Utilizing IoT in Hazardous Work Environments

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Abstract

In New Zealand, the forestry industry is one of the most dangerous industries to work in. Workers in the forestry industry are three times more likely to be killed while at work than any other industry in New Zealand (WorkSafe, 2021). Internet of Things (IoT) devices are being leveraged to increase the safety of workers in other industries. However the forestry industry has not adopted this technology.

This thesis proposes a new IoT solution for safety in the forestry industry, with a primary focus on the forestry task of 'breaking-out'. This solution utilizes geofencing and GPS technology to ensure that workers are out of a 'danger zone' when a cable hauler is operating. To implement this solution, two IoT devices were developed: a carried unit which the breaker-outs carry with them, and an in-cab unit which is mounted within the hauler cab. The two units communicate via radio frequency, and a button located on the carried unit allows the workers to set a geofence that outlines the 'danger zone'. This allows the cable hauler operator to see the location of all breaker-outs at all times, and be notified when any of them are at risk, i.e. inside the danger zone.

Two tests were performed to evaluate the viability of this solution for use within the forestry industry. The first test evaluated the technical requirements of the devices, while the second test evaluated the device performance when deployed in an active forestry harvesting operation. While some limitations were found, these tests prove proof-of-concept and illustrate how this solution

could be used to mitigate the risk of incidents in the forestry industry.

Finally, the proposed IoT solution can be used for additional applications within other areas of the forestry industry. One such application is that of proximity detection on the skid site. This thesis illustrates how the devices can be used to allow machine operators and workers on the ground to be alerted when they are too close to a machine. This can mitigate the risk of an incident occurring, not just for breaker-outs, but for additional workers across the forestry industry.

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Chapter 1

Introduction

In New Zealand, the forestry industry is one of the most dangerous industries to work in. The workers in the forestry industry are three times more likely to be killed while at work than any other industry in New Zealand (WorkSafe, 2021). A proposed solution to mitigate the number of incidents is to utilize Internet of Things (IoT) in the forestry industry with the aim of improving workers' safety. The solution outlined in this thesis uses GPS tracking and a notification system to ensure that workers are aware and outside of potential hazard zones. The hardware created can also be used in an additional application of proximity detection, for use around machines on the skid site.

1.1 Motivation

New Zealand has approximately 1.665 million hectares of plantation forests, allowing the forestry industry to contribute approximately 6 billion dollars per year to the New Zealand economy. Yet, the forestry industry is one of the most dangerous industries in New Zealand. The fatality rate is 64.23 per 100,000 full-time-equivalent (FTE) workers, three times higher than that of the Fishing, Hunting, and Trapping industry (Garland, 2018).

New Zealand has an incident reporting system called Incident Recording

Information System (IRIS) which can be used to categorize the incidents that occur within the forestry industry. The IRIS system is not a mandatory system, therefore companies must opt-in to use it (Dodunski, 2017). However, by using the IRIS system, companies can gain trend analysis and reports from their own data, alongside being able to benchmark their company against the industry. The data gained from companies is collated each quarter and an industry report is created for the public. These reports show the top contributing categories to the incidents that occurred that quarter, along with the types of injuries that occurred, and a plethora of other data on time lost, near hits, and critical risk areas. From these quarterly reports, the category of *Hit by Object* is consistently one of the largest contributors to all incidents that have been reported between 2018 and 2021 (FISC, 2018b,a,c,d, 2019b,a,c,d, 2020b,a,c,d, 2021).

One such *Hit by Object* incident that tends to occur involves breaker-outs being hit by stems as they are hauled back to the skid site by a cable hauler. A breaker-out is a worker who is tasked with attaching fallen logs to a cable system. This cable system then drags the logs up to the skid site for processing. This introduces risks such as the logs swinging and hitting the breaker-out, or the logs dislodging another log which could hit the breaker-out. This can result in fatalities, particularly if the breaker-out is not at the correct safe retreat distance. I propose that technology can be leveraged to assist the workers and reduce the risk of this type, and other types of incident occurring.

1.2 Proposed Solution

The forestry industry has a set of protocols, and a set of personal protective equipment (PPE) that are mandatory, and that aid in the mitigation of incidents occurring. With the recent advancements in the field of Internet of Things (IoT), there is great potential here for integrating technological solutions to further mitigate these risks. This technology could be used to create an added layer of safety for the workers.

IoT is not widely used for safety in the forestry industry. However, I propose that IoT can be used as a solution to assist the hauler operator and breaker-outs in ensuring that workers are at a safe distance from the cable line before hauling begins. This would reduce the chance of the breaker-out being struck by a log or debris as the log(s) are hauled to the skid site. This would also allow the hauler operator to see where the workers are when visibility is low, a situation that is considered the most dangerous for breaker-outs.

Another technology that can assist in this application is geofencing. Geofencing is a location-based service that is often integrated into IoT solutions. It allows an application to create a virtual boundary, and uses GPS location data to trigger an event when the boundary has been crossed. While this is typically used for marketing, the ability to detect and alert when a worker crosses a boundary could be used to ensure that the breaker-outs are at a safe distance before the logs are hauled in.

In this thesis, I propose a technological solution that leverages IoT and geofencing technology to help mitigate the risk of incidents in the forestry industry. The proposed solution has been tailored to one specific forestry operation, that of 'breaking-out'.

The solution involves a set of two devices: a carried unit and an in-cab unit. Each breaker-out will be provided with a carried unit that can gather their GPS location and transmit data to another device within the hauler cab – the in-cab unit. The in-cab unit can then display the locations of the breaker-outs. Utilizing geofencing, the breaker-outs can set the edge of their safe-retreat zone, typically shown by high-visibility flags, to generate a virtual zone on the in-cab unit's screen. This zone will show as the area where the breaker-outs should not be whilst the machine is operating, i.e. a danger zone. The machine operator can then see where the breaker-outs are before they begin to operate the machine, both allowing them to have an additional check and also allowing them to see which breaker-out is standing too close to the cable line.

Finally, in addition to the ‘breaker-out’ solution, I propose that these devices can also be applied to additional applications. One such example is that of ‘proximity detection’ on the skid site. An in-cab device can be placed on each of the machines on the skid site, and each of the workers can hold a carried unit. Radial geofences could then be set up around each machine. When a worker enters a geofence, the worker and the machine operator could receive alerts, ensuring that both parties are aware that a worker is in a potentially dangerous situation.

1.3 Scope

This thesis is laid out as follows. Chapter 2 covers background information on the forestry industry and relevant IoT concepts. Chapter 3 presents related work that utilizes IoT in forestry and other industries, focusing on health and safety. Chapter 4 outlines the design of a system to locate and display the positions of the breaker-outs to a hauler operator. This chapter shows the system design, data flow diagram and hardware selection used, alongside two concepts that are evaluated and a final concept that is selected for development. Chapter 5 details the implementation of the system, including the creation of the two devices, the creation of a case for each, and the software developed for both devices. Chapter 6 covers an evaluation of the devices, consisting of an in-house test and a field test, with respective results and discussion. Chapter 7 outlines an additional application – i.e. proximity detection – and Chapter 8 concludes this thesis, discusses the limitations, and proposes future work that could be undertaken.

Chapter 2

Background

This thesis introduces a technology-based solution that leverages IoT and geofencing technology to help mitigate the risk of incidents in the forestry industry. As such, this chapter begins by outlining a series of commonly used forestry terms. It then provides some detail about the topic of health and safety for forestry, with a specific focus on injuries and statistics, and safety culture within the forestry industry. Next, I introduce one of the higher risk forestry operations – harvesting – and discuss the types of incidents that occur, and the current safety protocols that relate to this operation. Finally, this chapter outlines some of the technology that will be used throughout this thesis, including Internet of Things (IoT), Radio Frequency (RF), and Geofencing.

2.1 Forestry Terms

Throughout the thesis, there is heavy use of forestry related terms and jargon. These terms have been listed below to explain them for a better understanding of the concepts and procedures discussed.

Forest (Plantation Forest): Area of managed forest that has been planted with the intent to maximise the production of wood (MBIE, 2012).

Felling: The process of cutting a tree down. Can be performed by a person or machine (Visser, 2016).

Stem: A felled tree trunk prior to processing (MBIE, 2012).

Forest Area: Area where the trees are felled and await extraction to the landing area (Visser, 2016).

Landing/Skid Site: Area where the stems are taken to be processed and loaded onto logging trucks (MBIE, 2012).

Choker: A cable and fitting that is wrapped around a log and secured to be dragged by a skidder or cable system (Visser, 2016).

Ground-based Harvesting: Method of extracting the stems from the forest area by means of a vehicle on the ground. Two common methods are Skidding and Forwarding. Typically used on terrain that is easily traversable by wheeled or tracked machines (Visser, 2016).

Skidding: Method of extracting stems where the stems are connected to a machine via choker cables and dragged from the forest area to the skid site (Visser, 2016).

Forwarding: Method of extracting the stems whereby they are loaded onto a trailer by a machine and hauled to the skid site (Visser, 2016).

Cable Yarding: Method of extraction where the logs are attached to a cable system and dragged from the forest area to the skid site. This method is typically used when the terrain is steep or too dangerous for a wheeled or tracked vehicle to traverse (Visser, 2016).

Yarder/Hauler: A machine that typically consists of a tower to elevate the cables, tracks or wheels for mobility, and a series of winches and brakes to control the cables (Visser, 2016).

Breaker-Out: The worker whose primary job is to fasten the choker to the stems in a cable yarding extraction team (MBIE, 2012).

Tailhold: A stump, machine, or anchor that the hauler cables are attached to on the opposite end from the hauler (MBIE, 2012).

