Development of an Underground Mine Scout Robot

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Abstract

Despite increased safety and improved technology in the mining industry, fatal disasters still occur. Robots have the potential to be an invaluable resource for search and rescue teams to scout dangerous or difficult situations. Existing underground mine search and rescue robots have demonstrated limited success. Identified through literature, the two primary concerns are unreliable locomotion systems and a lack of underground mine environment consideration. HADES, an underground mine disaster scout, addresses these issues with a unique chassis and novel locomotion.

A system level design is carried out, addressing the difficulties of underground mine environments. To operate in an explosive atmosphere, a purge and pressurisation system is applied to a fibre glass chassis, with intrinsic safety incorporated into the sensor design. To prevent dust, dirt and water damaging the electronics, ingress protection is applied through sealing. The chassis is invertible, with a low centre of gravity and a roll-axis pivot. This chassis design, in combination with spoked-wheels allows traversal of the debris and rubble of a disaster site. Electrochemical gas sensors are incorporated, along with RGB-D cameras, two-way audio and various other environment sensors. A communication system combining a tether and mesh network is designed, with wireless nodes to increase wireless range and reliability. Electronic hardware and software control are implemented to produce an operational scout robot.

HADES is $0.7 \times 0.6 \times 0.4$ m, with a sealed IP65 chassis. The locomotion system is robust and effective, able to traverse most debris and rubble, as tested on the university grounds and at a clean landfill. Bottoming out is the only problem encountered, but can be avoided by approaching obstacles correctly. The motor drive system is able to drive HADES at walking speed (1.4 m/s) and it provides more torque than traction allows. Six Lithium-Polymer batteries enable 2 hours 28 minutes of continuous operation. At 20 kg and ~\$7000, HADES is a portable, inexpensive scout robot for underground mine disasters.

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Chapter 1

Introduction

1.1 Motivation

The 'World Disasters Report 2014' by the International Federation of Red Cross and Red Crescent Societies states that between 2004 and 2013, 1,059,072 people were killed in 6,525 disasters, with a further 1,997,932 directly affected, costing 1,700 billion USD [1]. In the last five years, despite technological advancement, hundreds of lives have been lost at mine disasters such as the Pakistan Methane Explosion (2011), West Virginia's Upper Big Branch explosion (2010), the Soma Mine disaster (2014), the Zasyadko Coal Mine (2015), the Gypsum Mine in China (2016), the Lily Mine Disaster (2016) and the incentive for this system: The Pike River Mine in New Zealand (2010).

Disasters put lives at risk leading to the formation of response teams who are tasked with locating victims and mitigating immediate hazards. These search and rescue teams are dedicated to specific disaster types, often operating in extreme environments which each present unique challenges. Disaster management and specialised equipment, such as a search and rescue robot, can assist in significantly reducing deaths, damage and disruption. They can provide an internal view of disaster sites when conditions are too dangerous or confined for humans. Underground mine robots are still in their infancy however, and require further development to become regularly and effectively deployed at disasters. Chapter 2 explores this development.

The short history of rescue robotic deployment contributes to the motivation for this thesis, due to the short-comings and failures they experienced. The first rescue robot deployment was at the World Trade Centre in 2001 [2]. Since then robotic systems have been deployed 59 times at 48 disaster sites, as of Jan 2016 [2] [3], 12 of those sites were underground mines. This information is summarised in Table 2.1. The mission for four mine disasters were data 1

collection and victim location, while another five were for mine recovery in order to get the mine operational again. At the remaining three disaster sites, search and rescue robots were available but not deployed due to inadequate robots (further discussed in Chapter 2). Of those nine deployments the mission was completed at only three. Success rates higher than 33% are desirable when lives are at risk. Further research and development of underground mine robots aims to improve this statistic.

Additionally, the motivation for this thesis was derived from a recent disaster in New Zealand. The Pike River Mining disaster occurred on the 19th of November 2010. A methane explosion resulted in 29 deaths. Due to the desperation of the situation, four non-mining robots were deployed to investigate: two Australian Water Corporation Robots and two New Zealand Defence Force bomb disposal robots, one of each shown in Figure 1.1. The New Zealand Defence Force bomb disposal systems were deployed first. One short-circuited due to inadequate moisture ingress protection and was restarted but subsequently ran out of battery, the other was obstructed and could not progress. The third and fourth robots were Australian waterworks industry robots, which were also too large to pass through the obstructed tunnel. A fifth, mine specific robot was on route from the United States but recovery operations were terminated before arrival [4] demonstrating rescue robots' general lack of availability. Pike River highlighted the need for bespoke engineered robotic solutions tailored to underground mines.



Figure 1.1: Australian Water Corporation (left), NZDF Bomb Disposal (right)

Technical inadequacies are not the only hindrance for the success of rescue robotics. Rescue robots are only deployed on average 6.5 days after disaster events, their accessibility and affordability is predominantly responsible for the delay [2]. This is significant due to the 48-hour mortality curve following disasters [2]. The deployment of rescue robotics therefore directly affects the chances of locating survivors. Additionally, this may contribute to rescue robots having yet to save a human life. Robots with great construction expenses deployed in dangerous situations incur high risk, which adds to the delay. A low cost, local robotic solution addresses these issues, and significantly increase the chances of saving lives in New Zealand disasters.

1.2 Mine Environment

Mining sites typically contain long rock-walled tunnels covered in mud, dirt and dust, with 114 mm high and 600 mm wide central track rails [5]. Post-disaster conditions are normally very hazardous, comprising some combination of heavy smoke, unstable surfaces, scattered rails, rocks and boulders, grit and gravel, leaked fluids, collapsed beams, slopes and stairs as well as fallen steel grids and electrical cables [6]. Examples of this rough uneven terrain can be seen in Figure 1.2.



Figure 1.2: Underground Mine Disaster Environments

Hard and soft rock require different methods of excavation leading to underground mine layout following various topologies. Mine maps are frequently available to outline the various topologies. They include long tunnels and entrances that are either sloping horizontal tunnels or shaft elevators [7]. An example of an underground mine with shaft access can be seen in Figure 1.3. Mine shaft tunnels contain slopes no larger than 18°, although this does not account for debris and rubble. They can reach maximum depths of 3.9 km [8], where atmospheric pressure can be greater than 1.5 times the surface pressure [9]. The temperature within a mine varies, regularly above 30° C, with the deepest mine in the world reaching 55-60° C [10]. Tunnel height varies between 0.6 and 1.8 m, with an average width of 3 m and a maximum width of 7.3 m [7], which leads to confined spaces after structural damage.



Figure 1.3: Typical Underground Mine Layout

Of twelve mine disaster sites where search and rescue robots were available, three were prohibited entry due to flooding, impassable terrain or explosive gases [2]. Flooding and explosive gases are common in underground mines as they frequently produce pockets of methane and are dug underneath bodies of water. Obstacles infrequently encountered by other search and rescue types include dust saturated atmospheres, heavy dirt and mud exposure, wireless denying tunnels and complete darkness. Non-underground mine robots are incapable of surviving in such difficult conditions and are usually not permitted entry into explosive environments. Specially protected and resistant equipment is therefore required.

1.3 Objectives

The goal of this project is to design a prototype search and rescue robotic scout: "HADES" (Hazard Analysis Disaster Environment Scout). HADES will be designed specifically for underground mine applications. In this thesis "scout" is defined as an agent which explores an area in order to obtain information.

All search and rescue robots are equipped with electronics for operation and sensory equipment for data collection, but few possess locomotion capable of reaching the disaster site and operating effectively within it (Chapter 2 discusses this further). In order to assist in determining the properties required by an underground mine scout, a group of industry experts were consulted (see Appendix A). Discussion revealed existing systems either contain robust mobility or electrical explosion-proof consideration but never a combination of both. The aim of HADES is to merge these features and produce a robot that reliably navigates in disaster situations while protected from hazardous environments. These two core properties of HADES make it unique and form the primary focus. Desirable characteristics to enhance HADES' ability to scout include:

• Adequate hazardous environment protection: To operate in an explosive environment.

- Robust, reliable and effective locomotion: To overcome debris and rubble.
- Chassis ingress protection: To prevent dust, dirt or water damage.
- Communication through mine tunnels: To allow teleoperation from the mine entrance

• Low manufacture cost: To reduce potential loss and provide semi-disposability

• Operate discontinuously for extended periods of time: To travel deep into a mine

• Surface deployment: To utilise existing mine entrance for deployment

• Small weight and size: To transport to and from a mine as well as access confined spaces

Search and rescue robots do not replace disaster response teams, but should instead supplement them when entry into underground mine disaster sites is too difficult or dangerous. HADES is thus designed as specialized equipment to assist disaster response teams by carrying out the following scouting tasks:

- Provide real-time video feed in dark, obscured conditions.
- Measure hazardous gas concentration.
- Monitor environmental conditions
- Traverse rubble and debris.
- Navigate within confined rocky spaces.
- Detect disaster victims.
- Self-monitor to ensure correct operation and fault detection.
- Communicate with survivors.

With these objectives and the quantitative specifications in Section 2.6, a scout robot can be produced with reliable, effective locomotion that is explosion-proof and resistant to an underground mine environment. This achieves the overarching goal of this thesis: to expand the field of search and rescue robotics by developing a novel underground mine scout robot.

1.4 Thesis Structure

This chapter discussed the motivation for the project, with high level objectives defined by the environment in which the system will operate. Chapter 2 introduces related work and similar systems. It explores their relevance to this project and assists in defining specific requirements for HADES' design. Chapter 3 begins the design process, by describing the design and construction of the chassis for an underground mine environment. The method of locomotion and its driving components are then discussed in Chapter 4. Chapter 5 explores the sensors required to scout in an underground mine and Chapter 6 addresses initial design considerations for the communication system. The electronic hardware required to power and control HADES are detailed in Chapter 7, on which the software control architecture, discussed in Chapter 8, is installed. Chapter 9 evaluates HADES' performance in terms of the specified objectives and requirements, while Chapter 10 summarises the major findings and makes recommendations for future work.

Chapter 2

2 Background

The successes and failures of other systems help define the requirements and functionality for HADES and are discussed in this chapter. Robots deployed in, and designed for, underground mines are summarised, with important features highlighted in Section 2.1. Methods of explosion-proofing these robots are investigated along with their sensor configurations in Section 2.2 and 2.4 respectively. The locomotion systems of both standard search and rescue robots and underground mine robots are discussed in Section 2.3. Finally, communication methods for underground mine systems and power sources used by mobile robots are investigated in Section 2.5. The background presented in this chapter is summarised for design considerations in Section 2.6.

2.1 Existing Systems

2.1.1 Deployed Robots

Very few search and rescue robots are dedicated to mine disasters. ANDROS Wolverine v2 [11] is the first and most frequently deployed mine rescue robot, pictured in Figure 2.1. It is one of the only known rescue robots in the world to be officially certified for explosive environments. Of the nine robotic deployments into actual mining disasters, Wolverine v2 was utilised at six of them, being the only available mine-permissible system at the time [2]. It was created by Remotec, who initially designed it for bomb disposal, with modifications later made for mine permissibility. It measures 1.27 m tall and weighs 500 kg, meaning it is not portable nor quickly deployed and therefore not optimal for mine rescue. Remotec President Michael Knopp stated that a smaller more mobile system is currently in development [12]. Wolverine v2 is equipped with rubber tracks for mobility and a robotic arm for environment manipulation. Sensory equipment includes cameras, lighting, atmospheric detectors, night vision and two-way voice communication.



Figure 2.1: Wolverine V2 Mine Permissible Robot

Other deployed systems include the Inuktun VGTV [13] and Defender ROV [14], displayed in Figure 2.2. Not a lot is known about these robots but both drive using tracks and include various sensors such as cameras and gas detectors. Inuktun is small, with dimensions $0.48 \times$ 0.3×0.15 m as it is designed for vertical bore hole entry through the mine ceiling while Defender is $1.5 \times 0.73 \times 1.2$ m entering via the mine's surface tunnel. The large dimensions of Defender and the high strength to weight ratio of its titanium frame supports a manipulator which accounts for approximately half its volume and weight. The robotic arm has 5 degrees of freedom and supports a two pronged claw which is actuated using a hydraulic assembly seen in Figure 2.2. It claims an operating life of 5 hours.

Table 2.1 displays a summary of the deployment of robots in underground mines. The data is summarised from [2]. The Wolverine v2 has been deployed at the largest number of mine disasters. This is primarily because up until 2007 it was the only existing mine-permissible system. Since then various other robots have been employed. The Defender ROV and the

Pike River Mine robots were deployments of systems that were not designed for underground mines. The Defender ROV was too heavy to be lowered into a void were a victim may have been trapped. The Pike River Mine robots experienced multiple failures as mentioned in Section 1.1. Failures have occurred at a number of these deployments as summarised in Table 2.1.



Figure 2.2: Defender ROV (left) and Inuktun VGTV (right)

Tethers are the single largest hindrance to underground mine rescue robots, with three known failures. Tethers are addressed in further detail in Section 2.5.1. Multiple other failures resulted in robots getting stuck in the mine, including two instances where the robot was too large to continue. Each failure is addressed in the appropriate section of this chapter.

Year	Mine	Country	Robot	Failure
2001	Jim Walter No. 5	USA	Wolverine V2	
2002	Barrick Gold Dee	USA	Wolverine V2	
2004	Brown's Fork	USA	Wolverine V2	Too tall*
2004	Excel No. 3	USA	Wolverine V2	Tether Severed
2005	DR No. 1	USA	Wolverine V2	Tether Severed
2005	McClane Canyon	USA	Wolverine V2	Tether Severed
2006	Sago	USA	Wolverine V2	Stuck/Crashed
2007	Midas Gold	USA	Defender ROV &	
			Inuktun	
2007	Crandall Canyon	USA	Inuktun	Stuck & Sensor Fouling
2010	Wangjialing Coal	China	Unknown	
2010	Upper Big Brach	USA	Wolverine V2	
2010	Pike River	NZ	NZDF bomb-squad	Stuck/Short-Circuit,
			& Western Australia	Stuck/Power loss,
			Water Company	Too large*
			robots	

Table 2.1: Robotic Deployments in Underground Mines

* The robot did not fail, but could not proceed

2.1.2 Non-deployed Robots

More recently, Gemini Scout [15] and Minbot [6] were specifically designed and developed for underground mine applications but neither have been deployed (see Figure 2.3). Gemini Scout is 600 mm tall and can operate in water up to 450 mm deep without damage to the electronics. Falling water such as in the Pike River Mine scenario or complete submersion in a flooded mine would impede this system. The Gemini Scout has no stated IP rating but Minbot has an IP67 ingress protection classification. These two tracked systems are equipped with two-way audio, cameras and a set of atmospheric sensors, which Gemini Scout mounts at the top of a 0.6 m tower. A unique feature on Minbot is its telescopic lifting device which can be raised to take sensor measurements. The footprints of Gemini Scout and Minbot are 0.6×1.2 m and $0.75 \times 1.5 \times 0.59$ m respectively. Only Gemini Scout states its battery life, being four hours.



Figure 2.3: Minbot II (left), Gemini Scout (right)

Inspection robot [16] was created by TUBITAK Marmara Research Centre as a four wheeled robot equipped with a variety of electronics for sensing and communicating. It is a large unit but exact dimensions are not stated. Inspection robot contains no real differentiating features but its design considers multiple aspects of explosion-proofing in detail, this is discussed further in Section 2.2.3. A solution that is unique to underground mine search and rescue robots is the GMRI [17]. It includes pneumatic supports to raise and lower its platform as discussed in more depth in Section 2.3.3. It can widen and narrow its back wheels to modify its width between 1.1 and 0.8 m. It is fabricated in metal and carries its cable spool on the robot. Its length and weight are not stated but it fits into a similar size category as Wolverine v2. Neither of these robots, shown in Figure 2.4, state their battery life.



Figure 2.4: Inspection Robot (left), GMRI (right)

The Numbat mine reconnaissance vehicle [18] was designed by the Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) for search and rescue tasks in underground mines. It has never been officially deployed, rather has only been used as a research tool and "never achieved its potential" [19], despite costing millions of dollars. It is tele-operated over a fibre-optic cable and claims 8 hours of battery life. The robot has eight wheels resulting in large dimensions (2.5×1.65 m) and its chassis is completely water resistant. An image of Numbat is displayed in Figure 2.5.



Figure 2.5: CSIRO Numbat Reconnaissance Vehicle

The Lurker robot [20] [21], manufactured by Shandong University of Technology, appears to be smaller than Inspection robot but its dimensions are not stated. It weighs between 15 and 30 kg and is manufactured from materials such as plastics and nylon to avoid metals, for reasons stated in Section 2.2. It features a manipulator, tracked locomotion and an operating
battery life of three hours. The Coal Mine Detection Robot (CMDR) was developed in China by the Beijing Institute of Technology [22] [23]. It includes a small anterior robotic arm, able to grasp and throw or push obstacles aside. Designers of the robot created this facility to deal with electrical wires, tunnel debris and poles blocking the road. Dimensions are not stated, but CMDR is described as 'small' and weighs 50 kg with an operating time of 4 hours. It is equipped with infrared gas sensors to detect methane and carbon. Images of these two robots are presented in Figure 2.6.



Figure 2.6: Lurker-3 (left), CMDR (right)

2.1.3 Summary

All robots but Inuktun are designed for surface entry, the most common rescue scenario. Many systems include manipulators which increase size, weight and complexity. Their large chassis dimensions and total weight limit portability and access to confined underground mine spaces. Additionally, tall robots (with manipulators) are less stable and with reduced locomotion reliability.

The average continuous usage of underground mine robots is four hours (longer for intermittent). Four hours' operating time factors in travel time to the disaster location as well as search and rescue tasks. Underground disaster conditions require environmental resistance with impervious material and component design. To attain this, existing systems are primarily constructed with metals as plastics are inadequate, but this increases weight and cost. Additionally, ingress protection varies among existing robots. This is concerning as flooded environments are common and obstruct designs with sub-IP67 ratings.

2.2 Explosion-proofing

2.2.1 Overview

Explosions occur when there is a coincidence of a flammable substance, an oxidizer and an ignition energy source, all in sufficient quantity [24]. Underground mines are considered hazardous environments because flammable gas, dust and vapour are frequently present with oxygen. Robots contain possible ignition sources and therefore ensuring they are explosion-proof is essential for mine-permissibility. Electric motors are obvious explosion hazards, drawing high power, dissipating heat and possessing sparking contacts (brushed). Further ignition sources include other high power electrical components, high temperature surfaces, static electricity and impact/friction sparks.

Explosion-proofing is the main factor that allows underground mine robots to obtain minepermissible certification. Multiple techniques exist [24], but three are primarily used by robots: flameproof enclosures, purged and pressurized enclosures and intrinsically safe circuitry [6] [16]. Flameproof enclosures do not prevent an explosion from occurring. Instead they contain explosions internally by suppressing energy escape through small flame paths. A flameproof chassis must therefore be able to contain the explosion, limit the escaping energy and prevent igniting the surrounding atmosphere. A purged and pressurized enclosure has had its internal air purged and replaced with positively pressurized inert gas. This prevents flammable gas, dust or vapour in the surrounding atmosphere entering the chassis where ignition sources are present. The New Zealand standard for implementation of a purged and pressurized enclosure is 60079.2:2007 [25]. Intrinsically safe circuitry is designed to limit storage, generation or flow of high power. Limiting energy in the circuit prevents ignition sources reaching flammable gas, dust or vapour. 60079.11:2011 is the New Zealand standard for intrinsic safety implementation [26].

Certified explosion-proof equipment is rated for a hazardous environment level as discussed as detailed further in [24]. The 'Class', is either I, II or III, determined by the type of ignition

source: gas, dust or fibre respectively. As the ignition levels of these sources varies they are often further categorised in group A, B or C by the energy required to ignite them. The 'Division' is the likelihood of explosive concentrations being present, with Div 1 being under normal conditions and Div 2 being under abnormal conditions. Finally, the temperature level (in degrees Celsius) is the auto-ignition temperature. Surface temperatures of a particular piece of equipment should never exceed 80% of the stated value. Many regions require the explosion-proof protection classification be externally labelled to show the type and level of protection applied.

Explosion-proofing is complex, expensive and time consuming so few robots obtain official explosion-proof certification. As a result, publications rarely provide detail on applied techniques. Flameproof or purged and pressurized enclosures are generally applied to motors or chassis, with all exposed electronics made intrinsically safe. GMRI robot was the only exception to this using explosion-proof pneumatic drive motors.

2.2.2 Flameproof Enclosures

Four systems previously detailed utilized flameproof enclosures. Wolverine v2 only had its motors in flameproof enclosures, whereas CMDR, MINBOT and the rocker-type designed a flameproof chassis. CMDR and MINBOT employed seals at flat surface contact points and gearbox axles to prevent energy escaping as seen for Minbot in Figure 2.7. Spaces for flameproof surfaces were mechanically designed into the enclosure. MINBOT encased its batteries in gum as additional sealing, due to insufficient battery space in the flameproof enclosure.



Figure 2.7: Minbot-II's flameproof surfaces

The rocker-type robot installed motors in its landing legs which are flameproof. Flameproof cavities, joints and cable entries were designed into the legs with motor shafts extended to achieve long flame paths. European laws require electrical equipment in flameproof enclosures to be turned off if hazardous gas concentrations are detected [17]. That is impractical for rescue robots. In addition, the tensile strength necessary to withstand internal explosions significantly increases the weight of certified enclosures.

2.2.3 Purged and Pressurized Enclosures

The Turkish Inspection robot, Luker-3 and Numbat contain purged and pressurized equipment, filled with nitrogen. The Inspection robot's pressure is initially 2 bar (200 kPa). If the pressure falls below 1.1 bar (110 kPa) the robot de-energizes. Additionally, the Inspection robot includes a failsafe mechanical pressure switch which de-energizes the systems if they are not shut down by the CPU. This robot is unable to increase pressure during operation and only attempts to maintain it through sealing.

Lurker-3 also maintains a positive pressure of nitrogen gas through a high pressure gas tank, shutoff valves, a safety valve, solenoid valve and pressure sensor all incorporated into the control system. O-ring seals maintain internal pressure while a sensor monitors pressure

level. If it falls below 200 Pa, Lurker-3 opens the solenoid valve to increase pressure from the tank. If it ever falls below 100 Pa the system is de-energized. The Numbat robot is also nitrogen flooded but the literature provides no further information on its purge and pressurization system.

2.2.4 Intrinsic Safety

Intrinsic safety is only necessary for circuits not already contained within flameproof or purged and pressurized enclosures. Most electrical components, such as thermocouples, LEDs and resistors are inherently safe as they do not store or generate greater than 1.5 V, 100 mA or 25 mW [27]. If a fault occurs, power draw can become hazardous and therefore an 'intrinsic safety barrier' is required. Power resistors, Zener diodes and fuses are incorporated into an intrinsic safety barrier circuit to prevent over-voltages and over-currents. An example of such a circuit is displayed in Figure 2.8.



Figure 2.8: Intrinsic Safety Barrier Picture

Other components such as mechanical contacts, large inductors and capacitors, or batteries are inherently hazardous due to sparking or high energy storage and generation. Circuits including these components cannot be deemed intrinsically safe and must remain behind the aforementioned enclosure protection techniques. Very few underground mine robots mentioned the use of intrinsic safety and those that did gave no detail about its implementation.

2.2.5 Summary

Typical robotic electrical components are inherently hazardous. There are various classification levels for protecting hazardous components, but for coal mines the highest level is required. While several protection techniques exist, robots generally employ flame-proofing or purge and pressurisation for their chassis. Robots with a metallic chassis require no additional components to apply flame proofing but are large, heavy and mechanically complex. Purged and pressurized chasses are typically smaller, lighter and portable with greater hazardous environment classifications. Components not contained in a protected chassis apply intrinsic safety. A summary of robotic explosion-proofing techniques is displayed in Table 2.2.

Robot	Technique
Wolverine V2	Flameproof
Gemini Scout	Flameproof
Luker-3	Purge & Pressurisation
MINBOT	Flameproof
CMDR	Flameproof
Rocker-Type	Flameproof
GMRI	Pneumatic Drive
Inspection	Purge & Pressurisation
Numbat	Purge & Pressurisation
Inuktun	n/a

Table 2.2: Summary of Robotic Explosion-Proofing

2.3 Locomotion Systems

2.3.1 Tracks

Mine disaster rescue robots are required to navigate the hazardous conditions described in Section 1.2 and pictured in Figure 1.2. Tracked locomotion is a common system employed to traverse rough terrain, such as snowmobiles or military tanks. The shape, size and length of a track determines the friction and traction that it provides. Wolverine v2, utilizes a standard dual track configuration. It has successfully navigated up an 18° slope but has recorded an instance of de-tracking, rear drive wheel deflating and crashing [2].

Several degrees of freedom are commonly integrated into continuous track locomotion systems in order to improve their rough terrain mobility. Gemini Scout opted for two passive degrees of freedom. A single central joint, as seen in Figure 2.3, allows the front and back sections of the chassis to rotate in both the pitch and roll axes relative to each other. This eliminates the need for a suspension system as the chassis twists and contorts in order to adapt to uneven terrain. This link significantly expands its mobility but also produces more complicated kinematics as neither of the two degrees of freedom can be controlled. Gemini Scout can reach a maximum speed of 5.6 km/hr.

Lurker, MINBOT and CMDR implement active tracked arm degrees of freedom. They access more motion patterns to facilitate movement over uneven terrain. MINBOT also includes an active suspension system. These modifications specifically assist MINIBOT to traverse stairs and trenches. The robot's length can increase by lowering its arms for crossing larger cavities. By raising them, better grip of obstacles can be obtained. Lurker reaches speeds of 1.2 m/s and can climb slopes of up to 38° (depending on the surface). Lurker's arms allow the ability to cross ditches of 490 mm and surmount obstacles up to a maximum of 320 mm. In comparison, MINBOT and CMDR attain maximum speeds of 0.5 m/s and 0.83 m/s respectively. MINBOT crosses ditches up to 400 mm wide and climbs obstacles 500 mm high while CMDR climbs slopes up to 30°. Reliability issues and failure have been reported for the tracked systems of MINBOT, Wolverine v2, Inuktun and a robot called USAR Whegs [28] (discussed further in the following section). Grit and gravel penetrate teeth causing lock ups, damage to links/teeth, driving wheel engagement failure, track failure or just significantly reducing the lifespan of the equipment. Wolverine v2 and USAR Whegs both experienced de-tracking during operation but no further information is known. A field mobility test evaluated MINBOT's ability to move up stairs and slopes, through water, along coal roads, over unstructured ground and down narrow lanes. Testing at a 'rescue training field' followed by the Changgouyu Coal Mine in Beijing demonstrated that the robot is very mobile, but tracks were damaged and the transmission system failed occasionally. Development improved reliability by tightening the tracks and reinforcing its wheel engagement which enhanced resilience but ingress was still not eradicated and the publication [6] stated further locomotion development is required.

2.3.2 Legs

LittleDog [29], shown in Figure 2.9 is a small system created by Boston Dynamics that weighs only 2.85kg and is battery powered with a runtime of up to 30 minutes. This quadruped was designed to develop algorithms and control systems for rough terrain. Each of its legs is powered by three electric motors giving up to 12 degrees of freedom and a wide range of motions. A spherical textured rubber foot at the end of each leg provides traction at any angle.



Figure 2.9: Little Dog

Background

LittleDog is a platform for development as opposed to a field-ready search and rescue robot and is thus useful to highlight the issues with its locomotion. One report noted that extended operation of LittleDog requires frequent maintenance and repair due to the complexity of the system [30]. Control issues include: foot slippage, unintentional collisions, modelling errors and sensor errors [31]. Average horizontal velocity was recorded by one team at only 0.112 m/s with a maximum of 0.2 m/s across uneven terrain [32]. Legged locomotion is not inherently slow though. The quadruped Cheetah, also created by Boston Dynamics, broke the world record for legged locomotion by exceeding 46 km/hr [29]. This speed is only possible on completely flat terrain via a tethered power supply. LittleDog and Cheetah are different sizes and prices but are similarly constructed and have no resistance to dust, dirt or water.

HyQ2Max [33] is a robot recently published by Istituto Italiano di Tecnologia (IIT) which focuses on the robustness, self-righting and manipulation aspects of legged locomotion (see Figure 2.10). HyQ2Max is upgraded from its original design called HyQ, and can mount two robotic arms for manipulation. It is robust and reliable against impacts and dirt by storing all sensitive components inside its frame structure that is constructed from aluminium, fibre glass and Kevlar. There are 12 hydraulically actuated joints with up to 270° motion and 250 Nm torque, providing effective rough terrain locomotion. The robot is tether powered with battery packs under development which will increase its size and weight. HyQ2MAX currently weighs 80 kg with its robotic arms adding 26 kg. As HyQ2MAX is a large torque controlled hydraulic robot, poor energy efficiency is stated as a challenge in addition to expensive custom-made parts.



Figure 2.10: HyQ2MAX quadruped

2.3.3 Standard Wheels

Standard round wheels operate most effectively on flat man-made surfaces but do have application on rough terrain. Four mine disaster robots discussed in Section 2.1 were equipped with standard round wheels, GMRI, shown in Figure 2.4, is one of them. It is equipped with two pneumatic supports, controlled through 2-state valves by a compressed nitrogen tank. These supports assist rough terrain mobility and ensure the system is horizontal irrespective of floor conditions. They operate independently, move slowly and are only positioned at discrete heights. The design surmounts 200 mm solid obstacles, 100 mm liquid obstacles and slopes of 30°.

Marmara Research Centre's Inspection robot, Defender ROV and Numbat also implement standard round wheels. The Inspection robot seen in Figure 2.4, has a wheel radius of 400 mm, selected to overcome the height of the mine railway. It utilizes bevel and helical reduction gears to reach the desired output torque all inside an explosion-proof enclosure. Developers justified wheels as tracked systems are considered more complex and difficult to explosion-proof [16]. Little information regarding the Numbat and Defender ROV has been published. The first has eight wheels and a large footprint $(2.5 \times 1.65 \text{ m})$, reaching speeds of up to 2 km/hr. Defender ROV climbs stairs 200 mm high at 45° with a top speed of 3.25 km/hr. It has six independently driven wheels that include suspension.

