

# Background

Tracked and wheeled robots are beginning to reach their limitations, and society is in need of more complex and versatile vehicles. For a land robot to successfully navigate extremely complex or cluttered environment, the designer must look to designing a legged robot. Legged designs introduce severe complexity into any system due to the intensive control theory required. With currently available legged platforms, the time it takes it navigate through the location could also cost precious time. A different approach would be to use an aerial drone that could do surveillance or complete the required task by simply flying over the complexities in the operating environment, thus avoiding the need for extensive control laws and speeding up the time to completion [1]. However, with conventional flight techniques and platforms, almost any sort of collision would cause a crash and the system would not be able to complete its mission. This limits this approach to only work in a situation where the drone would be able to fly over the obstacles [2].

Unfortunately many of the desired use cases are not found in this ideal environment and the drone would be required to navigate above, below and even through obstacles to complete its task, a good example of this is in search and rescue missions.

From the late 1800s South Africa has had a massive mining community, with coal, gold and diamond mining being a big source of income and job creation for the country. In response to this, two South African research institutes have agreed to a joint collaboration in solving some of these aspects for specifically in a mining environment. This project involves both The University of Stellenbosch (US) and the Council of Scientific and Industrial research (CSIR). A mining environment would be a perfect example of where a collision resistant drone could make significant contributions, such as the mapping of unknown and potentially hazardous environments. The drone would be able to fly in, conduct a survey of the environment and feed that information back to the miners, ensuring a safer work environment while minimising costly delays.

# Problem Statement

In complex environments the usefulness of land robots is limited and even with current mining technologies personnel are still on occasion required to enter dangerous areas to do mapping and inspections. This project will look at designing an aerial vehicle that can be used in a close quarter environment and be equipped to handle collisions. For the drone to have access into mines and other hazardous environments it needs to be designed to be explosion protected.

# Literature Review

A unique attribute of this drone is its intent for use in a close quarter environment. Some international organisations have begun research on designs of such systems [2]–[5]. Rotorcraft designs are consistently used as they give the user more flexibility and manoeuvrability than a fixed wing craft. The Principles of Helicopter Aerodynamics [6] is an important starting block to understanding the requirements for flight in any rotorcraft.

Modelling of the rotorcraft is a topic that has already been done in some depth [7], [8]. It is important to model the system as it will help better understand the control needed to obtain stable flight and all the dynamics and interferences involved. Understanding these dynamics becomes extremely important when enabling the craft to stabilise itself after a collision, some research done by Adrian Briod [9] involves implementing an up righting mechanism in a collision resilient system [2]. Briod’s entire system will prove useful as a starting basis for protecting the platform from collisions.

Although machinery has been put into hazardous locations for many years, an explosion protected aerial vehicle has not been done before. The majority of electrical equipment designed for hazardous locations are larger scale devices that use much more electrical power, which limits the relevance to this project. Some companies have released patents and design considerations for hazardous locations [10]–[12].

To design an explosion protected system it is important to be familiar with the set of standards that are based around designing for hazardous locations, including the different classifications of these areas [13]. South African Bureau of Standards has developed design criteria to be implemented in hazardous locations, the important ones for this design will be intrinsic safety [14], encapsulation [15] and flameproof enclosures [16].

# Detailed Problem Statement

Designing any aerial drone introduces many complexities by itself, including obtaining the required aerodynamics to achieve stable flight. There are modules that one can buy to achieve this, but in a close quarter environment, this specification gets enhanced with the need to stabilise itself after a collision or due to flight near surfaces. More defined integration of the sensor data will be needed.

Instead of implementing complex and unreliable collision avoidance systems this platform will be designed for impact resistance, this project will make the assumption that the robot will fly into obstacles during operations. This specification mainly affects the mechanical construction of the vehicle, but as stated above, intensifies the control laws required.

The drone will need to be small to increase its accessibility in confined spaces; this limits payload and flight time. Obtaining a flight time of half an hour will be a challenge, especially when the drone has more electrical strain placed on it through camera feeds or other relevant sensing data.

A wireless link to the drone will be required and will need to operate without line of sight.