2.2 Injuries & Statistics

Forestry in New Zealand is one of the most dangerous industry to work in, with the highest rate of injuries and fatalities (Worksafe, 2017). Since 2017, there have been 21 fatalities within the forestry industry and an average of 20 severe injuries each quarter, per 1,000 workers (NZFOA, 2020). From May 2020 through until April 2021, there were 4 fatalities in the Forestry and Logging industry, making it the industry with the fourth most fatalities in the workplace in New Zealand. When comparing the rates per 100,000 Full-Time Equivalent (FTE) workers, forestry has a rate of 64.23. Therefore a worker is 3 times more likely to be killed in Forestry than in the Fishing, Hunting and Trapping industry (20.01/100,000 FTE's), and 5.6 times more likely to be killed in Forestry than in Agriculture (11.37/100,000 FTE's) (WorkSafe, 2021).

The New Zealand forestry industry has an incident reporting system called IRIS (Incident Recording Information System) which allows forestry contractors and companies to upload their incident reports to a database, assisting in the discovery of incident trends and consequent safety changes to mitigate these. While IRIS participation is not mandatory (Dodunski, 2017), there are many companies and contractors that are using it already. This gives the IRIS database a large sample group for the New Zealand Forestry industry. Therefore the data shown within these reports can be seen as representing the industry as a whole. Data obtained from the quarterly IRIS reports shows more insight into the types of incidents that occur in the forestry industry.

Table 2.1: IRIS incident numbers for the period Q1 2018 - Q1 2021

Incident Cause	Number of Incidents
Hit by Object	761
Poor Technique	760
Loss of Control	638

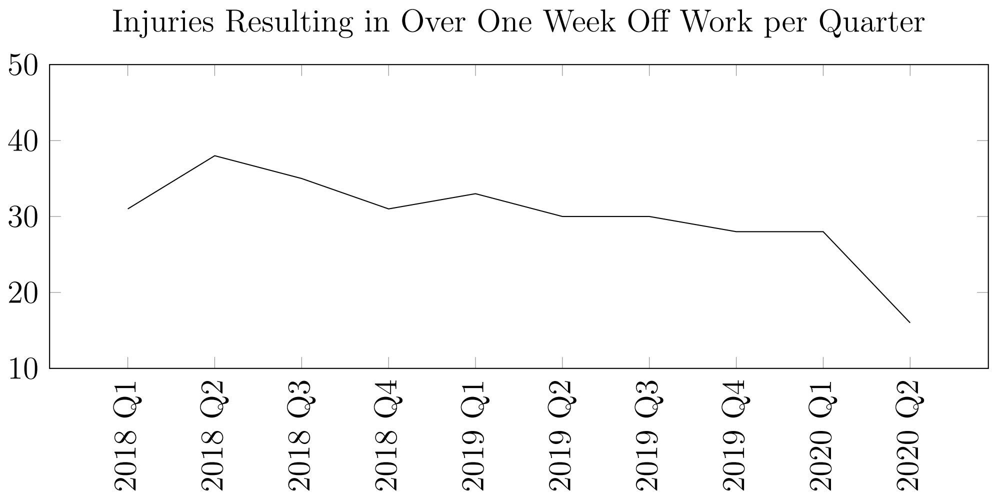


Figure 2.1: Graph of Incident Numbers for the period Q1 2018 - Q2 2020[1]

IRIS incidents are categorized by causes that contribute to their occurrence. This includes causes such as *Hit by Object*, *Poor Technique*, *Slip/Trip/Fall*, and *Loss of Control*.

Reports from Quarter 1, 2018 through to Quarter 1, 2021 have shown that in five of the last thirteen quarters, *Hit by Object* has been the top contributor to the incidents that have occurred within the forestry industry, and was one of the top four contributors each quarter in this time-frame (FISC, 2018b,a,c,d, 2019b,a,c,d, 2020b,a,c,d, 2021). Table 2.1 shows three of the most common incident types in the period from Q1 2018 until Q1 2021. Of these three incident types, Hit by Object and Poor Technique have the most incidents attributed to them, 761 and 760 respectively, and are also most likely to cause

[1] Safetree Reports are generated quarterly, with injury data posted in the quarter being 2 quarters behind, i.e Q4 2020 report shows injury data for Q2 2020. Therefore the data for both Q3 2019 and Q1 2020 are missing due to no report being generated Q1 2020 as a consequence of COVID-19.

injury to a worker. While both can be improved by better training of the workers, Hit by Object can also be improved by assistive safety equipment, explained more in Section 2.7. Typically the Loss of Control incidents occur within a vehicle, travelling to and from work, or loading trucks at the skid site.

Incidents in the context of the IRIS system can be anything from a missing warning sign, to a fatal incident where a worker has lost their life. Injuries that occur from these incidents, resulting in over one week off work, have been on a downward trend in the recent years, shown in Fig. 2.1. This could be due to changes in forestry culture (discussed further in the next section), increased safety training for the workers, better safety equipment, other external factors, or a combination of each. An independent safety review undertaken by a review panel also shows that the number of incidents where a worker was seriously injured by a moving object, such as a machine, is steadily decreasing from approximately 70 to 40 incidents in the period from 2010 to 2013. On the contrary, serious injuries as a result of workers being hit by falling objects are increasing steadily, approximately 15 to 35, over the same time period (Adams et al., 2014).

2.3 Culture of Forestry

The culture of the New Zealand Forestry Industry has been viewed as one of “get it done fast”. An independent forestry safety review conducted in 2014 showed that “there is a strong ‘can do’ culture on the forestry block which needs to become a ‘can do safely’ culture” (Adams et al., 2014). The “get it done fast” culture of the forestry industry could be an influential factor to the high rate of fatalities and incidents. This can lead to accidents and injuries occurring more frequently, as the priority lies on fast and efficient work, rather than safe work. This attitude, coupled with pressure to meet financial targets, could be leading workers to push themselves physically and mentally, in turn contributing to otherwise preventable incidents.

The culture has been changing since this investigation, which can be shown in the decreasing number of accidents and injuries that have occurred in the years since the review. This, along with stricter safety protocols and requirements, and better training is contributing to lowering the injury and fatality rate in the forestry industry (Adams et al., 2014). A Forestry Industry Safety Council (FISC) report from 2018 states that during a survey they undertook, 54% of respondents thought that there had been a positive change in the safety culture of the forestry industry over the past 2-3 years (Cosman, 2018).

2.4 Harvesting in the Forestry Industry

Although incident rates are decreasing, there are still high numbers occurring, and harvesting is one of the forestry operations with significant incident rates (FISC, 2018b,a,c,d, 2019b,a,c,d, 2020b,a,c,d, 2021). In the New Zealand forestry industry, 'Harvesting' refers to the process of felling a designated section of forest, extracting the stems, processing them at a skid site, and then loading the processed logs onto a truck for transport (ForestryFocus, 2013).

The felling of the trees in the forest can be performed manually or by a machine. The manual felling method involves a worker using a chainsaw and other appropriate tools to cut down a tree. The often faster and safer method is a machine with a felling attachment that allows the machine to grapple to the tree, cut the base and push the tree in a safe direction (ForestryFocus, 2013).

Once the stems are on the ground, there are two primary methods of extracting the felled logs. These are ground-based extraction and cable yarding. Ground-based extraction uses a wheeled or tracked vehicle to either skid (drag) or forward (load onto a trailer or carry) the stems to the skid site. Ground-based extractions is more commonly used on terrain that is easily traversable by wheeled or tracked machines and is cheaper and more efficient than cable yarding (Visser, 2016). Cable yarding is an extraction method where a Hauler is set up with a cable system spanning a valley or hill. This cable is attached to an anchor at the bottom of the hill or other side of the valley, allowing the cable system to be used to transport the stems from the forest area to the skid site. This system uses choker cables to attach the stems to the cable system. The attaching of the choker is performed by breaker-outs, who tend to stay on the hill for the entirety of the working day (Visser, 2016).

Once the stems have reached the skid site, machines are used to move the stems to the processing area. Some of the processes a stem may undergo include debarking, delimbing, and cutting to length. These are typically performed by an excavator with a processing head attached. This uses an on-board computer and the ability for the processing head to get the various data measures of the stem. The computer can then tell the operator what the most efficient use of the stem is and cut it to the appropriate lengths (Visser, 2016). The processed logs are then stacked, and quality control checked before being loaded onto a logging truck for transport to the destination of the logs. This is undertaken by a machine, typically an excavator with a grapple attachment or front-end loader.

2.5 Incidents in Harvesting

Two examples of potential accidents that can occur in the harvesting process involve breaking-out and movement around machines.

Breaker-outs are one of the most at-risk members of a harvesting team. Their job requires them to move around the fallen stems, and places them closest to the stems when they are pulled back to the skid site (PFOlsen, 2016). Fig. 2.2 shows a breaker-out waiting on a slope for hauling cables to be lowered. Once the cables have been lowered, the breaker-out is tasked with

Figure 2.2: Breaker-out waiting for the cables to be lowered

Figure 2.3: Typical cable hauler skid site

attaching the cables to the felled stems. Once the stems are attached, the cable hauler can begin hauling the stems down to the skid site. However, before the cable hauler can begin, all breaker-outs must move to a ‘safe retreat zone’. Whilst a safe retreat zone is a mandatory safety requirement, that is based on many factors such as the height of the trees and the terrain that they are pulling the stems from (Competenz, 2017). A breaker-out in the Gisborne area was recently killed when a stem struck him as it was being hauled to the skid site. A contributing cause of the accident was that a safe retreat distance was inadequately identified as 20 metres, when it should have been the mean tree height of 45m (Herald, 2021).

Another potential accident within the forestry industry involves movement around machines, specifically around the skid site. This is due to the nature of the work, and the size of the machines used to conduct the work needed. Fig. 2.3 shows a typical skid site. It can be hard for the workers to see out of these machines, with many having large blind spots due to the size and type of the equipment (Teizer et al., 2010). This can make moving around them on foot dangerous, and can cause potential accidents.