A small rocker-type mobile platform, displayed in Figure 2.11, was designed by students at China University of Mining & Technology to evaluate its locomotion in coal mine disaster zones [34]. Ground contact for all four independently driven wheels is achieved using a differential bevel gear and a passive rocker suspension system. Testing on a laboratory obstacle course and complex outdoor terrain bestrewn with bricks and stones showed the robot could cross 260mm high obstacles but larger debris impeded progress. Four-wheel drive provided improved performance over track-type robots of the same size with rocker suspension only improving adaptation to uneven terrain.



Figure 2.11: Rocker-type (four-wheel mobile platform)

SUVs, pickup trucks and monster trucks use large tyres and high powered engines to obtain off-road performance. Load haul dump (LHD) trucks are one example. Found in 75% of all underground mines, they scoop, load and transport extracted ores from the deposit stope to the crushing plant. The centre of their chassis is articulated in the yaw axis with either treaded or smooth tyres that are occasionally fitted with chains [35]. They operate in an undamaged mine environment where pathways are clear of rubble and debris. Wheel size determines the maximum climbable obstacles and these vehicles utilize large diameter wheels to achieve that.

2.3.4 Spoked-wheels

Spoked-wheels are a recent hybrid development which combine the benefits of both wheels and legs. Figure 2.12 shows an example of a spoked-wheel design. Large, evenly spaced spokes overcome obstacles through discontinuous ground contact. Simultaneously, they maintain speeds more closely comparable to standard wheels and significantly greater than legged robots [36]. Typically, a round wheel can only climb obstacles less than its radius in height while spoked-wheels surmount obstacles 1.5 times their wheel radius [37]. An additional benefit is the ability to move effectively through puddles of water as well as during submersion. Spoked-wheels come in a range of different shapes, sizes and materials depending on application as demonstrated by the following robots.



Figure 2.12: Example of a spoked-wheels design

Whegs-I [37] [38] the first robot to implement spoked-wheels, was inspired by the gait of a cockroach with a top speed of 5.5 km/hr. All six of its three-spoked wheels-legs are controlled by a single motor which reduces the weight and provides all on-board power to any single leg. Cockroaches modify their body posture while climbing over a barrier which Whegs-II [39] incorporated by adding a central active body flexion joint. This prevented the instability of high centering. Whegs I and II are shown in Figure 2.13.



Figure 2.13: Whegs II (left), Whegs I (right)

RHex [40] [41] [42] is one of the earliest spoked-wheel designs, which drew inspiration from Whegs. It is 200 mm long with a single curved, flexible leg on six wheels which mimics the gait of a cockroach when synchronized with a control system. The traction pads perform a slapping motion on the ground to grip and pull itself forward. The cockroach gait ensures at least three of its six legs have ground contact and enables RHex to perform a small jump.

Testing showed it could overcome small sticks, stones and debris but its slapping locomotion stirred up dust which interfered with the sensing platform [2].

Whegs evolved into three variations: Lunar [43], USAR [28] and Seadog Whegs [44]. Each of these are designed for different applications. Lunar Whegs is designed for low gravity environments and contains three spokes per each of its six wheels as seen in Figure 2.14. Its body joint builds on the actuated design of Whegs-II, incorporating a rack-and-pinion mechanism for steering. Concave shaped feet for increased surface area prevent sinking into loose substrate.



Figure 2.14: Lunar Whegs (left), USAR whegs (right)

USAR Whegs was the next iteration, incorporating four spokes on four wheels as well as tracked locomotion. Each wheel is manufactured from carbon fibre composite in a hollow curved P-shape seen in Figure 2.14. USAR Whegs can uniquely drive on its tracks by removing its wheels. This reduces size, but also reduces performance and must be done manually before deployment. The spoked-wheels surmount obstacles up to 152 mm high. It reaches speeds of 1.9 m/s with tracks, and even higher speeds with spoked-wheels. A major benefit of hybrid track-wheel locomotion is a reduction of bottoming-out situations as tracks prevent the chassis from getting stuck on terrain. The four-wheel configuration is the most common and reduces mechanical complexity and size but can cause uneven gait which USAR Wheg's control systems compensates for. The rack-and-pinion steering was replaced

with a differential drive that slightly reduced power-to-weight ratio but significantly improved the turning radius facilitating manoeuvring in more confined spaces.

SeaDog is the latest variation of the Whegs family with beach applications. Similar to USAR Whegs, SeaDog contains four hollow spokes on four wheels shown in Figure 2.15. Spokes are shaped as inverted pyramids with wide outer surface areas to facilitate travel over loose compressible substrate and through water. While other Whegs systems utilized Ackermann steering, this supposedly led to difficulties during the waterproofing process [44]. A two-motor differential drive was implemented instead. In order to improve aquatic locomotion, an actuated tail was included to provide additional propulsion and improve stability. The radius of Seadog's wheels is 190 mm allowing it to reach a maximum speed of 2.23 m/s and climb obstacles as high as 480 mm. This is increased from 400 mm by its tail, which acts as a balancing mechanism to shift its centre of gravity.



Figure 2.15: SeaDog transitioning from land to water

Other non-underground-mine four-wheeled spoked robots include ASGUARD [45], USAR Mother [46] and Loper [47] [48], all similarly sized (~0.5 x1.0 m). ASGUARD is a five-spoked robot created by the German Research Centre for Artificial Intelligence, seen in Figure 2.16. It was created for USAR as well as security and surveillance applications. The

ability to climb stairs is one of its primary objectives. Each of its wheels is individually actuated for differential drive steering. The radius of each spoke is 22 cm, designed with crumple zones and shock-absorbing tips. This allows it to reach speeds of approximately 2 m/s. A passive pivot in the roll axis, integrated into ASGUARD, serves as an elastic spinal column to increase ground contact. This feature improves its ability to adapt to uneven terrain without the cost and complexity of an active suspension system.



Figure 2.16: ASGUARD robot (left), Mother robot (right)

The Mother robot developed at Victoria University of Wellington took inspiration from ASGUARD. It also incorporated the passive roll pivot and a five-spoke design. It was considered the best compromise between smooth horizontal travel and maximum obstacle climbing (given the spoke shape and material) [49]. A photo of the Mother robot is shown in Figure 2.16.

Loper was developed to maximize stair climbing speed on a wheeled robot. Figure 2.17 shows its characteristic tri-lobe wheels. It out-paces other spoked-wheel platforms with speeds of 8 km/hr but is generally safely operated at 3 km/hr. The spokes are 406 mm in length allowing Loper to overcome stairs/obstacles as high as 200 mm. These wheel-legs are constructed from Buna-N rubber and polyethylene to help minimize vertical oscillation. Loper has no pivot, instead an aluminium plate floats inside a flexible steel rod frame to reduce rigidity of the chassis.



Figure 2.17: Loper

Ratasjalg [50] is the only known robot to add degrees of freedom to the spoked-wheel itself. Six spokes are used on two front wheels, as shown in Figure 2.18. Each spoke rotates at the base allowing Ratalsjalg to transform between spoked-wheels and standard round wheels, accessing the benefits of both. A single servo controls the spokes' position and rear caster wheels can be attached for balance.



Figure 2.18: Ratasjalg spoke-changing robot

2.3.5 Summary

A summary of the locomotion performance characteristics and relevant physical properties can be found in Table 2.3. An 'X' indicates that the value was not stated or reported for that particular robot.

While recent years demonstrate significant development, legged robots are not yet suited for search and rescue applications. Their custom parts, high complexity and complicated control are expensive meaning deployments into unpredictable disaster situations are high risk. In addition, legged robotic developments are primarily research tools with insufficient battery life and inadequate resistance to dirt or water.

Round wheels, with effective tread and high motor power can overcome obstacles but are still limited by shape. Competent performance over rough, uneven terrain necessitates suspension systems which complicate explosion-proofing and significantly increase cost. Tracked locomotion exhibits explosion-proofing difficulties with multiple robots demonstrating unreliability and failure. Cost and complexity are disadvantages of tracked locomotion also noted. Spoked-wheels combine wheels and legs providing benefits from both. They suit the long distances and rough terrain of underground mines and their simplicity avoids typical problems encountered by tracked locomotion. Spoked-wheels can also be driven independently to produce zero radius turning circles in tight spaces of collapsed mines.

During a disaster a mine can be structurally damaged and the equipment can break into pieces. Additionally, the rock composition and the structural beams vary between mines. As a result, it is difficult to predict the size and shape of debris and rubble. Obstacles that can be predicted are possible stairs and the track rail that runs through the mine. The maximum British standard rail height is 114 mm [5] and maximum stair height in the New Zealand build code [51] is 220mm. As spoked wheels can climb obstacles 1.5 times their wheel radius, the wheel diameter lower limit should be at least 293 mm (~300 mm) to ensure both of these obstacles can be traversed. However it should be considered that debris and rubble may pose obstacles greater than 300 mm.

Degrees of freedom for the chassis are proportional to complexity, component count and power consumption (if active) and inversely proportional to the improvement of rough terrain locomotion. Therefore, the largest gain comes from the first degree of freedom, with additional joints increasing ingress potential.

 Table 2.3: Locomotion Summary

2.4 Sensors

A comprehensive list of sensory and protective equipment on robots designed for access to mines is discussed in this section and summarized at the end of this section in Table 2.5.

2.4.1 Environment

Gas detectors carry out one of the essential tasks of a rescue robot: scouting and monitoring the environment, and are therefore common to all mine-ready robots. Gases commonly found in underground mines are: nitrogen, oxygen, carbon dioxide, methane, carbon monoxide, nitric oxide, nitrogen dioxide, sulphur dioxide, hydrogen sulphide, and hydrogen [52]. These gases including their properties and effects on humans are summarised in Table 2.4.

Methane and carbon monoxide are found in high concentrations and should be strictly monitored. Methane, typically found in coal mines, is highly flammable. It is produced during the coal-forming process and stored in explosive pockets within coal beds. Carbon monoxide is produced after explosions from coal combustion at high temperatures and is extremely harmful to the respiratory system [22].

Electrochemical sensors are most commonly used for monitoring these gases. They employ chemical reactions to provide gas concentration measurements. As these sensors require direct contact with explosive mine atmospheres explosion-proofing is essential. Infrared (IR) gas sensors avoid this issue as they emit infrared radiation, characteristic wavelengths of which are absorbed by the target gases. These sensors are expensive and do not detect nitrogen, oxygen and noble gases [17]. Temperature and pressure should be monitored to accurately measure gas concentration. Additionally, when temperature and pressure are high, the atmosphere contains large amounts of energy and therefore a higher explosion probability [24]. Many robots monitor temperature and pressure values, as displayed in Table 2.5.

Gas (symbol)	Explosive	Source(s)	Toxic Effects	TLV (PPM)*	
Air	No	Atmosphere	-	-	
Nitrogen (N2)	No	About 4/5th of atmosphere.	Asphyxiant from oxygen deficiency	-	
Oxygen (O2)	No	1/5th of atmosphere	Oxygen deficiency	-	
Carbon Dioxide (CO2)	No	Coal oxidation. Rotting timbers. Breathing, blasting, explosions, fires, diesel engines	5% conc. produces shortness of breath and headaches. 10% con. can produce death due to oxygen deficiency	5,000	
Methane (CH4)	Yes 5%- 15%	Coal and rock strata, carbonaceous shale, and rotting mine timbers	Oxygen deficiency	-	
Carbon Monoxide (CO)	Yes 12.5- 74%	Diesel engines, fires, explosions, and blasting	High conc. can produce nausea, vomiting, collapse, coma and death	50	
Nitric Oxide (NO)	No	Blasting or burning of dynamite, diesel engines, and electrical discharge.	Irritation of eyes, nose and throat. Drowsiness and unconsciousness	25	
Nitrogen Dioxide(NO2)	No	Blasting or burning of dynamite, diesel engines, and electrical discharge.	Irritate eyes and mucous membranes and cause pulmonary irritation. Corrosive when inhaled – cause severe burns	5	
Sulfur Dioxide (SO2)	No	Fires involving iron pyrites. Some diesel fuels	Respiratory irritation. Corneal burns	5	
Hygroden Sulfide (H2S)	Yes 4.5%- 45%	Rotting mine timbers, mine water and rock strata in some mines	Irritation of eyes & respiratory tract. May cause immediate coma & respiratory paralysis	10	
Hydrogen (H2)	Yes 4.1% -74%	Fires, explosions, battery chargering. Water or steam contacting hot carbonaceous material. Strong acids on metals	Oxygen deficiency	-	

Table 2.4: Summary of Mine Gases (adapted from [53])

2.4.2 Video

Image sensing is primarily required for tele-operation and to provide an internal view of the disaster site. All previously mentioned underground mine robots include at least one forward mounted camera. A single camera significantly limits the field of view and the amount of information gathered, which can mean that important details are missed in deployments [2]. Multiple cameras as well as pan and tilt functionality are solutions to increase the field of view.

Infrared and RGB cameras are used on underground mine robots for different reasons. IR cameras do not require lighting to capture images in complete darkness and their infrared spectrum facilitates searching for human body heat or remains of an explosion. Colour delivers important visual clues about the environment that IR cameras are unable to provide but which RGB cameras can. In addition, RGB cameras have higher resolution which allows smaller details to be easily discerned. Electrical equipment such as lighting are unlikely to be operational after an underground mine disaster. Therefore, supplementary lighting is required to facilitate RGB cameras. In darkness, even with supplementary lighting, RGB cameras do not generally capture enough detail or provide the depth perception information achieved by IR cameras. The Midas mine is evidence for this, as a robot was looking in the right area for the victim's body but had inadequate illumination to see it at distance [2].

RGB-D cameras introduce relatively new technology that improves depth perception through range measurements for individual image pixels. A projected infrared laser grid combined with an RGB camera produces images that include both colour and depth information. These devices have larger dimensions than individual cameras but provide superior performance. The Xbox Kinect was one of the first released to the consumer market with a second version released in 2014. These depth cameras are becoming increasingly common on robotic systems, but installation on an underground mine robot is novel.

The resolution of a camera is important when attempting to gather information about a disaster site. As colour cameras are extremely common, the cost for high resolution images

is small with 1080p and 4K devices widely available. Equivalently priced IR cameras only provide 480p resolution and HD devices are expensive. For the same reason, the Field of View (FOV) for IR cameras is generally low in comparison to RGB and depth cameras, but can be widened with the appropriate lens. USB is the most common way to interface a video device, but several camera modules can be purchased which employ Camera Serial Interface (CSI).

MINBOT discovered RGB camera inadequacies by trial and error as standard mining lamps initially installed on MINBOT [18] were insufficiently bright. Depth perception for operators was significantly reduced and MINBOT crashed into walls of the underground mine resulting in the deployment of IR replacements to remedy this issue. Inuktun VGTV Xtreme, a water industry robot, was deployed into Midas Gold Mine in 2007. It also struggled with lighting and failed its mission [2].

Audio on robots provide operators with aural clues about events in the mine, such as the determination between slippage and damaged motors. It also assists in locating survivors or detecting gas leak sounds. Many cameras feature a built-in microphone but two-way audio is important for communication with survivors and explosion-proof speakers are extremely rare. The majority of underground mine robots include two-way audio as shown in Table 2.5.

2.4.3 Positioning

The importance of sensor positioning is often noted in the literature. Multiple gases in underground mines have lower molecular mass than air and their concentration at ground level would not necessarily be indicative of the high ceiling concentrations [6]. Two mechanisms have been used to raise the sensor platform to a suitable height; linear actuators and scissor lifts. Robots containing manipulator arms generally position sensors near the end effector, rendering dedicated raising mechanisms obsolete, while two systems mount sensors on raised platforms.

MINBOT's first prototype used a scissor lift and a linear actuator in its second. This enabled a height of 1500 mm to be reached. Linear actuators are lighter than scissor lifts while simultaneously providing yaw axis rotation for multi-directional sensing. The GRMI robot incorporates a jib which sucks air in from a greater height removing the need to raise its sensor platform.

Robot	Camera Number	Camera Type	Camera Positions	Lighting	Gas Sensors	Audio	Тетр	Pressure
Wolverine v2	2	RGB/IR	-	Yes	Yes	Two-way	Yes	-
Defender ROV	6	RGB	-	-	Yes	Two-way	Yes	-
Gemini Scout	2	PTZ RGB + IR	Front	Yes	Yes	Two-way	Yes	-
Lurker	2	RGB + IR	-	-	Yes	Microphone	-	Yes
MINBOT	4	RGB + IR	Front, Back, Top, Bottom	Yes	Yes	Two-way	Yes	-
CMDR	1	-	Front	Yes	Yes	Two-way	Yes	-
Rocker-Type	-	-	-	-	-	-	-	-
GMRI	2	-	Front, Rear	Yes	Yes	-	Yes	Yes
Inspection	3	Greyscale + IR	Front, Rear	-	Yes	-	Yes	Yes
Numbat	4	-	Front, Mid, Rear	-	Yes	Two-way	Yes	Yes
Inuktun	3	Colour	Front, Mid, Rear	Yes	-	-	-	-

Table 2.5: Sensor Summary

2.4.4 Summary

Underground mine search and rescue robots employ a wide range of sensors. Cameras and gas sensors are crucial. Colour and infrared cameras have respective trade-offs with infrareds providing better teleoperation in darkness, however combining both is most beneficial. Number and positioning of cameras affects the volume of information gathered with multiple cameras and directions recommended. All robots installed anterior cameras for teleoperation, with rear cameras second priority and centrally positioned cameras (top, bottom or sides) the least common. Each robot mounted on average 2-3 cameras, although the type of camera is

infrequently stated. As discussed in Section 2.5 communication in an underground mine is difficult. Therefore, communication bandwidth and storage space are important considerations which pose constraints on the number of cameras and maximum resolution of video files.

Ten gases are most commonly found in underground mines and all should be monitored. Infrared sensors are prohibitively expensive and should not be included. Electrochemical sensors are however, cheap and widely available. Other typically mounted sensors include temperature, pressure and humidity. Elevated sensors should be considered but not should inhibit reliable locomotion. Two-way audio is common on existing systems and is employed to communicate with survivors.

Sensor reading degradation is a likely problem in underground mines due to dust, dirt, mud and smoke. Publications do not mention any form of self-cleaning mechanism, despite at least one recorded instance of robot reinsertion into a mine due to mud fouling the sensory equipment [13]. Protection and self-cleaning mechanisms should be investigated to prevent compromising sensor data.

2.5 Communication & Power

2.5.1 Tethers

Tethered systems dominate all areas of rescue robotics for power and communication, but their restrictive nature and inefficiency is well documented. Tether damage has caused 30% of rescue robot mission failures [2] and 43 % of underground mine failures, as displayed in Table 2.1. The World Trade Centre disaster data shows tether managers of rescue robots had to pull, flip or otherwise manipulate the tether 7.75 times per deployment to prevent tangle [2].

All rescue robots have difficulty with tethers as they catch and snag on rubble and debris caused by disasters. Underground mine systems experience further problems due to the long tunnels they have to travel down which very quickly increased the weight and therefore drag

of the cable. Robotic tethers are used in all known underground mine systems except the Defender ROV as it is difficult to guarantee wireless communication reliability and range [2].

2.5.2 Wireless

Wireless communication in underground mines is difficult. Research shows higher frequency signals travel better through air but lower frequencies propagate further through ground and soil [54], thus air-soil boundaries cause reflection problems. Tele-operation in this environment was achieved with Load Haul Dump (LHD) trucks but is limited to line of sight [35]. Portable wireless networks are short ranged as poor electromagnetic wave propagation in tunnel-like structures results in severe attenuation and poor reliability [6]. Reliable communication over large distances is often achieved with large antennas and high power transmitters, but this consumes significant quantities of power. Attempts are being made to increase the range between the transmitter and receiver through channel modelling [55] [56] but multi-nodal networks are currently the most effective technique to increase the range and reliability of wireless networks.

Gemini Scout, CMDR and Lurker contain supplementary wireless communication, but none have been officially deployed. The Gemini Scout utilises the 2.4 GHz band to achieve the high data rates required for video and audio streams, but 900 MHz is also incorporated to attain greater range. Lurker robot uses the 2.4 GHz band for the same reason but its wireless access point also operates on the 5 GHz band. CMDR robot uses a combination of wireless bands as well. The 915 MHz band provides a line of sight range of 4500 m while its 1.2 GHz provides 10 km line of sight. Coal Mine Surveillance robot initially attempted wireless communication with a Bluetooth module but its short range limited its effectiveness. This was then replaced by a ZigBee module which negates this issues.

The ZigBee IEEE 802.15.4 protocol [57] is popular due to ultra-low power, unlicensed 900 MHz and 2.4 GHz bands, and reliable, secure links. They accommodate one master and up to 254 slaves with line of sight transmission range between 10-100 m, extended to 1-3 km

by increasing transmission power. Digi International created XBee modules which utilize this standard on a small, cheap device [58]. Several papers have designed a network for use underground with successful simulations [59] [60]. Practical implementation of these networks in an underground mine is untested however, and more experimentation is required.

2.5.3 Power Systems

When power is not supplied via copper cable, a portable power supply is required. Not all publications identify the battery type. Lithium-Polymer (Li-Po) battery packs were used by The Mother Robot, Lurker-1 & 3 and ASGUARD. MINBOT and Gemini Scout used Nickelbased, Inspection robot incorporated Valve Regulated Lead Acid (VRLA) and Loper included Lithium-Ion batteries. The high energy density of Nickel and Lithium batteries makes them desirable for electric vehicles. Nickel batteries have longer life cycles but cost more than Lithium batteries [61].

The distance from the mine entrance to the accident site can be greater than 1500 m [6] [62], doubled for a return trip. Rough terrain puts an even larger load on the motors. Battery powered systems need strategies to maximise battery life and operating time. Deployment of the New Zealand Defense Force's robot into the Pike River Mine in 2010 is an example where a robot was lost due to battery energy depletion [2]. Robotic systems have been operated for close to 24 hours in mining related disasters. This is significantly longer than other disaster types where robots are usually inserted for short time periods in multiple locations rather than penetrating deep into a mine [2]. Large battery capacities and minimal power consumption is thus required into to achieve this.

2.5.4 Summary

All existing underground mine systems have employed tethers. Tethers however, produce too many issues for reliable communication or power, irrespective of (copper or fibre optic) design. Therefore, communication systems capable of wired and wireless mediums are desirable as exhibited by various underground mine robots. Their deployment is via a tether, transitioning to wireless if problems are encountered. As the communication distance is large, mesh networks provide improved range and reliability with sufficient bandwidth to support sensor and command data. To enable wireless operation, batteries are required with Lithium Polymer being the most frequently incorporated. The communication systems and power sources are summarised Table 2.6.

Robot	Tethered	Wireless	Battery
Wolverine V2	×	-	n/a
Defender ROV*	-	×	Lead Acid
Gemini Scout	×	×	Nickel-based
Lurker	×	×	Lithium-based
MINBOT	×	-	Nickel-based
CMDR	×	×	n/a
Rocker-Type	×	-	n/a
GMRI	×	-	Lithium & Nickel-based
Inspection	×	-	Lead Acid
Numbat	×	-	n/a
Inuktun	×	-	n/a
Mother Robot*	-	×	Lithium-based
ASGUARD*	×	-	Lithium-based
Loper	×	-	Lithium-based

Table 2.6: Summary of Communication Methods for Underground Mine Robots

Note: **Not underground mine systems,* n/a = information not available

2.6 Specifications

The successes and failures of underground mine robots enable an informed design for HADES resulting in both similarities and differences compared to existing systems. HADES is a scout, designed for surface entry into mines. Thus, environmental manipulators are not required. Without a manipulator, the robot size and weight is reduced dramatically, restricted to $1.0 \times 1.0 \times 0.5$ m (L × W × H). The total weight is accordingly limited to 20 kg for portability, as HADES should be carried by a single operator. As internal temperatures can exceed 30° C due to external temperatures (see Section 1.2), the chassis should be monitored and maintained below 50° C. IP65 is specified to manage dust and water. As mentioned in Section 1.2 underground mines are saturated with dust, dirt and mud, therefore HADES should be buoyant to overcome flooded areas and not sink to the bottom of muddy water

where vision is obscured. As a result, IP67 testing should be carried out for floating and limited submersion in flooded areas, as well IP65 for water splashes.

Spoked-wheel locomotion will be employed as a compromise between high speed and rough terrain manoeuvrability with the ability to paddle in water. HADES should travel at walking speed (1.4 m/s) on land to keep up with humans and cover 4 km during operation as required by typical surface entry robots. At 1.4 m/s (5 km/hr), it would take just under an hour for travel along the access tunnel. With an hour for continuous scouting, this totals a required operating time of two hours. A roll axis pivot is included in HADES' design to increase adaption to rough terrain but restrict chassis complexity and ingress.

Operation is intended within the most hazardous environment. Therefore, Class 1 Division 1 hazardous environment classification is desirable designed in accordance with New Zealand standards. Mechanical properties of flameproof enclosures are challenging and increase weight so purge and pressurization will be applied according to standard AS/NZS 60079.2:2007. The chassis itself will be the pressurized enclosure which requires the application of sealing techniques. Any electronics, such as sensors, which cannot be contained within the enclosure will be designed as intrinsically safe in accordance with AS/NZS60079.11:2011.

HADES will include a variety of sensors to gather disaster site information. Four cameras, capable of infrared vision will be mounted in all four horizontal directions to ensure vision in darkness. Two headlights and an anterior RGB camera will provide colour information and assist with teleoperation. Sensors will measure temperature, pressure as well as the concentration of ten of the most common underground mines gases. All ten gases are never present simultaneously so a modular sensor platform will be designed. This eliminates intrinsic safety on individual sensors and allows operators to select the most appropriate sensors. In addition, a range of internal sensors will be integrated for system self-monitoring. This will enable HADES to detect and prevent problems with power distribution or internal conditions and provide motion feedback for the control system.

Operation will be primarily wireless for prototyping with the ultimate goal of transitioning to a wireless node mesh network, completely unrestrained by a tether. In order to achieve this, wireless nodes should be stored on board for deployment within the mine. The network range should exceed 4 km with sufficient bandwidth to support a video feed, two-way audio, control commands and sensor data. Without reliance on a tether, the robot will be battery powered by Lithium Polymer cells. The system will be designed to integrate and interface with the XBee communication nodes but is developed separately [63].

Chapter 3

3 Chassis Design

As discussed in Section 1.2, a post-disaster underground mine environment poses a number of challenges. There may be a high possibility of falling debris, scattered construction material and wiring, and partial collapses that significantly obstruct the mine tunnel. The robot chassis must be designed to cope with these challenges.

The robot must be able to traverse through this environment, posing constraints on overall dimensions and ability to deal with uneven terrain. The chassis must therefore cope with torsional stresses as well as the stresses resulting from moderate drops. As debris may continue to fall, the chassis should also possess resilience to moderate instances of such occurrences. Additionally, the mine may contain explosive gases and therefore the chassis should allow safe operation of internal electronics.

3.1 Mechanical Characteristics

3.1.1 Material Selection

As outlined in Section 1.2, underground mines pose multiple challenges to HADES which influence the construction material selection. The largest challenge is rubble and debris as these create uneven terrain, put torsional stress on the chassis, can snag or fall on top of the chassis and produce obstacles that can be collided with. Mines are often located in remote, difficult to access areas and robots constructed from heavy materials are expensive and difficult to deploy. Further considerations for the material selection include wireless signal propagation and resisting explosive atmospheres.

Chassis strength is a primary attribute which prevents falling debris, uneven terrain and collisions with rubble from damaging the chassis. The explosive atmosphere means chassis

sealing for purge and pressurisation, discussed in Section 2.2 should be possible. A material which facilitates this should be given high priority during selection. To minimize wireless signal attenuation, a radiolucent chassis material is desirable. Additionally, a chassis with rounded surfaces avoids snagging of debris. The material selection is a significant portion of HADES' weight and therefore should be minimized to meet the 20 kg specification and assist with deployment. For the unit cost of the robot to fall below \$10,000, the manufacturing and raw cost of the material must be inexpensive.

A number of options were considered to determine the most suitable material for the chassis. Table 3.1 displays strength, cost and weight properties of five applicable materials. This information was collected and calculated from [64] [65] [66] as well as alternative online sources including [67] [68].

Material	Specific Strength (kg/m ³)	Cost (USD/kg)	Ratio (Strength/USD)
Stainless Steel	63.1	0.5	126.2
Aluminium	204	1.50	136
Titanium	288	4.0 - 5.0	64
Fibre glass	1307	1.5 - 3.0	581
Carbon Fibre	2457	10 - 11	234

 Table 3.1: Material Strength-Cost Comparison

Aluminium, carbon fibre and fibre glass have superior specific strength to cost ratio for this application. Although carbon fibre has the greatest specific strength it is also the most expensive. As sufficient strength can be attained with aluminium and fibre glass at a significantly reduced cost, carbon fibre was rejected early during the design process.

Aluminium.

One clear advantage of an aluminium chassis is its conductivity and therefore ability to provide a single circuit grounding point. However, any high voltages or currents environmentally exposed become hazardous. Additionally, excessive exposed metal colliding with metal equipment in the mine is a sparking hazard and not explosion-proof [24]. Generally, for an aluminium chassis, multiple components are milled in a subtractive manufacturing process and either welded or fastened together. The individual cost is large as excess metal is purchased and specialised, time consuming labour is required. An advantage however, is that aluminium can internally contain explosions, which allows flame-proofing to be employed (see Chapter 2.2.2).

Fibre glass

A chassis manufactured from fibre glass is a thermal and electrical insulator that is not susceptible to sparking. High power electric motors dissipate a significant portion of heat (brushed more than brushless), which is not conducted by fibre glass and can cause overheating. The manufacturing process requires an expensive mold with an extended setup time. However once complete, laying fibre glass mats interlaced with resin makes producing individual units cheaper than aluminium. The process naturally produces filleted edges, which is advantageous as it decreases the likelihood of snagging on debris. Unlike aluminium, fibre glass cannot internally contain explosions to achieve the flame-proof explosion technique, mentioned in Section 2.2.2, but can be easily purge and pressurisation as specified in Section 2.6. Other benefits of fibre glass include less radio frequency attenuation than aluminium and a greater modulus of elasticity, which can increase its yield strength. Given these advantages, fibre glass is the preferred construction material.

