerous task especially in the latter case. Recent developments in active and passive consumer grade sensors, as well as quadcopter drones present the opportunity to automate these challenging tasks providing cost and safety benefits. The goal of this research is to develop an autonomous vision-based mapping system that employs quadrotor drones to explore and map sections of mine tunnels. The system is equipped with inexpensive, structured light, depth cameras in place of traditional laser scanners, making the quadrotor setup more viable to produce in bulk. A modified version of Microsoft's Kinect Fusion algorithm is used to construct 3D point clouds in real-time as the agents traverse the scene. Finally, the generated and merged point clouds from the system are compared with those produced by current Lidar scanners.

## Declaration

I declare that this dissertation is my own, unaided work. It is being submitted for the degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

Stuart Edwards

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# List of Abbreviations

**CT** computerized tomography.

**EDM** Electronic Distance Measurement.

**EKF** Extended Kalman Filter.

**FAST** Features from Accelerated Segment Test.

**GPS** Global Positioning System.

**ICP** Iterative Closest Point.

**IMU** Inertial Measurement Unit.

**MAV** Micro Aerial Vehicle.

**MRI** Magnetic resonance imaging.

**PCA** Principle Component Analysis.

**RANSAC** Random sample consensus.

**RC** Radio Controlled.

**SAD** Sum of absolute distances.

**SfM** Structure From Motion.

**SLAM** Simultaneous Localisation and Mapping.

**SSD** Sum of squared distances.

**ToF** Time of Flight.

**TSDF** Truncated Signed Distance Function.

**UAV** Unmanned Aerial Vehicle.

**VTOL** Vertical Take Off and Landing.

# Chapter 1

# Introduction

Mining has always been a hazardous occupation and although the fatality rate from mining related accidents has dropped in recent times due to modern safety procedures and equipment, the profession still carries significant risk. Common hazards that miners face include physical dangers such as rock fall, falls from height and entrapment, as well as less noticeable ones such as long term exposure to various environmental factors involved in mining [Donoghue, 2004]. In South Africa, the Gold mining industry continues to display the highest fatality rate when compared to other commodity mining operations, contributing 33 of the 77 reported fatalities in the South African mining industry for 2015 [Zwane, 2016].

The mining industry in South Africa is also affected by the country's high crime rate: illegal mining is becoming more prominent in both abandoned and operational mines, and it is estimated that there are over 14 000 people involved in these activities [CoM, 2016]. It is difficult to determine the financial impact caused by these activities on legal operations and on the country as a whole, but the most credible estimates put the annual losses at R6 billion. Additionally, illegal mining is accompanied by gang related activities, prostitution, mining accidents and irreparable damage to the environment [Jamasmie, 2016].

Both the safety and the security issues faced by mines are progressively being resolved with the introduction of improved operating procedures and advanced equipment. Modern security systems, such as thermal cameras and contactless smart card access points have helped to reduce the number of crime-related incidents on mine sites over the past few years [isds.com, 2017; minealert.com, 2017]. These measures are, however, expensive and have proven to be insufficient in some regions of the world.

The Digital Mine project at the University of the Witwatersrand, School of Mining Engineering aims to take these measures further by developing a digitised "smart mine" [Cawood, 2015]. The goal of the project is to work towards the notion of an intelligent mine. Several research projects have been initiated, which include:

- Bringing real time, two-way, high-speed communications and environmental surveillance technologies that are currently available at the surface to the underground mining environment;
- Underground positioning, mapping and navigation;
- Action recognition and detection of abnormalities;
- Remote, visual inspections; and
- Visual environmental and rock monitoring.

Ultimately, the project aims to be able to fully automate a mining operation, thus removing the need to deploy people in the dangerous conditions present underground. In order to achieve this, a 67 meter long mock-tunnel, as shown in Figure 1.1, has been constructed using authentic mining materials in order to allow research and development in this space.

One of the mining processes that is the focus of research in the Digital Mine Project is that of mine surveys. Mine surveying is vital to any mining operation and the data produced by surveyors is critical during mine management, construction and planning. Total stations are one of the most popular tools in mine surveying and consist of an electronic theodolite, used for measuring horizontal and vertical angles, and an Electronic Distance Measurement (EDM) device for measuring distances. Surveyors can use this equipment to measure the locations of mine tunnel features for later analysis. Laser scanners are another useful, but expensive tool for mine surveys, enabling the surveyor to capture high precision point clouds from the scene [minesurveyor.net, 2016].