2.6 Current Safety Protocols

The forestry industry has numerous safety protocols that are designed to help mitigate the risk of accidents occurring. The following are the safety protocols that relate to breaking-out and movement around machines. These protocols have been quoted from the Approved Code of Practice for New Zealand Forestry (MBIE, 2012). In the codes of practice, “Shall” means the instruction is mandatory for compliance with the code. “Should” means that the recommendation be adopted where practicable .

4.1.3: When cutting vegetation with hand tools workers shall be separated by either: a minimum of three metres, or twice the height of the tallest vegetation being cut.

12.2.3: An audible or verbal signal shall precede each major rope movement.

12.2.11: During outhaul all breaker-outs shall be a minimum of 15 metres away from any moving rope.

12.2.12: Breaker-outs shall not be positioned underneath: any moving rope, a mechanical slack-pulling carriage feeding slack, any carriage or butt rigging being raised or lowered during break-out, a tensioned skyline during inhaul or outhaul, operating ropes being shifted by a mobile tail hold.

12.2.13: Breaker-outs shall not enter the hook-on area until: the “stop” signal has been given, the carriage or rigging has stopped moving, swinging strops can be safely controlled.

12.2.18: Service brakes shall be applied when the breaker-outs are under the rigging.

12.2.19: All breaker-outs shall be facing the drag at the safe retreat position before the go-ahead signal is given.

16.3.1: All truck drivers (and if applicable passengers) shall remain in a designated safe area during loading. Designated safe areas include: inside the truck cab, outside the cab forward of the cab guard and on the same side of the truck as the loader, an alternative safe area, e.g., crew shelter. Furthermore, it is recommended that the truck driver stand six metres forward of the cab guard during loading of the truck packet.

16.4.1: The loading zone is deemed to be a minimum of six metres around the truck and trailer. This zone may need to be larger during loading of long logs

Along with these protocols, there is a set of Personal protective Equipment (PPE) that the workers are required to wear to protect themselves from the dangers of the work they are doing (MBIE, 2012).

2.7 Current Safety Solutions

The forestry industry currently has numerous safety solutions in place, alongside the safety protocols above. These range from Personal Protective Equipment (PPE), communication, and technology.

The PPE that the workers wear varies between roles, but generally includes safety helmets, safety boots, high visibility clothing, ear protection, and cut-resistant legwear. The use of PPE has reduced, and in some cases, eliminated certain types of incidents. For example, once high visibility garments were introduced the number of incidents that occurred in the category of 'not seen' were reduced significantly, to the point of elimination. In a study conducted by Sullman et al. (1999) in New Zealand, it is stated that in 1991 there were 10 "not seen" incidents prior to the introduction of the high visibility garments. Once the high visibility garments were introduced and used within the New Zealand Forestry industry, the category of 'not seen' incidents was completely eliminated.

Cut resistant legwear has also been a large contributor to the decrease in injuries. In 1983 cut resistant legwear was introduced to the New Zealand forestry industry. At this time, approximately 29% of all injuries were attributed to chainsaw cuts to the leg. By 1985, the wearing of this legwear was made compulsory for any chainsaw operator in the New Zealand forestry industry. In 1986, the percentage of injuries that were attributed to chainsaw cuts to the legs were reduced to 8% (Sullman et al., 1999).

As well as PPE, clear communication between workers is essential. Communication between ground worker and machine operator is paramount to ensure that the workers all stay safe, such as radioing for a machine operator to cease work and lower the grapple to the ground to ensure that the ground worker can move around the machine safely, or move around the hauler cable. For the breaker-outs, the primary method of this communication is a series of "toots" which the lead breaker-out can control with a handheld device. This allows a Morse code style communication system to the hauler operator. The "toots" are also audible to the entire team of workers on site, which are utilised to also alert the other workers when the hauler is dragging logs in or out (MBIE, 2012).

There is also an increasing amount of technology being used within the forestry industry, with the intention of increasing the safety and wellbeing of the workers. Radio communication and use of cameras and GPS devices in and around machinary has been used to ensure that the terrain and immediate surroundings of the machines is known to the operator (Parker et al., 2020). Man-down systems have been used by workers as an added layer of safety, alerting other workers, a base station, or emergency services when an impact is detected. These are primarily used by lone workers, where there is a singular worker working a large distance away from other workers (Guilbeault-Sauvé et al., 2021).

The PPE worn by forestry workers has improved the safety of the workers since the introduction in 1991. This, alongside the communication between the workers, which has been enhanced with the advancing technology of handheld radios and beepers, and the increasing amount of technology such as man-down systems and devices attached to machines, drastically improves the safety of a forestry worker. I propose that Internet of Things (IoT), which has been adopted by many other industries (see Chapter 3) could be used to improve the safety of forestry workers even further.

2.8 The Internet of Things

This thesis focuses on utilizing Internet of Things (IoT), Radio Frequency (RF), and geofencing technology to improve the safety of workers in the forestry industry. As such, this section introduces IoT, while subsequent sections discuss radio frequency and geofencing.

Internet of Things (IoT) is used to describe a system in which objects in the physical world can be connected to the internet via sensors. Whilst the term "Internet of Things" is relatively new, the practise of connecting computers and network devices to monitor and control devices has been around for many years (Ashton et al., 2009). The architecture of IoT is base on several layers, from data gathering at the bottom, to application layers at the top.

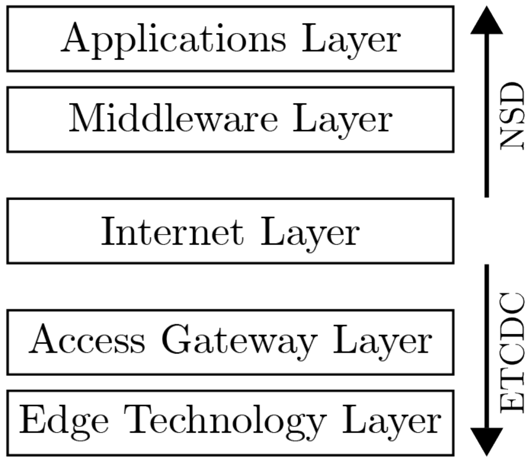


Figure 2.4: The Internet of Things (IoT) stack

This layered approach is designed in such a way that it can meet the requirements of various industries, enterprises, societies, institutes, governments, etc. As shown in Fig. 2.4, the architecture has a clear divide, with each side of the 'Internet Layer' serving a distinct purpose. The bottom two layers contain edge-technology data capture devices (ETCDC), which are responsible for capturing data. The top two layers contain network supported devices (NSD), which are responsible for processing and using the data in applications (Atzori et al., 2010). Below are brief descriptions of each layer's functionality.

Application Layer: the top layer is responsible for the delivery of the data to a suitable application. This is the layer that a user will typically interact with, or receive alerts from, depending on the application.

Middleware Layer: this layer is responsible for the bi-directional interface between the hardware and application layer above. Performing functions including data filtering, data management, access control, device management, and data analysis.

Internet Layer: the middle layer that is responsible for facilitating the communication between the Middleware and Access Gateway layers.

Access Gateway Layer: this layer is responsible for handling the data and publishing and routing the data to the intended destination, with cross-platform communication if required.

Edge Technology Layer: this is primarily the hardware layer of an IoT device. These are typically data sensors used in the field to provide the data for the application.

IoT devices can be characterised as devices that have embedded connectivity, typically to a wireless network, that allow the device to gather, process, or display data in some capacity. This can be used to create ecosystems for applications such as smart homes, smart work environments, e-learning , and smart health (Bandyopadhyay and Sen, 2011).

IoT devices can also include 'IoT edge devices', which typically do minimal processing of the data that is gathered, leaving the processing and analysis to the middleware, and/or applications. This can lead to extending the battery life of an edge device, making the device smaller as the components are not as complex, and therefore cheaper to manufacture as there are not as many components required. In general, an IoT edge device contains three components (Ashton et al., 2009) as outlined below.

Processing Unit: some form of processing unit is used to process the data from the sensors and prepare it to be transmitted on to the upper levels of the IoT stack.

Sensors: as the device is designed to gather data, a sensor must be included in order to gather such data as needed. The sensors used on a specific device can vary depending on what data the unit is designed to gather.

Network Module: each device must connect to a network, whether this is Wi-FI, Bluetooth, Radio Frequency (RF), or wired. A network module allows the device to connect to a network and transmit the data to the rest of the IoT stack.

IoT devices can be as simple or as complex as an application requires. It could be as simple as a temperature sensor feeding data to a dashboard in a residential home, or as complex as a device with multiple sensors monitoring a time-critical process which feeds the data to a service.

2.9 Radio Frequency

Radio Frequency (RF) is often used by IoT devices, as it is a technology that is used to transmit data wirelessly. This is done at various frequencies, depending on the application or situation. RF frequencies that are generally used in data transmission include: High Frequency (HF) which ranges from 3–30 MHz, Very High Frequency (VHF) which ranges from 30–300 MHz, Ultra High Frequency (UHF) which ranges from 300–3,000 MHz, and Super High Frequency (SHF) which ranges from 3–30 GHz (Terasense, 2019). Lower frequency ranges (i.e. HF and VHF) reduce the data rate that the devices can send, but increase the range at which the communication can be received. Higher frequency ranges (UHF and SHF) allow a higher data rate, but consequently less distance and object penetration/avoidance. RF waves typically propagate via line-of-sight, therefore can be blocked by hills, mountains, and buildings. However, they can travel through the walls of a building if the transmitter is powerful enough.

The HF band is used for aviation air-to-ground communication and military and governmental communication systems (Terasense, 2019). The VHF band is used for air navigation systems and some bands within this frequency can be used for amateur radio (Terasense, 2019). The UHF band of frequencies is commonly used for applications such as terrestrial television broadcasting, Wi-Fi, mobile phone communication, Bluetooth, and two-way radios. It is also common to see IoT devices using this frequency band for RF communication. This allows IoT devices to communicate with a network wirelessly, allowing the device to be applied in situations where running cables is not an option. The

SHF band is used for high-speed Wi-FI, and to cook food within a microwave (Terasense, 2019).