The chassis is designed from 2 mm thick fibre glass, which has suitable strength and weight for an underground mine robot according to Solpont [69]. A general purpose fibre glass mat is used which consists of a biaxial 45/45 Chopped Strand Mat (CSM) where two layers of fibre cloth are laid perpendicularly (+/- 45°) to reinforce and strengthen the mat. Alternate CSM layers of 450 g/m² and 600 g/m² are interlaced with epoxy resin for a light weight design as recommended and constructed by the manufacturing company [69]. To reduce cost, 47

the chassis was designed in two identical halves which require a single mold. As fibre glass is a thermal insulator, heat dissipation is managed through motor selection in Section 3.4.4, motor mounting in Section 3.4.2 and power component mounting in Section 7.2.7.

3.1.2 Physical Characteristics

An underground mine disaster environment contains debris, uneven terrain, large slopes and confined spaces as discussed in Section 1.2. Reliable locomotion is therefore a major consideration when selecting HADES' physical characteristics. Ensuring reliable locomotion in this environment poses constrains on HADES' physical characteristics.

- Small dimensions to enter and turn in confined spaces;
- Centre of gravity low enough to avoid toppling over
- Shape flexibility to traverse uneven terrain
- Curved edges for maximum strength and to reduce snagging
- Bright colour for easy identification

Dimensions should be minimized for confined spaces without crippling mobility or restricting internal component space, and is therefore limited to a maximum $1.0 \times 1.0 \times 0.5$ m (L × W × H) as outlined in Section 2.6. Exact dimensions are assessed by modelling major internal components. Dimensions are then decreased from $1.0 \times 1.0 \times 0.5$ m until all components fit with sufficient clearance for cables and mechanical mounts (as seen in Figure 3.1). Toppling over is a constant risk while traversing debris, rubble, slopes and uneven terrain. A wide, flat shape achieves low centre of gravity, to reduce this risk. The final dimensions are $0.7 \times 0.6 \times 0.1$ m (L × W × H).

Fibre glass's elasticity allows a certain degree of flex in the chassis, but is still inadequate to adapt to the sharp contours formed by debris and rubble. Existing search and rescue robots have solved this with suspension systems, as discussed in Section 2.3. They effectively adjust to terrain but become complex and expensive as terrain becomes rougher and more uneven.



Figure 3.1: CAD model with components to show space restraitns

Incorporation of a roll-axis pivot is a simpler solution, which allows wheel movement along an arc and significantly improves adaption to uneven terrain. When approaching an obstacle, the front and rear section independently passively rotate to adapt, as seen in Figure 3.2.



Figure 3.2: 3 Stage Figure of pivot adapting to terrain

An active pivot adds cost, complexity, and power consumption. The pivot joint is therefore passive and detachable if an actuated upgrade is desired in future. Male and female parts are machined from aluminium, seen in Figure 3.3. To prevent the plates rubbing, counter sunk screws are used. It can be mounted extending into either the back axle or front body depending on space requirements. The central 30 mm hole is twice the required size for cabling which ensures additional clearance for auxiliary devices and cable movement.



Figure 3.3: Pivot disassembled (left), Assembled (right)

The pivot is required to carry high current cables to the motors, but should avoid tangle and twisting. This inhibits the use of an electrical slip ring due to excessive prices of high current contacts. As rotation beyond 180° rarely occurs, the pivot is mechanically locked instead. A shoulder bolt screws into the male pivot section through a slot cut into the female section (as seen in Figure 3.3). This restricts rotational movement and prevents lateral movement, thereby eliminating the need for a circlip and slip ring. The slot potentially impairs the structural integrity of the female pivot, therefore it is only cut 120° around. If this is restricting HADES' locomotion it can be increased in future.

As discussed in Section 2.6, HADES should be buoyant to traverse large bodies of water. Fibre glass contributes to HADES buoyancy due to its strength-to-weight ratio and its density. Buoyancy is calculated before manufacturing, using Equation 3.1, 3.2 and 3.3.

$$\boldsymbol{m} = \boldsymbol{d}_{f} \times \boldsymbol{V}_{shell} \tag{3.1}$$

$$\boldsymbol{F}_{\boldsymbol{b}} = \boldsymbol{V}_{int} \times \boldsymbol{d}_{\boldsymbol{w}} \times \boldsymbol{g} \tag{3.2}$$

$$\boldsymbol{F}_{\boldsymbol{g}} = \boldsymbol{m} \times \boldsymbol{g} \tag{3.3}$$

The internal volume of HADES chassis V_{int} is estimated in SolidWorks at 0.0205 m³. The volume of the fibre glass shell V_{shell} is 0.001968 m³, which with a fibre glass density of 1522 kg/m³ allows a mass of 3.0 kg to be calculated. The density of water *d* is 1000 kg/m³
and gravitational acceleration g is 9.81 m/s². If half the chassis volume is submersed, the buoyance force F_b is 201.1 N. The buoyance force has to be greater than the force of gravity acting on the chassis. Estimating a final mass of 20 kg, the force of gravity F_g is 196.2 N and therefore HADES's chassis is buoyant for half submersion.

3.1.3 Sensor Cut Outs

The visual sensors must be contained within the chassis to maintain explosion-proofing. Sufficient Field of View (FOV) is required without compromising structural integrity. To facilitate this, windows are cut into the fibre glass chassis and covered by fibre glass submolds containing embedded windshield glass, shown in Figure 3.4. For high strength and to prevent shattering, laminated glass designed for automotive applications is used.



Figure 3.4: Front window (left), initial side window (right)

The cut out dimensions fit the visual sensors and camera lenses and prevent an excessive reduction in structural integrity. Initially dimensions were set 250×40 mm at the front and 32×32 mm on either side. Side windows were resized for upgraded cameras as discussed in Section 5.1.3, seen in Figure 3.5. While the front sensor changed, the front window remained the same to allow space for headlights and future supplementary cameras. To minimize video feed interference with the wheels, the side windows are centred. Sensors need direct contact with the environment and therefore cannot be contained within the pressurised chassis. They

are mounted on a small hatch, as discussed in Section 5.3.2. All features of the latest chassis design are shown in Figure 3.5.



Figure 3.5: Most recent chassis redesign, includes resized side windows

3.1.4 Chassis Construction

Chassis construction was carried out by Solpoint Composite Engineering company. A splithalf design allows for one mold to create two identical pieces, which are then bonded together to form the chassis. This halves the construction setup expense. Solpoint manufactured, layered and assembled the chassis based on Computer Aided Designed (CAD) engineering drawings.

Sub-molds for camera windows, sensor hatches and axle ends were created separately to the main chassis. Sub-molds are bonded on for camera windows, sensor hatches and axle ends with embedded glass or metal inserts. The individual sub-molds and chassis pieces of HADES are painted with 'Organic Orange' to enhance visibility.



Figure 3.6: Fibre glass mold (left), half pieces (right)

3.2 Purge and Pressurisation

This section details the aspects of the robot designed to purge and pressurise the chassis according to AS/NZS 60079.2:2007, as discussed in Section 2.2.

3.2.1 Sealing

Sealing should be applied to the chassis to minimize leakage of inert gas to maintain pressure for long periods of time. For adequate sealing, an IP rating of at least IP4X is recommended by the NZ standard. For dust ingress protection HADES should be designed to IP5X. Fewer joints and contact points result in less discrete seals and therefore a lower chance of leakage.

A combination of static and dynamic discrete seals are implemented at 16 points around the chassis. Five hatches allow access to internal components and are sealed using O-ring cord that is cut to length, bonded together and fitted into slots (main hatch shown in Figure 3.7). This includes two main access hatches, two sensor mounts and the tether mount. The main access hatch panels are constructed from fibre glass. These will be replaced with aluminium at a later date to provide improved heat conduction out of the chassis.

The male and female pivot parts require static seals as well as the four gearbox mounts discussed in Section 3.1.2. These six seals use the same 63 mm diameter O-ring. The four gearbox shaft seals and the pivot seal all require rotary lip seals.



Figure 3.7: Main access hatch, neoprene O-ring with 8 fasteners

3.2.2 Backup On-board Gas Cylinder

Ideally the chassis will be pre-pressurised. An on-board gas cylinder is then required to main pressure. The backup cylinder should be small in order to fit in the chassis and capable of being filled with nitrogen. High Pressure Air (HPA) paintball cylinders are inexpensive and easily filled. As they are used in portable applications, small, lightweight options are available. Small cylinders that are suitable range from 13 CI to 50 CI. As the cylinder is designed for backup functionality, and therefore intended for infrequent use, the smallest size (13 CI) is desirable.



Figure 3.8: Gas cylinder, solenoid, 3D printed mount and attachments

The New Zealand standard requires the pressure differential be maintained above 50 Pa. A 100 Pa positive pressure provides a safety factor of 2.0 to allow time to shut the system down if a moderate leak occurs and is not sufficiently large that gas will escape quickly during a small leak.

The 13 CI cylinder displayed in Figure 3.8 is aluminium, weighs less than 400 g and is capable of being pressurised up to 3000 psi. The volume of gas that can be supplied at 100 Pa is calculated using Boyle's law in Equation 3.4. With a chassis volume of 20,468 cm³, a 13 CI (213 cm³), 3000 psi (20 MPa) cylinder is capable of refilling the entire chassis to a positive pressure of 100 Pa (14.7 psi) 2.12 times. If HADES is adequately sealed this is sufficient. It is mounted in a custom designed bracket which supports and prevents lateral movement while enabling quick removal with two thumbs screws.

$$PV = PV \tag{3.4}$$

In order to release nitrogen from the cylinder and maintain 100 Pa, a solenoid value is required. 3000 psi is extremely high pressure and most valves are unable to operate at this pressure. An in-built regulator on the cylinder regulates the pressure between 850 and 450 psi for compatibility with lower rated components. An on/off tank adapter and a 1/8 inch NPT male-to-male adapter couples the cylinder to a solenoid valve. The valve is opened when the pressure falls below 100 Pa, the control system for which is discussed in Section 10.2.1. The solenoid operates using a 12 V, 100 mA DC signal with a maximum pressure rating of 500 psi.

3.3 Summary

Underground mine environments contain dust, dirt, water, debris, rubble and explosive gases. These pose various mechanical constraints on HADES' chassis design. Fibre glass was selected as the chassis construction material as it is light-weight and provides adequate environment protection through sealing. This enables both ingress protection as well as the purge and pressurisation explosion-proof technique to be implemented. A positive pressure is maintained within the chassis through a solenoid and small nitrogen cylinder. The physical characteristics of the chassis facilitate the spoked-wheel locomotion system (discussed in the following chapter). The small weight and size, the roll-axis pivot, and the low centre of gravity design assist when traversing rough terrain and navigating in confined spaces. The chassis design was modelled in CAD, as displayed in Figure 3.9, and manufactured by an external company. This provided a platform for the spoked-wheel locomotion system.



Figure 3.9: Chassis CAD model

Chapter 4

4 Locomotion

4.1 Wheel Characteristics

Chapter 2 highlighted the issues with round wheeled, legged and tracked locomotion for underground mines, and identified spoked-wheels as a suitable replacement. A spoked-wheel only requires a single motor to generate movement. This simplicity maintains low power consumption, ensures high rotational velocity and increases reliability of both explosion-proofing as well as ingress protection. Spokes imitate legs as they lock on top of obstacles in order to climb over them. It is the discontinuous contact of spokes with the ground that facilitates clambering over rough terrain (as pictured in Figure 4.1) and paddling through water. This chapter details the design of a spoked-wheel locomotion systems.



Figure 4.1: Spoked-wheels clambering over rough terrain

4.1.1 Wheel Configuration

As discussed in Section 2.3.5, the spoked wheel locomotion system must be capable of traversing debris and rubble as well as covering long distances over flat terrain. Existing spoked-wheel systems demonstrate that four wheels are most suitable for rough terrain as discussed in Section 2.3.4. As discussed in Section 3.1.1, a low centre of gravity assists to prevent toppling over. As reliability of locomotion is a major consideration during HADES' design, the wheels are configured, in conjunction with the chassis, for inverted locomotion. An invertible chassis and locomotion system, ensures that if toppling occurs, regardless of resulting orientation, HADES is able to continue driving. Invertibility is implemented by positioning the wheels in the corners, with axles vertically centred for symmetry.

To design the wheel diameter, an estimation of the size of expected obstacles in a mine disaster is required. As discussed in Section 2.3.5, the lower limit on the wheel diameter is 300 mm in order to traverse stairs and the track rails that run through mines. The wheel diameter also cannot exceed 600 mm, due to chassis dimensions, as front and back wheels could collide. The larger the diameter, the larger the obstacles the spoked-wheel can overcome. For prototyping, acrylic sheets are used as part of the wheel assembly, as discussed in Section 4.1.5. A manufacturing constraint on these acrylic sheets is their maximum width of 400 mm, which limits the realisable wheel diameter. This is adequate to ascend the maximum stair and track rail height and therefore the wheel diameter is initially set at 400 mm.

4.1.2 Spokes Configuration

While underground mine disaster sites contain debris and rubble, Pike River Mine demonstrates that flat terrain leading to the disaster site can be as long as 2 km [62]. A common misconception, evident in [49], is the assumption that the number of spokes alone controls the trade-off between rough terrain ability and flat terrain speed. This is incorrect. For spoked-wheels with rotational symmetry, the trade-off is determined by the circumference duty cycle. In this thesis, the percentage of the circumference that aligns with

load bearing sections (spokes) is referred to as the circumference duty cycle. The circumference duty cycle determines the type of contact the wheel makes with the ground. This ranges from the extremely discontinuous Rhex (10% duty cycle, $\sim 36^{\circ}$ of contact) to the continuity of a standard round wheel (100% duty cycle, 360° of contact). Figure 4.2 displays a diagram of three different circumference duty cycles for a wheel with four spokes.



Figure 4.2: 20% duty cycle (left), 40% duty cycle (middle), 60% duty cycle (right)

A combination of the number of spokes per wheel and the shape of each spoke determines the circumference duty cycle. Rough terrain negotiability and flat terrain speed can be exchanged through these two variables. Figure 4.3 displays the circumference duty cycle of two alternative spoked-wheel designs.



Figure 4.3: Standard straight spoke ~10% (left), Loper's trilobe design ~15% (right)

For constant angular wheel velocity and torque, flat terrain speed is dictated by how efficiently wheels convert angular velocity into linear velocity. For round wheels, the only major concern here is traction, but for spoked-wheels there are other problems. During transition from one spoke to another, some rotational energy is converted into vertical movement rather than horizontal movement, due to spoke-ground collisions. Additionally, rather than rolling along the circumference like round wheels, each spoke acts as an inverted pendulum and therefore the motor has to lift the chassis against gravity (see Figure 4.4). By increasing the circumference duty cycle, a larger percentage of the wheel circumference rolls along the surface, reducing the amount of motor torque required to counteract the inverted pendulum effect.



Figure 4.4: Diagram of spoke collision

For a constant wheel diameter, the theoretical maximum obstacle height that can be overcome is also a product of the circumference duty cycle. An illustration of this can be seen in Figure 4.5. The greater the circumference duty cycle, the less space between spokes and therefore the lower spoke two is when making contact with the obstacle. This reduces the overall maximum obstacle height.



Figure 4.5: Obstacle climbing, 20 % duty cycle (left), 60 % duty cycle.

4.1.3 Design Implementation

As illustrated in the Section 4.1.2, there is no perfect spoked-wheel design due to variable debris size. HADES should therefore be designed to allow wheels with different diameters and spoke configurations to be easily interchanged. This is achieved using an M6 bolt screwed into the shaft of the gearbox as seen in Figure 4.6 and Figure 4.9. Once terrain properties are known, a quick pit-stop allows the wheel size or shape to be changed for optimum locomotion.



Figure 4.6: Close up of wheel hub assembly, M6 shaft bolt is in the centre

The spoked-wheel of Seadog, displayed in Figure 4.7 is designed for traction over loose terrain (discussed in Section 2.3) and would be suitable for an underground mine. As outlined in [49], spoke-ground collisions reduce maximum horizontal speed and therefore modifications should be made to Seadog's spoke shape to increase maximum horizontal speed. The new design (Figure 4.7) reduces the weight slightly and allows the 'arms' of the T-shape to bend, compress and absorb more of the spoke-ground collision.





Water is not normally present in functioning underground mines, however previous disasters have caused flooding and water leaks [7]. In one instance a robot was not deployed due to mine flooding [2]. A unique benefit of spoked-wheels over other ground locomotion systems is the ability to paddle through water [44]. Existing spoked-wheels have spokes with a surface area (which is perpendicular to the direction of travel) that is insufficient to act as an effective paddle. Noting that HADES is buoyant and includes an interchangeable wheel design, a unique paddle-like spoked configuration could be used in flooded mines.

4.1.4 Manufacturing & Assembly

Important design considerations for manufacturing spoked-wheels include weight, cost, mechanical strength and traction. The section of the wheels which make contact with the ground should be constructed from rubber to maximize friction for effective traction. As discussed in [49], rubber dipping and rubber shoes are not suitable for rough terrain locomotion.

Instead a rubber sheet is bolted between two plates for strength and adherence, following the design of Loper and the Mother Robot. Figure 4.8 contains an exploded diagram of the wheel assembly. The wheel shape is designed in CAD and water jet cut from 18 mm thick BS1154 rubber sheeting. This allows the rubber to be bought in bulk and cut with speed and accuracy.



Figure 4.8: Exploded wheel assembly

Strengthening plate prototypes were fabricated in acrylic plastic, which has sufficient strength, low weight and ease of fabrication. 4 mm thick acrylic plates cracked under load;

6 mm plates endured numerous tests over five months with only two instances of cracking. Although acrylic plates have proven effective for prototype testing they will need aluminium replacements for an actual deployment.

Torque transfer from the shaft to the wheels is required, spreading the highly concentrated torque to prevent damage to the acrylic plates. Aluminium wheel hubs transfer motor torque to the wheels through a key way. Five barrel nuts and bolts are employed to reduce the load on individual fasteners. The small aluminium cap seen in Figure 4.6, is part of the interchangeable design.



Figure 4.9: Small aluminium cap (left), aluminium wheel hub (right)

4.2 Driving & Mounting

4.2.1 Base Gearbox

HADES should consistently travel at 1.4 m/s to meet the specifications in Section 2.6. Additionally, the spoked-wheels require sufficient torque to climb debris and rubble. Therefore, speed and torque are primary constraints for motors and gearboxes. The minimum RPM for each wheel can be calculated from the linear velocity v and wheel diameter D. This is achieved using Equation 4.1 and the wheel diameter of 400 mm to produce an RPM of 67.

$$RPM = 60 \times \frac{v}{\pi \times D} \tag{4.1}$$

Sufficient torque is required for HADES to pull itself over obstacles and scale inclined terrain. The worst case scenario is two wheels attempting to pull the whole chassis vertically over an obstacle. In this situation the entire mass *m* of HADES (20 kg) is being rotated about a pivot point halfway along *d* the wheel radius (100 mm) directly against gravity. Given that two wheels are independently providing power, the total torque required to pull HADES up and over the obstacle can be halved. The weight force F_w required to overcome gravity is calculated using Equation 4.2. The total required torque of 19.62 nm is calculated using Equation 4.3.

$$F_w = ma \tag{4.2}$$

$$\tau = F_w d \tag{4.3}$$

The speed and torque values calculated above were used to determine the gearbox and motor selection. Inexpensive electric motors tend to lack torque but exhibit high RPM, which is undesirable for rough terrain. A large gear ratio is thus needed in order to obtain greater torque and closer control at lower speeds. The P60 planetary gearbox range has a compact size and maximum torque specification of 47.5 Nm which can withstand the torque calculated above. The motors installed (discussed in Section 4.2.4) have a no load RPM of 19300 and a stall torque of 0.486 Nm, which is fed through a gear ratio of 104:1. This can produce a maximum torque of 50.5 Nm and speed of 186 RPM that both exceed requirements mentioned above.

4.2.2 Chassis Mount

The gearbox assembly should be fastened directly onto the chassis for effective torque transfer. Light-weight mechanical strength is thus a major consideration for mounting to guarantee reliability over rough terrain. Additionally, the motors dissipate significant quantities of heat. The mount should therefore be manufactured from aluminium for thermal

conductivity and a high strength-to-weight ratio. The mount should also accommodate the sealing discussed in Section 3.2.1.

The stock P60 gearbox lacks sufficient threaded holes for mounting and is not capable of sealing, therefore a new mounting design is needed, as shown in Figure 4.10. When assembled, the design ensures the motor, gearbox and mechanical hardware are fastened together, allowing all components to be removed from the chassis simultaneously. This is a major benefit during prototyping as well as maintenance and repair.



Figure 4.10: Exploded gearbox assembly

The chassis mount holds all seals and bearings, as displayed in Figure 4.11, as well as the fastener holes for screwing into the chassis. Standard seal and bearing sizes were selected and the chassis mount block sized to suit. The end cap allows the gearbox to be attached onto the mounting block using four long bolts. As the strength of the gearbox shaft is more important than weight or conductivity, it is machined from steel to withstand the level of torque delivered through this small part.



Figure 4.11: Cross section (left) and Photo of assembly (right)

Figure 4.11 shows a cross section of the assembly. Two ball bearings are used, placed 14 mm apart to support the shaft under large radial loads. They are separated by a central spacer that is designed into the chassis mount. The circlip on the rear end of the inner bearing and the 16 mm diameter section of shaft prevent axial movement. The gearbox assembly has tight mating tolerances which can lead to gearbox lock-up if not assembled correctly. A small pinion is press-fit onto the end of the motor shaft as the input gear, refer to



Figure 4.14. 67



Figure 4.12: Undamaged gearbox shaft (left), damaged gearbox shaft (right)

The gearbox shaft is manufactured from stainless steel. Continual radial loading of it causes deformation against the gearbox output carrier plate resulting in 0.3 inch flats that become increasingly circular, as shown in Figure 4.12. Replacement shafts are manufactured from a higher carbon steel than stainless which mitigates this issue.

4.2.3 Brushed Configuration

The initial motor configuration is inherited from a working prototype developed by VUW [49]. The RS550 motors are brushed, with speed (19300 RPM) and torque (0.486 Nm), properties that have exhibited competent rough terrain locomotion. They are a standard 550 model with 36 mm body diameter and 0.125-inch shaft diameter that mates directly with the P60 gearbox. While their efficiency is only 70% they cost \$5 each which is budget-friendly as an early project purchase. These RS550 motors are powered by two 2X25 Sabertooth drivers, which can each supply 50 A to two different motors. Figure 4.14 shows the original brushed motor.

After extended periods of use within the fibre glass chassis, the motor's low efficiency became apparent. Infrared images in Figure 4.13 show the motor after thirty minutes of continuous operation, reaching up to 43° C. Figure 4.13 also shows the insulating properties

of the fibre glass chassis, limiting the motor's ability to dissipate heat. This resulted in further investigation into brushless motors.



Figure 4.13: Infrared images after motor operation

4.2.4 Brushless Motors

Brushless motors are superior to brushed motors in almost all aspects, although they can cost about twenty times the price of brushed motors. Brushless motor efficiency and stator winding position significantly improve heat dissipation

Brushless motors are either sensored or sensorless. Sensorless models measure the motor's back Electro-Magnetic Force (EMF) to control the timing of motor pole current pulses. Sensored models however, provide pole information to the ESC through Hall effect sensors allowing the motor control pulses to be more accurately synchronized. Therefore, these models have greater start up torque with finer control at lower RPMs [70], which is important for a system operating at low speeds over rough terrain. Sensored models are therefore more suitable for HADES.

A rescue robot navigates in confined spaces where the ability to reverse is required. Additionally, motors on opposite sides of the chassis rotate in opposite directions. Therefore, motor reversibility is required. HADES has to pull itself over debris and rubble which demands torque rather than speed. Most sensored brushless motors have timing advance for single direction rotation. Pulsing the motor poles in advance increases the motor speed in one direction (commonly used in Remote Control (RC) racing), but significantly decreases efficiency and torque, which is exacerbated further when operating in the opposite direction. Zero-timing provides efficient multi-direction rotation, but reduces maximum speed. Multidirectional rotation is critical for HADES. Additionally, for this particular chassis design, maximising efficiency is important due to the insulating fibre glass chassis. Therefore, zero-timing is required for sensored brushless motors.

Additional benefits of sensored brushless motors are the built-in thermistors and Hall effect sensors. The temperature reading produced by these thermistors is more accurate and indicative of the true value as the thermistors are internal, thus not measuring just the motor casing temperature. The Hall effect sensors provide a pulse each time they are crossed by a motor pole and therefore enable a microcontroller to measure angular velocity and position. There are three motor poles, each with a sensor, which transfer power through a 104:1 gear ratio. This provides 312 wheel positions or an angular resolution of 1.15°. For wheels with 72° between spokes, this resolution does not require an additional separate encoder. Without external thermistors and encoders, the motor assembly size and complexity is reduced in comparison with brushed motors.

The brushless motors installed on HADES are Reedy Sonic M3 540s, displayed alongside the original brushed model in Figure 4.14. They are the latest model from Reedy Sonic whose previous Mach 2 model was 96% efficient (Mach 3 value is not stated). The 540 design and the 3.15 mm shaft ensure that it mounts correctly onto the gearbox and the pinion can be press-fit. The M3 is sensored with adjustable timing down to zero. The speed and torque of brushless motors is not always given in the catalogue as their marketing is aimed at RC hobbyists. They can however be estimated by considering their function and application. The number of turns is a trade-off between speed and torque, the higher turns produce more torque while lower turns give greater RPM. A 13.5 turn motor was selected based on: similar motors that provide RPM (2700 Kv) and power specifications (210 W), and comparison with the brushed motor (1608 Kv and 245 W).



Figure 4.14: Brush motor (left), brushless motor (right)

4.2.5 Electronic Speed Controls

As brushless motors are controlled differently to brushed motors, a new set of driving electronics is required. Electronic Speed Controls (ESCs) are devices originally designed for RC vehicles which interface with the receiver's throttle control channel and are powered Li-Po batteries. They too can be purchased for either sensored or sensorless control with a wide range of current rating classifications.

There are three considerations for ESC selection: Li-Po cell count, zero timing and dimensions. The Xerun XR10 was developed specifically for zero timing racing, permanently set to 0° . Displayed in Figure 4.15, it is compatible with three cell Li-Po batteries. The dimensions ($33.5 \times 28.5 \times 30.5$ mm) of the XR10 are smaller than similar devices, which saves space. This is made possible by the modified heat sink and cooling fan. As the current draw of Reedy Sonic motors is not stated, a similar comparative approach for ESC selection had to be taken. A 60 A Xerun XR10 combo can be purchased (paired with a 13.5T motor) that draws a maximum of 58 A. As other models of ESC had been paired similarly, the 60 A rating was selected.



Figure 4.15: Electronic Speed Control (ESC)

While ESCs come pre-programmed, there are several items which can be modified in to maximize performance. These items are changed manually using the built-in switch or separate programming box.

Table 4.1 shows the programmable items with selected values shaded in grey. Additional functionality is added to the low level control circuit as described in Section 7.3.3 which allows automatic ESC programming for convenience and for re-programming during operation.

The ESC's Running Mode is programmed to be able to operate in reverse without a training brake (designed to prevent accidental reverse during braking). The Drag Brake Force is the power produced when releasing the throttle to simulate the braking effect of a neutral brushed motor while coasting. As this consumes power and is an insignificant benefit it is reduced to 0%. The third item is the cut off voltage, which is set to 3.0 V as that is the lowest voltage considered safe for Li-Po cells. The punch of an ESC determines the amount of initial acceleration provided to the motor when accelerating from stationary. As search and rescue robots climb debris and rubble with steady, controlled movements, the lowest punch is desirable. Similarly, the neutral range is set to 6% to decrease the sensitivity of acceleration.

Programmable Items	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7	Option 8	Option 9
1. Running Mode	Forward w/Brake	Forward/ Reverse w/Brake	Forward/ Reverse						
2. Drag Brake Force	0%	5%	10%	20%	40%	60%	80%	100%	
3. Cutoff Voltage	Disabled	2.6V/Cell	2.8V/Cell	3.0V/Cell	3.2V/Cell	3.4V/Cell			
4. Start Mode (Punch)	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Level 7	Level 8	Level 9
5. Max Brake Force	25%	50%	75%	100%					
6. Max Reverse Force	25%	50%	75%	100%					
7. Initial Brake Force	Drag	0%	20%	40%					
8. Neutral Range	6% (Narrow)	9% (Normal)	12% (Wide)						
9. Timing	This item has been permanently set to 0 degree								
10. Overheat Protection	Enabled	Disabled							

 Table 4.1: ESC Programming Modes

With the first item programmed to Forward/Reverse, intentional braking is not possible and therefore the Max Brake Force and Initial Brake Force are left as default. The Max Reverse Force however, should be set to 100% due to the different motor mounting orientations and to ensure torque, speed and efficiency of forward motion is equal to that of reverse.

4.3 Summary

The debris and rubble of underground mine disasters is difficult to traverse. Additionally, surface deployment means travelling down long entrance tunnels. A spoked-wheel locomotion system is employed to address these issues. For robustness and reliability, a four-wheeled, invertible design is implemented. The form of the spoke configuration determines the trade-off between obstacle height and flat terrain speed. HADES is designed with an interchangeable wheel design to allow the optimum spoke configuration to be employed

according to each situation. A brushless motor and planetary gearbox combination provide sufficient speed and torque for traversing debris and rubble as well as to travel long distances. As the gearbox is unable to provide sealing, a custom mount is designed. Applying a spoked-wheel locomotion system to the fibre glass chassis, seen in Figure 4.16, produces a platform on which sensors, electronics and communication devices can be mounted.