Figure 1.1: Nick's tunnel, located at the school of mining engineering, at the University of the Witwatersrand.

Despite having access to these tools, surveying mines can still be a lengthy process. Even modern laser scanners can take up to 10 minutes to complete a single scan, which may not include much of the scene when working in an underground environment. Additional measures must also be taken to ensure accurate registration of the resulting point clouds and often involve the deployment of markers in the scene.

Taking the above issues into account, this research aims to develop an affordable and autonomous indoor mapping system that uses quadrotor drones to autonomously survey and patrol a series of mine tunnels while constructing a 3D map of the tunnels in real-time. This 3D map could then be used for:

- drone navigation;
- providing management with a semi-real-time overview of the mine system, including the locations of mining staff.

Additionally, future work could look at using these maps for:

- search and rescue of injured mine workers trapped underground;
- hazard detection, such as potentially dangerous structural changes to the mine shaft;
- security surveillance, with the help of pose and facial recognition techniques.

This work develops a system using a modified version of Microsoft's Kinect Fusion algorithm [Newcombe *et al.* , 2011] to perform real-time, markerless, point cloud capture, registration and mesh reconstruction. Cloud registration is done using an optimised implementation of the Iterative Closest Point (ICP) algorithm that is designed to take advantage of modern GPU hardware. The current implementation only records projected infra-red light, which it uses to infer depth and does not record and make use of any RGB data for cloud alignment or presentation. This is due to the inherent lack of light in the underground mining environment, which adversely affects RGB-dependant systems. This dissertation does, however, investigate and compare RGB-D related methods with the implemented depth-only method.

While not on par with industrial laser scanners, the accuracy of consumer depth sensors is sufficient for use in mine management and planning, and for search and rescue operations. The rapid improvements to consumer level depth sensors also mean that the accuracy of future systems will likely approach that of current laser scanners. Current laser scanners have millimeter or even sub-millimeter accuracy, which is ideal for detecting gradual changes to the underground structure of a mine which may indicate a potential collapse. This work investigates whether this system is able to detect similar changes to the environment using only the consumer depth cameras.



As a result of consumer depth sensors' prominence in the gaming industry, there already exist a variety of libraries for object and person recognition, as well as pose estimation. These libraries and methods show the potential for use with the developed system and could allow for future research in person identification and general security. Such a system could provide smart, mobile security surveillance, which would be far more difficult to predict and avoid than traditional static surveillance systems. Pose estimation techniques and machine learning methods could potentially be used to detect suspicious behaviour of individuals recorded along an agent's route. This may help identify potential criminal activities. Object recognition could also be used to tag equipment, vehicles and people within the mine, thus allowing management to better keep track of resources and personnel.

This research is composed of two sub-problems: The problem of generating and merging 3D maps of a scene in real-time, and the problem of autonomous positioning and navigation in a GPS-denied environment. The next chapter looks at previous work done in the field of 3D mapping and autonomous navigation; and describes the techniques used in this research. Chapter 3 presents the methodology that was followed during the completion of the autonomous mapping system and describes the two experiments that were performed in order to evaluate the system. Chapter 4 lists the results of these two experiments and discusses their implications with regards to the goals of this research. Finally, chapter 5 summarises the contents and findings of this research and concludes the dissertation.

# Chapter 2

# Background and Related Work

## 2.1 Introduction

In recent years, quadcopters (quadrotor helicopters) have become increasingly popular due to their decreasing cost and growing availability. These small, four-rotor UAVs are currently used in a wide variety of applications ranging from film production to archaeological field surveys [Seitz & Altenbach, 2011]. Most commercial quadcopters are controlled manually via a radio controller (RC) or smart-phone application, but often make their underlying software API available to developers. This has allowed them to be the focus of many computer vision and artificial intelligence related projects.

The majority of quadcopters are deployed in outdoor environments, be it for hobbyist activities or for industrial applications. In these cases, the availability of GPS allows for easy automation of the quadcopters. Existing data sources, such as Google Maps [Google, 2016], can be used to implement waypoint following systems with minimal effort. For indoor applications, on the other hand, the GPS denied environments mean that autonomous quadcopters must employ other positioning techniques for navigation. In such cases, the common approach is to implement some form of Simultaneous Localisation and Mapping (SLAM), which allows the agent to map its environment and estimate its position within its surroundings.