Some radio frequency modules can measure the strength of an incoming signal. This is called the Received Signal Strength Indicator (RSSI) and is displayed in decibels (dBm). The closer a signal source, or more powerful the transmitter, the higher the dB rating. The closer to 0 the RSSI is, the better quality the signal (Xu et al., 2010).

2.10 Geofencing

IoT devices often incorporate GPS services and geofencing technology into their solutions. Geofencing is a location-based service in which an application uses the location of a device to trigger an action when it enters, leaves, or idles inside or outside a virtual boundary (Rodriguez Garzon and Deva, 2014). Geofences can be set up using physical boundaries, such as buildings, rivers, restricted areas, and landmarks, or virtual boundaries that are coded into the device. These boundaries are typically stationery and require the user to have a GPS enabled device to track their movement as they travel through the area. The actions that the application triggers tend to be application dependent, and can trigger things such as notifications to the user, notifications to a server, marketing material, alerts to the user, or information about the location they are entering (White, 2017).

Geofencing is typically configured by an administrator or developer as they define the virtual boundary in which they would like to fence (Google, 2021). This can be as simple as a location, longitude and latitude, and a radius, to draw a circular boundary, as shown by Fig. 2.5. These virtual boundaries are often defined within the code of the application on the location-enabled device and users need to opt-in to the location services.

Geofencing has a wide use-case pool, with a wide number of systems and

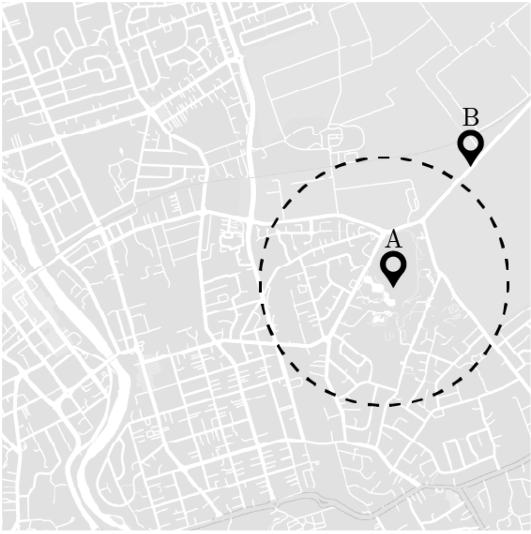


Figure 2.5: Geofenced area with a user inside (A) and a user outside (B)

methods for implementing geofencing services. One such use case involves smartphones, as they have access to a network, wireless or cellular signal, and capability to record a device's GPS location. The uses of geofencing on smartphones is varied. Some companies or enterprises will use the location of the phone to serve marketing content to the user as they get close to a shopfront. Other companies may use specialised hardware to track assets, such as a fleet management system that tracks their vehicles using their geolocation (White, 2017). Geofencing also has great potential for use in health and safety. For example, ensuring workers are notified when entering a potentially hazardous area could mitigate or remove the risk entirely of an incident occurring. The following chapter provides some examples of IoT, radio frequency, and geofencing in hazardous industries.

Chapter 3

Related Work

While IoT for safety in the forestry industry has not been well researched, the use of IoT in other hazardous industries, with an emphasis of worker safety, has been. Mining, oil and gas, and construction are three of the main industries where work has been undertaken to utilise this technology to improve the well-being and safety of their workers. This section first discusses the concept of IoT for safety in forestry. It then outlines, in more detail, IoT solutions that have been applied for safety in mining, oil and gas, construction, and other industries.

3.1 IoT in Forestry

The forestry industry has leveraged IoT technology in numerous ways (Salam, 2020; Bayne et al., 2017; Sahal et al., 2021). However, IoT for safety in forestry has largely been conceptual. Hock et al. (2016) states that there is a use case for IoT in the forestry industry, but none, for safety, have been implemented past the conceptual phase. One concept that was trialled by Zimbelman et al. (2017) used hand-held GPS devices (Garmin Alpha 100 GNSS-RF and Garmin T5 transponders) with tree fellers. The Garmin Alpha 100 units are a handheld Radio Frequency (RF) radio with a screen and GPS capabilities, while the T5 transponders are designed to be worn by dogs. This allowed a mobile geofence to be created around each of the fellers. When these geofences overlapped, an alert was sent to both fellers via the radios alerting them to the fact they were too close. The purpose of the study was to assess the accuracy of these mobile geofences at different angles of approach, as in the application of safety, the accuracy of the detection of overlapping zones is paramount. The study was undertaken using Garmin T5 transponders on the feller, while a number of stationary Alpha 100 units were set out at regular intervals, perpendicular to the direction the feller was walking. The stationary devices could then be used to detect when a geofence of a specific radii intersected with it when the feller got within range. It was found that utilising these devices without the application of a correction method is not advised for fine resolution work areas. However, the uncorrected geofences may be used for coarse geofencing applications (Zimbelman et al., 2017).

Research and development of safety based IoT for the forestry industry is limited. This could be due to the remote nature of the industry, with little to no existing infrastructure and the rugged nature of the work. However, IoT is starting to be adopted in the forestry industry in the form of monitoring technology. These monitoring applications include but are not limited to environment monitoring (Salam, 2020), tree growth monitoring (Bayne et al., 2017), and disaster protection and prevention (Sahal et al., 2021).

3.2 Mining

While IoT has not been adopted much in forestry safety, it has been more commonly researched for usage in the mining industry. This research is primarily based around building technology into a mining helmet, as all workers are required to wear one when in the mine shafts. This ensures that the IoT will be able to benefit the workers the most as it will be with them at all times.

The primary dangers of mining are natural gas, explosions, and mine collapse (Donoghue, 2004). As such, the helmets use gas sensors, the location within the mine shaft, and some form of wireless connectivity to transmit the data from the helmet to a central control station.

One helmet by Roja and Srihari (2018) has a bank of sensors for measuring the air quality, primarily targeting CO and CO^2, and infrared (IR) sensors to detect whether the helmet is being worn. The helmet can then display this data to the worker, or give them an alert when the conditions are too dangerous for safe work to occur. The helmet was designed using an Arduino Uno microcontroller as the main processor, with a MQ6 and MQ7 gas sensor to monitor the air quality, and an IR sensor running across the inside of the helmet, detecting whether it is currently worn. A GSM unit, used to communicate wirelessly using a SIM card, was used as a means for transmitting data from the helmet to another device for data logging. Testing showed that the removal system worked well, as soon as the IR beam was unbroken, the helmet notified the worker via the LCD screen, and an alert is sounded via the buzzer. The gas sensors also worked, showing that it can be fairly easy to integrate a system like this into a mining helmet to detect odorless gasses and alert the worker about them before it becomes a health hazard (Roja and Srihari, 2018).

Another helmet utilised similar air quality sensors, and also used Radio Frequency (RF) technology to locate the workers within the mine using beacons. The helmets also use an LCD screen and audio alarm to display the data to the workers and alert them if the conditions were too dangerous. The RF connectivity of the helmet also allowed it to relay the information back through the mine to a control room module, allowing the display of all the workers information and locations on one screen. The helmet was designed using an AT89C52 microcontroller, a BPV10 fire sensor, a HC02 humidity sensor, a LM35 temperature sensor, a buzzer alarm, and an RF transmitter and receiver for communication between the unit and the control center, and to the localizer units. The localizer units consist of RF transceivers and a smaller microcontroller, allowing the control center to know where a worker is, based on which localizer unit they are closest to. The use of the RF technology in underground mining operations has the high potential to save the lives of miners with the ability to locate them, and/or detect the presence of gasses, fire, humidity, and temperature and display this information in one place (Shabina, 2014).

Hazarika (2016) utilized two gas sensors, an MQ7 and MQ2 are used for sensing CH^4 and CO respectively. The device also includes an X-Bee unit, which allows processing and networking capabilities up to 1000 meters with line-of-sight, and a battery and charging circuit to power the device. The device was designed to be fitted to a mining helmet. This device was configured and used to output the data to a control panel using LabVIEW, created by National Instruments[1]. This shows the states of each device, the gas levels, and whether an alert is being triggered. Another data display was tested using another X-Bee to feed the data received into an Arduino Mega and then to a series of LED's and LCD display. This method is much more cost-effective compared to purchasing a licence for the LabVIEW software. The findings were that detecting an odourless and colourless gas is not easy, but with the right placement of the right hardware, it can be done. Utilisation of a smart helmet for the mining industry would be a useful addition to the current safety equipment (Hazarika, 2016).

[1]National Instruments is an American, multinational company that produces automated test equipment and virtual instrumentation software. Examples of the applications for these are data acquisition, instrument control and machine vision.

3.3 Oil and Gas

In the oil and gas industry, utilisation of monitoring hardware to measure data such as heart rate and stress levels of the workers and the environment in which they are working in is starting to become more widely adopted (Shoker, 2021). It is stated that in an industry such as oil and gas, gas detection is the primary concern, and whilst there are portable gas detectors that are used, if a worker happens to become incapacitated from the gas, then they may not be able to alert anyone, as the gas detectors are local to the worker. This has the implication that while the alert will be heard/seen by the worker, nobody else will be alerted to the gas levels or potentially incapacitated worker in the room.

As an example, Shoker (2021) utilised an IoT system called the Accenture Life Safety Solution, which brings together multiple technologies from various companies allowing the gas sensors to be connected to a central monitoring station. This system uses Wi-Fi to triangulate the location of the workers, and have motion sensors and built-in panic button on the gas sensors (Shoker, 2021).

Another concept for an IoT system for worker safety in the oil and gas industry utilises wearable sensors and a "connected workforce" to ensure that the right decisions can be made about a workers health and safety in the shortest time possible. The proposed system would utilise a heart-rate monitor, toxic gas monitor, non-verbal gesture monitor, and motion sensors to create a "worker black box" that can gather and transmit this data to a hub, ideally in the same place as the worker, to ensure that the response from the system can be as fast as possible. This system would be best utilized in larger workforce's that are deployed remotely (Geng, 2017).