Figure 4.16: Images of the entire chassis and locomotion system.

Chapter 5

5 Sensors

Rescue robots are deployed into underground mine disaster zones to collect data and gather information as outlined in Section 1.1. This allows response teams to locate survivors, assess the conditions and evaluate safety. This chapter explores HADES' sensors, which enable search and rescue tasks to be carried out. Various sensors are integrated to provide sufficient information for the response team. The sensor types listed below are considered core to underground mine search and rescue and therefore are included on almost all existing underground mine systems (as summarized in Section 2.4). They include vision, lighting, audio and gas concentrations. These sensor types, among others, are discussed below, detailing the problems they address, the design considerations and their implementation.

5.1 Vision and Optics

As stated in Section 1.2, underground mines are in complete darkness after a disaster as lighting systems are often damaged or the power is switched off for safety [71]. This poses challenges for gathering visual information as well as teleoperation, highlighted by Minbot in Section 2.4.2. A noted oversight of existing systems is a lack of detailed visual information [2], which results in missing important features of the disaster site. This section addresses the issues through the selection and implementation of adequate visual sensors.

The visual sensors must provide a large spatial coverage of the disaster site to maximize information collection. The images should contain colour and high resolution for clarity and hazard identification. To enable colour images in darkness, sufficient lighting must be installed. Infrared images should also be included to improve teleoperation as stated in Section 2.4.2. Communication in an underground mine is difficult (see Section 2.5), therefore limited bandwidth is expected. All video files should be stored on-board for access after exiting the mine.

A combination of the Kinect-v2 device and multiple webcams formed the initial approach. These were replaced by the RealSense which became available midway through the project. The design decisions and implementation of each device is discussed in the following subsections.

5.1.1 Kinect-v2

In addition to low lighting, two dimensional images during teleoperation create the 'keyhole' problem [72], where lack of depth information obstructs spatial awareness and obscures distance judgement. Furthermore, providing both night vision and colour images is a challenge for visual sensors. Usually multiple devices are required, but this consumes space and power while producing more cables, connectors and interfacing.

Infrared spectrum cameras are required for adequate vision in darkness, while depth information should be collected to assist teleoperation. To identify features with sufficient detail, at least 720p resolution colour cameras are needed. The cameras must be small to fit in the chassis, with minimal power consumption to extend battery life. The Field of View (FOV) of incorporated devices should be large to increase coverage of the disaster site.

A combination of Position Sensing Devices (PSDs), colour, as well as infrared cameras could achieve these performance requirements. However, RGB-D cameras consolidate these functions into a single device which is less expensive, smaller and provides significantly greater depth detail. An RGB-D camera (Kinect-v2) was available and selected for HADES. Later the RealSense became available as discussed in Section 5.1.3.

The Kinect-v2 is employed as the anterior visual sensor for depth information during teleoperation. Figure 5.1 shows the device mounted in the chassis. As infrared, colour and depth information for all four cameras is impractical, webcams were installed for the back and sides of the chassis, as detailed in Section 5.1.2. The Kinect-v2's colour camera has a FOV of $84 \times 54^{\circ}$ in the horizontal and vertical axes while the infrared is $71 \times 60^{\circ}$ [73]. The Kinect-v2 uses Time of Flight (TOF) on each pixel of a 512×424 infrared image to

determine the distance up to a maximum of 8 m [74]. It displays distance in a greyscale image which enables depth perception and vision in darkness.



Figure 5.1: Kinect-v2 mounted in chassis

The Kinect-v2 contains two cables, USB 3.0 for data and a 12 V DC power supply. Its current draw, measured using a current clamp, is 1.17 A average, with a peak of 1.57 A and 0.43 A at standby, which exceeds the capacity of the USB cable. At $250 \times 66 \times 64$ mm it fits in the chassis only once the case is removed. The Kinect's size and power consumption is acceptable, given its functionality and data output. It is therefore incorporated as the anterior visual sensor, despite not being ideal for portable applications.

5.1.2 Webcams

Vision on all four sides of HADES is necessary, as displayed in Figure 5.2, but the Kinectv2 is too large, expensive and power hungry for this. Therefore, separate devices are required which can also provide infrared and colour images with high resolution and a large FOV. Along with the aforementioned specifications, the primary requirements of these devices are small size and low power consumption.



Figure 5.2: HADES' FOV with four cameras

The webcams had to have at least 720p resolution and hardware autofocus (to ensure clear, detailed images). An upper limit was placed on price (\$100) and size ($50 \times 50 \times 50$ mm). USB Video Class (UVC) device functionality was desirable during selection to ensure it was compatible with the robot development environment discussed in Section 8.1.1

Online reviews were consulted to ensure reliability. During this process Microsoft's LifeCam Cinema [75] was discovered, which meets the above specifications but can also detect near IR spectrum by easily removing the IR filter lens. With IR emitters and additional software filtering, near IR images can be utilized for video in complete darkness. This meant second cameras, with IR vision, would not need to be integrated alongside the webcams. The LifeCam Cinema has a wide angle lens for 73 degrees diagonal FOV. The physical dimensions are reduced to $37 \times 25 \times 20$ mm by removing the microphone and extracting the Printed Circuit Board (PCB) from the case, as seen in Figure 5.3.



Figure 5.3: Webcam out of case

5.1.3 RealSense

As mentioned in Section 5.1.1, the size and power consumption (14 W) of the Kinect-v2 is undesirable. Aside from Intel's RealSense camera, only one other RGB-D devices was found, Asus's Xtion [76]. The Xtion camera is similar in size to the Kinect-v2, but only exhibits 2.5 W of power consumption. It has an IR resolution of 480p and 1280×1024 colour resolution, both at 30 frames per second (fps). Its maximum range is 3.5 m with a FOV of 58 \times 45 ° (H \times V). A picture of the Xtion is displayed in Figure 5.4.



Figure 5.4: Xtion

The RealSense's power consumption ranges from 0 - 0.1 W when idle and 1.0 - 1.6 W when active [77]. Its dimensions are $102 \times 9.5 \times 3.8$ mm (pictured in Figure 5.5) with a detection range of approximately 0.5 to 3.5 m indoors and up to 10 m outdoors. Its colour FOV is 70 79

 \times 43 degrees (H \times V) while IR is 59 \times 46 degrees. An additional benefit is that HADES' robotic development environment includes original manufacturer software and driver support for the RealSense (see Section 10.2.3). The maximum resolution and frames per second of the RealSense are 1080p colour and 480p IR, both up to 60 fps.



Figure 5.5: RealSense

Although the RealSense's FOV is 15-20% less than the Kinect-v2, it is greater than the Xtion's and can detect longer distances than both devices (10 m). The RealSense's power consumption is lower than the Kinect-v2 and Xtion. The RealSense is also significantly smaller than the other devices. While the Kinect-v2 and the RealSense can both produce 1080p images the Xtion cannot, nor can it produce 60 fps. The Xtion cannot compete with the other two devices and is therefore rejected. Similar performance but superior size and power consumption of the RealSense camera renders it more suitable than the Kinect-v2.

The RealSense currently has limited stock; however, HADES is designed to integrate the device into its sensing platform when it becomes available, by including the necessary software and USB 3.0 ports. With the RealSense also outperforming the webcams in all aspects, the RealSense are placed at the front, back and sides for multidirectional data collection. To account for this, chassis window dimensions were resized as mentioned in Section 3.1.3.

5.1.4 Lighting

Complete darkness prevents colour information from being gathered, therefore a lighting system is required. The lighting should include: sufficient brightness for teleoperation; a colour temperature that maximizes visibility; low power consumption and a large angle of illumination. LEDs have better efficiency and a wider range of colour temperature than

halogen, incandescent and fluorescent light sources, therefore are the obvious choice. It is observed that most modern miner cap lamps have converted to LEDs from incandescent bulbs [78] [79].

LEDs improve peripheral vision in low lighting conditions over other light sources due to increased short-wavelength content of their spectral power distribution [80], with different colours having different applications. Red LEDs are often utilised for night vision; green is employed by pilots and the military to distinguish objects. White is shown to produce the least glare and optimize colour rendering [81]. This makes white preferential, as colour rendering is high priority. The exact colour temperature required is dependent on the state of the environment. A low temperature white (~4300 K) will penetrate through dust and water, while a cool white (~6000 K) better illuminates complete darkness [82].

Lighting brightness is also important. [83] recommends that mining cap lamps should provide a peak illuminance of at least 1500 lux at 1.2 m. Typical mining cap lamps certified in Australasia have a luminous flux of 90 Lm and an illuminance of greater than 4000 Lux at 1 m [84]. To achieve similar performance, super bright LEDs were investigated.

Both 4300 K and 6000 K LEDs were mounted, one for each headlight, to balance penetration and illumination to ensure visibility in any conditions. The selected components exhibit a viewing angle of 120° and 700 Lux at 1.0 m (2200 lm). Three of these LEDs, mounted on all four sides, each produce 2100 Lux at 1.0 m. The circuit design for these components is displayed in Figure 5.6



. It is controlled by a PWM signal, greater than 120 Hz to avoid detection by the 60 Hz cameras, allowing variable brightness.



Figure 5.6: Schematic for PWM control of headlights

5.2 Audio

When searching for survivors, communication with the response team is highly desirable. Therefore, two-way audio capability is implemented. The explosive environment makes it difficult for audio equipment to be effective. Microphones are inherently intrinsically safe as they do not store or generate dangerous levels of power, but speakers are not. Their high power inductive coil requires direct contact with the explosive atmosphere to produce loud, clear sound and therefore they are hazardous.

One of the few options is flame-proof speakers, but these are large and expensive [85]. An innovative solution is applied to this problem. The surface vibration transducer displayed in Figure 5.7, can vibrate HADES' chassis to produce sound waves thereby avoiding exposure to the hazardous environment.

The transducer is compact, 50 mm in diameter and 31 mm in height, and is placed on flat surfaces anywhere inside the chassis. The 4 Ω coil has a resonant frequency of 530 Hz and maximum input power of 6 W [86] producing loud, clear audio. A stereo, Class D audio amplifier drives it, with 3.7 W maximum power output. The board (manufactured by Adafruit) is 28.25 x 24.15 mm and can drive two 3 Ω speakers at 3.7W with 10 % THD, allowing a second surface transducer if needed. The audio amplifier input connects to the main control unit headphone jack. The jack has four conductors for stereo output as well as an input audio signal. This enables a waterproof microphone to be integrated, which has an IP67 rating to survive the underground mine environment and a typical output impedance of 2.2 k Ω .



Figure 5.7: Surface transducer attached to chassis with class D amplifier

5.3 Environment Sensors

As discussed in Section 2.2, ten gases are commonly found in underground mines: hydrogen, oxygen, methane, carbon monoxide, carbon dioxide, hydrogen sulphide, nitrogen dioxide, nitric oxide, nitrogen and sulfur dioxide. A gaseous environment poses two major safety concerns for response teams: explosivity and toxicity. Therefore, it is necessary to detect the gas concentration to predict the likelihood of explosions and determine if human entry is safe. The following section evaluates the available sensors and describes their operation and mounting.

5.3.1 Electrochemical sensor ranges

Three primary options are available to measure gas concentration: electrochemical sensors, IR sensors and spectrometers. Initial investigation into IR sensors and spectrometers revealed expensive devices with IR limited to only two or three gases. The size and cost of electrochemical sensors are more suitable and capable of detecting necessary gas concentrations.

Electrochemical gas sensors contain electrodes between which a chemical reaction takes place producing a current proportional to the gas concentration. They generally require calibration against known gas concentrations. A disadvantage of electro-chemical sensors is their maximum operating life as the electrodes corrode slowly reducing measurement accuracy. Operating lives tend to range between six months and three years, which is acceptable for this application.

Two electrochemical sensor ranges are available which are inexpensive, small and effective: MQ and AlphaSense (one of each shown in Figure 5.8). Between these two brands almost all ten gases can be detected.



Figure 5.8: MQ (left), AlphaSense (right)

MQ sensors only state "long life" for their devices with no further information. They use internal heaters to assist with the chemical reaction. They are easily accessible and cheaper than the AlphaSense range. MQ sensors have a diameter of 14.5 mm with a total height of 16.5 mm. Comparatively, AlphaSense provides more specification information, stating their devices have 80 % accuracy after 24 months. AlphaSense's 'miniature range' are 13 mm in diameter with an overall height of 12.3 mm.

MQ and AlphaSense both include devices with currents and voltages below any gas ignition point (see Section 7.4.1). Both are sufficiently small with operating ranges that cover explosive as well as toxic concentration limits. As neither range covers all ten gases a combination of both is required, their implementation is discussed below.

The MQ range is preferable as their sensors are inexpensive and readily available so were initially purchased to detect as many gases as possible; 5 of the possible 10: hydrogen, methane, hydrogen sulphide, carbon monoxide and oxygen. AlphaSense devices measure nitric oxide, nitrogen dioxide, carbon dioxide and sulfur dioxide, which the MQ range cannot. As long as harmful gases concentrations are low and oxygen concentration is sufficient, nitrogen is considered safe [87] and therefore its concentration is not measured.

The MQ and AlphaSense sensors detect gas concentrations over various ranges, which each include the Threshold Limit Value (TLV) or Lower Explosive Limit (LEL) of the respective

gas given in Table 5.1. Two of the sensors (CH_4 and H_2) have ranges which do not include the TLV or LEL. This is not ideal, but still provides for safety detection, as the concentration range still indicates if the concentration is hazardous.

Gas (symbol)	Sensor Range	LEL (%)	TLV (PPM)	Sensor Range
Nitrogen (N2)	-	-	-	-
Oxygen (O2)	MQ	-	-	0 - 25%
Carbon Dioxide (CO2)	AlphaSense	-	5,000	5,000 to 90%
Methane (CH4)	MQ	5	-	0.1 - 1 %
Carbon Monoxide (CO)	MQ	-	50	20 - 2000 ppm
Nitric Oxide (NO)	AlphaSense	-	25	0-100 ppm
Nitrogen Dioxide (NO2)	AlphaSense	-	5	0 – 20 ppm
Sulfur Dioxide (SO2)	AlphaSense	-	5	0 – 20 ppm
Hygroden Sulfide (H2S)	MQ	-	10	1 – 200 ppm
Hydrogen (H2)	MQ	4	-	0.01 – 1 %

Table 5.1: Underground Mine Gases Sensors

After purchasing MQ sensors, it was discovered that AlphaSense provides documentation which ensure their sensors meet intrinsic safety approval standards [88]. Although both sensor ranges require low current and voltage, the guarantee of intrinsic safety AlphaSense provides outweighs an increase in cost. As intrinsic safety is a top priority, it is recommended that future design replaces MQ sensors with their respective AlphaSense devices. The only exception to this is the hydrogen sensor, which the AlphaSense range does not include.

5.3.2 Temperature, Pressure, Humidity

Gas concentrations are not the only environment variables which response teams wish to monitor. Temperature, pressure and humidity are commonly measured in underground mines to provide further indication of the conditions and therefore safety of the disaster site. Various other sensors may also be desired in future, such as anemometers, Geiger counters or light
sensors. HADES is therefore required to allow easy attachment of additional sensors without major modifications. Furthermore, attached sensors should not require supplementary intrinsic safety circuitry.

The interchangeable JST connectors mounted on the fibreglass plate, enable most digital and analogue sensors to be integrated (more detail in Section 5.3.3). They are connected to the intrinsically safe ports (see Section 7.4.2) which allows most off-the-shelf sensors to be utilized. Temperature, pressure and humidity sensors have been purchased and interfaced. The sensors used are identical to their internal counterparts therefore detail is provided in Section 4.4.3.

5.3.3 Protected Mounting

An underground mine environment is filled with dust, dirt, smoke and water which can damage sensors mounted on the outside of the chassis. Additionally, as all gases do not need simultaneous measurement, installing all sensors at once consumes space, power and processing. Mounting plates are designed, which allow different sensor combinations to be employed, with filters to protect them. It accomplishes this without disturbing the explosion-proofing of the purge and pressurisation system. The design is modelled in CAD software, with future implementation required.

Plate dimensions (40 x 40 mm) are maximised given existing chassis dimensions. The plates are then bolted to the sides of the chassis. Each plate includes an O-ring seal to maintain internal pressure without sacrificing detachability. Holes are cut into the plates for three pin (and four pin, see Section 7.4.2) JST connectors, as seen in Figure 5.9. The connectors are bonded into the fibreglass and wired to the intrinsically safe PCB-mounted connectors on the control board. The mounting plates are positioned at the rear of the chassis, near the control board's intrinsically safe ports to reduce wiring length.



Figure 5.9: Sensor Panel with connectors (left), Sensor Hatch with filter slot (right)

5.4 Internal Sensors

Various other sensors are employed to monitor power components, internal conditions as well as HADES' motion. They provide fault detection to prevent system damage. All sensors are monitored by a microcontroller on the control board discussed in Section 7.3.

5.4.1 Power Components

Many of HADES' components are high power and therefore may exhibit elevated temperatures during operation. This includes the power converters, main control unit, audio amplifier and motors. Elevated temperatures can cause component damage if overheating occurs or otherwise diminished efficiency, which reduces battery life. Battery life is a general consideration to ensure sufficient remaining battery capacity for HADES to exit the mine.

Monitoring the temperature, voltage, current and power consumption of the high power components allows their operation to be contained within an acceptable range. This is achieved by limiting or disabling components that overheat or exhibit low efficiency. The temperature sensors do not require high accuracy but should cover the component operating range and be sufficient to identify undesirable operation. The electrical measurements can also be used to estimate remaining battery capacity as well as avoid the battery's operating limits. The accuracy of the electrical measurements is detailed in Section 7.2.

3S Li-Po batteries have voltage levels that safely fluctuate between 9.6 V and 12.6 V (9.0 - 12.75 V absolute maximum) with a nominal voltage of 11.1 V. These voltages indicate empty, full and half battery capacity respectively. Current flow from the batteries is monitored with current sense circuits (detailed in Section 7.2.5), which allows remaining operating time t_{op} to be calculated with Equation 5.1.

$$\boldsymbol{t_{op}} = [\boldsymbol{C_B} - \left(\sum I_i \times \Delta t_i\right)] \times I_{curr}$$
(5.1)

By summing previous current measurements I_i and the difference between current measurements Δt_i , the expended battery capacity can be calculated. Subtracting the expended battery capacity from the total battery capacity C_B provides the remaining capacity. The calculation of remaining operating time *t* and percentage is then based on the most recent current measurement I_{curr} .

As previously mentioned, the motors contain thermistors and do not require additional sensors. For the remaining components, a digital thermometer with an internal model is employed, which exhibits 0.5° C accuracy. The digital thermometer utilizes Maxim Integrated's 1-wire interface powering itself from the data line, which reduces the amount of wiring. This bus communication protocol enables multiple daisy chained devices thereby removing the need for multiple parallel cables running throughout the chassis. All temperature sensors are monitored by the embedded control board discussed in Section 7.3.

5.4.2 Motion Feedback

HADES' motor encoders provide inaccurate linear displacement due to wheel slippage. Therefore, an alternative form of odometry is necessary. Additionally, as spoked-wheels climb rubble and debris, motion feedback can assist HADES to maintain balance and improve obstacle climbing ability. Inertial Measurement Units (IMUs) measure angular and linear position, velocity and acceleration for motion feedback. An LSM9DS0 9-axis Inertial Measurement Unit (IMU) produced by ST Microelectronics contains an accelerometer, gyroscope and magnetometer all condensed into a tiny LGA-24 package. It is mounted on the embedded control board discussed in Section 7.3. It has I²C and variable measurement scales, so the user can select between either large range or high accuracy. The accelerometer has a full scale of $\pm 2g/\pm 4g/\pm 6g/\pm 8g/\pm 16g$, the magnetometer has a full scale of $\pm 2g/\pm 4g/\pm 6g/\pm 8g/\pm 16g$, the magnetometer has a full scale of $\pm 2g/\pm 4g/\pm 6g/\pm 8g/\pm 16g$, the magnetometer has a full scale of $\pm 2g/\pm 4g/\pm 6g/\pm 8g/\pm 16g$, the magnetometer has a full scale of $\pm 2g/\pm 4g/\pm 6g/\pm 8g/\pm 16g$, the magnetometer has a full scale of $\pm 2g/\pm 4g/\pm 6g/\pm 8g/\pm 16g$, the magnetometer has a full scale of $\pm 2g/\pm 4g/\pm 6g/\pm 8g/\pm 16g$, the magnetometer has a full scale of $\pm 2g/\pm 4g/\pm 6g/\pm 8g/\pm 16g$.

The device is powered by a maximum of 3.6 V, but only 5 V and 12 V power rails are available from the DC-DC converters. Therefore, power conversion and signal level shifting is required to interface with the rest of the circuit. As the IMU draws insignificant current, efficiency is not a concern. A standard 3-pin 3.3 V linear voltage regulator from Texas Instruments is employed, with input and output capacitors decoupling to ground.

To communicate on the I²C bus, the IMU's SDA and SCL signals are level shifted to 5 V. The bi-directional voltage-level translator IC requires a bypass capacitor as well as I²C and enable line pull-up resistors for a permanently-on configuration. The IMU also includes a larger 4.7 μ F reservoir capacitor and a reset capacitor both with an Equivalent Series Resistance (ESR) less than 200 m Ω for correct operation, as suggested by the datasheet [89]. The two chip select lines CSG and CSX are pulled high through resistors to enable I²C mode. Pulling the SDOX pins modifies the least significant bit of the I²C address. All capacitor and resistor values are displayed in Figure 5.10.



Figure 5.10: IMU Schematic with level shifter

5.4.3 Conditions

There are various conditions which require monitoring to ensure correct and safe operation of HADES. While an IP67 rating is desired, water leaks are still theoretically possible under fault conditions or exceeding 1 m submersion for longer than 30 minutes. If water ingress continues undetected, the electronics could be damaged. Over or under-pressure are possible problems as well. If too much gas is escaping the chassis, the internal positive pressure will not be maintained and HADES will lose explosion-proofing. Alternatively, an overpressure could damage the chassis.

Humidity and pressure sensors should be included to detect water and gas leaks such that electronics can be powered off to prevent damage and explosion-proofing is maintained. Humidity sensors should be capable of detecting large, sudden changes in humidity to detect water leaks and pressure sensors must be capable of indicating sufficient internal pressure (200 Pa) or a breached lower limit (100 Pa). It is desirable to have multiple sensors for redundancy and error checking. The temperature device only requires sufficient accuracy to indicate safety for the response team.

Two pressure sensors monitor the purge and pressurisation system. A gauge measurement type is selected which measures the difference in pressure to atmospheric. The device comes pre-calibrated with a digital interface, which allows temperature compensation with 16-bit measurement over 0 to 1 psi (6895 Pa) providing 0.105 Pa resolution. These specifications ensure a positive pressure of 100 Pa can be accurately maintained and does not fall below the 50 Pa limit.

Two humidity sensors detect water ingress, which is the primary cause of humidity increase. The HIH-5031 provides an analog voltage with rated accuracy of 3 %. The digital temperature sensor discussed in Section 5.4.1 is utilized as its 0.5° C accuracy is sufficient. The humidity and temperature sensors are mounted on the control board with the other previously mentioned sensors, as displayed in Figure 5.11. Measurement redundancy is achieved by incorporating two pressure and humidity sensors. This is however a limitation if the sensors display different values, as the true value cannot be identified without a third sensor. Therefore, a third of each sensor will be added in future revisions of the board. As the digital temperature sensor is a bus device additional sensors can be daisy chained for sufficient redundancy.



Figure 5.11: Central Unit on-board sensors

Chapter 6

6 Communication

The main challenge for effective communication in underground mines is that neither wired nor wireless systems are reliable on their own. As discussed in Section 2.5, this is largely due to the unfavourable physical characteristics of the environment, such as soil composition and tunnel structures. Attempts have been made to improve tethers through light weight cables, tether managers [2] and de-snagging robots [90], however snagging and dragging has not yet been completely eliminated. Very few existing systems include a wireless adapter on-board as signal propagation is poor (see Section 2.5).

Wireless communication has poor range and reliability, whereas tethers have excellent range and reliability. Conversely tethers catch and drag whereas wireless communication allows completely cable free roaming. The communication network for HADES should therefore combine both wired and wireless mediums. This chapter outlines the design and operation of both mediums, as well as the transition between the two.

6.1 Tethered communication

The difficulties of tethered communication are outlined in Section 2.5. They include tearing on rubble and debris, dragging on uneven terrain, snagging and breaking, and for copper cable, large power consumption. These issues have been illustrated in real disaster deployments [2] and pose constraints on the design of the tethered communication system:

- Lightweight to avoid drag.
- High tensile strength to prevent snapping.
- Communication distance exceeding 2 km in order to reach the disaster zone.
- Minimal power loss over 2 km.
- Sufficient bandwidth for teleoperation.

A tethered communication system is designed in this section. While calculations are carried out and components selected, implementation of this system was not completed.

6.1.1 Cable Type

As previously mentioned in Section 2.5, two primary cable types are employed by search and rescue robots for tethered communication: copper and fibre optic. They are explored further to determine suitability.

Copper

Copper cables communicate via electrical conduction, allowing both power and signal transmission. As copper cable possesses length dependent electrical resistance, power is lost during transmission. The cable bandwidth is moderate, with CAT6 (standardized twisted pair cable) providing 10 Gbps. Copper exhibits relatively high tensile strength (380 Mpa) but is a metal, which produces heavy cables (~188 kg/km for 4 AWG [91]). However, the cost of copper's end connectors (transceivers) are common and inexpensive.

Fibre Optic

Fibre optic cables transmit light waves through a glass or plastic core, which is encased in plastic cladding. This construction allows total internal reflection of light due to different refractive indices of the core and cladding, therefore producing significantly larger bandwidths than copper. Generally, fibre optics do not transmit high power. Optical fibre interfaces are more complex and therefore expensive than copper. Fibre optic glass has higher tensile strength (20 GPa theoretical [92]) and lower weight (~50 kg/km for low number of fibres [93]) than copper, the fibre cable jacket is also reinforced for protection. The maximum angle to which optical fibre can bend is however limited.

The underground mine tunnel length produces disadvantages for copper. Voltage loss along copper cables increases with distance and is intolerable over 2 km as calculated using Equation 6.1. Given 20 A nominal current draw, even the largest wire size (4/0 AWG) with the lowest resistance (0.164 Ω /km) produces a 6.56 V drop. The power dissipation is also

large too, as calculated with Equation 6.2, producing 131.2 W, which is roughly equal to half the system power consumption.

$$V = I(\mathbf{R} \times \mathbf{d}) \tag{6.1}$$

$$P = I^2 \times R \tag{6.2}$$

The smallest wire capable of transmitting 20 A is 8 AWG, which has a resistance of 2.061 Ω /km, producing an 82.4 V voltage drop and a power dissipation of 1649 W. Cable weight is a trade-off with power dissipation, as more copper increases weight, but reduces resistance and therefore power dissipation. For 4/0 AWG with 952 kg/km, 2 km of cable would weigh 1904 kg which is impractical. For 8 AWG (70 kg/km) it would weigh 140 kg but power consumption would be roughly 7 times that of the system itself. Based on weight and power consumption, fibre optic cable is selected.

6.1.2 Implementation

Considerations for fibre optic cable design should include:

- Sufficient data rates for teleoperation.
- High strength cable sleeve (Jacket) to support high tensile loads and prevent damage from rubble and debris.
- Be capable of 2 km operation.
- Minimize cost
- Minimize weight

Fibre optics are either single or multi-mode, which describes the cable's fibre count. Multiple fibres significantly simplifies interfacing, but exhibits a lower bandwidth-distance product resulting in reduced data rates [94]. The additional fibres increase the weight and strength of the cable. As single mode fibre is difficult to produce, it is more expensive. A dual-fibre cable is therefore desirable for a high bandwidth-distance product without excessive weight or cost.

A fibre optic network requires significant power for 2 km operation. To achieve this, a power margin greater than zero is desired. The power margin can be calculated using Equations 6.3, 6.4 and 6.5. The power margin P_M is the amount of available power remaining after link losses L_L . The power budget P_B is the amount available before link losses, calculated as the difference between minimum transmitter output power P_T and minimum receiver input power P_R .

$$P_B = P_T - P_R \tag{6.3}$$

$$L_L = (d \times P_F) + P_C + P_H \tag{6.4}$$

$$P_M = P_B - L_L \tag{6.5}$$

Fibre optic cables greater than 100 m in length are uncommon which restricts options. The wavelength of light also influences cable and component selection. The 850 nm wavelength components are the most commonly stocked by suppliers and therefore simplifies component interfacing.

For selected 850 nm wavelength transceivers [95], minimum values of output P_T and input power P_R are -9.5 and -21 dB, providing 11.5 dB of power budget. The fibre optic cable produces link losses. It is a standard 62.5/125 µm core thickness, which for 850 nm, has an attenuation P_F of 3 dB/km: 6 dB for 2 km tunnels *d*. However, cable is only available in 300 m segments requiring 6 interconnectors, each with 0.2 dB signal attenuation (P_C total 1.2 dB). The connectors are LC type [96], including latches to prevent disconnection under tensile loads. Finally, high mode losses P_H are also incorporated [97] which are roughly 0.5 dB, resulting in 7.7 dB total link losses. This produces a 3.8 dB power margin, indicating sufficient communication power. The cable selected includes a Kevlar jacket for high strength and durability and is capable of 1 Gbps data rates [98] which is more than sufficient for teleoperation.

6.2 Cable Detachment Transition

Tearing, snagging and dragging are problems associated with tethers, which if encountered, require a method of tether detachment in order to wirelessly extend the communication range. 97

The detachment mechanism should be electronic for software activation. Additionally, the mechanism should not allow accidental detachment during operation.

Detaching a fibre optic connector is difficult, therefore a pseudo-wired solution is required. This is realised with a wireless transceiver installed at the end of the tether, which interfaces with a fibre optic connector. This allows simple tether detachment, without the intricacies of fibre optic connectors.