To increase the scope of the device, it will be designed to be certified for explosive/flammable areas such as a coal mine. This entails ensuring the device is explosion protected. Main areas of concerns for obtaining this will be encapsulating the motors to prohibit arcing even during fault conditions. The other circuitry that is not intrinsically safe can be encapsulated but weight then becomes an issue and will need to be compensated by an increased disk loading ratio, which will shorten flight duration.

Most designs for hazardous environments are used in big, high power systems that traditionally are built to remain inside the mines and repeatedly complete a given task. This separates the intended output of the project in two ways; firstly the system being developed will be on a much smaller power scale than the big machinery found in mines. Secondly the drone will not be intended to ever remain in the mine for extended periods of time, it will be put inside to complete a certain task and after that be taken out again. Both of these factors play a significant role in the certification process, which directly affects the design.

Atmospheric conditions inside hazardous locations are generally abnormal and this affects the flight conditions and potentially will require compensation.

# Infrastructures

The research is being done as a part time engineering master’s project and is a joint collaboration between the University of Stellenbosch and The CSIR’s Mechatronics unit.

The CSIR has facilities to assist with design and production of the device as well as access to useful publications. This includes a PCB milling station and laser cutter, more complex fabrications can be done by the workshop located at the CSIR. Software licenses are also available from the CSIR including Alitum Designer and Solidworks.

The University of Stellenbosch has acquired necessary technologies to assist with testing and modelling of aerodynamic systems.

There has been a funding opportunity from The Chevron Oil Company; the potential contract will cover procurement needs as well as salary, with the CSIR covering the deficit.

# Research Plan

For most aerodynamic systems the flow of power is the same, chemical potential energy (in most cases the form of a battery), gives power to an electronic system. The electronic power is then transferred to a mechanical load, mainly in the form of kinetic energy. This mechanical energy is used to generate aerodynamic power, which in this case would be the form of a rotating blade producing thrust or lift. Each part of this stream incorporates important design decisions and each different leg will introduce complexities and specifications that need to be researched.

To fully understand the operational requirements of such a drone, initial research into existing platforms needs to be done. This will include looking at theories behind flight, which will help better understand the system’s aerodynamics. Such theories include the Rankine-Froude momentum theory and blade element analysis, which both look at rotating blades and attempt to quantify the effects they have. Since the drone will be of a smallish size and needs to be able to have a significant flight time, disk and power loading will also become two very important design criterions.

After an understanding of flight systems has been gathered, initial thoughts and designs behind the rotor configurations can be done. Different rotor placements, numbers and sizes all create very different flight profiles and control methods.

When a rotor set up has been established and flight dynamics analysed, the electronic drive system will need to be assessed. As the drone’s end use case will be in a mining environment, certain standards behind circuit design and manufacture must be kept. The reason behind this is that any machinery placed in a hazardous location has the possibility of causing an explosion.

There is a set of standards compiled by the South African Bureau of Standards (SABS), which will be extensively looked into, to ensure that the robot will be allowed inside the mines and not be a risk to the workers. These South African born standards have been recognised by the international IECEx set of standards and are documented as the SANS 60079 set [13]–[16].

Before specifics behind explosion protection can be looked at, the general requirements of the standards must be understood [13]. Traditionally there are three main approaches to explosion protection techniques, Intrinsic safety [14], encapsulation [15] and the use of flameproof/explosion proof enclosures [16]. Initial approach is to design for intrinsically safe circuits.

Intrinsic safety is a design technique where the electric power in a circuit is never high enough to create a spark which could create an explosion. Along with limiting the ratios of current and voltage the standards also specify how these limits change when more inductance or capacitance is added to your circuits. The trick behind intrinsic safety is not solely in designing low powered circuits, but also in limiting stray inductance and capacitance in your circuits. Certification procedures assume that the device will fail catastrophically and testing procedures are done under such conditions. Thus the device must be built to follow these standards even under such severe strains that the device breaks.

Ideally all the circuits will be designed to conform to the intrinsic safety standards, however this is not always plausible, especially when buying modules off the shelf. Designing this platform to be intrinsically safe will be difficult to accomplish since there is a need to drive motors, which both introduce higher power requirements as well as more inductance.