Thibaud et al. (2018) outlines another system that can be used for workers in the oil and gas industries. This system utilizes multiple layers of smart clothing to monitor physiological and environmental variables. Some of these include the heart rate, galvanic skin response, respiration, gas levels, and carry load, alongside an array of vibration disks to alert the worker. The data is gathered via an under-vest, outer jacket, pair of shoes, and a carabiner with embedded hardware to monitor and report the data. The data that is gathered is sent via a mesh network to a dashboard, displaying each of the workers exposure to hazardous chemicals and physiological stats. These can then be monitored and the worker can be alerted if their exposure or physiological signs are approaching an unsafe level.

3.4 Construction

In construction, IoT is being utilised to ensure that workers are safer and more well informed when working in close proximity to heavy machinery. This was explored using RF technology and the strength of the signal assessing the proximity of the worker to the machines. Teizer et al. (2010) used a system where an in-cab device would alert the operator when a worker was too close to the machine. The worker on foot had an arm mounted device which would sound an audible alarm and vibrate when the worker was too close to a machine.

Another concept experimented on by Teizer (2015) was a device called the SMARTHAT (Self-Monitoring Alert and Reporting Technology for Hazard Avoidance and Training), which used a high-power RF antenna mounted on a machine, with a hard hat mounted passive device. This passive device would be powered when a worker wearing it had come too close to the machine, being powered by the RF waves from the antenna. This would then cause an audible alarm to be triggered on the hard hat and an in-cab device hooked up to the antenna. The hard hat would also send data to the antenna for data logging purposes (Teizer, 2015).

Kanan et al. (2018) also utilized radio frequency in their system to reduce the incident number in the construction industry. This system consisted of a wearable radio frequency device, and an array of directional radio frequency antenna and ultrasound distance sensors, mounted to the rear of a truck or machine. This would then service alerts to workers that are too close to the rear of the truck or machine when it is moving backwards. A secondary use case outlined for this system was to attach radio frequency modules to areas where a worker is likely to fall over, such as the edge of a hole or building. This then alerts the worker when they come close to the edge, ensuring they know they are approaching the edge, and therefore reducing the risk of them falling. Multiple tests were conducted to demonstrate the system's feasibility and effectiveness. The results show that the system reduces the risk of construction site accidents with low capital and operational costs

3.5 IoT in Other Industries

Majority of this chapter focuses on IoT for safety in industries with similar hazard risks to forestry (mining, oil and gas, and construction). However, they are not the only industries utilising IoT for safety. Suyama and Inoue (2016), for example, have developed a system to service alerts and information to people in certain areas prior to or after a natural disaster by dividing a city or area into separate zones. This allows each zone to get relevant alerts and information faster and easier. This was implemented using iOS and the Core Location framework as part of the Apple ecosystem. An example that is used is a zone that is prone to flooding. In this case, a user can be alerted when entering the zone, and be notified that it is a high risk flood area. During evaluation, the geofence used was only 100m in diameter and circular. In the real use case, the area would be several kilometers in length, which would require more testing. During small scale testing, the activation and de-activation zones were shown to be outside of the defined zones by 20-30m, which is fine for this application as it is serving alerts prior to the user fully entering the zone (Suyama and Inoue, 2016).

Fleet management is another application where IoT is being used to monitor the health of a vehicle and track the vehicle for security. Penna et al. (2017) created a fleet monitoring system that tracks the fuel level and distance travelled. This allowed them to maximize the fuel mileage of the vehicle in a cost-effective manner. The in-car system consisted of a fuel level sensor, GPS odometer, Arduino Uno, and a GSM-SIM900A Modem for communicating with the cloud database. A website was built to display the fuel usage of the car in the last 5 minutes, alongside the distance travelled in the last 5 minutes. This can be used to monitor the fuel consumption of the vehicles in the fleet and restrict the chance that a driver will siphon fuel from the vehicle. Future work for the system consists of utilizing RFID to identify each driver and an alcohol sensor to ensure the safety of the driver.

Farming is another area that could benefit from IoT. An IoT and geofencing solution was developed for tracking livestock on a farm. The solution used ultrasonic sensors setup at a predetermined boundary, where there was nothing stopping the livestock from leaving. These sensors would then alert the farmer when the livestock were approaching the boundary. Once they had exceeded the boundary, the livestock could be tracked via GPS tags on the animals themselves. The farmer then has an easier job to locate and retrieve the livestock if they have left the area in which they were meant to be (Ilyas and Ahmad, 2020).

Finally, a paper written by Yang et al. (2016) outlines many uses for IoT in the manufacturing industry. Some of their suggestions include: (1) utilizing IoT to streamline processes and automate workflows to optimize the time used, (2) the proactive maintenance of machines – using IoT to monitor and diagnose issues before they occur, and (3) leveraging IoT to reduce the amount of energy used – monitoring on a finer scale than is possible manually.

The use of IoT and geofencing can be, and is currently being used to keep workers safer in other hazardous industries. However, the forestry industry has several additional challenges. For example, a mining site contains large fixed infrastructure which can be leveraged to implement IoT solutions, and a construction site is typically a fixed area with access to electricity and an internet connection. Farming may appear to have less fixed infrastructure to leverage, but the area that is being farmed and monitored is fixed. What makes forestry a more challenging domain is the remote and dynamic work-sites, with little to no permanent infrastructure. Nevertheless, I propose that similar technology, with additional considerations, can be applied to situations in the forestry industry, adding an additional layer of safety to the workers. The remainder of this thesis introduces and outlines an IoT solution for forestry, leveraging GPS and communication technology to keep forestry workers safe.

Chapter 4

Design

There are many situations in the forestry harvesting process that would benefit from an IoT safety solution, but the one that is focused on in this thesis is 'breaking-out'. Breaking-out involves a worker or team of workers fastening a choker to the stems in a cable yarding extraction team. Breaking-out was selected as it is one of the most dangerous roles within the harvesting operation.

The devices that are outlined in this thesis have been designed to add an extra layer of safety for breaker-outs. Two devices have been created, one for the breaker out to carry that can track them, and one for the hauler cab to show the operator the location of the breaker-out. This can then alert the operator when the breaker-out is too close to the cables for them to be moved in or out. This chapter first outlines the current procedure around breaking-out. It then outlines the requirements and design features that were considered during the development of the safety devices.

4.1 Problem Scenario

As discussed in Section 2.5, breaking-out is the process of removing logs from where they were felled, and moving them to a skid site for processing. An example of this can be seen in Fig. 4.1. This figure shows two workers called

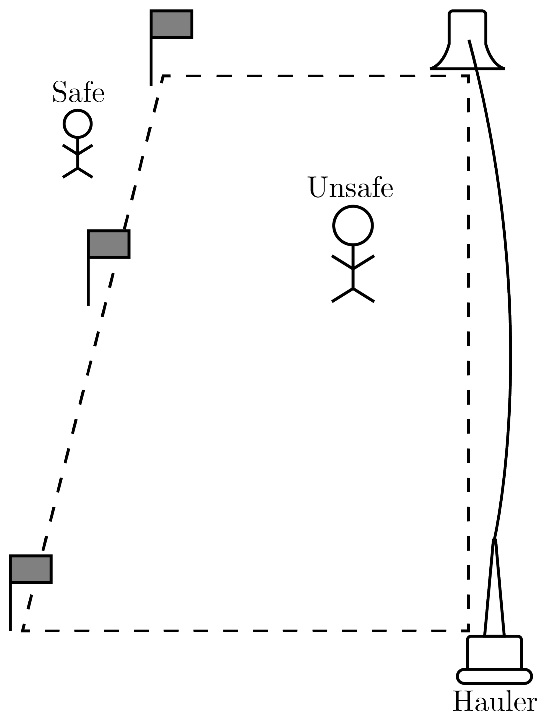


Figure 4.1: Diagram of current system

breaker-outs. Fig. 4.1 shows the hauler in the bottom right, and the tailhold in the top right, with a cable running between them. The breaker-out will attach the fallen stems to a cable that runs from the hauler to the tailhold. The stems are connected by the breaker-out wrapping a cable around the stem and attaching it with a choker. Once the stems have been attached, the breaker-outs must retreat outside of the ‘danger zone’, to a safe distance, typically two times the average height of the trees. Fig. 4.1 shows the danger zone as a dotted rectangle. Shown on the left-hand side of Fig. 4.1, the edge of the ‘danger zone’ is marked with high-visibility flags placed in the ground, with the left of the flags being safe. Once all breaker-outs have retreated outside of the ‘danger zone’, the stems are then hauled to the skid site, and the cable is returned to the area where the breaker-outs can attach more stems. For the duration of the hauler moving the cables, the breaker-outs must stay beyond the safe retreat line, i.e. to the left of the flags, outside of the danger zone.

4.2 Design Requirements

Before an IoT safety solution can be built, the system needs to be designed and a set of requirements must be outlined. These requirements are broken down into two broad categories: technical requirements, and usability requirements. Technical requirements define the specifications that the system must meet in order to be considered viable. Usability requirements define the users requirements of the system, in terms of size, interfacing and alerts. These requirements were sourced through talking with an industry expert. The industry expert has over 10 years experience in the forestry industry, manages a group of up to 15 workers, and currently employs people in the forestry industry.

4.2.1 Technical Requirements

Typically forestry work is undertaken in remote areas of New Zealand. This can pose many challenges as there is little to no existing infrastructure to utilize for IoT. This introduces a set of unique requirements around wireless communication, battery life, and durability. As such, the following requirements relate to the hardware and technical aspects of the device(s).