Figure 6.1: Detachment mechanism, disassembled (left), mounted on chassis (right)

A prototype detachment mechanism is designed, as seen in Figure 6.1. The left-most piece connects to the end of the tether, is inserted into the opening of the right-most piece and twisted to lock into place. The tether is unable to detach while rotated as the central piece (connected to a servo) prevents reverse rotation. The servo can rotate to unlock and release the tether. A 3D printed prototype is designed, but a final iteration should be manufactured from aluminium.

6.3 Wireless communication

As mentioned in Chapter 2.5.2, wireless communication in underground mines is challenging. The mine tunnel structures produce narrow channels with limited bandwidth, and tunnel corners attenuate signals sharply. Even high power transmitters are unable to sufficiently penetrate the rock and soil. Low transmission frequencies propagate further but

lack the bandwidth required for teleoperation. In order to attain greater range after tether detachment a novel wireless solution is required.

A mesh network avoids rock and soil attenuation by allowing wireless transceivers to be positioned at tunnel corners and intersections to create a multi-link network as seen in Figure 6.2.



Figure 6.2: Typical mine layout with required node locations

The software and electronic implementation of this mesh network was designed in a parallel project [60] but not completed in time for integration on to HADES. The study evaluated ZigBee mesh network modules [60], which were small, lightweight, exhibited long battery lives, sufficient range and easily interfaced. However, transmission was limited to black and white video feeds at 6 fps with average latencies of 1.08 seconds over forty hops and therefore are not suitable for teleoperation.

Mesh network implementation presents physical challenges for this application, especially node storage on-board HADES. Physical space limitations constrain the maximum number of nodes. Another challenge is deploying the nodes as HADES moves through the mine. The final position of a dropped node greatly affects the wireless network range and reliability. Globally, nodes must be located at tunnel corners and intersections. Locally, node locations should avoid debris or rubble and raise their antennas. The nodes should also be capable of operating unaffected by dirt or water.

6.3.1 Deploying Mechanism

Mesh network nodes must be carried on-board for distribution in the mine, which requires a deployment mechanism. The primary design constraint is explosion-proofing. Complex mechanisms complicate explosion-proofing and increase cost, component count and power consumption, which should be avoided. For a mobile robot application, the deployment mechanism must also be light weight and compact. Non-intrinsically safe actuators are required to deploy nodes, which poses a challenge for explosion-proofing. Nodes should be stored internally within the chassis and dropped without pressure loss, or stored externally with internal actuators. Two concepts are evaluated for node deployment: electromagnets and push-spirals.

Electromagnets

A magnetic design is advantageous for this application because explosion-proofing can be guaranteed as the magnetic forces act from within the chassis. This can be realised through an electromagnet for each node. To avoid excessive power consumption, mechanical latches should be incorporated to provide the holding force while the electromagnet only provides the release force. A benefit of this concept is the ability to individually deploy any node, which is useful if different node variations exist. Drawbacks include latch release complications when the chassis is inverted, dirt and debris clogging the latches, as well as a high component count.

Push-Spirals

A Push-Spirals design operates using helical spirals which rotate, pushing a queue of nodes forward along a pipe. When nodes reach the pipe opening, they drop out. To increase node storage, push-spirals can be placed either side of the chassis. A single motor would be required per spiral, positioned in the chassis, with its shaft rotating through a lip seal for explosion-proofing. The pipe is advantageous as it protects the nodes from being knocked or damaged. Additionally, nodes can be dropped regardless of chassis orientation. A disadvantage is that nodes are only dropped according to the queue order.



Figure 6.3: Spiral-push node deployment mechanism

Although electromagnets avoid additional sealing, the cost, complexity and component count outweighs the benefit of sealing and therefore push-spirals are a more suitable mechanism for node deployment. A designed CAD model of this mechanism is shown in Figure 6.3. It would require movement of the side cameras to the top and bottom of the chassis, facing vertically.

6.3.2 Node Enclosure

40 nodes are required to cover all of the corners and intersections of Pike River Mine according to [63]. If nodes are stored either side of HADES' central body, their enclosure size is constrained to $40 \times 50 \times 80$ mm. The node enclosure should be explosion-proof as well as resistant to dirt and water, with an enclosure design that ensures an elevated antenna. It is the operator's responsibility to drop nodes at corners, unobstructed by debris and rubble (on level, elevated ground where possible).

The node antenna needs to be elevated to increase signal strength. However, dropping nodes in this orientation is difficult to achieve, therefore self-orientating enclosures are designed. Self-orientating means the node enclosure should be monostatic, with a low centre of mass, which produces a single stable resting point. A concept design is displayed in Figure 6.4



Figure 6.4: Self-orientating node enclosure

The enclosure is designed from two pieces: a cone and a hemisphere. It is 70 mm high with an outer diameter of 45 mm. Positioning the antenna at the cone peak effectively guarantees a raised antenna after dropping. A low centre of mass can be achieved by positioning the batteries as well as an additional discrete weight, near the enclosure base. The hemisphere and the cone are both threaded to open and close, while allowing sealing. As slopes up to 18 degrees are possible in underground mines, the node enclosure should not roll down them. Testing on sloped surfaces demonstrated that the enclosure slides cone-first. Protruding petals are designed in a second revision (Figure 6.5), to dig in the ground and prevent rolling. Although 3D printed for prototyping, this node enclosure would be designed from a plastic stronger than ABS to withstand the shock of dropping.



Figure 6.5: Second revision of node enclosure

Chapter 6

7 Electronic Hardware

7.1 Power Supply

At least two hours self-contained operating time is required as per the specifications in Section 2.6. To achieve this, affordable batteries with a high energy density are required.

As mentioned in Section 2.5.3, LiPo and Nickel batteries are most desirable for electric vehicles due to their high energy density. The trade-off when comparing the two is longer life cycles versus cost. Nickel batteries retain a greater maximum capacity over time but are 200-350 USD/kWh [61]. As the batteries in HADES have to be removed for charging, maximum capacity over time is not advantageous. The lower cost of Li-Pos (125 USD/kWh) is thus more suitable for this application.

Table 7.1: Estimated System Current

Component	Estimated Current (A)	
Motors	$14 (3.5 \times 4)$	
Power Distribution Board	8 (see Table 7.2)	
Total	22	

Obtaining high capacity Li-Po batteries is difficult due to their flammable/hazardous nature. Li-Po batteries are available which have three cells (3S) and 8 Ah capacity. Initial system current draw estimates indicate an average continuous current of 22 A (see Table 7.1). To achieve at least two hours operating time, six of these Li-Pos are required.

7.2 Power Distribution

7.2.1 Overview

The various electrical and electronic devices incorporated into HADES have differing power supply requirements. Providing a separate battery or power converter for each device is impractical and inefficient. All components require two hours continuous operation to adequately carry out rescue missions (see Section 2.6) and hence optimization of battery life via power management is crucial.

A power distribution board simplifies power management by centralizing power converters on a single board in the middle of the chassis. In order to understand where power is being consumed, the board should continuously measure the current draw of all devices and monitor their power flow to detect faults. Transistor switching of this power flow should prevent damage and be capable of disabling devices with high current draw. This allows digital control over system power management and enables features such as battery saver mode to be implemented. An additional benefit of a single power distribution board is consolidation of protection circuitry from individual devices to one PCB.

The power distribution board is pictured in Figure 7.1. A separate PCB that digitally controls power distribution is mounted above it and will be detailed in the following section.



Figure 7.1: Power Distribution Board

7.2.2 Input Stage

The goal of the input stage is to monitor and control battery power before it reaches the power converters, ensuring fault conditions do not damage on-board electronics. All components require power conversion, except the ESCs. The four ESCs are designed to be individually powered directly by a 3S Li-Po battery and therefore are not channelled through the input stage (discussed in Section 7.2.6). The power converters are thus supplied by the remaining two batteries (through the input stage). Two batteries requires a parallel configuration that risks back-charging (fire hazard). Back-charging can be avoided using diodes or transistors.

Current flow through the input stage is nominally 8 A (see Table 7.2). For a 0.35 V drop rectifier, 2.8 W of power is dissipated. This is compared against the 0.32 W of a typical 5 m Ω on-resistance transistor. As transistors dissipate 8.75 times less power, they are more suitable to prevent back-charging. The transistors are incorporated into the circuit through high side switches discussed later in this section.

Battery Power

Bullet connectors attach the batteries and act as mechanical reverse polarity protection. Two identical input stages use transistors to switch between the batteries, which avoids back-charging; one input stage is shown in Figure 7.2. To increase efficiency and save PCB space a high side switch IC (U3) is implemented as opposed to discrete components.



Figure 7.2: Schematic of one of the input stages

Battery voltage along with previous current draw is the best indication of battery life. However, the battery voltage is between 9.6 V and 12.6 V but the microcontroller's Analog to Digital Converter (ADC) only measures between 0 and 5 V. The battery voltage is therefore divided down with 1 and 2.5 k Ω resistors. This is implemented before the fuse in order to avoid any conduction losses from series components.

Protection Circuitry

Overcurrent protection is achieved using a fast blow Positive Temperature Coefficient (PTC) fuse (F2). This is selected over a standard fuse, as PTCs' resettable nature is beneficial if its blows during deployment where an operator is unable to access it. The nominal operating current passing through the high side switches is 8 A. A PTC fuse rating of 10.7 A is calculated using Equation 7.1 as described in the Fuseology Selection Guide [99].

$$Fuse Rating = \frac{Nominal Operating Current}{0.75}$$
(7.1)

Transient Voltage Suppressors (TVS) work like Zener diodes to conduct when overvoltage conditions occur, but with higher current ratings. As described in [100], the standoff voltage is the point at which the TVS begins conducting. It should be just higher than maximum operating voltage. For the batteries' 12.6 V maximum, a TVS with 13 V standoff is selected. The clamping voltage is reached by the TVS during complete avalanche mode (full conduction) and is the maximum tolerable circuit voltage. Of the components that follow after voltage protection, the lowest absolute maximum voltage is 24 V (one of the converters). A TVS (D3) with 21.5 V clamping voltage is the closest available value below 24 V. A diagnostic LED (D6) is placed at the end of the power path, turning off if the fuse blows, the TVS conducts or the high side switch fails.

Switching

A problem frequently encountered by digitally controlled distribution boards is the digital controller being unable to switch on the main power unless it is already being powered. A separate battery could solve this but would require supplementary circuitry. A simpler solution is a normally-on and normally-off configuration, displayed in Figure 7.3 (extracted from Figure 7.2).



Figure 7.3: A normally-on configuration for the high side switches

NMOS pass transistors pull the high side switch 'IN' line to ground which turns the switch on. A Single Pole Single Throw (SPST) main switch is incorporated to disable the IC and turn the whole system off. The normally-on path is configured with two MOSFETs (Figure 7.3) to enable operation without a digital signal. R12 pull the gate high, turning the first MOSFET (Q4) on while the second (Q2) allows a digital line to switch it off. The normallyoff configuration, (not shown) requires a single transistor and a digital line to turn the IC on. The normally-off configuration creates a primary and secondary battery system where the primary battery is normally on. When this battery is depleted the digital controller can switch to the second battery.

The high side switches (U3) are BTS50055 devices [101] which include current sense functionality requiring configuration. The IC outputs a sense current proportional to the load current, which a gain resistor converts to a voltage for microcontroller ADC measurement. The ratio of sense to load current is roughly 20,000 at ambient temperatures of 25 °C. At a maximum load current of 21 A (see Table 7.2) this produces a maximum sense current of 1.05 mA. To scale this measurement between 0 and 5 V for microcontrollers, a resistor of 4.7 k Ω is required.

When the microcontroller switches from the primary to the secondary battery, voltage droop can occur. The power converters allow 0.6 V droop. Large bypass capacitors are placed on the high side switch output to prevent this; their minimum value is calculated using Equation 7.2.

$$C = \frac{I \times dt}{dV} \tag{7.2}$$

The switching time dt of 120 µs is determined from transistor turn on/off times. Nominal current *I* is 8 A, as displayed in Table 7.2, and droop is dV. A minimum value of 1.6 mF is calculated, and implemented with two 1 mF components, as shown in Figure 7.2.

7.2.3 NUC Backup Power

Several intermediary components between the batteries and the Intel NUC can fail and cause system shut down, such as high side switches or power converters. A backup solution is required to prevent brown outs. It should be adequately separated from the main power path so that fault conditions which damage intermediary components do not also damage the NUC.

The NUC specifications state the minimum supply rail voltage is 12 V, but testing demonstrated reliable operation down to 11.6 V. As battery cell voltages vary between 12.5 V and 9.6 V it is possible to power the NUC directly from a battery while the capacity remains above 11.6 V. As the batteries are configured normally-on and normally-off, the normally-on battery will drop below 11.6 V before the digital controller switches to the second (fully charged) battery. Therefore, if a fault occurs, power is routed from the secondary (normally-off) battery. To ensure fault conditions do not also damage the NUC, a separate fuse is placed in line with the backup power path after the TVS (to include voltage protection).



Figure 7.4: Schematic of NUC backup circuitry

If intermediary components and backup power are both controlled by the same microcontroller, then software bugs or hardware failure would affect both the standard and

backup power paths. A backup microcontroller could address this but the analog circuitry in Figure 7.4 is simpler and exhibits low latency and therefore fast response to failure.

A comparator (U7) and high side switch (U8) are the core components, as shown in Figure 7.4. The comparator takes the divided battery voltage (halved) and compares it with the 12 Vcc supply rail from which the NUC is powered. If the 12 V rail is not active, the comparator outputs a low, sinks current and turns on the high side switch, which routes the secondary battery directly to the NUC's output connector. Large 1.5 mF capacitors are placed on the output connector of the NUC to prevent voltage droop when backup up power is rerouted. They were calculated similarly to main input bypass capacitors using Equation 7.2, with current from Table 7.2, 0.4 V droop and switching time of 2.4 ms.

7.2.4 Power Conversion

Three DC voltage rails are required to power the electrical components. Fluctuating voltages can cause brownouts and incorrect operation for most of HADES' electronic components and must be avoided. In order to meet the voltage requirements of every component, the battery voltage needs to be regulated or converted.

DC-DC Converters

As long battery life and therefore high efficiency is required, DC-DC converters rather than regulators are primarily incorporated after the input stage. There are two options for implementation, a combined package or individual components. Designing a buck-boost converter from individual components would be under half price (~\$100) and allow a custom configuration. Purchasing a single package is more expensive (~\$250) but saves space and guarantees performance with a host of additional features. For this application, space and performance are more valuable and so packaged DC-DC converters were selected.

Input and output voltages are the primary considerations when selecting a device. The input range should accommodate between 9.6 and 12.6 V in order to interface with the batteries. Three output voltage rails and therefore converters are needed to power all components: 3.3 V, 5 V and 12 V. The only 3.3 V component is the IMU discussed in Section 5.4.2. The 111

converters selected must contain sufficient output power to supply the required peak load current. Table 7.2 displays the estimated nominal and maximum current draw of devices on each of the 5 V and 12 V rails.

	Component	Nominal Current	Maximum Current
5 Volt Rail	Total 5V	4	10.25
	Servo Output	1	2
	LED Output	0.5	2
	Sound Output	0.75	1.5
	Network Output	0.25	0.75
	Aux5 Output	1	2
	5 V On-Board	0.5	2
12 Volt Rail	Total 12 V	4	12.5
	Intel NUC Backup*	1	2.5
	Intel NUC Output	1	2.5
	Node Deployment Output	1	3
	Solenoid Output	0.5	2
	Aux12 Output	1	2
	12 V On-Board	0.5	0.5

Table 7.2: Nominal and Maximum Component Current

* Only operates when a failure occurs

The half brick package is standard for DC-DC converter high power applications with various brands and suitable input and output voltage ranges available. The DC-DC converters selected are CINCON products exhibiting 88 and 83 % efficiency. The converter power rating was calculated for the maximum current draw of all components on the rail using Table 7.3. Power ratings of 75 W and 150 W were selected as the closest rating for the 5 V and 12 V rails respectively.

Table 7.3: Power Converter Ratings

	Max Current (A)	Voltage (V)	Power	DC-DC Converter (w)
5 Volt Rail	10.25	5	51.25	75
12 Volt Rail	12.5	12	150	150

The converters claim internal over-current and temperature protection to enable maximum power output without damage However, their data sheets still recommend input fuses [102].

The values for these fuses were calculated using Equation 7.1 in Section 7.2.2. Maximum current values of 10.25 and 12.5 A produce PTC fuse ratings of 13.5 and 16.5 A. In accordance with the datasheet, trim resistors maintain exactly 5 and 12 V output voltages as shown in Figure 7.5.



Figure 7.5: Typical DC-DC converter circuit

The DC-DC converter is U6, a MOSFET is used to pull its enable line low for shut down. A diagnostic LED (D8) indicates the converter and output status. A discrete current sense amplifier U5 monitors the output current as further detailed in Section 7.2.5. It measures the total current being supplied to the rail to observe power consumption as well as determine efficiency.

7.2.5 Output Modules

To simplify the design and potential troubleshooting, all outputs should be designed as a 'module' which has similar components and layouts. Each module must include current sensing and digital control to enable intelligent monitoring. Low side power switching to the 113

outputs has the potential to produce floating grounds. This leads to unpredictable voltage potentials as well as live circuits that could be hazardous or accidentally shorted to ground. Therefore, high side switching should be employed.

Protection circuitry should be included in the module so that devices without power protection can be safely connected. To assist with prototyping and development, it is desirable for each module to include manual control. Table 7.2 displays all the devices that are expected to be powered by the distribution board including their nominal and maximum current draw. An output module is designed for each, with components rated for the respective maximum power. The signals to and from each module should be routed to the embedded control circuit mounted above.

12V Rail

The 5 V and 12 V output modules use different high side switch ICs due to the minimum supply voltages. A BTS50055 Infineon IC is implemented on the 12 V rail, with 4.4 m Ω on-state resistance and current sensing capabilities. It features over-temperature and short circuit protection to prevent damaged to connected devices. A schematic for the 12 V output module is shown in Figure 7.6. The BTS50055's enable line is active low, requiring an NMOS transistor to pull it to ground. The gain resistor on the current sense line converts current to voltage for an ADC.



Figure 7.6: Schematic of a typical 12V output module

5V Rail

The 5 V rail uses a Texas Instruments TPS2001C power distribution switch IC. It is one of the few affordable 5 V supply high side switch as capable of load currents up to 2 A. Intended for USB applications, it is rated for high current applications with short-circuit protection. It features a digital diagnostic fault line pin, which is asserted active low during over-current or over-temperature conditions. Figure 7.7 shows the 5 V rail output module. As per the TPS2001C datasheet [103] pull-up and pull-down resistors are placed on the FLT and EN lines.

Unlike the BTS50055, the TPS2001C does not include internal current sensing and therefore external circuitry is required. An issue for low side current sensing, placed on the ground return path, is its inability to detect a short-circuit which occurs before the sense resistor. Discrete current sensing is therefore placed on the high side of the module circuit.

The discrete current sense circuit uses an amplifier IC to measure a small voltage drop across a high precision series resistor, producing an output current proportional to the load current. As noise can affect the measurement accuracy, a bypass capacitor across the sense resistor filters it. To allow a microcontroller to read this measurement, a gain resistor is required to convert output current to voltage. Equations 7.3, 7.4 and 7.5, and The value of 0.004 is given in the current sense amplifier's datasheet . V_{sense} is the voltage across R_{sense} and is selected as it's a small voltage drop with a 7.6 % error (as determined by the datasheet). V_{out} and I_{out} are the maximum values produced by the current sense amplifier and I_{load} is the maximum load current.

Table 7.4 and Table 7.5 are used to calculate R_{sense} and R_{gain} for each 5 V output module.

$$I_{out} = 0.004 \times V_{sense} \tag{7.3}$$

$$R_{sense} = \frac{V_{sense}}{I_{load}} \tag{7.4}$$

$$R_{gain} = \frac{V_{out}}{I_{out}} \tag{7.5}$$

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The value of 0.004 is given in the current sense amplifier's datasheet [104]. V_{sense} is the voltage across R_{sense} and is selected as it's a small voltage drop with a 7.6 % error (as determined by the datasheet). V_{out} and I_{out} are the maximum values produced by the current sense amplifier and I_{load} is the maximum load current.

Output	V _{sense} (V)	Iload (A)	V _{out} (V)
Servo	0.03	2	4.5
On Board	0.03	2	4.5
LED	0.03	2	4.5
Sound	0.03	2	4.5
Aux5	0.03	2	4.5
ESCs	0.04	50	4.5
Network	0.03	0.75	4.5
12V DC	0.03	12.5	4.5
5V DC	0.03	10.25	4.5

Table 7.4: Current Sense Resistor Set Values

Output	Rsense (Q)	$R_{gain}(\Omega)$	Iout (A)
Servo	0.015	37500	0.00012
On Board	0.015	37500	0.00012
LED	0.015	37500	0.00012
Sound	0.015	37500	0.00012
Aux5	0.015	37500	0.00012
ESCs	0.0008	28125	0.00016
Network	0.06	37500	0.00012
12V DC	0.0023	37500	0.00012
5V DC	0.003	37500	0.00012

 Table 7.5: Current Sense Resistor Calculated Values

Shared Design

To ensure continuous overcurrent does not damage the high side switches, the power rails include series PCT fuses (F21). The same method of design outlined in Fuseology [105] was applied. If the output module load suddenly changes, a local current supply is required to prevent voltage droop. Input and output capacitors (C63, C62 and C64) decouple noise and

supply local current. Standard 100 μ F and 100 pF capacitors are implemented to avoid parasitic inductance and cover a larger bandwidth. Sudden voltage spikes from inductive loads are suppressed by fly back diodes (D51). For diagnostic and testing, status LEDs (D52) are placed on the microcontroller's switching signal and output lines. All signals to and from each output module are routed to a microcontroller through a central 40-pin board to board connector discussed in more detail in Section 6.2.3.



Figure 7.7: Schematic of a typical 5V output module

Digital monitoring and control of the distribution board is highly recommended to extend battery life; but manual circuit operation is possible. The manual override also ensures a particular output can be permanently switched on to simplify troubleshooting and fault identification. Two-pin jumpers (P29) pull the enable lines high, as seen above in Figure 7.7. Due to time restraints, digital control was not implemented and instead the jumpers manually enable the distribution board.

The distribution board is designed to power HADES' existing components, but additional devices may be integrated in future. In anticipation of this, auxiliary output modules are

designed for the 5 V and 12 V rails. They are identical to the standard output modules in design, with 2 A of available current.

7.2.6 ESC Relay Switching

The ESCs draw the largest current of all system components. Their maximum current rating (60 A continuous, 380 A peak, see Section 4.2.5) is too large for most surface mounted packages. As a result, specialised switching is required. Normal operation on flat ground is expected to draw between 3.5 and 15 A, which spikes during movement in rough terrain. HADES' high power motors and ESCs are a potential safety hazard under fault conditions as excessive current (e.g. in the event of an ESC failure) can cause the ESCs to catch fire.

A switching circuit is therefore required which deals with the ESC current draw while allowing isolated disconnection of power in an emergency. Additional over-voltage and overcurrent protection circuitry should also be included to guarantee power faults do not cause damage. The switching circuit should be controlled by a microcontroller but overridden by a 'safety switch'. The 'safety switch' should be manually controlled by an operator.

Relay Implementation

Relays isolate the ESCs from the batteries to guarantee safety, while switching high current without dissipating excessive heat. Each relay controls one battery suppling two ESCs. A schematic of one relay circuit is shown in Figure 7.8. A battery plug supplies power to the input terminal of a CB1AH Panasonic relay, which has a 70 A continuous contact rating. A voltage divider drops the battery cell level for measurement before power division between the two ESCs.

The relay's coil switches on at 12 V, 150 mA, which necessitates another high side switch (FDC6326L). As recommended by the datasheet [106], R2 determines slew rate which is irrelevant and therefore set at 470 Ω . R1, selected as 1 k Ω , obtains an R1/R2 ratio of 47, which according to the datasheet is sufficient to switch the IC on.



Figure 7.8: Schematic of one of the ESC switching circuits

Safety Switch

The safety switch is designed as a manual override during testing, to disable the ESCs under fault conditions. It is integrated into the relay's high side switch circuitry. A microcontroller or 2-pin jumpers control the high side switches and therefore the ESCs. These signals are overridden by the safety switch as a fail-safe. The safety switch is positioned at the rear, as pictured in Figure 7.9, to allow an operator to walk behind HADES. Pulling out a 6.35 mm audio jack breaks the connection between pin 1 and 2 of a JST connector (not pictured in Figure 7.8, but pin 1 is connected to the *'safety'* line). This disconnects an N-channel MOSFET gate from ground, allowing it to be pulled high, thereby turning the FET on and grounding the digital control signal.



Figure 7.9: Safety Switch plugged in at the rear.

Protection Circuitry

A TVS and fuse prevent over-voltage and over-current. The fuse should be fast-blow, rated at 30 A (20 A estimated motor maximum current draw), while possessing small dimensions to fit on the PCB. Cartridge and blade type fuses meet these requirements, but cartridge fuses were selected as they are half the height. The fuses are rated at 30 A for 4-hours minimum blow time and 70 A for 20 seconds maximum opening time. The PCB mounted cartridge holder contacts can also conduct 30 A.

Two large bypass capacitors, displayed in Figure 7.10, supply local current, while the same TVS used in Section 7.2.2 avoids voltage spikes. The same discrete current sense circuit monitors the ESC power consumption but requires a significantly smaller R_{sense} (0.8 m Ω) and R_{gain} (28 k Ω).



Figure 7.10: Schematic of an ESC's protection circuitry

7.2.7 PCB Design

The ESCs and output modules have high current flow, which must be accounted for in the PCB design. High currents can produce noise coupling into signal lines and may dissipate significant power. These problems are exacerbated by thin, long traces which have high resistance. Another challenge faced by the PCB design is the control circuit board mounted above, as displayed in Figure 7.11. Vertical space is limited; therefore, it can only be raised 12.5 mm off of the distribution board which limits the maximum height of components beneath it.



Figure 7.11: Control board mounted above power distribution board.

The DC-DC converters require mounting directly against an access hatch plate for heat transfer. This constrains the board size to 250×95 mm in order to fit through the access hatch. Trace widths are thus limited by board dimensions. Furthermore, as the PCB requires a compact layout, the distance between high power components and sensitive signals is restricted. The layout must endeavour to keep high current traces and components away from sensitive components or signal lines. Power traces should be short with maximum width given the board size constraints. The height of all components should be less than 12.5 mm to prevent contact with the control board mounted above.

Copper Heat Conduction

All primary power paths use copper planes to spread the heat over a greater area. The width *W* of other major copper traces is calculated according to Equation 7.6 and 7.7 from [107].

$$A = \left(\frac{I}{K \times (\Delta T)^B}\right)^{\frac{1}{C}}$$
(7.6)

$$W = \frac{A}{d \times 1.378} \tag{7.7}$$

The chassis temperatures should not exceed 50° C (as specified in Section 2.6) for safe operation, therefore at 30° C ambient, the allowable temperature rise ΔT is 20° C. The copper

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area *A* is calculated first from the constants, *B* (0.44), *C* (0.725) and *K* given in [107], which results from curve fitting to standard IPC-2221 [108]. Signal traces are routed on a two-layer board, meaning they are all external, producing K of 0.048 from [107]. The PCB is manufactured from 2 oz copper thickness *d*, rather than the standard 1 oz, to increase lateral heat flow. This improves heat dissipation and therefore allows narrower traces and fewer thermal vias.

Due to large load currents, the high side switches employed by the 12 V output modules and the input stage require additional PCB copper for heat dissipation. The on-resistance of the IC in combination with the current draw determines the power dissipation, as displayed by Equation 7.8. The device power dissipation and Equation 7.9 allow calculation of the copper area required to prevent overheating.

$$\boldsymbol{P}_{diss} = \boldsymbol{I}^2 \boldsymbol{R}_{on} \tag{7.8}$$

$$Area = \frac{P_{diss} \times \theta_{SA}}{T_{max} - T_{amb} - P_{diss}(\theta_{JC} \times \theta_{CS})}$$
(7.9)

Similar temperatures as for the trace width calculations above and the maximum current values from Table 7.2 are used. The on-resistance R_{on} and thermal resistance values θ are obtained from the BTS-50055 datasheet [101] and a thermal design application note [109]. Using only a single side of the board produces an area that is impractical given the board size constraints mentioned earlier in this section. Doubling the amount of heat dissipation can be achieved by using both sides of the board with thermal vias. 12 mm vias is recommended in the application note; spaced 1 mm apart. The power dissipation and area required by each chip is listed in Table 7.6 and shown in the 12 V output module pictured in Figure 7.12.

Component	Pdiss (W)	A (cm2)
Input	0.28	11.3
NUC	0.04	1.6
Aux	0.0176	0.7
Node	0.0176	0.7
Solenoid	0.0176	0.7

Table 7.6: Heat Dissipation Area



Figure 7.12: Thermal planes and vias required by the 12V modules

Component Positioning

The motors and ESCs are located at either end of the chassis and therefore the relays are placed at the PCB ends to reduce cable length. This also separates them from sensitive signals to prevent noise coupling, and positions them out from underneath the control board as they are 25 mm tall.

The PCB is mounted in the middle of the chassis against the bottom hatch as displayed in Figure 7.13. Centralizing the DC-DC converters allows the PCB to be horizontally centred against the hatch such that room is provided either side for the ESCs.



Figure 7.13: PCBs mounted in the chassis against bottom hatch

For interchangeable components and reduced size (within comfortable soldering range), imperial 1206 surface mount packages are employed where possible. Inter-layer signals are restricted by primarily using surface mount components, however vias and through-hole connectors account for this.



Figure 7.14: PCB layout of 5V module, top layer (left), bottom layer (right)

Mounting the embedded control board (see Section 7.3) on top of the distribution board, as displayed in Figure 7.11, creates additional design considerations. The embedded control PCB should be adequately supported by the board-to-board connectors. Additionally, the connectors should not complicate trace routing or prevent circuit troubleshooting. To minimize signal trace lengths and act as the primary support, the main board-board connector is orientated vertically and positioned centrally between the DC-DC converters as in Figure 7.1. This also allows pin probing on the bottom layer of the board for debugging. Forces acting on the embedded control board are distributed more evenly (preventing flex) by two outer board-to-board connectors, parallel to the shorter edges of the boards. The entire PCB layout is available in Appendix B.