A second technology that has grown in popularity and availability over the past decade is consumer depth cameras, such as the Xbox Kinect [Microsoft, 2015]. As with quadcopters, the emergence of these devices into the entertainment and gaming industry has helped to significantly boost the research and development of improved depth cameras, while gradually reducing retail costs.

In this research, these two technologies are employed in order to develop the autonomous indoor mapping system. This chapter presents the background and relevant studies in the context of these technologies, with focus on the aspects that are discussed in Chapter 3.

## 2.2 Quadcopters

### 2.2.1 Overview

Quadrotor helicopters (or quadcopters) are Vertical Take-Off and Landing (VTOL) Micro Aerial Vehicles (MAVs) with four fixed-pitch rotors arranged around the ends of a cross frame [Hoffmann *et al.* , 2004]. This simple, symmetric design allows the quadcopter to manoeuvre in any direction and without the need for much adjacent space. This versatility, coupled with their rapidly falling prices, has lead to a tremendous rise in popularity over the past few years, initially as a toy and later as a research tool. Today the vast amount of attention that quadcopters and similar micro-drones receive in research and industry has led to an almost exponential growth in the capabilities of these devices that is reminiscent of Moore's Law. Section 2.2.2 recounts the important milestones in the history and development of quadrotor aircraft with a discussion of their modern popularity and applications in Section 2.2.3. Finally, the technical aspects of the quadrotor design and operation are discussed in Section 2.2.4.

### 2.2.2 History & Development

Unmanned Aerial Vehicles (UAVs) have been the subject of much interest from as early as 1917 [Mueller, 2009]. A number of prototype unmanned aeroplanes were commissioned and built during World War I, but the first successful unmanned aircraft, called the "Kettering Bug", was completed in 1918 by Charles Kettering and was too late to be deployed in the war. Research continued after the war, producing a number of increasingly sophisticated unmanned aerial drones over the last century. The first mass produced UAVs were used for target practice by anti-aircraft gunners during World War II [Naughton, 2016], shortly before a variety of UAVs were deployed in various combat roles.



Alongside the development of UAVs, which usually consisted of manned aircraft that were adapted for unmanned flight, came the development of Micro Aerial Vehicles (MAVs). UAVs with wingspans shorter than 6 meters and weighing under 25kg are generally classified as MAVs, although there is no exact definition [Mueller, 2009]. The small scale of MAVs added additional complexity to their development, such as the requirement of smaller combustion engines, radio components and actuators. The pre-existing model airplane community made large contributions in these areas, as well as in the design and development of MAVs as a whole. The first successful flight of a radio controlled (RC) model airplane took place in Germany, 1936. Following World War II, the popularity of model RC planes increased, leading to numerous improvements over the next few decades. It was not until the 1970s, however, that MAVs were produced for any serious applications [Mueller, 2009]. It was around this time that video camera and other remote sensing technologies became suitable for use in unmanned aviation. Over the next decade, the United States military began the research and development of small UAVs mainly for reconnaissance applications and produced a number of small unmanned aircraft in the process, some of which fall under the MAV classification.

The majority of these first MAVs were fixed winged aircraft and were not designed with high manoeuvrability in mind. Multi-rotor MAVs only became viable in the early 21st century despite multirotor aircraft being the first VTOL aircraft to be developed [Krossblade, 2016]. When engineers first experimented with the idea of VTOL aircraft at the beginning of the 20th century, a multi-rotor design was chosen for the first prototypes rather than the single main rotor design seen in modern helicopters. The main rotor of modern helicopters generates torque that must be counter balanced by a secondary tail rotor. Early VTOL pioneers saw this as an inefficient use of engine power and opted for a multi-rotor design instead. Early experiments however, proved the quadrotor design to be highly unstable and completely infeasible for practical use. The most successful quadcopter during this period was the Oehmichen No 2 shown in Figure 2.1. It was developed by Étienne Oehmichen, who set a world record by flying it a distance of 360m [QuadcopterArena, 2015]. More efficient quadcopter designs were produced over the following decades, but were temporarily replaced with single rotor designs for the following reasons:

1. The rotors of a quadcopter must be constantly adjusted while in use in order to provide stable flight. This made quadcopters very unstable and made the piloting of the quadcopter an extremely difficult endeavour. Single rotor helicopters, on the other hand, have their center of gravity below the main rotor, which allowed them to easily maintain stable flight

[Krossblade, 2016].