- **Accuracy:** as advised by the industry expert, the device(s) positional accuracy must be within 5m of the actual location.
- **Range:** the device(s) need to be able to transmit data across a distance of at least 500m, with an ideal transmission distance of 800m as this is the maximum distance a cable hauler would likely run a cable.
- **Reliability:** the device(s) must be able to update their location at least once every 5 seconds to ensure that there is an up-to-date location of the breaker-out at all times.
- **Battery Life:** the device(s) must be able to function fully for at least 12 hours on a single charge. This reflects the operating time required on

a long working day.

- **Charging Time:** the device(s) must be able to charge fully overnight for use the next day. Therefore the charge time must be less than 8 hours.
- **Durability:** the device(s) must be durable enough to withstand being worn/carried by a breaker-out.

4.2.2 Usability Requirements

The following requirements relate to the workers experience with the device(s).

- **Ease of Use:** the setup and use of the system must be as streamlined and easy as possible..

- **Size:** the device(s) must be small enough to fit comfortably inside a pouch or backpack that is carried by a worker.

- **Notifications:** the device(s) must be able to alert the respective worker to the danger or potential danger they or another worker in their area are in. The alert option used must be able to alert the worker without becoming a hazard itself, and also be able to be recognised in a loud environment[1].

4.3 Proposed Solutions

Two concepts were generated to meet the requirements stated in Section 4.2. These concepts utilize IoT to create a system that mitigates the risk of incidents for breaker-outs.

[1]Here, it should be noted that, as part of the 'notifications' design requirement, the notifications must not become a hazard themselves. As such, it was decided that notifications would not be continuously sent while the worker was within the geofenced area. When in a forestry setting, the breaker-outs would spend up to 10 minutes within the geofenced area to attach the stems to the cables, and constant notifications could become an issue.

4.3.1 Concept 1: RSSI Location Tracking

The first proposed concept uses Received Signal Strength Indicator (RSSI)[2] values from multiple nodes to allow the wearable device to be tracked. This requires the development of a carried unit and multiple nodes to allow the tracking of the carried unit around the work area. These nodes will be placed on the breaker-outs flags so that a zone can be created that can be used as a "danger zone". This can be achieved without any outside network, therefore can be used in a remote location. An in-cab device will also need to be created, with a screen to show the hauler operator where the breaker-out is in relation to the zone. The screen would also display alerts when the breaker-outs are not at a safe retreat distance.

There are both benefits and potential downsides to this concept. The use of RSSI would allow a signal to be relayed up the chain of flags to the cab. This would give the hauler driver the information as reliably as possible. These devices would also be small and lightweight as they would be composed of an Arduino or similar Microcontroller, a radio, and a battery to power the units. It would be easy to fit this into a small form factor that would fit a wearable well.

In contrast, using RSSI also means that a definitive location is not used, just the relative distances to each of the flags. This may be less accurate than a GPS or another method that has a definitive location for the breaker-out. This design also has many moving parts. It would require radios on each of the flags, on the breaker-outs, and on the cab (for the hauler driver to receive the positions of the breaker-outs). As such, this concept would require significant setup and maintenance to ensure that it is working correctly.

[2]See Chapter 2 for more information about this.

4.3.2 Concept 2: GPS Location Tracking

The second proposed concept uses a GPS tracking device to gain a longitude and latitude of the breaker-out. The location data can then be sent via a radio frequency (RF) module to a base station device located within the cab of the hauler. The breaker-out will be required to use a button on the device to ‘set’ where the flags are as a safe retreat zone. The base station will then use these points to generate a geofenced zone around the hauler cables across to the safe retreat zone flags. The base station device will then show the operator where the breaker-outs are in relation to the hauler and the zone created by the breaker-out. This concept utilizes RF technology, which does not require network connection, and therefore would be able to function in a remote location, such as a forestry situation.

Again, this concept has both positive and negative features. First, it only requires two main devices: the device in the cab of the hauler, and the device that is on the breaker-outs. This reduces the number of devices needed and therefore the number of devices that can malfunction or cause issues. It also requires relatively low setup. The breaker-outs would need to set the flags in the morning, and then alter them if they move them during the day. However, this would require minimal additional work, with the breaker-outs only needing to push a button.

The use of GPS also has positives and negatives. In comparison to the RSSI concept above, GPS allows the exact locations to be used, rather than a relative position to the flags. This allows the base station device in the hauler cab to show the actual position of the breaker-outs. However, the devices will consume more power in doing so. This means that a larger battery, or shorter battery life, will be required. The device size will also increase if there is a larger battery.

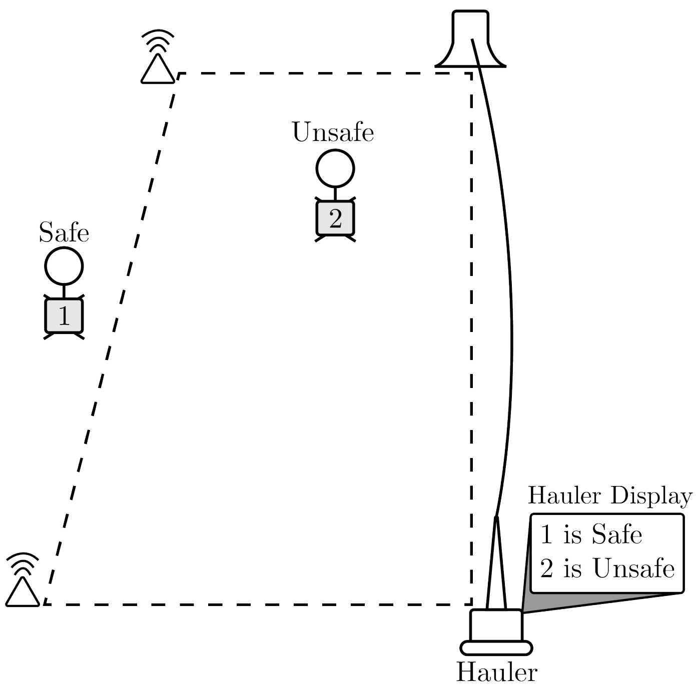


Figure 4.2: Diagram of proposed system

4.4 Selected Concept

From the two concepts above, the second concept is the one that was chosen for this project. This was chosen as it gives a more accurate and definitive position for the breaker-outs and the safe retreat zone flags. For this project the accuracy is one of the top priorities as it is being used to assist decisions that could impact a worker's safety. Using the longitude and latitude of the worker also allows this system to be scaled up to include multiple geofences for multiple zones site-wide. This would allows the system to be used for various applications, such as proximity sensing around large machines, and ensuring all workers are safe around the skid site.

This system uses two separate units, one that will be carried by the breaker-out (i.e. the carried unit), and one that will be installed in the cab of the hauler (i.e. the in-cab unit). The carried unit uses GPS to locate itself, and radio frequency to send the location data to the in-cab unit. The in-cab unit uses radio frequency to receive the location data from the carried unit, and to send

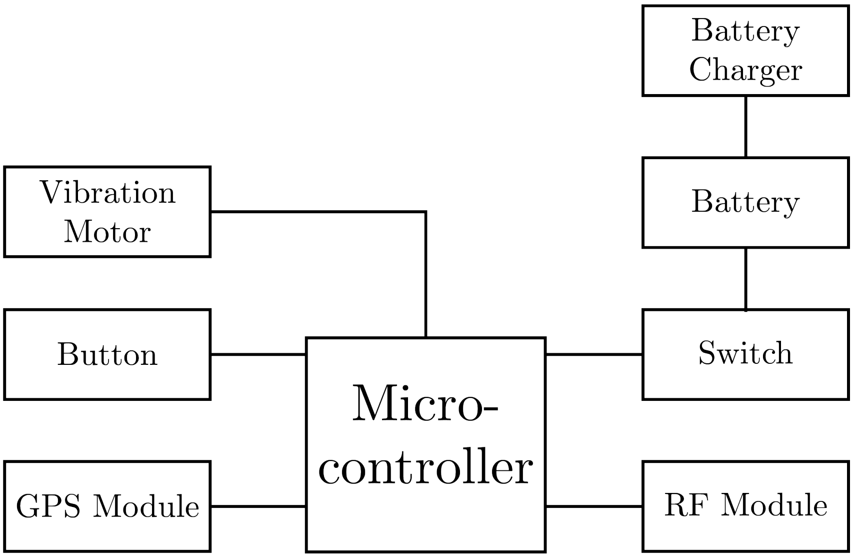


Figure 4.3: System design diagram for the carried device

alerts to the carried unit when applicable. The in-cab unit also uses GPS to locate itself to assist in the creation of a geofenced area that can be considered a danger zone.

Fig. 4.2 illustrates how the system works. The geofenced area is set up by the breaker-outs. They use the carried units to set virtual flags where the top and bottom physical flags are located, shown on the left-hand side of Fig. 4.2. This then generates a geofenced area between the flags and the cable of the hauler, designated as a 'danger zone', shown by the dotted rectangle in Fig. 4.2. The in-cab unit then checks, each time a carried unit's location data is received, whether the unit is inside the 'danger zone' or outside of it. This then updates the status of each carried unit, shown in the bottom right of Fig. 4.2.