7.3 Embedded Control Board

The embedded control board operates on the hardware level, managing power distribution, controlling the motors and interfacing with sensors and actuators. These low level tasks require an embedded microcontroller (see Section 7.3.1), with a large number of pins as well as adequate processing ability. The PCB must be mounted on top of the power distribution board to save space.

There are two main options for processing: centralised or distributed. Centralised control is incapable of parallel processing unless it includes multiple CPU cores, which are not generally available on microcontrollers. Multiple distributed controllers save development time as the circuits and code can be structured and isolated according to function, which significantly simplifies troubleshooting and debugging. Additionally, small microcontrollers are less complex and easier to program. A large, central microcontroller consumes less PCB space but this complicates PCB layout as all the traces have to be routed to the same chip. To facilitate fast development and for greater flexibility, a distributed control system was employed.

This section covers the circuit design for the motor and sensor interfacing microcontroller. As the power management microcontroller does not include any features not already discussed by the motor control and sensor interfacing microcontrollers, detail on power management is primarily provided in Section 7.2. Full embedded control board schematics and PCB layout are available in Appendix B.

7.3.1 Microcontroller Selection

The microcontroller features required for power management, sensor & actuator interfacing and motor control are:

- 12 Interrupts
- 2 Timers
- 36 Analog to Digital Conversion channels (ADC)

- 4 PWM signals
- I²C communication
- UART

Almost all microcontrollers are capable of these features. Manufacturers produce a wide range of microcontroller families with varying clock speeds, memory sizes, pin counts, case styles and power supply requirements. As a result, almost all manufacturers include a device which is suitable for this application and therefore the primary consideration is development time. Development time consists of development environment setup, understanding documentation, learning curve for the programming language and programming environment and the availability of libraries and device support. As the author has a comprehensive knowledge of the Arduino IDE, its libraries and advanced features, an AVR mega device is selected.

The wheel velocity measurements require microcontroller interrupts to accurately detect the motor encoders' pulses. When the wheels spin fast and cause high frequency interrupts, a microcontroller can lock up or miss interrupts and incorrectly measure wheel velocity. The number of pulses per second (pps) constrains the maximum number of operations the microcontroller can perform without getting locked up. The pps can be calculated using Equation 7.11 and the revolutions per second (rps) from Equation 7.10.

$$rps = \frac{v}{\pi \times D} \tag{7.10}$$

$$pps = rps \times p \times G \times m \tag{7.11}$$

We assume that HADES can travel safely at a linear velocity v of roughly twice walking speed (3 m/s), driving its 400 mm diameter D wheel through a 104:1 gearbox ratio G. HADES' four motors m have encoders which monitors and produce a pulse (interrupt) for each of its three poles p. This produces 12 total interrupts for 2495 pps. Each pulse must be detected while also processing motor control signals and communicating with the main control unit.

To assist current and future development, the three functions (power management, motor control, sensor interfacing) are divided between three microcontrollers. This provides a dedicated motor microcontroller, ensuring all motor encoder pulses are detected. The largest constraints when selecting a device are the 36 ADC channels and the 12 interrupts required. Atmel's ATmega2560 range are low cost, user friendly devices with 100 pins available. Three of these devices, in conjunction a multiplexor, are capable of achieving 36 ADC channels; a single ATmega2560 can also provide 12 interrupts for the motors.k

The standard ATmega2560 layout is displayed in Figure 7.15. The logic high voltages are dictated by the supply rail of the ATmega2560, which can range between 1.8 and 5.5 V. Most components require 5 V but the IMU operates at an absolute maximum of 3.6 V. As only the IMU requires a 3.3 V rail, Vcc is set at 5 V, with a level shifter as mentioned in Section 5.4.2. Each pin on the Vcc net is bypassed to ground with standard practice 0.1 μ F capacitors. The ADC voltage reference pin also requires bypassing in order to configure the internal voltage reference. For troubleshooting an LED is attached to an unused digital pin.



Figure 7.15: Schematic of a typical ATmega2560 microcontroller layout

The ATmega2560 has a built-in default 16 MHz clock, which due to its RC design can exhibit a frequency that varies up to 50 % [110]. A 16 MHz external crystal achieves greater frequency accuracy and stability for UART, I²C, SPI and USB communication as well as internal timers and pulse generation. The selected crystal exhibits a frequency stability of \pm 50 ppm and tolerance of \pm 30 ppm. All three microcontrollers include an external crystal, as well as the recommended 18 pF capacitors.

Individually programming multiple microcontrollers through the same SPI lines is not possible. A 2-pin jumper allows switching the SPI clock signal between the three microcontrollers such that only one receives the signal at a time. To reset all microcontrollers at once, their reset pins are connected to a push button, tied to ground by a 100 nF switch bounce capacitor and to Vcc by a 4.7 k Ω pull-up resistor.

Communication is required between the three microcontrollers. I²C and SPI are the two most popular protocols. As both provide sufficient speed, and available pins to implement communication are not limited, either protocol is possible. SPI is already used to individually program the ATmegas, therefore it cannot be used for communication and so I²C is implemented.

7.3.2 Central Unit

The central unit is the I²C bus master. The analog and digital sensors, headlights, solenoid valve and tether release mechanism are all controlled by the central unit. These require a variety of different functions including ADC, PWM, digital outputs and digital communication.

The PWM and digital outputs require minimal components and are primarily dealt with through software (see Chapter 7). For increased ADC resolution, sensor output voltages are adjusted between 0 and 5 V through voltage divider networks. To avoid floating grounds, 4.7 k Ω resistors pull-up all digital communication lines. Auxiliary connectors are incorporated to allow supplementary sensors and actuators to be connected in the future. An

auxiliary connector is wired to each of the aforementioned functions, with voltage dividers and pull-up resistors left unsoldered.

Communication between the embedded controllers and the main control unit (discussed in Section 7.5) is carried out over USB, requiring a UART interface bridge. All three microcontrollers cannot connect via USB as the interface bridge requires expends available USB ports and PCB space. Therefore, the main control unit communicates to all microcontrollers through the central unit (I²C master).

A schematic of the interface bridge, including supplementary components, is displayed in Figure 7.16. The FTDI FT232RL chip is selected as the USB-UART serial interface. It is regularly employed in ATmega circuits and well supported by the Arduino community, with drivers that are regularly updated. 47 pF bypass capacitors are used on the data lines as recommended in the datasheet [106] as well as LEDs connected for visualisation of the TX and RX data lines. To meet USB standards, an EMC filtering ferrite bead is wired in series with the USB power line.



Figure 7.16: Schematic of the FTDI chip layout

7.3.3 Motor Control

As mentioned in Section 6.2.2 a dedicated microcontroller is required to monitor and control the ESCs and motors. The ESCs are purchased with three cables: JST connectors for PWM signals, sensor cables (for sensored brushless motors) which provides the ESC with encoder and thermistor information, as well as a toggle-switch push-button combination for enabling and programming. These three ESC cables have to be modified to gain access to the signals. The thermistor requires an ADC channel, the 3 encoder pulses require interrupts, and digital lines are needed for enabling and programming the ESC. This requires a total of: 4 PWM signals, 8 digital lines, 4 ADC channels and 12 interrupts.

The 4 PWM signals are possible on any digital pin with timers and a software library. The thermistors can be measured on any ADC channel. As an ATmega2560 only includes eight external interrupts, a combination of external interrupts and Pin Change (PC) interrupts are required. External interrupt vectors have higher priorities than PC interrupt vectors, therefore Pole A of each motor is connected to an external interrupt to ensure it is detected. The remaining two pin change interrupts on Pole B and C just provide additional accuracy at lower speeds, greater angular resolution and direction identification. The pin attachment of all signals is shown in Figure 7.17.



Figure 7.17: Pin connections for the motor control microcontroller

Digital lines alone are insufficient to enable and program the ESCs. Figure 7.18 displays the additional circuitry required, where high side switch packages are used to simulate the toggle switch and push button. The FDC6326L device is employed identically to the power distribution board (see Section 6.1.6).



Figure 7.18: Circuit which takes advantage of existing ESC attachment



Figure 7.19: Completed embedded control board

7.4 Intrinsic Safety

As mentioned in Section 2.2.4, some components can be exposed to explosive environments provided they are intrinsically safe. These components do not store or generate greater than 1.5 V, 100 mA or 25 mW and are considered simple apparatus as defined in the NZ standard [26]. However, even simple apparatus can become hazardous under large voltage or current spikes (fault conditions) not experienced during normal operation. They are hazardous if they reach the external explosive atmosphere. In order to guarantee intrinsic safety, protection components are required which contain faults within the purged and pressurised enclosure. These are incorporated into the sensor ports of the embedded control board.

7.4.1 Requirements

New Zealand standard 60079.11:2007 outlines the specifications for intrinsic safety protection [26]. For simple electronic devices such as sensors, an intrinsic safety barrier should be implemented to contain voltage or currents spikes. The schematic of an intrinsic safety barrier for an I²C device is displayed in Figure 7.20. It is necessary on each electrical line, with a ground connection that returns to a non-hazardous environment. An I²C device requires four pins, while other analog sensors only require three. Intrinsic safety circuitry is applied to both three and four pin connectors.

The maximum voltage and current allowed (within temperature limits) by the intrinsic safety barrier is determined by circuit type and the target gas ignition curve. None of HADES' exposed sensors include significant capacitance or inductance and therefore only resistive ignition curves are relevant. If suppressed voltage and current values can be guaranteed below the ignition curve, a device is considered intrinsically safe for that particular gas. For underground mines, methane is the most common and hydrogen is the most explosive. Their resistive ignition curves are displayed in Figure 7.21.



Figure 7.20: Intrinsic Safety Barrier for an I²C device

There are three levels of protection (ia, ib, ic) for an intrinsically safe barrier, as defined in the NZ standard. The protection level is dictated by the number of allowable component faults that still maintain voltages and currents below the ignition curve. The highest level of protection (ia) limits allowable faults to two. One fault is allowed for ib while ic does not allow any faults. Two TVSs, a current limiting resistor and a fuse provide sufficient protection for an 'ia' level intrinsically safe barrier. The first component fault occurs prior to the intrinsic safety barrier and is the cause of a voltage or current spike. The second allowable fault is then one of the protection components; TVS for voltage faults or the resistor/fuse for current faults. Therefore, even if two faults occur an additional component is available to prevent the overvoltage or current. The implementation of this intrinsic safety barrier is discussed below.



Figure 7.21: Hydrogen Ignition Curve

7.4.2 Implementation

The implemented intrinsic safety barrier is displayed in Figure 7.20. As none of the expected sensors, such as electrochemicals, require more than 0.1 A or 5 V, these values are selected for the maximum operating power. Voltages less than 10 V are almost guaranteed to fall below the minimum ignition curve, therefore TVSs with maximum clamping voltages of 9.1 V are employed. Their 5 V reverse standoff voltage maintains correct operation of the

sensors. Two TVSs are placed in parallel (for 'ia') with large current ratings (298 A). The current limiting resistors are 47 Ω which restricts current to 0.106 A. They are film type resistors which only fail to an open circuit state. To withstand 1.5 times the maximum power (0.5 W) and withstand 1.5 times the maximum voltage (9.1 V) as specified in the standard, power and voltage ratings of 0.75 W and 400 V are selected, provided by imperial 2010 packages. To guarantee the fuse blows before 0.5 A, fast blow fuses with 0.25 A fuse ratings are selected. If fault conditions occur, voltage is limited to 9.1. V and current to 0.5 A. This produces an ~11 V safety cushion between the fault conditions and the ignition curve.

7.5 Main Control Unit

7.5.1 Device Selection

The main control unit requires large amounts of processing power to carry out complex control calculations, high level decision making and data processing from audio or video sensors. A 64-bit architecture with a clock speed of at least 2 GHz and a minimum of two CPU cores would be sufficient. Additionally, a small form-factor is desirable to ensure it is compact, lightweight and low powered for a mobile robot. HADES moves over rough terrain, therefore the device should avoid mechanical hard drives that are susceptible to vibration and shock damage, and instead include a Solid State Drive (SSD). The control unit must include at least 4 GB of RAM for multitasking and sufficient storage space for data that cannot be transmitted over the network. Finally, USB 3.0 is required to interface with RGB-D cameras. A range of small form factor PCs are compared, as displayed in Table 7.7.

Table 7.7:	[.] Comparisons	of PC's
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PC	Most Suitable CPU	RAM	Storage	Features	Size (mm)	Price USD
Dell Inspiron	2.67 GHz, Quad Core,	2 GB	32 GB		52.5 × 131 × 131	\$229
Micro	Pentium					
Intel NUC	Intel i5 and i7 ranges	16 GB	>1 TB	USB 3.0, M.2	$32.7 \times 111 \times 115$	~\$350
Gigabyte BRIX	Intel i5 and i7 ranges	16 GB	>1 TB	USB 3.0, M.2	$62 \times 111.4 \times 114.4$	~\$400
HP Stream Mini	1.4GHz, Dual Core,	2 GB	32 GB	USB 3.0	$54.1 \times 145 \times 145$	\$200
	Celeron					

Asus	1.7 GHz, Dual Core,	4 GB	16 GB		$43.2 \times 124.5 \times 124.5$	\$300
Chromebox	i3					
Samsung	2.5 GHz, Dual Core,	4 GB	16 GB	Speaker	$32.5\times190.5\times190.5$	\$329
Chromebox	Intel i5					

Many available small form factor PCs are designed primarily for cloud operation. Therefore, their RAM and on-board storage is limited, embedded and not upgradeable. As internet access is not available during deployment these devices are unsuitable.

The remaining two non-cloud devices (Intel NUC and Gigabyte BRIX) are capable of 4 GB of RAM and large storage space. They are both bare-bone PCs, which allows hardware customisability; specifically, their memory and storage can be increased. The M.2 standard that Gigabyte and Intel include allows integration of SSD cards as small as 12×16 mm, which reduces the overall motherboard size. Both the NUC and the BRIX are available with any mobile i5 or i7 Intel processor and include USB 3.0 ports to interface with RGB-D cameras. The biggest differentiating factors between the two PCs are size and price. The BRIX costs more with slightly larger dimensions. Low cost and small size is desirable, therefore the Intel NUC is most suitable for HADES.

7.5.2 Implementation

The NUC5i5MYHE model, shown below in Figure 7.22, has chassis dimensions $32.7 \times 111 \times 115$ mm, making it small and compact. Common robotic functionality such as computer vision, localization and mapping as well as image and audio processing are not implemented in this project, but may be desired in future. An i5 fifth generation dual core 2.3 GHz processor with 2.9 GHz turbo and 8 GB of RAM is included to enable this. Four USB ports are available on-board, but five are required for four cameras as well as communication with the embedded controller. A USB hub is added to provide more options.



Figure 7.22: Next Unit of Computing (NUC) with 3D printed mount

Video File Storage

As mentioned in Section 5.1, not all the gathered information can be transmitted over the wireless network due to bandwidth constraints. The solution is transmitting crucial compressed information and storing the remaining high quality data on-board. This means retrieval of HADES is not mission critical as only additional high detail data is retrieved when HADES exits the mine. This data includes detailed sensor information, high quality audio, 3D depth data and high resolution video. Video files consume the most storage space due to four cameras with RGB, IR and depth data. Two hours of total operation and therefore video storage is required.

The Kinect-v2 and the RealSense can output RGB images at 60 fps, but only 30 fps is needed to detect salient features in a video feed. Using the H.264 video file format [111], data rates of 8.4 MB/s are produced. With an operating time of 7200 seconds, each RGB camera requires 60 GB of storage. The infrared and depth images are 360×480 pixels at 30 fps which are stored at a rate of 0.7 MB/s. These images produce 2.5 GB video files each. Three video types from four cameras totals 260 GB of storage space. The SSDs are available in

capacities of 2^n , therefore 256 GB is insufficient and 512 GB is required. This provides 252 GB for the operating system as well as other sensor and audio streams.

7.6 Summary

HADES is powered by six Li-Po batteries. To monitor and control the power supplied by the batteries, a distribution board is required. The board routes power to the ESCs and the DC-DC converters. The ESCs are powered directly from the batteries and are controlled by relays. The DC-DC converters are supplied by the input stage, which provides protection and switching capabilities. The output power for all components is arranged into modules which measure current and utilize high side switches for digital control. The entire power distribution board fits on a 250 mm \times 95 mm PCB which is mounted against the main access hatch.

The embedded control board is mounted above the distribution board and provides low level control for power management, motor operation and sensor interfacing. Three distributed ATmegas are used for each of the aforementioned functions, communicating between each other via I²C. Intrinsically safe sensor ports are designed on the embedded control board to allow environment sensing in an explosive atmosphere. The embedded control board communicates over Rosserial with the Main Control Unit, which carries out all the high level processing. The device is an Intel NUC with specifications that endeavour to provide future-proofing.

Chapter 8

8 Software Control Architecture

As discussed in Section 1.3, programming semi-autonomous operation of HADES' is outside the scope of this project, but will be a future development. This chapter therefore presents the software control architecture for basic operation, with design considerations for semiautonomous operation. A software control system is required to monitor and manage inputs and outputs of the system. It is distributed between multiple devices: The Intel NUC, the Operator's laptop and the Embedded Controllers. The setup, coding and operation of these are discussed in this chapter.

8.1 Robotic High Level Controllers

Only simple high level control is needed to achieve functions for basic operation, which requires some processing of actuators and sensors. Filtering and processing of sensor data is carried out at the hardware interface layer discussed in Section 7.3.3. Actuator coordination and motor control is implemented in a higher level ROS node discussed below. The proposed design for more complex actuator and sensor processing is outlined for future work in Section 10.2.4.

8.1.1 Robotic Development Environment

Communicating between devices within a robotic system can be complex, as each may operate with different software, hardware, inputs and outputs. Robotic Development Environments (RDE) are middleware which simplifies the integration of the devices by creating a transparent communication layer. This is achieved through a flexible software framework which includes tool libraries and conventions for transparent communication.

A survey by James Kramer, of the nine most common RDEs [112] evaluated their practical usability in designing, implementing and executing robotic architectures. The PlayerStage

Project was ranked highest, but is no longer maintained. Robot Operating System (ROS) was based on the Player Stage project. It is collaborative and open source, with a large active community, which have produced a wide variety of packages that cover most robotic functionality (computer vision, 3D transforms, navigation etc.).

ROS operates on a peer-to-peer network of executable processes called **nodes** which can be distributed on a number of different host devices. They are individually designed, but all communicate at runtime through **messages**. A **message** is comprised of data types (ints, bools, floats, strings etc.) as well as other messages and is **published** to a topic. A **topic** is named for identification and is advertised for nodes to **subscribe** and thereby receive messages that are published. ROS is designed to be language-neutral for individual preference and therefore any programming language can be used. The nodes in the following sections are written in C++. A **package** is a combination of related nodes, libraries, datasets and configuration files, consolidated for easy distribution.

8.1.2 Intel NUC

The Intel NUC is best suited to carry out the majority of the heavy processing, achieved through the aforementioned RDE called ROS. The *HADES* ROS nodes is written to achieve functionality for basic operation.

```
157
    int main (int argc, char** argv)
158 🗐 🕻
          ros::init(argc,argv, "OperatorNode"); // standard ROS node initialisation
159
160
          ROS_INFO ("Initialisation Complete");
161
          HADES Operator HADESNode;
                                                // creates HADES node object, which calls constructor
162
          ros::spin();
                                                // maintains synchronisation with other nodes
163 L}
164
165 - void HADES Operator::mainLoop() {
166
        ros::Rate r(10);
                                                // maintains a constant rate of 10 Hz
167
          while(ros::ok())
                                                // checks for a shutdown call (ctrl + c in a terminal)
168 🛱
         - {
             motor_pub.publish(op);
169
170
                                                // publishes the operate message
             ros::spinOnce();
                                                // synchronises with other ROS nodes at 10 Hz
171
                                                // sleeps if idle
             r.sleep();
172
          }
173 L}
```

Figure 8.1 ROS node initialisation and main loop

A standard ROS node initialisation is carried out as per [113], seen on line 159 in Figure 8.1. The node constructor shown in Figure 8.2, instantiates and assigns data and variables, sets 141 initial actuator positions and creates the appropriate publishers and subscribers. The constructor then jumps to *mainLoop*, displayed in Figure 8.1 above. The main loop maintains a constant refresh rate of 10 Hz using the *Rate* function to synchronise with all other nodes through *spinOnce* and to regularly publish messages.

```
45
      HADES Operator::HADES Operator() // class constructor
46
   ⊟ {
47
           acc scale = 50;
                                        // Scales the acceleration Xbox controller analog stick
           ang_scale = 1;
leftmod, rightmod = 1;
                                       // Scales the turning Xbox controller analog stick
// Direction modifiers
48
49
50
           prevRB,prevLB,prevRev = 0; // Previous button values for event handling
           lin_right, lin_left = 0; // Holds the calculated pulsewidth for linear velocity
51
                                        // IMU data flag
52
           op.IMU = 1;
53
           op.env = 1;
                                        // environment data flag
54
55
           op.internal = 1;
                                         // internal data flag
                                        // Reverse direction modifier
           revmod = 1;
56
57
58
           // Publisher initialised following template: <message-type>(topic-name, buffer-size, callback function, object)
          motor_pub = nh.advertise<HADES::operate>("operate", 1000); // operate topic advertised
59
           op.FRmotor = 1500;
                                        11
                                         // Sets all motor speeds to zero
60
           op.FLmotor = 1500;
           op.BRmotor = 1500;
61
62
                                         // by publishing to the operate topic
           op.BLmotor = 1500;
                                         11
63
64
65
           // Subscribers initialised following template: <message-type>(topic-name, buffer-size, callback function, object)
           joy_sub = nh.subscribe<sensor_msgs::Joy>("joy",5, &HADES_Operator::joyCallback, this);
env_sub = nh.subscribe<HADES::environment>("environment_data",10, &HADES_Operator::envCallback, this);
66
67
           imu_sub = nh.subscribe<HADES::imu>("imu_data",10, &HADES_Operator::imuCallback, this);
68
           int_sub = nh.subscribe<HADES::internal>("internal_data",10, &HADES_Operator::internalCallback, this);
69
70
           mainLoop();
                                         // Jumps to the main loop
```

Figure 8.2: HADES node constructor

The 'joy' node is a pre-made package which runs on the operator's laptop. The message it publishes to the joy topic contains information from the Xbox controller: Boolean data for buttons and Floats for the analog stick axes (between -1 and 1), shown in Figure 8.3. The HADES node subscribes to the joy topic. When a joy message is received, the callback function (Figure 8.4) stores this information in variables and calculates the pulse-width that should be sent to each motor. Buttons are processed first, they have three events: *held*, *pressed or released*.



Figure 8.3: Xbox Controller Button Assignment

The analog sticks are sensitive to movement making it difficult to gain fine control over HADES' speed. To solve this, the maximum pulse-width is scaled by the LB and RB button. It begins between 1450 and 1650 μ s long pulses (1500 μ s is stopped/neutral) and can be increased and decreased by 25 μ s to a maximum range of 1000 to 2000 μ s. These buttons are *pressed* and therefore require event handlers which monitor the previous button value to detect a rising edge.



Figure 8.4: Callback function and speed scaling logic

Each wheel should be controlled independently, as opposite sides are required to rotate in different directions (see Section 4.2.4). Additionally, HADES should be capable of reverse and rotating on the spot (zero turn-radius). This is achieved by rotating wheels on either side in opposite directions, realized in code with direction modifiers, see Figure 8.5. The brake, spin and reverse buttons all affect the direction modifiers. In order to rotate on the spot, the X or B button is *held*, depending on rotation direction. The reverse button is *pressed* and therefore also requires a similar event handler to LB and RB.

```
121
          // zero-turning radius, direction modifier logic
    ¢.
122
          if (leftspin == 1) {
                                                  // X button 'held'
123
             rightmod = 1;
124
             leftmod = -1;
          } else if (rightspin == 1) { // B button 'held'
125
126
             rightmod = -1;
127
             leftmod = 1;
          } else{
128
129
              rightmod = 1;
130
              leftmod = 1;
131
         }
132
133
         // reverse direction modifier logic
134 🖨
          if(reverse == 1 && prevRev == 0){
                                                 // Y button is 'pressed'
135
             if(revmod == 1){
136
                revmod = -1;
137
             }else{
138
                 revmod = 1;
139
              }
140
          ł
         prevRev = reverse;
141
```

Figure 8.5: Spin and reverse logic

As a safety measure, the brake button should override control of the motors as displayed in Figure 8.6. This is implemented with an if-else statement than either assigns the calculated pulse-width or overrides it with 1500 μ s. The pulse-width values are then published to the *Operate* topic which the embedded controller subscribes to over *Rosserial*. A custom message type also called *operate* is used, which contains the pulse-widths as integers.

```
143
          // data assigned to 'operate' message
144
                                                     // A button is 'held'
           if(brake == 1){
145
              op.FRmotor = 1500;
               op.FLmotor = 1500;
146
147
               op.BRmotor = 1500;
               op.BLmotor = 1500;
148
            }else{
149
            // if not braking direction modifiers and scaled acceleration applied to PWM signal
               op.FRmotor = lin_right*-rightmod*revmod+1500;
151
152
               op.FLmotor = lin_left*leftmod*revmod+1500;
153
               op.BRmotor = lin_right*-rightmod*revmod+1500;
154
              op.BLmotor = lin left*leftmod*revmod+1500;
155
          }
     L
156
```

Figure 8.6: Brake override and PWM signal calculation

Most of the internal and external sensor data such as temperature, pressure or gas concentration do not change at a fast rate. Therefore, the microcontrollers should only poll them once a second to prevent processing overload. As a result, the HADES node does not require a stream of sensor data. To allow the *HADES* node to request sensor data when it is needed, the *operate* message also includes flags. Internal monitoring, external environment and IMU sensors all provide a large amount of data which do not fit standard ROS message types. Three custom messages are created to handle this data: *environment, imu, internal*. They are published to the *imu_data, environment_data* and *internal_data* topics. When new data is required from a topic, the respective flag gets set high and the embedded controller publishes a message to the respective topic with the latest sensor data.

Before the webcams were removed from HADES, the *libuvc camera* ROS package was used as an interface [114]. Prior to the Kinect's replacement, the *iai_kinect2* ROS package provided drivers and software [115]. Both of these packages are no longer used. As Intel are providing direct support for ROS with the RealSense, a ROS package is available for integration and provides all the necessary functionality [116]

8.1.3 Laptop

A generic laptop connected to an Xbox controller is needed to operate HADES. As most of the processing is carried out on the NUC the laptop does not need special consideration and should be capable of running a simple ROS node and displaying a 720p video file.

Interfacing with and control of human-robot coordination is an established issue as identified by [72] and [2]. It is also illustrated in Section 5.1 with the 'keyhole problem'. Implementing an effective interface for HADES is beyond the scope of this project but suggestions for future work can be found in Section 10.2.4.

Only a single node runs on the operator laptop, the joy node. This node uses Linux's joystick drivers to interface with the Xbox controller. It then publishes the Boolean button and the Float analog stick data to the *joy* topic. For an operator to view the sensor data published to the internal, environment and imu topics, an additional node is not required. Instead sensor data can be printed in a terminal using ROS' built in command: 'rostopic echo *topicname*'. Additionally, the 'image_view' command can be used to display the video feeds.

8.2 Central Unit

Low level control is distributed across three intercommunicating microcontrollers, however only the central unit interfaces with ROS. The other two microcontrollers only interface with ROS by communicating information through the I²C master.

8.2.1 ROS Communication

The integration of the Rosserial C++ library through *ros.h* is required for the embedded controller to communicate with ROS. This library includes the functions to set up a node, publish and subscribe to topics as well as integrate custom ROS message types. A nodehandler and initialisation are both required during setup of the ATmega, as seen in Figure 8.7. C++ objects are created for each of the custom message types required. Publishers and subscribers are both initialised with their respective topics.

```
1 #include <Wire.h>
      #include <ros.h>
     #define LED 10
5
     // create node handler
6
      // increase baud rate from 9600 to 57600
      class NewHardware : public ArduinoHardware
 9
    ₽{
        public:
10
11
        NewHardware():ArduinoHardware(&Serial1,57600){};
     Lit
12
13
     ros::NodeHandle <NewHardware> nh;
14
15
      HADES::internal int_msg;
      HADES::environment env_msg;
16
                                                                            // creates custom message type ojects
17
18
     HADES::imu imu msg;
19
     ros::Publisher int pub("internal data", &int msg);
     ros::Publisher env_pub("env_data", &env_msg);
ros::Publisher imu_pub("imu_data", &imu_msg);
20
                                                                            // create publisher objects
21
22
23
24
25
     ros::Subscriber<HADES::operate> op_sub("operate", op_callback); //create subscriber object
   Pvoid setup() {
26
        nh.initNode();
                                            // Initialise the ROS node
27
28
29
30
        pinMode(LED,OUTPUT); // Configure a diagnostic LED
        Wire.begin();
                                            // Initialise I2C interface
        nh.subscribe(op_sub);
                                            // Subscribe to operate topic
        nh.advertise(int_pub);
        nh.advertise(env_pub);
nh.advertise(inu_pub);
nh.advertise(inu_pub);
31
                                            // Advertise topics
32
                                            // Blink the diagnostic LED
        blinkLED(LED);
34 L1
```

Figure 8.7: Central unit setup code

8.2.2 I²C Communication

In order for the microcontrollers to communicate with each other and to allow power management and motor control to be carried out by the NUC, I²C communication is required as discussed in Section 7.3.1. To simplify this task, the 'Wire' C++ library is employed to carry out the I²C protocol at the hardware level [117]. The central unit is the I²C master (no I²C address), as discussed in Section 7.3.2. The motor control and the power management ATmegas are the slaves (I²C addresses 0x03 and 0x04 respectively). In order for the NUC to manage power and control the motors over I²C, a slave instruction set is required, displayed in Table 8.1.