2. The size of early combustion engines meant that it was only feasible for a quadcopter to carry a single engine, usually positioned at the center of the quadcopter. The engines torque then had to be transferred to each of the four rotors using shafts and belts. This added to the mass of the vehicle and added undesirable weak points to the quadcopter. The engines of single rotor helicopters are also positioned centrally within the vehicle, but can be connected almost directly to the main rotor, which is directly above it.

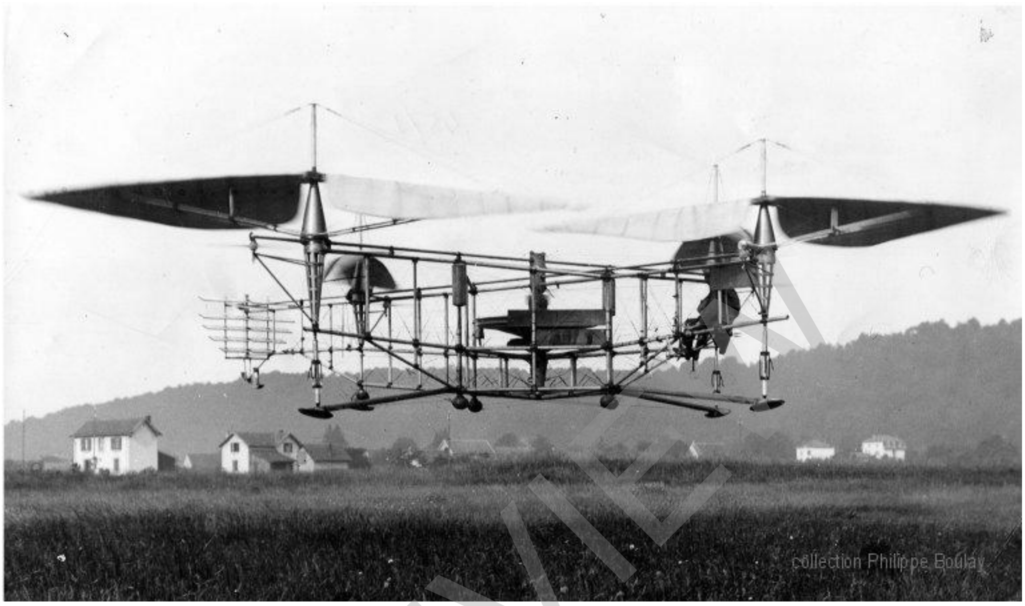


Figure 2.1: The record setting Oehmichen No 2 Quadcopter designed by French engineer Étienne Oehmichen [Shosa, 2015; Krossblade, 2016].

Roughly a century after the first quadcopters were prototyped, modern electronics had advanced to the point where developing stable multi-rotor aircraft was feasible. The existence of microelectronics meant that stable unmanned quadcopters could be built at a considerable fraction of the size and cost of the multi-rotor aircraft of old. Small electric motors could be placed directly under each of the four rotors and on-board electronics could act as the flight controller in order to regulate the rotors and maintain stability. The resulting quadcopters that we see today are therefore small enough to be classified as MAVs, cheap enough to appeal to hobbyists and researchers alike, and manoeuvrable enough to be flown both indoors and outdoors.

### 2.2.3 Modern Popularity

The past few years have seen a massive surge in the consumer drone industry, with an estimated 700 000 quadcopters sold in 2015, marking a 63% increase from 2014 [CNBC, 2016]. While the current value of the drone industry is estimated to be around \$3.3 billion, it is projected to hit \$90 billion by 2025 [Inc.com, 2015].

As this new technology has begun to flood the world markets, authorities are still in the process of developing laws and regulations to keep these potentially dangerous tools in check. Before the emergence of multi-rotor MAVs onto the market, the majority of unmanned aircraft belonged to the model airplane community. This almost century old community follows a strict set of regulations and community members usually belong to clubs where they are provided with a safe and open airspace in which to fly. There have thus been extremely few accidents involving