4.5 System Design

Based on the selected concept above, the system is comprised of two devices: the carried unit, and the in-cab unit. The carried unit transmits the location of the breaker-out to the in-cab unit. The in-cab unit allows the operator to

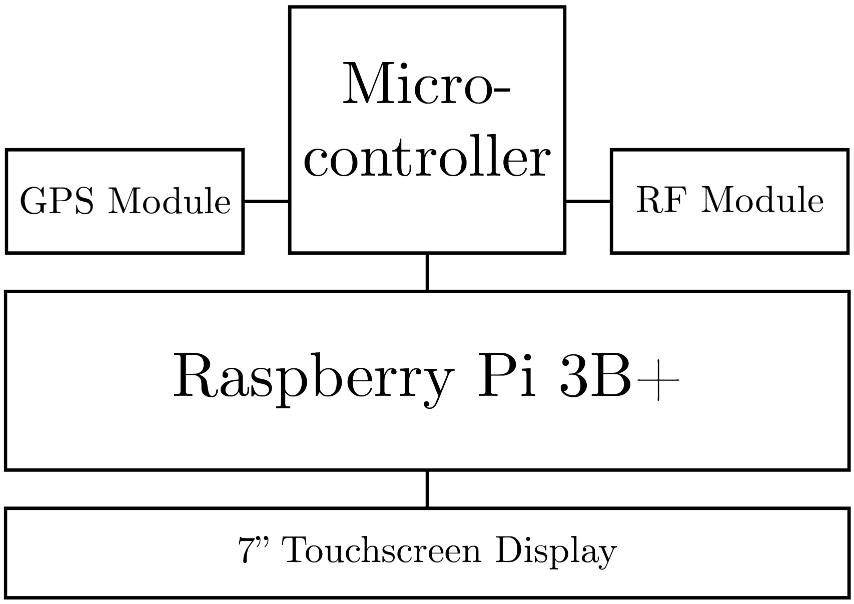


Figure 4.4: System design diagram for the in-cab device

see where the breaker-outs are and show the operator when the breaker-outs are in an unsafe area.

As seen in Fig. 4.3, the device the breaker-outs carry is comprised of:

- a microcontroller to process the data and prepare it for transmission.
- a GPS module to get the location of the worker.
- an RF module to send and receive data from the in-cab device.
- a battery to power the device.
- a battery charger to charge the battery between uses.
- a button to allow the device to signal that it is setting a flag.
- a vibration motor to provide feedback to the breaker-out.
- a power switch to turn the device on and off.

The in-cab device is comprised of similar components as it utilises the same microprocessor, GPS module and RF module, allowing the device to know it's own position geographically, as well as send and receive data from the breaker-out's devices. This can then send the data to a Raspberry Pi with a screen attached via USB cable to display the data to the hauler operator.

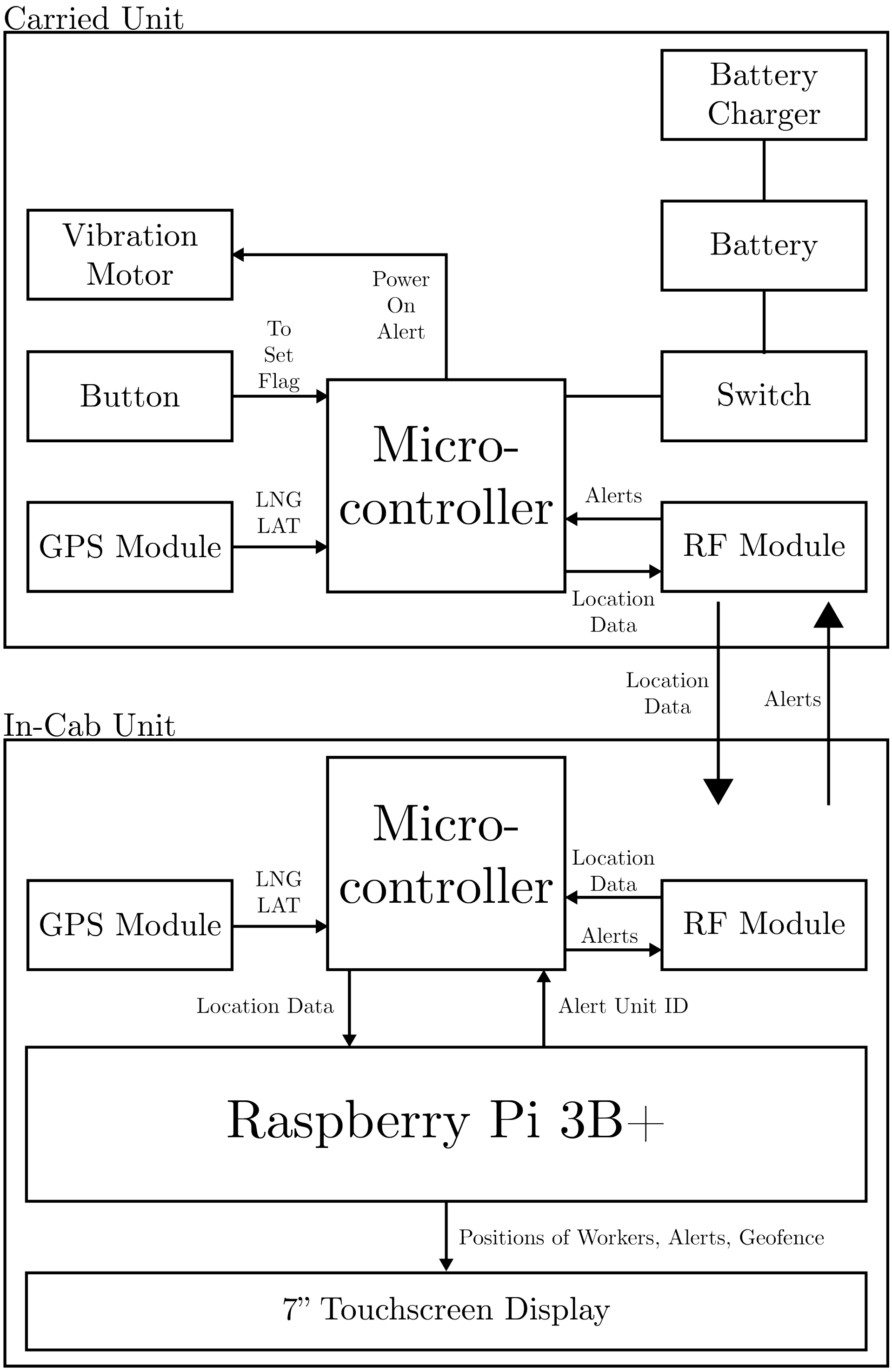


Figure 4.5: Data flow diagram

As seen in Fig. 4.4, the device in the cab of the hauler is comprised of:

- a microcontroller to relay the data to the Raspberry Pi 3B+.
- a GPS module to get the location of the hauler.
- an RF module to send and receive data from the carried unit.
- a Raspberry Pi 3B+ to process the incoming data and perform the geofencing calculations.
- 7" touchscreen display to display the geofence and carried unit locations to the hauler operator.

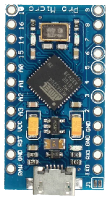
Fig. 4.5 shows the flow of data within the carried unit, within the in-cab unit, and between the two. The data flow of the system is bi-directional. The carried units send location data to the in-cab unit and, when applicable, the in-cab device sends an alert to the breaker-outs when they are not behind the safe retreat line.

4.6 Hardware Selection

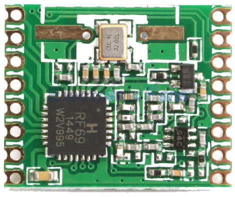
To build the system, a selection of hardware is needed for the in-cab and carried units. As the system will not be mandatory for industry, it is reasonable to assume that the lower the cost of the system, the more likely the forestry industry would be to adopt it. As such, the cost of individual components has been taken into consideration when selecting the hardware. This section outlines the specific hardware that has been chosen for this implementation. The individual components listed below can be seen in Fig. 4.6.

Microprocessor The microprocessor used by both the carried and in-cab units, shown in Fig. 4.3 and Fig. 4.4, is an Arduino Pro Micro.[3]. This was chosen due to it's small size, low power consumption, number of inputs and outputs, and compatibility with other hardware that will be used. This is also

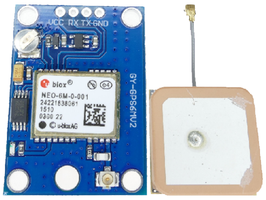
[3]https://www.mindkits.co.nz/store/p/8728-Pro-Micro-3V3-8MHz.aspx or similar



(a) Arduino Pro Micro



(b) RFM69HW Radio Frequency Module



(c) Ublox Neo-6M GPS Module

(d) 2000mAh 3.7v Li-Po Battery

Figure 4.6: Primary hardware used in the GPS tracking device

a well documented platform for basing IoT devices on, and consequently has a large pool of documentation, which will make creating and troubleshooting much easier.

GPS Unit The GPS unit used in the carried unit and in-cab unit, shown in Fig. 4.3 and Fig. 4.4, is an Ublox NEO-6M GPS module with a puck style antenna,[4] shown in 4.6. This is a simple GPS module with a small footprint and the ability to save the most recent location for "hot-start" GPS lock time of 1-5 seconds.

Radio Frequency Module The radio frequency module that was selected is an RFM69HW-868S2.[5] This module is very small and has a line-of-sight transmission range of up-to 1km. This module runs on the frequency band 868MHz, with a power of up to -120dBm, providing a range that meets the requirements in 4.2.1. This RF transceiver also has the ability to obtain RSSI readings each time data is sent between devices, with the inclusion of acknowledgements to ensure data is received and encryption options to ensure the data

[4]https://surplustronics.co.nz/products/7255-gps-module-for-arduino-with-antenna

[5]https://nz.element14.com/hoperf/rfm69hw-868s2/ism-transceiver-868mhz-fsk-ook/dp/2759293

is only read by the intended recipients.

Battery A battery is required on the GPS tracking units which the breaker-outs would be carrying to power the device. This was selected after power consumption calculations were completed to ensure the battery life on the device would meet the requirements. The formula to calculate battery size is as follows.

$$BatterySize = \frac{100 \times CurrentDraw \times RequiredDuration}{100 - RemainingCharge}$$

where *CurrentDraw* is the current drawn from the battery in amperes, *RequiredDuration* is the required powerd on duration in hours, and *RemainingCharge* is the remaining charge in the battery when the time is up. Based on the measurement of the device while powered on, and the duration that the device needs to run for, by inputting the *CurrentDraw* as 0.158, *RequiredDuration* as 12, and *RemainingCharge* as 0, the resulting calculation is as follows.

$$BatterySize = \frac{100 \times 0.158 \times 12}{100 - 0}$$

This calculation results in a battery size of 1.896Ah, therefore a 2000mAh battery[6] will meet the requirements and is also small enough if a flat form-factor battery is chosen.