Table 8.1: Slave Instruction

Byte Value (Hex)	Task
0x02	Set Motor Position
0x04	Set Motor Velocity
0x06	Request Motor Temperature
0x08	Request Motor Position
0x0A	Request Motor Velocity
0x0C	Request Diagnostic Information
0x0E	Set Diagnostic Information

The instruction is the first data byte written to the I^2C bus by the master, which orders the slave to carry out a particular task (discussed in more detail in Section 7.3.2). A typical *set* function is displayed in Figure 8.8. The *beginTransmission* function allows selection of a slave by its address as an argument. The *write* function is used to queue a byte for transmission to the slave. When *endTransmission* is called the queues bytes are transmitted.

```
95 __void setMotorSpeed(byte m, signed int val){
      Wire.beginTransmission(0x03);
96
                                                  // Communicate with address 0x03
97
       Wire.write(0x04);
                                                  // Set motor speed instruction
98
                                                  // Motor number to be set
       Wire.write(m);
99
       Wire.write(val & OxFF);
                                                  // Motor speed low byte
100
      Wire.write(val >> 8);
                                                  // Motor speed high byte
101
      Wire.endTransmission();
102 L}
```

Figure 8.8: Typical set function (motor speed)

An instruction is also required for the slave to know which data to send. The master first sends an instruction, then reads sensor data by performing a request. A typical *request* function is shown in Figure 8.9. It begins similarly to the *set* function in Figure 8.8. Once the instruction is sent, the *requestFrom* function is called, specifying the slave address and number of data bytes requested. The number of bytes to be read is returned by *available*, called in a loop to ensure all bytes are processed. To transfer bytes from the I²C buffer, *read* is called.

```
104 = void requestTemp(){
105
106 Wire.beginTransmission(0x03); // Communicate with address 0x03
107 Wire.write(0x06); // Request temperature command
108 Wire.endTransmission(); // Send queued bytes
109
100 Wire.requestFrom(0x03, 4); // Request 4 bytes from 0x03
111 Wire.available()){ // While data available to read
112 for (int i = 0 ; i < 4 ; i ++){ // For all 4 motors
113 motorTemps[i] = Wire.read(); // Read motor temps and store in array
114 }
115 }
116 }
</pre>
```

Figure 8.9: Typical request function (motor temperatures)

8.3 Motor Control

8.3.1 Open loop Control

Open loop control of motor speed is achieved through PWM signals sent to the ESCs, discussed further in Section 8.3.4. High torque loads are difficult for open loop control as the ESCs apply a voltage to the motor which increases its speed. If a speed increase is resisted, the motor applies torque in an attempt to overcome this resistance. A wheel with open loop control that does not have ground contact (or loses traction), incurs high speed wheel spins which consume power, unbalance the robot and hinders regaining traction. Additionally, open loop control results in wheels travelling at slightly different speeds and therefore driving straight or turning accurately can be difficult.

8.3.2 Closed Loop Control

Closed loop control allows wheel synchronization to produce locomotion gaits which improve speed over flat as well as rough terrain [48] [45]. Furthermore, exact wheel speeds can be produced for improved navigation of debris and rubble, which prevents wheel spins. Feedback from the motors is required to implement closed loop control locomotion. This is realized by speed measurement, achieved through the encoders discussed in Section 4.2.4. Speed calculated from the encoder pulses are used as inputs to a Proportional Integral Derivative (PID) controller.

The PID C++ library developed by Brett Beauregard [118] [119] is integrated in order to reduce the amount of low level PID programming required. Functions provided include carrying out the main computation (*Compute*), setting the output limits in order to prevent integral wind up (*SetOutputLimits*) and the ability to modify the tuning parameters (*SetTunings*).

A C++ class simplifies motor control by combining the properties and functions required for closed loop control into a single object. An *ESC* object is created for each motor: Front Left (FL), Front Right (FR), Back Left (BL), Back Right (BR). It allows initialisation and execution of the PID as well as calculating the motor speed and setting the PID parameters. 149

The object includes a number of variables for PID parameters, motor properties and to assist with motor measurements. All these functions and variables are displayed by the header file in Figure 8.10.

```
17 class ESC
    E (
18
19
           public:
                int temp;
20
                                                                     // Motor temperature
                                                                     // Measured position from encoder pulses
// Velocity set by ROS through rosserial and I2C.
21
                double measuredPos;
22
                double setVel;
               double measuredVel;
                                                                     // Measured velocity from encoder pulses
23
24
               int motorDir;
                                                                     // Motor direction determined by encoder pulses
25
26
27
               int pulseWidth = 1500;
                                                                     // The PWM pulse width: the PID output
                unsigned long tickDiff = 0xFFFF;
                                                                     // The timer count difference, calculated from prevTicks
28
                unsigned int prevTicks;
                                                                     // Previous timer count
29
                int lastPole;
                                                                     // The last motor pole, used to determine direction
30
                bool extFlag;
                                                                     // Flag which tells the PID that an interrupt has occured
31
                uint8 t overflows;
                                                                     // Keeps track of the number of timer over flows
32
                int pulseCount;
                                                                     \ensuremath{{\prime}}\xspace number of pulses for position calculation
33
34
35
                double Kp;
                                                                     // Proportional PID constant
                double Ki;
                                                                     // Integral PID constant
36
                double Kd;
                                                                     // Differential PID constant
37
38
                PID* velPID;
                                                                     // PID which controls velocity
39
40
                                                                     // Constructor
               ESC(uint8 t pin);
41
42
                void CalcVel(bool overflow);
                                                                     // Calculates velocity using the timer variables
                                                                     // Calculates position from the pulse count
// sets the PID parameters
43
                void CalcPos(bool overflow);
                void setK(double kp, double ki, double kd); // set
void configVelPID(int upper, int lower, int sample);
44
45
46
                void runPID(int target, bool overflow);
                                                                     // executes the PID
47
     -};
```

Figure 8.10: Header file variables and functions

PIDs are setup for each motor. The upper and lower PWM output values (2 and 1 ms) as well as the frequency at which the PID is calculated are all set using the *configPID* function. Initial tuning parameters are selected (and set through *setK*) using the Ziegler–Nichols method [120] but finer tuning is required to reduce overshoot and minimize oscillations. The *CalcVel* function is called once during the setup of the PID and then continually called in the main loop. It uses the stored timer value (discussed in Section 7.4.2) to calculate the motor velocity in RPM using Equation 8.1.

$$RPM = \frac{D \times f \times 60}{tickDiff \times G \times S \times P}$$
(8.1)

The frequency of the microcontroller clock f is divided down by the prescaler S, and converted from seconds to minutes. The difference in ticks then has to account for the gearbox ratio G and the three motor poles P, as well as the motor direction D. This measured

RPM is fed into the PID as the input for comparison with the desired value. The PID library then produces a pulse-width output in microseconds, as discussed in Section 7.4.3, using the tuning parameters specified.

The entire closed loop process begins with a desired speed obtained from the master through an I²C *set* function (discussed in Section 7.3.1). The first received byte is an instruction which triggers the *receiveEvent* function, seen in Figure 8.11. The instruction modifies the mode of the motor control ATmega through an if-else statement. As I²C can only communicate a byte at a time, a Boolean OR and bit shift is required to receive integers through the bus.

```
84
       __void receiveEvent() {
 85
     while (0 < Wire.available()) { // While I2C data available</pre>
 86
 87
             mode = Wire.read();
               mode = Wire.read(); // Read instruction
if (mode == 0x02) { // Motor position instruction
byte m = Wire.read(); // Read the motor number
int pos = Wire.read(); // Read the position low byte
pos |= Wire.read() << 8; // OR with the position high byte
set_Pos[m] = pos; // Store position in array
 88
                                                        // Read instruction
      É
 89
              if (mode == 0x02) {
 90
 91
 92
 93
              } else if (mode == 0x04) { // Motor velocity instruction
 94
 95
                byte m = Wire.read();
 96
                int mvel = Wire.read();
 97
              mvel |= (Wire.read() << 8);</pre>
 98
               set Vel[m] = mvel;
            } else if (mode == 0x0E) { // Motor diagnostics instruction
 99
100
              byte d = Wire.read();
101
                int diag = Wire.read();
                diag |= (Wire.read() << 8);</pre>
102
103
              diagnostics[d] = diag;
104
             } else {
105
              Wire.read();
106
              }
       E,
107
            }
108
```

Figure 8.11: Motor controller receive event function

8.3.3 Motor Measurements

The next step in closing the loop is the speed measurements required to determine the error. Wheel position measurements are also beneficial to allow HADES to know where the spokes are. Calculating the speed or position of the motors requires reading the encoder pulses. As discussed in Section 4.2.1, the three motor poles travel through a 104:1 gearbox ratio which provides 312 encoder pulses per wheel rotation (angular resolution 1.15°). The encoder pulses are tied to the ATmega's external and Pin Change (PC) interrupts for accurate timing, as discussed in Section 7.3.3. The setup is displayed in Figure 8.12. The ATmega's registers are modified to enable and mask the interrupts being used, to prevent other pins causing accidental interrupts.

```
321

- void setupInterrupts() {

322
        SREG |= 0x80;
                               // Enable all interrupts (global)
323
324
       /* External Interrupts */
        EICRB |= 0xFF; // Sets rising edge to generate external interrupt
325
       EIMSK |= 0 \times F0;
326
                               // Enable external interrupts 4-7
327
       /* Pin Change (PC) Interrupts */
328
        PCICR = 0x06; // Enable the PC interrupts
329
330
       PCIFR = 0x06;
                                // Reset all PC interrupt flags
      PCMSK2 = 0x1B;
PCMSK1 = 0xD8;
331
                               // Mask encoder pins that cause PC interrupts
332
                               // Mask encoder pins that cause PC interrupts
333 L}
```

Figure 8.12: ATmega Interrupts setup code

Interrupts tell the microcontroller when an encoder pulse has occurred but discrete timers are required to measure the time between *interrupts* and therefore calculate speed. Timers are also used for PWM signals as discussed in Section 7.4.3. Figure 8.13 displays the setup for the 16-bit ATmega timers: Timer5 (Measurement) and Timer3 (PWM) [121]. A prescaler of 64 is used for Timer 5 to scale the 16 MHz clock to a frequency of 250 kHz. Frequency is a compromise between timer resolution (4 μ s) and timer overflow (262 ms). A resolution of 4 μ s is short enough that at maximum speed (2.5 kHz pulse frequency, see Section 7.3.1) two encoder pulses will never be mistaken for one. The timer overflow is long enough that even at very low speeds the total cumulative timer count (which cumulates due to overflows) will never require greater than a 32-bit number (that the ATmega cannot handle).

```
335 - void setupTimers() {
    /* Timer 3 setup for PWM */
336
      TCCR3B = 0x00;
337
                                // Clear registers
338
      TCCR3A = 0x00;
      TIMSK3 |= 0x02;
339
                                // Interrupt mask for compare A interrupt
                                // Set initial compare value
340
      OCR3A = 0;
341
      TCNT3 = 0;
                                // Clear the timer counts/ticks
      TCCR3B |= 0x02;
342
                                // Set prescaler of 8
343
344
       /* Timer 5 setup for interrupts*/
      TCCR5B = 0;
                                // Clear registers
345
346
      TCCR5A = 0:
      TIMSK5 |= 0x01;
347
                               // Interrupt mask for over flow interrupt
348
      TCNT5 = 0;
                               // Clear timer counts/ticks
      TCCR5B |= 0x03;
349
                                // Set prescalar of 64
350 L}
```

Figure 8.13: Setup code for ATmega Timer 3 and Timer 5

Interrupt service routines (ISRs) are set up for each external and PC interrupt. The ISR for the PC interrupts triggers whenever any pin on the microcontroller's port reads an encoder pulse. Therefore, the pin which caused the interrupt needs to be isolated, as shown in Figure 8.14. Upon a PC interrupt, the ISR is called and the current Timer5 count (called ticks) is stored for later calculation. The current port value is XORed with the previous port value in order to create a mask containing the pins which have toggled. The mask is ANDed with a constant hexadecimal value to remove pins that do not have an encoder line physically attached. Finally, in order to detect a rising edge, the current port value is ANDed with the pins that have toggled.

```
      124
      ISR (PCINT1_vect) // Rear motors' encoder pulses

      125
      ↓

      126
      unsigned int currentTimer = TCNT5; // Samples and hold the current port value

      127
      byte mask = PINJ ^ prev_Back; // Mask pins that have changed

      128
      prev_Back = PINJ; // Stores port value for future comparison

      129
      mask &= 0x6C; // Removes non-encoder signals from the mask

      130
      mask &= PINJ; // Mask rising edges
```

Figure 8.14: ISR logic to mask rising edges on the PC interrupts

The mask is ANDed with pin-corresponding constant values. If a non-zero value is produced by the AND the code in Figure 8.15 is executed. Figure 8.15 displays the logic used for a single motor pole (Back Left 3). The difference between the previous and the current number of timer ticks is calculated and stored in the ESC object. It is used later by the ESC object for *calcVel* as discussed in Section 8.2.1. A flag is also set to tell the object that an interrupt has occurred and reset the timer overflow count. The ESC object keeps track of the last motor pole which caused an *interrupt*. As the current pole is known, this allows the motor direction to be identified, as per the last few lines Figure 8.15. The external interrupts store the difference in timer ticks and identify motor direction identically to the pin change interrupts. The only difference is that they do not require a mask as only a single pin can trigger their ISRs.

```
132 📋 if (mask & 0x04) {
                                    // Back Left Pole 3 Pulse
            ESC_BL->tickDiff = currentTimer - ESC_BL->prevTicks
                                                                                           // Calculate count/tick difference
134
            ESC BL->tickDiff = ESC BL->tickDiff + (ESC BL->overflows * 0xFFFF);
                                                                                           // Account for overflows
            ESC_BL->prevTicks = currentTimer;
                                                                                           // Stores value for next interrupt
136
137
            ESC_BL->extFlag = 1;
                                                                                           // Sets the interrupt flag high
            ESC BL->overflows = 0;
                                                                                           // Resets number of overflows
138
139
            /* Logic to determine motor direction*/
140 🛱
            if (ESC_BL->lastPole == 2) {
    ESC_BL->motorDir = -1;
} else if (ESC_BL->lastPole == 1) {
141
142
              ESC BL->motorDir = 1;
143
144
145
            ESC BL->lastPole = 3;
146
         }
```

Figure 8.15: Code to determine time difference and motor direction

8.3.4 PWM Signals

The PIDs produce pulse-width values in microseconds. Timer 3 produces the PWM signals for the ESC. Figure 8.13 shows the configuration of microcontroller registers required to achieve this. The pulse-width should have a resolution of at least 1 μ s for fine control over the ESC. Additionally, 4 PWM signals should be possible with a single timer. To achieve this, a timer overflow greater than 8 ms is required to account for four ESCs each with a possible maximum pulse-width of 2 ms. A prescalar of 8 scales the 16 MHz clock down to 2 MHz, producing a resolution of 0.5 μ s and a timer overflow of 33 ms. Software to produce the PWM signals is written using Timer3 of the ATmega, using similar logic as in [122]. Code implementation is attached in Appendix B.

Chapter 9

9 Evaluation & Discussion

9.1 Locomotion

As access to an underground mine has yet to be granted, HADES' locomotion was evaluated in a controlled environment as well as in the field (See Section 8.1.4). The results of these tests are presented in this chapter.

9.1.1 Obstacle Climbing

Step

As mentioned in Section 2.6, HADES should be capable of climbing stairs as well as traversing the track rails which frequently run through mine tunnels. The test to evaluate this is a step obstacle that is 220 mm high as defined in Section 2.6. The simulated step platform should be wide enough for both wheels and must be free of protrusions or handles which could assist the spoked-wheels climbing. The setup is shown in Figure 9.1.



Figure 9.1: Step obstacle used for testing

Runs were carried out incrementing step heights by 20 mm, using wooden blocks under the platform, seen in Figure 9.1. Runs were successful if HADES could pull both front and back wheels over the step, in at least four out of five attempts. The step was first approached perpendicularly. HADES is able to climb a 250 mm high step, but struggled to overcome 270 mm, only managing two of five attempts. The pitch and roll data, measured with an IMU, was collected for a typical 250 mm high run, displayed below in Figure 9.2.



Figure 9.2: Pitch and roll data during climbing a step

HADES begins moving after 1 second. During build up to the obstacle, some oscillation occurs due to spoke collisions, discussed further in Section 8.1.2. The chassis tilts by 20° as the front wheels ascend the step. The 20° tilt in the opposite direction at 8 seconds, illustrates HADES dropping sharply down the other side of the step platform. It is not immediately obvious, but there are short 4° pulses in the roll axis, at 3 and 8 seconds. These pulses indicate HADES did not approach the step perpendicularly. Instead, one wheel ascended/descended the step slightly earlier than the other, causing a small rotation in the roll axis. The influence of the roll axis is discussed later in this section.

As mentioned in Section 2.2, spoked-wheels can climb obstacles 1.5 times their wheel radius. HADES should therefore be able to climb 300 mm high obstacles. However, results show a 50 mm deficit. This disparity of 50 mm is due to the underside of the chassis bottoming out, 157 rather than the spoked-wheels' inability to climb the step. The underside of the chassis is 150 mm off of the ground. HADES' front wheels always ascend the step, but as the step is greater than 150 mm, the step edge catches the underside of the chassis. As the back wheels continue to push the chassis (against friction) up the step edge, the front wheels become suspended and lose contact with the ground, as seen in Figure 9.3. The back wheels are unable to overcome the friction and push the chassis all the way over the step. This problem is reduced when climbing multiple steps such as a staircase. So long as the horizontal distance between steps is short enough, the front wheels reach the second step before the chassis bottoms out. As the front wheels ascend the second step, they lift the underside of the chassis higher, which prevents it catching on the first step.



Figure 9.3: Bottoming out on the step

The step edge, catching the chassis and causing it to bottom out, is avoided by modifyingHADES'angleofapproach.


Figure 9.4 displays the gyroscope data from a run where the step was approached roughly 20° from normal. By increasing the angle of approach from perpendicular, the wheels encounter the step individually, reducing the dead zone shown in Figure 9.5.



The green zones illustrate areas where the wheels can overcome obstacles. The red areas are dead zones, which the wheels cannot reach, and where obstacles can cause bottoming out. Additionally, when the wheels encounter the step individually, larger rotation in the roll axis (12°) is produced, as illustrated in



Figure 9.4. In comparison to Figure 9.2 (4° roll rotation), the additional 8° moves the underside of the chassis away from the step edge, avoiding catching and preventing bottoming out.



Figure 9.5: Varied angle of approach over an obstacle

Although bottoming out prevents perpendicularly climbing steps greater than 250 mm, the largest known step obstacle in an underground mine tunnel is 220 mm as mentioned in Section 2.3.5. As HADES can climb 250 mm high steps, this specification is exceeded. If debris or rubble greater than 250 mm are encountered, an increased angle of approach reduces the dead zone and increases roll axis rotation to inhibit bottoming out.

Single Obstacle

The 300 mm obstacle height specification holds for a single obstacle as well. A single obstacle, without protrusions or handles to assist the spoked-wheels, is assumed to be worst case, as shown in Figure 9.6. The single obstacle is also incremented by 20 mm, similarly to the step.



Figure 9.6: HADES climbing a single obstacle

The angle of approach for a single obstacle has little effect on HADES' ability to overcome it, provided the wheels, rather than the chassis, make contact with it. The maximum climbable obstacle height is limited by the pivot's 30° rotation lock, the design for which is discussed in Section 3.1.2 As a result, the maximum climbable obstacle is 530 mm. Figure 9.6 displays an obstacle at 550 mm which lifts the rear axle off the ground due to pivot lock.

As discussed in Section 2.3.4 spoked-wheels are capable of climbing obstacles 1.5 times their wheel radius, which is 300 mm for HADES. But this 300 mm height only accounts for spokes locking on top of obstacles to pull the wheel over. The high torque motor-gearbox assemblies and rubber wheels use friction to overcome objects as high as 530 mm, exceeding 161

the 300 mm specification. As long as sufficient friction is available, only the pivot (rather than the spoked-wheels) limits the maximum obstacle height. Increasing the size of the slot angle, mentioned in Section 3.1.1 would increase the maximum obstacle height.

9.1.2 Spokes

Cables

Electrical cables run along underground mine tunnels and therefore are likely to be encountered amongst rubble in a disaster, as discussed in Section 1.2. Cables lying flat on the ground (flat cables) and cables suspended between debris and rubble (raised cables) could be encountered. Raised cables up to 400 mm (based on wheel diameter in 4.1.1), are expected to immobilise HADES more frequently than flat cables, due to tangle with the spokes. The probability and severity of tangling in loose cables is assessed.



Figure 9.7: Cable tests, raised (left), flat (right)

The cable scenarios are simulated by laying loose electrical cables flat on the floor and suspending them between debris, as seen in Figure 9.7. Displacing cables more than half a metre could lead to cables becoming taut, resulting in immobilisation. To account for this, runs were considered successful if cables did not tangle or were not displaced by more than half a metre. HADES drove each scenario twenty times, as displayed in Table 9.1. As expected, raised cables increase the chance of tangle significantly but still resulted in a 60 % estimated success rate.

Cable Layout	Successful Runs	Success Rate
Flat	19	95 %
Raised	12	60 %

Table 9.1: Cable Test Summary

Visual analysis of the eight failed raised-cable runs indicated tangle primarily occurs during the upward movement of a spoke. As HADES moves forward, this movement pulls the cable up, over and on top of the wheel producing further tangle and eventually immobilisation. Of those eight failed runs, reversing detangled the cable on three occasions (37.5 %). Evaluating HADES' ability to traverse cables predicts that raised cables up to 400 mm causes immobilisation 25 % of the time, and therefore should be avoided where possible. Flat cables however, do not pose a problem.

Speed

As discussed in Section 2.6, HADES should be able to operate at walking speed (1.4 m/s) over flat ground. Visual inspection of HADES' locomotion during indoor tests, indicated the spoke shape limits the maximum speed. To confirm this, HADES was operated in a straight line over flat ground, constantly accelerating. Horizontal velocity was measured with an IMU, displayed in Figure 9.8.



Figure 9.8: Forward velocity measured over flat ground

Figure 9.9 displays the spoke collision in more detail, produced by driving forward with four discrete spoke collisions before coming to a halt. The alignment of vertical acceleration and horizontal velocity displays the relationship between them. During downward movement of the chassis, (the negative acceleration spikes) the velocity increases. As spokes collide with the ground the velocity slows. The positive acceleration spikes are the chassis bouncing back up again as a result of the spokes' elasticity. As the spokes are made of rubber, the arm of the T-shaped tip (see section 4.1.2) compresses when it collides with the ground. This stores elastic potential energy which is released, producing a bouncing motion. It is this reflection of vertical energy which causes the vertical oscillation and which reduces horizontal velocity.



Figure 9.9: Comparison of vertical oscillation and forward velocity

The spoke design concept was intended as a form of mass-spring-damper to absorb the shock of spoke collisions. However, the spring constant of the design is too large in comparison to the amount damping and therefore is unable to produce efficient locomotion above speeds of 1.6 m/s. Improving the wheel design could produce slightly more efficient locomotion or higher speeds. Modifying the tip of the spoke to reduce the spring constant is a possible solution, as discussed in Section 9.2. However, as HADES is designed to operate at walking speed (1.4 m/s), the spoke collisions do not restrict locomotion and the specification is exceeded.



Figure 9.10: Pitch and roll data over flat terrain

Torsional forces on the chassis, produced by movement in the pitch and roll axis, causes inefficient locomotion which reduces operating time. The data in Figure 9.10 was collected during operation on flat ground. The offsets (from zero) of pitch at 0 seconds and roll at 12 seconds are because HADES' wheels are out of phase while stationary, causing a slight tilt in the pitch and roll axis. Oscillations in the pitch and roll axis are a result of varying heights between each wheel axle. Unlike round wheels, spoked-wheels produce vertical movement of each wheel's axle depending on the position of the spokes. An open loop controller is unable to coordinate the phase of the wheels, and as a result large movements in the pitch and roll axes cannot be prevented. Integration of a closed loop control could solve this issue by providing control of wheel phase and speed (see Section 9.2).

9.1.3 Slopes

Driving

As mentioned in Section 2.6, HADES must be capable of climbing an 18° slope (the maximum tunnel slope in underground mines). To evaluate this, the angle of a large wooden board was varied to simulate slopes. At each angle, five attempts were carried out. All five attempts had to be successful to ensure HADES could climb the slope. Angles were incremented by 10° until HADES was unable to ascend the slope. The angle was then decremented by a single degree for more accurate results.

Tests demonstrated that traction is lost before the motors' torque limit is reached. This occurs at 30° . In an attempt to evaluate the motor torque, a vinyl sheet was placed over the wooden board to increase the surface friction. Traction was still the primary restriction on slope angle, despite the vinyl sheet. HADES was able to ascend a 35° slope without losing traction, but only managed three of five attempts at a 36° angle.

Angle (°)	Success Rate Wood	Success Rate Vinyl
10	5/5	5/5
20	5/5	5/5
30	5/5	5/5
40	0/5	0/5
39	0/5	0/5
38	0/5	1/5
37	0/5	1/5
36	0/5	3/5
35	0/5	5/5

Table 9.2: Slope Climbing Summary

The ability to climb a slope greater than 18° on both wood and vinyl exceeds the specification. This is beneficial when debris or rubble causes slopes greater than 18° . Increased traction could be applied to these spoked-wheels through treaded spoke tips, such as can be seen on some off-road vehicles.

Stability

The risk of toppling over and becoming immobilised is a serious issue for teleoperated robots, therefore HADES' is design with an invertible chassis and a low centre of gravity. The likelihood of toppling over was also evaluated by varying slope angle. Vinyl was again added to increase traction.

Static friction between spoked-wheels and vinyl allow slopes of up to 55°. Beyond this, traction is lost, but the chassis does not topple. A possible position in which HADES would be immobilised is landing with the plates of two wheels touching the ground as seen in Figure 9.11. This occurred when traction is lost above 70°. On a flat surface this position is in a relatively stable equilibrium, and even rotating the wheels against the ground cannot self-right HADES. On rough or angled surfaces, this position is an unstable equilibrium and rotating the wheels causes an imbalance which self-rights the chassis.



Figure 9.11: Chassis on its side with wheel plates touching the ground

The likelihood of immobilisation by toppling is also evaluated in the field tests, carried out in Section 8.1.5. HADES was driven over 1 m banks and slopes in an attempt to invert the chassis but was unsuccessful. During the entire testing process HADES did not land with the wheel plates on the ground or in an inverted position. This result illustrates that integration of complex self-righting mechanisms is not required.

9.1.4 Field Tests

During a disaster flooding and explosions structurally damage mine tunnels and equipment is broken into pieces. This makes the size and shape of debris and rubble difficult to predict and quantize. In order to understand how HADES' locomotion performs over debris and rubble, field tests were carried out. Two primary locations were used: the university grounds and a clean construction landfill. This produced a variety of terrain for testing, as displayed in Figure 9.12. This section discusses the field test findings which are summarized in Table 9.3 and can be viewed in the video in Appendix B.



Figure 9.12: Field testing terrain examples

Qualitative analysis of HADES' spoked-wheel system displays effective rough terrain locomotion. HADES is capable of climbing most encountered rubble and debris if approached correctly. There are two primary limitations: bottoming out and slopes comprised of loose substrate. Controlling the speed and angle of approach prevents bottoming out by ensuring the spoked-wheels rather than the chassis make contact with terrain. It was observed that reversing can remove HADES from a bottomed out state if the back wheels have ground contact. Figure 9.13 provides an example where HADES approached an obstacle from the wrong angle. The piece of rock, caught on the back right wheel, is preventing forward movement and therefore reversing is required to come unstuck. Figure 9.13 is a situation where having an active pivot could be useful and allow HADES to overcome the rock by raising the rear axle.



Figure 9.13: Rock caught chassis, bottoming out

The biggest modification to HADES' design which would assist locomotion is increasing wheel diameter. One of the major reasons HADES bottoms out is because of the dead zone between the front and back wheels as illustrated previously in Figure 9.5. An obstacle located in this dead zone, underneath the chassis does not make contact with any of the wheels and therefore causes the chassis to bottom out. An increase in wheel diameter (or an angled

approach) reduces this dead zone and reduces the likelihood of bottoming out. Another method of preventing bottoming out is to install caster wheels on the underside of the chassis. These wheels would roll along an obstacle rather than creating friction. Bottoming out is a problem shared by spoked-wheels, round wheels and tracked systems and therefore development in this area is required.

Slopes with loose gravel and debris are difficult for HADES to climb. The power in the motors cannot be fully utilised as gravel and debris causes HADES to lose traction and slide down slopes. This was observed on a range of slopes up to 40° (Figure 9.14). Although lack of a traction is a problem encountered by all ground vehicles, HADES' open loop controller exacerbates it. When ascending slopes upwards of 20°, relatively large torque is required by the motors to pull HADES' weight up. If one of HADES' wheels loses traction, the open loop controller produces large wheel spins which unbalances the robot and makes it difficult to regain traction.



Figure 9.14: 40° slope with loose debris that HADES lost traction on

Test	Result	Analysis	
Parallel Slopes	Passed	Does not topple, loses traction at large angles	
Up Perpendicular Slopes	Passed	No torque limit, loses traction at large angles	
Down Perpendicular Slopes	Passed	Does not topple	
Grit and Sand	Passed	No problems on flat ground, slopes lose	
		traction	
Through Grass and Brush	Passed	Thick brush stalks require high torque	
Over Broken Concrete	Passed	Bottoms out if not approached correctly	
Over Obstacles > 0.5 m	Failed	Limited to 0.53 m by pivot mechanical lock	
Over Obstacles > 0.3 m	Passed	Requires traction	
Over Obstacles > 0.1 m	Passed	Overcome through spokes locking on top	
Stairs	Neutral	Limited performance due to open loop control	
Over Steps and Low Walls	Passed	Larger than 250 mm requires angled approach	
Cable	Passed	Only raised cables may pose problem	

Table 9.3: Summary of HADES' Field Tests.