In the case where the design cannot be considered intrinsically safe, a method of explosion protection is encapsulation. This could be an appropriate method for the drive circuits along with any other high powered circuits. Encapsulation is a method where the circuit board is covered in a resin or compound which prohibits the ignition of the surrounding hazardous environment. Ignition could be caused by sparks or even from a heated surface. These compounds are generally some sort of thermoplastic.

Encapsulation is a very useful method for explosion protection when dealing with high powered electronics, but is not possible to enclose moving parts with this method. This can be problematic since most machinery used in a mine uses a motor to drive some mechanism to complete the given task. Flameproof enclosures solve this problem by enclosing all parts of the device that can cause an explosion, thus prohibiting the potential risk from escaping to the surrounding atmosphere. Since the design is for an aerial vehicle, flameproof enclosures will be considered as a last resort due to the extra weight they introduce to the platform.

Weight is a massive design area for any aerial vehicle, research into different materials will be done. The whole mechanical design of the system will need to closely consider which materials are used. Ensuring light weight, robust and collision accepting materials is crucial to the success of this project. Material selection must also ensure that on impact, no sparks are created with any surface that might be found in a mine.

For any micro aerial vehicle (MAV) motor selection can be tricky, this particular use case however introduces significant constraints due to the need for explosion protection. The motors need to be selected based on their power to weight ratio as well as their electrical power consumption. Inevitably finding a balance between the two will be a very important design consideration, and can prove to be tricky based on what is available off the shelf. Due to the need for explosion protection, brushless motors will be the first option the design looks at, but research into alternative acceptable motors will be done. It is very likely that off the shelf motors might be modified to fit into the explosion protection standards.

After the mechanical design has been modelled and rough aerodynamic capabilities have been deduced, it is necessary to now drive the mechanics with an electronic system. Initial approach would be to distinguish what can be purchased, but because of the specific use case, it might be necessary to design a drive system. This way the circuits can be designed to adhere to the appropriate explosion protection standards. Ensuring the drive circuits are efficient and not power hungry will become important when trying to optimise the flight duration of the drone. Along with the drive circuits research into on board sensors, such as accelerometers and other inertial sensors, including GPS will be required. These will all feed into the control laws to ensure stable flight.

To handle this information and control the aircraft, there will need to be a central processing unit (CPU). This CPU will handle the control of the drone as well as all the information gathered from the sensors.

For an unmanned aerial vehicle (UAV), it is necessary to have a wireless control link. Ensuring reliable communications and a fail case scenario (i.e. losing communications) are both important design considerations. Generally off the shelf components can be found and will be considered for use in the project.

After there is a rough estimation of all the drive circuits and the electronics, a power analysis can be done. The focus will be on maximum current draw as well as estimated regular current draw, these different conditions can give a better idea of what battery capacity and chemistry is needed. Careful monitoring of the battery will be required to ensure safety in the hazardous locations. To reduce complexity and size, battery charging will be an external module. The charging module will be purchased and not designed. Throughout the project limiting power consumption will be a heavily weighted design characteristic.

A large part of the final stages of the project will involve stabilising the platform post collision. This will mean using the available data to implement control theories into the software. Modelling the system is a crucial step to understanding the required control laws for stable flight. This also includes ensuring there is significant data from the on-board instrumentation; any gaps here will need to be rectified in the electronic design.

After the system is functioning to an acceptable level, testing can be done to determine where there is still more work to be done. Conclusions can be based around this information and can feed recommendations into the next iterations of the device.

# Proposed Outcomes

The project will incorporate research and design of a new platform that can meet some of the needs described above.

A successful platform will be able fly and hover stably in normal conditions as well as successfully navigate through a cluttered, close quarter environment. This iteration of the platform will be able to withstand collisions, rectify itself and carry on its desired flight path and complete its mission.

Although the project will involve designing the device to pass explosion protection certification tests, obtaining a certified status will not be a required output for this project.

The drone will require a remote connection to the user. This wireless link will feed information to the and from the aircraft. For the scope of the project that link will be for simple directional control.

For the drone to be a useful platform it will need the ability to hold a payload or sensor pack.

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