9.2 Power Consumption

As discussed in Section 2.6, 2-hours continuous operation is required. The power consumption of HADES' major components is measured to obtain an estimated battery life. The major components analysed are the motors, the NUC and the power distribution board, as they draw the largest portion of current.

The current drawn by the ESCs (as well as motors) is measured using an oscilloscope and a current clamp. Figure 9.15 contains data from a single ESC.

HADES is travelling at a speed of 1.4 m/s across a flat surface. The torque load and therefore current draw produces the oscillatory motion displayed in Figure 9.15, which results from the inverted pendulum effect, discussed in Section 4.1.2. The smoothed data highlights the oscillation more clearly, displaying an average current draw of 3.9 A. As all four motors draw similar current, they consume an average of 15.6 A total, at the operating speed of 1.4 m/s. A current draw of 3.9 A per motor does not differ significantly from the 3.5 A estimated in Section 7.1 and therefore allows the battery life specifications to be met, as calculated below.



Figure 9.15: Current drawn by one ESC at 1.4 m/s over flat terrain

The current draw of the NUC and the distribution board is also measured using a current clamp and an oscilloscope. As HADES is capable of running without the distribution board, the current draw of the NUC with USB components attached was measured first, exhibiting a constant 1.2 A. During standard operation, the distribution board draws a constant 2.9 A. The majority of the components plugged into the distribution board (see Section 7.2.5), such as servos, solenoids or the speaker only experience intermittent use. As a result, their current draw is not considered for constant current calculations. Instead the average current draw of all these components over time is estimated at 1 A to produce a total of 3.9 A for the distribution board. Total operating time t is calculated using Equation 9.1.

$$t = \frac{C \times n}{I_m \times I_D} \tag{9.1}$$

The battery capacity *C* is 8 Ah, multiplied by the total number of batteries *n* produces the total system capacity. This is then divided by the total current draw, consisting of the average motor current I_m , and the average distribution current I_D of 3.9 A. Using the results collected

above, the total operating time is estimated at 2.46 hours, 25% more than the required operating time discussed in Section 2.6.

Although the estimated operating time exceeds the specification, there are additional factors which should be considered. Firstly, the motors draw more current when climbing over debris and rubble. This is only occurs once HADES has driven down the entrance tunnel and arrived at the disaster site. The exact amount of current draw over debris and rubble is difficult to quantify as it varies significantly depending on the quantity, type, size and traction of the terrain.

However, while traversing through debris and rubble it is uncommon for the operator to be continuously driving. Debris and rubble is not always overcome on the first attempt and extra time and care is required to ensure obstacles are traversed correctly. Additionally, for clear audio and video feeds HADES should be stationary. The additional current draw from the debris and rubble is estimated to be negated by the slower speed and intermittent operation of HADES in the disaster zone. This was observed during field tests, where HADES experienced intermittent operation of 4 hours without depleting the power supply.

Component	Average Current (A)
Motors	4×3.9
Intel NUC	1.2
Power Distribution Board	2.9
Intermittent Components	1
Total	19.5

Table 9.4: Table of High Power Components

9.3 Ingress Protection

As discussed in Section 1.2, large quantities of dust, dirt and water are present in an underground mine disaster. To ensure HADES' internal electronics do not get damaged, an IP rating of IP65 [123] is specified. Although IP67 rating is not required, its submersion tests

are carried out to evaluate floating and brief submersion, as discussed in Section 2.6. Details of the tests for dust and water ingress are discussed below and summarised in Table 9.5.

9.3.1 Dust

As an underground mine is filled with smoke and dust (discussed in Section 1.2), HADES' chassis should prevent their ingress. A dust ingress test chamber was not available, and therefore was simulated instead. The chassis was placed in a plastic bag (1100×1400 mm) which is filled with 200 g of talcum power. The bag and chassis are intermittently shaken and re-orientated over 20 minutes in order to regularly disperse the talcum powder. Although this do not guarantee the required ingress protection it is indicative of the results from a test chamber. Figure 9.16 displays the chassis after testing.



Figure 9.16: Chassis after dust ingress test

Although talcum powder found its way into every external hole and crevasse, it did not ingress into the chassis. When the access hatch was removed, dust was not found inside. This finding confirms HADES's IP6X rating. As talcum powder is an order of magnitude

finer [124] than the grit and sand which saturates an underground mine environment, this result demonstrates HADES's effectiveness for use in sand and dust filled underground mine environments.

9.3.2 Water

As discussed in Section 2.6 HADES should be rated for water ingress. Two Ingress Protection water ratings are considered: IPX5 and IPX7. An IPX5 protection rating states that 12.5 l/min water jets should not penetrate the chassis and compromise operation. IPX7 states that ingress should not occur during submersion of 0.15 - 1 m. As the chassis is buoyant, (displayed in Figure 9.17) submersion for IPX7 should not occur, however brief submersion is possible if falling into water from a height greater than 0.3 m. To ensure ingress does not occur during brief submersion or while floating, IPX7 testing is also carried out.



Figure 9.17: HADES buoyancy test

An IPX7 rating was evaluated first as it guarantees an IPX5 rating. The test involved pushing HADES underwater to a depth of 0.6 m as displayed in Figure 9.18, and held down for 30 minutes. A slow water ingress of roughly 750 ml over 30 min occurred, a rate of 25 ml/min. It is important to note that this test was not carried out while the chassis is pressurised, which would provide additional resistance against water ingress. Upon inspection of the chassis two screw holes had been compromised and had contributed to the water ingress. Another possible leak source includes the main access hatch plates which may not be rigid enough to

apply an even pressure to the O-ring seal. To achieve an IPX7 rating, improvements to chassis sealing are required as discussed in Section 9.2. As a result of this pressurisation tests were not carried out, as the discovered lack of sealing would allow gas to escape and prevent a positive pressure being achieved.



Figure 9.18: Chassis held underwater

As an IPX7 rating could not be guaranteed, two further tests are carried out. Firstly, as HADES is buoyant, the chassis is left floating for 30 minutes as displayed in Figure 9.17. During this period, it was twice briefly submersed (~500 mm) and allowed to float to the surface. Inspecting the chassis afterwards showed no visible water ingress. The second test was carried out with a water jet capable of 12.5 l/min, for a duration of 3 minutes, as specified by the IPX5 rating. No visible ingress occurred.

Although 1 m submersion of the chassis for 30 minutes is unlikely, the chassis does not meet the IPX7 spec. It is however ingress protected against floating, brief submersion and subjection to a high pressure water jet and so achieves IP65.

Possible methods of improving protection against water ingress include repairing damage to the screw holes and installing the aluminium plates which may be more rigid. Augmenting the pressure control system for submersion could also provide supplementary ingress protection by increasing the internal pressure beyond 200 Pa when HADES is submerged. This would create a smaller pressure differential between the internal gas and the water thereby resisting the ingress flow. Augmentation of the pressure control system is only possible once complete IPX7 sealing has been achieved.

Test Name	Specification	Test Description	Result
Dust Ingress	IP6X	Talcum powder	Passed
Water Ingress	IPX7	Submersion 70 cm	Slow Leak
Water Ingress	IPX7	Floating	Passed
Water Ingress	IPX5	12.5 L/min jet	Passed

Table 9.5: Ingress Protection Summary

9.4 Chassis Temperature

As fibre glass is an insulator, overheating of the chassis is possible if high power electronics operate for extended periods of time. In order to predict thermal equilibrium, the temperature within the chassis is monitored over time. As specified in Section 2.6, the internal temperature should rise to no greater than 50° C to ensure correct operation of all electronic components.

All major high power electronics are left operating in standby during the test, with motors running at 60 RPM. As the temperature of an underground mine is hotter than 30° C (as discussed in Section 1.2), the air inside the chassis was warmed with a heat gun before data was collected. The internal temperature was monitored in the middle of the chassis by a digital temperature sensor for 30 minutes. The data collected is displayed in Figure 9.19.



Figure 9.19: Measured and predicted internal chassis temperature

Over half an hour the temperature rose by 6° C. A curve was fitted to this data to predict the temperature over three hours. The estimated temperature after three hours is 40.5° C. As most calculations were carried out for a maximum internal temperature of no greater than 50° C (see Section 2.6), the temperature rise meets this specification.

9.5 Intrinsic Safety

As discussed in Section 7.4.1, large currents or voltages produced by a fault, have the potential to ignite explosive gases. The intrinsic safety circuitry, discussed in Section 7.4, is applied to the power and data lines of the sensors to suppress hazardous voltages or currents. Tests were set up to evaluate their effectiveness.

9.5.1 Overvoltage

Voltages greater than 10 V are hazardous. A TVS is employed in the intrinsic safety barrier to prevent over-voltage (see Section 7.4.2) by suppressing any voltages greater than 7.4 V. To test this, the input and output voltages were measured on an oscilloscope, as displayed in Figure 9.20.



Figure 9.20: Input and output voltage of an intrinsic safety barrier

The input voltage was manually increased over time from the nominal 5 V. At 4 seconds the voltage reaches 7.4 V and a current of roughly 0.5 A is shunted to ground by the TVS. This blows the fuse, resulting in the output voltage dropping to zero, despite the input continuously increasing. This conforms to the theoretical operation of a TVS and fuse. As the output voltage does not exceed 7.4 V the intrinsic safety barrier is successful in preventing overvoltage.

9.5.2 Overcurrent

Currents greater than 0.5 A are considered hazardous as discussed in Section 7.4.1. As mentioned in the previous section, the fuse installed in the intrinsic safety barrier blows if 0.5 A is applied. A 47 Ω resistor is installed in series along the power and data lines as additional protection to limit the current to 0.1 A (see Section 7.4.2). It is measured with a multimeter at 48 Ω . In order to ensure current does not exceed 0.5 A, the limiting resistor of a sensor data line is observed under the effects of a short circuit. The voltage across the resistor was measured on an oscilloscope during an applied short circuit. The data is displayed in Figure 9.21.



Figure 9.21: Voltage of the current limiting resistor during a short circuit

Initially, the intrinsic safety barrier output is open-circuited and therefore no voltage is dropped across the resistor. At 0 seconds, a short circuit is applied between the data line and ground causing a sudden in-rush of current, the oscillations of which die out over the following 0.2 microseconds. Using Ohm's law, the current flowing through the resistor after three seconds is 0.104 A. The first peak after the in-rush current is 5.2 V, producing a peak current of 0.108 A. The collected data follows theory as expected and illustrates effective overcurrent protection through a current limiting resistor.

Table 9.6: Intrinsic Safety Test Data

Test Description	Specification	Evaluation Method	Result (Max)
OverVoltage	10 V	Large Input Voltage	7.4 V
OverCurrent	0.5 A	Short Circuit Output	0.108 A

9.6 Miscellaneous

9.6.1 Kinect

Although the Kinect is being replaced by the RealSense it is still valuable to evaluate its performance for underground mine environments as its specifications are similar to the

RealSense. As discussed in Section 5.1, clear, detailed images must be provided in both light and dark conditions. Figure 9.22 displays a set of frames from the Kinect's data.



Figure 9.22: Kinect data. RGB with light (bottom left), RGB without light (bottom right), IR camera without light (top right), IR depth data (top left).

These images are taken in a room with no natural light in order to simulate the darkness of an underground mine. The bottom left figure shows a standard RGB 1080p image as a reference point. The image is clear and detailed, with three major objects, used to simulate a structural beam, a rock and a human. The top left image portrays the depth information as an additional reference in order to understand how far away the objects are from the camera. The image uses colours to indicate depth with green as far, and red as near. The red object is approximately 1 m from the camera and the door is 1.5 m. The bottom right figure is also a standard RGB image but is taken with the lights off. The small light in the middle at the bottom of the figure is the only light source coming from underneath the door. Neither the near nor far objects can be detected in this darkness. The top right image uses the Kinect's IR emitter and sensor to produce a greyscale image. It allows clear, detailed vision of the scene in complete darkness. All three objects and the distinctions between them can be detected, which demonstrates the suitability of IR cameras for dark underground mines.

The Kinect does not differentiate heated bodies such as humans from other objects despite being an IR sensor. This is because the Kinect uses an IR emitter with a wavelength of 830 nm [125] from the near-infrared spectrum, and a matching a filter. The wavelength of IR light emitted by human bodies is long-infrared, between 8000 and 15,000 nm [126] and therefore the Kinect is not designed to detect this light. The RealSense exhibits similar properties, operating on IR emissions of 860 nm [127]. This is unfavourable in the context of search and rescue where human bodies should be detected. As HADES includes spare USB ports and additional space in the front camera window, thermal imaging cameras, which operate in the long-infrared spectrum could be employed to supplement scouting capabilities.

The depth information provided by the Kinect is extremely useful when teleoperating HADES. Figure 9.23 displays the amount of data and detail provided with each frame. When this depth information is overlaid with the RGB or IR frame, an operator is able to judge distances more easily when moving between rubble and debris. Additionally, this depth data could be used to produce a 3D map as discussed in [128]. Possible future work using depth data is discussed in more detail in Section 10.2.4.



Figure 9.23: Kinect depth data displayed in 3D space

9.6.2 Weight

To ensure the weight specification of 20 kg is met, discussed in Section 2.6, HADES' major components are weighed. Table 9.7 displays the various component weights.

Component	Unit Weight	Quantity	Total Weight
Chassis	5	1	5
Motor Assembly	0.85	4	3.4
Intel NUC	0.22	1	0.22
PCBs	0.72	1	0.72
Wheel	1.3	4	5.2
Kinect	0.6	1	0.6
Cylinder	0.68	1	0.68
ESC	0.06	4	0.24
Battery	0.65	6	3.9
Misc	0.5	1	0.5
Total			20.46

Table 9.7: Major Component Weights

The four largest contributions to the total weight are the gearbox assemblies, wheels, chassis and batteries. The excessive weight of the Kinect-v2 is also highlighted here. The total weight of 20.46 kg is close to the 20 kg specification and therefore means it achieves the desired goal of portability.

9.6.3 Cost

Existing systems for underground mine search and rescue are expensive. This has affected deployment due to the financial loss if the robot is lost or broken. Therefore, the specification of \$10,000 defined in Section 2.6 minimises the expense and allows for a semi-disposable system. Table 9.8 displays the individual costs of major components, priced as one-off purchases.

Component	Quantity	Unit Cost (NZD)	Cost (NZD)
Main Chassis	1	450	450
Sub-Molds	3	120	360
Gearbox Mount	4	300	1200
Gearbox	4	80	320
Motor	4	89	356
ESC	4	60	240
Intel NUC	1	550	550
Control Board	1	450	450
Distribution Board	1	750	750
Batteries	6	44	264
Cylinder	1	70	70
RealSense	4	130	520
Audio Components	1	40	40
Pivot	1	165	165
Wheel	4	80	320
Gas Sensors	10	8	80
Headlights	2	10	20
Total			6155

Table 9.8: Major Component Costs

The gearbox mounts, power distribution board and RealSense cameras are the most significant contributions to total cost. As discussed in Section 3.1.2, the manufacturing process of metal is expensive and therefore the cost of the gearbox mounts cannot be reduced from \$1200. The RealSense is the most suitable RGB-D camera for HADES, as discussed in Section 5.1.3, and are only \$60 more expensive than the Kinect and webcam combination. Therefore \$520 for the RealSense cameras remains a significant portion of HADES' total cost. The power distribution board is an area where costs could be reduced. A number of components, such as the DC-DC converters and the high side switches were purchased despite being the more expensive option. Their decision was justified as HADES' total cost is well below the specification, however creating power converters or high side switches from discrete components could reduce cost if needed.

The total cost of HADES' major components is \$6155. The fibre optics and wireless nodes are excluded as only an initial design was carried out, which may change during implementation in future development. If these were to be include their cost is estimated at an additional \$3000. Components such as nuts and bolts, wiring, 3D printing etc. are not included in Table 9.8, but a 15 % increase in cost is included. This produces a total for HADES of \$7078, which falls below the \$10,000 specification

9.7 Summary

In evaluating HADES' test results, the expectations and specifications of Section 2.6 were all exceeded. The chassis is waterproof against high pressure jets, floating and temporary submersion. Complete submersion for 30 minutes (IP67) was not altogether prevented, however this scenario is considered unlikely due to HADES' ability to float. It does impact on HADES ability to maintain a positive pressure, and prevented the purge and pressurisation system from being evaluated. The chassis' ingress protection also demonstrates it is impenetrable by dust and therefore the IP65 specification is achieved.

HADES' locomotion is both reliable and effective, bottoming out being the only issue encountered. While presenting itself as a major issue, the significance of bottoming out is

dependent on the skill of the operator. Approaching obstacles from an appropriate angle (see Section 9.1.1) can avoid the problem and allows HADES to traverse obstacles (530 mm) greater than its wheel diameter. The motor assemblies demonstrate sufficient power, capable of providing more torque than traction allows as discussed in Section 9.1.3 and sufficient speed to reach 1.4 m/s as discussed in Section 9.1.3.

The efficiency of the motors was also demonstrated as their power dissipation was insufficient to cause internal overheating of the chassis. Motor efficiency also contributed to HADES' battery life, which is 2 hours 28 minutes in excess of the 2-hour target. At a development expense of \$7078, HADES is constrained below the \$10,000 limit and therefore exhibits locomotion which appears to outperform round-wheel and tracked units at a fraction of the cost.

Chapter 10

10 Conclusion

This chapter reviews HADES' overall design and evaluates its performance. Future additions and improvements are outlined in Section 9.2. The chapter concludes with a final summary of HADES's capabilities.

10.1 Review

The complications of operating a robot in an underground mine disaster, and the lack of existing robots to effectively and reliably navigate through this environment are described in Chapters 1 and 2. This thesis and resulting publication [129] present the design for a solution to fill this void.

HADES' chassis is designed from a fibre glass composite and is manufactured to be strong and light-weight. O-rings and lip seals are used around all access points of the chassis to prevent the ingress of the water, dirt and dust from an underground mine environment. Sealing also contributes to the purge and pressurisation system, which maintains an internal positive pressure through a nitrogen cylinder, allowing HADES to operate in an explosive environment. The low centre of gravity design for the invertible chassis significantly assists locomotion and prevents toppling or immobilization in rough terrain.

Spoked-wheels in combination with a passive roll axis pivot provides reliable locomotion to climb debris and rubble produced after a disaster. The wheels are driven by brushless motors and 104:1 gearboxes. For strength and effective sealing, an additional gearbox mount is designed. Although bottoming out appeared to be an issue with this locomotion, further testing showed that operator skill in correctly approaching obstacles could mitigate this.

Various sensors for search and rescue tasks are implemented on HADES. Depth cameras provide data for teleoperation and data collection. The Kinect was originally selected but is being replaced by Intel's RealSense, which exhibits significantly improved size and power consumption. Explosion-proof speakers are rare, so the innovative application of a surface transducer, positioned internally against the chassis, produces sound through vibration of the chassis. Temperature and pressure sensors are implemented as well as the MQ and AlphaSense range of electrochemical sensors to detect toxic and explosive gases. The modular intrinsically safe ports enable a large range of different sensors to be installed without individual explosion-proofing.

To interface with these sensors and control HADES' low level hardware, a control circuit board was designed. The design required a compact layout with three microcontrollers for each of the power management, sensor interfacing and motor control. Power to the control board and the rest of HADES' components is supplied from six Li-Po batteries, converted and distributed through a custom designed central power distribution board.

High level control is implemented on an Intel NUC portable PC, running Ubuntu and ROS. The *Rosserial* package communicates with the low level control board, allowing HADES to be operated via an Xbox gamepad. The NUC and ROS were selected for flexibility and with a view to provide sufficient processing power and robotic software packages for future development. The foundations are laid for closed loop control, with hardware and initial software assembled for future development as discussed in the following section.

10.2 Future Work

HADES is a prototype of an entire robotic system design. The following section addresses both improvements and possible extensions for development.

10.2.1 Environmental Resistance

Underground mine disaster environments are saturated with water, dust, dirt and explosive gases as mentioned in Section 1.2. The resistance of the chassis to this environment requires

repair and extension to guarantee internal components are not damaged and explosionproofing is assured.

As displayed in Figure 10.1, dust and dirt can build up on the camera windows obscuring vision. Utilising the lotus effect [130] is a suggested improvement. The Lotus effect refers to a surface's ability to self-clean due to super hydrophobicity. The surface has a nanostructure which is extremely repellent to water and therefore prevents wetting, as a result it also reduces adhesion of dust and dirt. There are two primary methods of achieving super hydrophobic surfaces: materials constructed with the nanostructure or sprays which apply the nanostructure. Constructed materials are expensive. The drawback of super hydrophobic sprays is that they require recoating. Recoating can be applied before deployment and so sprays are suitable for this application. The application and effectiveness of a super hydrophobic spray requires investigation in the future.



Figure 10.1: Camera window obscured after dust test

A spray nozzle, similar to the way a car cleans its windshield, could be incorporated to assist the super hydrophobic solution. Nozzles should be placed at the perimeter of each camera window pointing towards the centre of the window to remove dust or dirt from the surface. The spray solution could be a gas such as nitrogen from the internal cylinder or alternatively a small water tank and pump. Although the chassis is waterproof while floating and sprayed with jets, it failed the IP67 rating. Obvious fixes include applying sealant to damaged screw holes, but further investigation into other sealing may be required. Protection against water ingress should also be evaluated once the purge and pressurisation is complete, as an internal positive pressure provides greater resistance to ingress. Seals and components for purge and pressurisation system have all been designed and implemented as discussed in Section 3.2. It was not tested due to gas escaping too quickly as a result of the aforementioned sealing issues. Assuming sealing is improved, future development should implement software for the control system, to regulate the internal pressure. Evaluation of the purge and pressurisation system should then be carried out to determine if two hours pressurised operation is possible.

10.2.2 Communication System

HADES is currently operated over a WiFi module for prototyping. The communication system needs completion to enable long range, reliable communication between HADES and the operator. An initial design is carried out in Chapter 6 for a fibre optic tether and wireless mesh network. This communication system needs implementation and evaluation in an underground mine tunnel environment.

10.2.3 Intel RealSense

As discussed in Chapter 4, the Kinect-v2 is being replaced with Intel RealSense devices which have significantly smaller dimensions and power consumption. Intel provide direct support for ROS, therefore integration should be straight-forward. The official ROS packages provide all the RGB, IR and depth data for processing. In terms of hardware, the RealSense will require a mount and chassis window size modifications. as described in Section 3.1.3 and 9.2.5. A USB hub was purchased to ensure sufficient ports are available for all four devices. An overview of possible robotic feature applications for the RealSense can be found in [131].

10.2.4 Software Architecture

High level software architecture was designed for ROS to ensure robust control of HADES as described in Section 8.1.2. This project combined many possible ROS nodes into a single node called *HADES*, which allows simple non-autonomous operation. The ultimate goal is for HADES to be a semi-autonomous system; controlled by an operator but making low level decisions to assist operation and search and rescue tasks.

Forms of artificial intelligence such as computer vision and pattern recognition are useful for detecting features in an underground mine such as humans, flooding, or areas of high gas concentration. Additionally, computer vision could be applied to process control, such as detecting dirt on camera windows to automate the spray nozzle. RGB-D cameras supply depth as well as colour, which could be processed for scene reconstruction to produce an extremely detailed 3D map as seen in [128].

A GUI is recommended to display operating data without distracting from driving. Devices such as the Oculus Rift [132] could provide an operator with more immersion and information through an augmented reality that provides telepresence [133]. This would significantly reduce the effect of the "keyhole problem", as mentioned in Section 8.1.3

10.2.5 Chassis Modifications

Some modifications to the chassis could improve performance. As the fibre glass company associated with HADES possess the mold used to construct the chassis for this project, additional modifications should not require significant time or resources. Side windows were designed for webcams and therefore are not wide enough for RealSense, this was re-modelled as mentioned in Section 9.2.3. The sensor filter gratings slots were also modelled and require implementation, as discussed in section 3.1.3.

Main access hatch panels should be re-constructed from aluminium, as discussed in Section 3.2.1.. Although thermal equilibrium of the chassis is only predicted to reach 42° C,

this value is estimated for nominal operation. If all of HADES' components are operated simultaneously while moving through an ambient mine temperature of 40° C, overheating is theoretically possible. An aluminium plate, with all components mounted against it for heat dissipation out of the chassis, would provide a lower thermal equilibrium thereby reducing the likelihood of overheating and increasing the efficiency of operation.

10.2.6 Locomotion Control

Closed loop control is required to optimise HADES' locomotion, as discussed in Section 8.3.2. The foundations are realized in this project, but the software control system requires further development. The PID closed loop controller produced in Section 8.3.2, was initialised with some basic parameter tuning. Future developments should tune the PID parameters to achieve a system response with a faster settling time and reduced overshoot. Tuning must also be carried out for each individual motor assembly. Field tests are then required to ensure the closed loop system parameters are reliable and robust for rough terrain locomotion.

10.2.7 Spoked-wheels

The T-shaped spoked-wheel was designed to absorb and damp the impact of spokes with the ground. Instead it contained too much elasticity and therefore produced undesirable vertical movement. Alternative spoked-wheel designs may exhibit superior performance. Additionally, different spoke designs have different applications, as discussed in Section 4.1.2. In order to identify these applications, different spoke designs should be investigated in more detail. Several spoke designs have been modelled, as displayed in Figure 10.2 and are a suggested starting point for future development. Furthermore, the potential of spoked-wheels to paddle through water is highlighted in Section 8.1.4 and a unique wheel design can enable effective paddling locomotion. The plates used to construct all of these designs should be manufactured from aluminium instead of acrylic sheets for increased strength and reduced weight.


Figure 10.2: Alternative Spoke Wheel Designs

10.3 Summary

The objectives of this research (Section 1.3) and the design specifications (Section 2.6) have all been met or exceeded. HADES includes a variety of sensors for teleoperation and scouting of a mine environment. Electrochemical gas sensors are incorporated with an intrinsically safe circuit design for operating in an explosive environment. RGB-D cameras and surface transducer speakers are integrated into the design, where darkness and explosive atmospheres are present. They are the first known implementation of these two devices on an underground mine robot.

The chassis is sealed against dust and high pressure water jets with an IP65 ingress protection rating, including the ability to float and be briefly submerged. Sealing also allows purge and pressurisation for explosion-proofing to be implemented. The fibre glass chassis is inexpensive as well as strong and light. The cost and weight specification were both exceeded with a \$7078 construction price tag and a weight of 20.46 kg. HADES is capable of continuous operation for 2 hours and 28 minutes, exceeding the 2-hour specification set out in Section 2.6.

Although the communication system was not implemented, a dual design of tethered and wireless communication was investigated and presented. The mesh network concept of deploying wireless nodes is yet to tested in underground mines and identifies great potential for future research and development. The NUC as well as the custom power and control

PCBs, bring all of HADES' subsystems together for digital electronic control. These controllers, in combination with high and low level software, allow teleoperation of HADES.

Locomotion is effective, robust and reliable, capable of being deployed from the surface to navigate through the debris and rubble of an underground mine disaster. This was thoroughly tested through controlled indoor evaluations as well as debris and rubble field tests. While several existing systems exhibit spoked-wheels, no search and rescue robot demonstrates reliable, effective locomotion while simultaneously containing explosion-proofing and extensive considerations for an underground mine. The design of this novel scout robot was validated and published through the IEEE Safety Security and Rescue Robotics (SSRR) 2015 conference at Purdue University, U.S.A [129]. A final picture of HADES the underground mine disaster scout, is displayed in Figure 10.3 on the following page and summarised by the Extractive Industries Advisory Group (EIAG) below. The full text of which can be seen in Appendix A.

"...the 'mining robot' project you presented to the EIAG is of great interest to the Group members, representing one of the most significant attempts we are aware of, to combine the rapidly advancing state of robotics with the additional difficulty factor of operating under the restraints of electrical Intrinsic Safety (IS) within an explosive methane environment in a post fire or explosion coal mine. The unique traction unit drive system, spoked-wheels and lightweight but robust operating chassis from which monitoring services can be mounted or deployed appears to represent real potential and the Group both commend the work undertaken by Lance Molyneaux thus far and encourage the University to continue in its development."



Figure 10.3: Final figure of HADES

Appendix A

EIAG Statement

The Extractives Industry Advisory Group (EIAG) was established to oversee and advise the Board of WorkSafe New Zealand on the activities of the Mining Regulator - High Hazard Unit (HHU) Extractives. One of the key roles of the HHU Extractives Regulator is to keep under review the effectiveness of emergency preparedness as specified within the Principal Control Plans required under the Health and Safety in Employment (Mining Operations and Quarrying Operations) Regulations 2013. An Inspector from the HHU also sits on the Board of the Mines Rescue Trust who are charged with providing emergency services for underground coal mines. Following the Royal Commission of Inquiry into the disaster at Pike River, a key recommendation was that significant improvement in emergency preparedness for underground coal mines should be secured.

Therefore, the 'mining robot' project you presented to the EIAG is of great interest to the Group members, representing one of the most significant attempts we are aware of, to combine the rapidly advancing state of robotics with the additional difficulty factor of operating under the restraints of electrical Intrinsic Safety (IS) within an explosive methane environment in a post fire or explosion coal mine. The unique traction unit drive system, spoked-wheels and lightweight but robust operating chassis from which monitoring services can be mounted or deployed appears to represent real potential and the Group both commend the work undertaken by Lance Molyneaux thus far and encourage the University to continue in its development.

Post explosion or fire incident, the lack of information immediately available to mine managers and rescue workers is acute and having a robot which could explore the territory ahead of rescue teams providing information and laying down a communication system would be invaluable.

Yours sincerely,

Gavin Taylor,

Chair EIAG



Appendix B

Digital Content

The attached DVD contains the following:

- PDF of SSRR 2015 Publication
- PDF of this thesis
- Photo Gallery
- Code
 - Embedded Controller
 - ROS
- Altium PCB Files
 - Schematics
 - Layout
- Videos
 - Node Inside
 - Node Outside
 - Field Tests Compilation

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