[6] https://www.phoenix-tech.co.nz/products/lipo-3-7v-2000mah-slab

Chapter 5

Implementation

The previous chapter outlined the design of two IoT devices: a carried unit and an in-cab unit. This chapter outlines the implementation of these devices, including the assembly of the hardware, the design of custom built cases, and the development of the software on each device.

5.1 Carried unit

First, as mentioned in Chapter 4, the carried unit will be carried by the breaker-out. It will use a GPS module to locate itself and a radio frequency module to transmit the location to the in-cab device. It also has a button to enable the breaker-out to configure a geofence around the 'danger zone'.

5.1.1 Hardware

Fig. 5.1 shows the completed carried unit. The carried unit contains a micro-controller, a GPS module, a radio frequency module, a battery charger module, a momentary push button, a power switch, and a battery. The specific components are outlined in more detail in Chapter 4 and are as follows.

- Micro-controller: Arduino Pro Micro

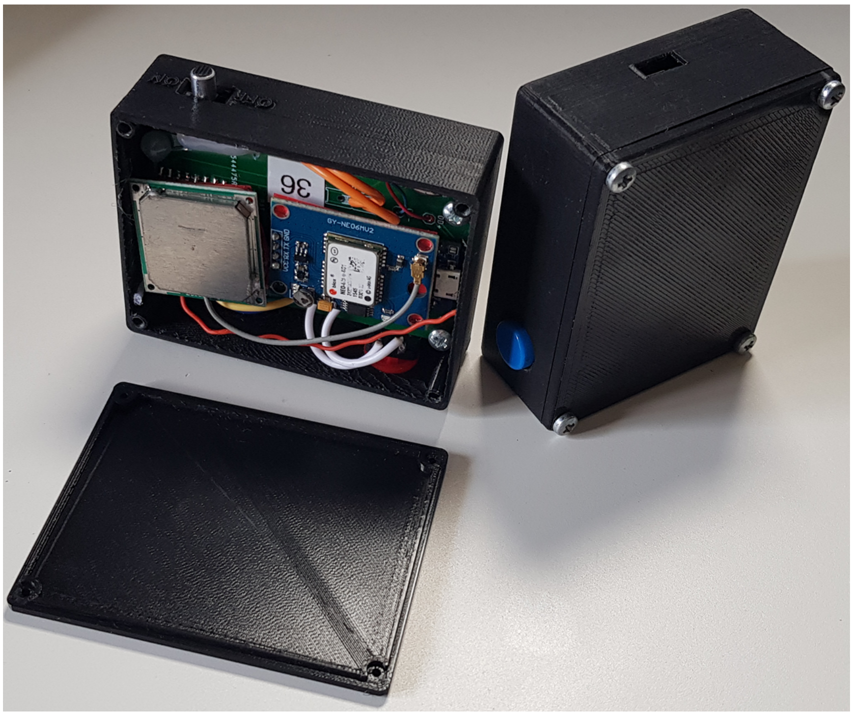


Figure 5.1: Completed carried unit

- Radio frequency module: RFM69HW RF module
- GPS module: Ublox NEO-6M
- Battery charger module: 5V 1A TP4056 lithium battery charger
- Button: Momentary push button
- Power switch: SP/DT switch
- Battery: 2000mAh 3.7v Li-Po battery

A custom Printed Circuit Board (PCB) was developed in order to mount all of the hardware components. The PCB was designed in Autodesk EAGLE, allowing the importation of all of the components' footprints from the respective manufacturers. This ensured that all of the pin placements would match the hardware. The design seen in Fig. 5.2 shows the PCB with the Arduino Pro Micro, RFM69HW RF module, a header for the Ublox Neo-6M GPS module, power pins for the battery charger and through-holes to mount a power switch, button, and alert device.

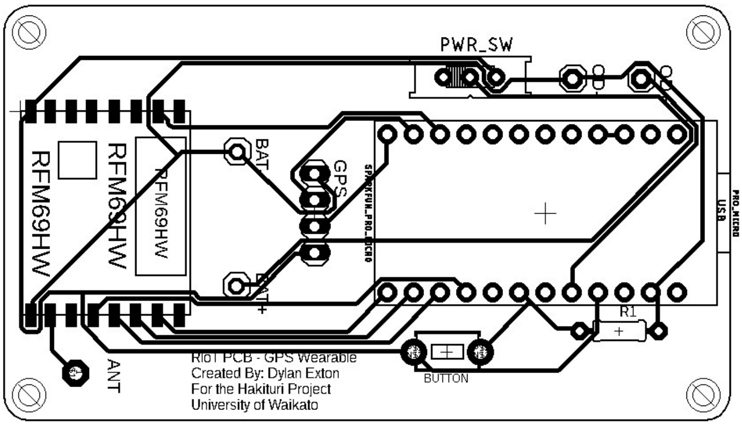


Figure 5.2: Circuit board schematic

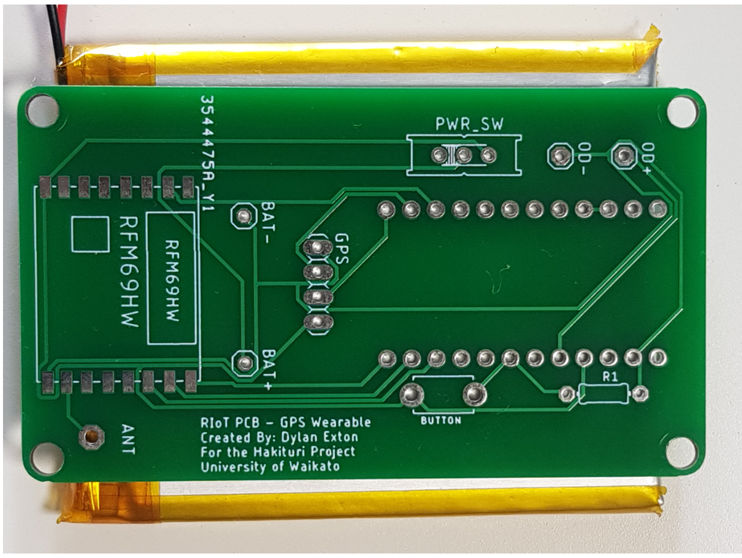


Figure 5.3: PCB shown over the battery

The PCB is approximately 70mm long by 40mm wide. Its size was decided by the dimensions of the battery chosen, as it was the largest component. The PCB and battery can be seen in Fig. 5.3. This shows that the PCB overhangs the battery enough to provide mounting points for it to mount to the case without making the form factor too large, as the carried unit must be able to be easily carried by a breaker-out.

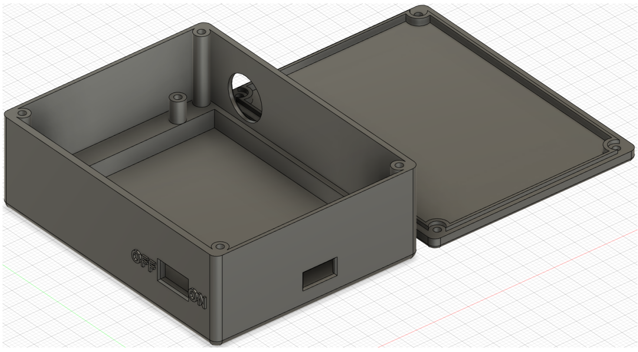


Figure 5.4: 3D model of carried unit case

Figure 5.5: 3D printed case for the carried unit

5.1.2 Custom Casing

A custom case was designed and 3D printed for both the carried unit and in-cab unit. The cases were designed in Autodesk Fusion 360, a 3D modelling software application that allows the creation of a 3D model, with an emphasis on 3D printable models.

The measurement of the assembled carried-unit hardware was used to determine the dimensions for the custom built case. Fig. 5.4 shows a sample of the schematics exported from Autodesk Fusion 360, while Fig. 5.5 shows the printed case. The case is approximately 30mm high, 75mm wide, and 60mm deep. It has three external openings: one for the charger, one for the button, and one for the power switch.

By using the measurement of the device to determine the measurement of the case, I was able to ensure the case would fit snugly around the device, while still providing as much protection as possible from the environment. This allowed the case to be as small as possible, to ensure the device could be easily carried by a breaker-out.

The number of external openings was also kept to a minimum. Breaker-outs tend to work in or around wet or dusty areas, which could potentially compromise the electronics in the unit and cause it to stop working. Limiting the number of external opening mitigates this risk, while also allowing the device to be as simple as possible. The workers only have two interaction points: the power switch, and the button for setting the geofence 'flags'. This simplicity helps ensure the breaker-outs are not distracted by the device.

Finally, the case also features four standoffs for the PCB to be screwed into. This helps to ensure that the device does not move around in the case. The lid is also secured with four screws, ensuring that the lid will not come loose whilst the device is carried around.

5.1.3 Software

The software running on the carried unit was written in Arduino C. Arduino C was chosen because it includes libraries that can interface with other hardware that the device is connected to. The carried unit's primary purpose is to gather it's geolocation in the form of longitude and latitude, and send that data along with the time, for logging purposes, to the in-cab unit. The secondary purpose of the unit is to receive alerts from the in-cab unit when the unit is located within a defined geofence. The GPS module outputs National Marine Electronics Association (NMEA) sentences. This is a standard message format for almost all GPS receivers and consists of formatted data lines, called sentences, which can be seen in Coding Example 5.1. These sentences

Coding Example 5.1: Example NMEA sentences

```
$GPRMC,152926,V,6027.8259,N,025.6713,E,10.8,0.0,1903,5.9,E,S*22
$GPRMB,V,,,,,,,,,,,,A,S*0E
$GPGGA,152926,6027.829,N,025.673,E,8,09,2.0,4.7,M,20.6,M*79
$GPGSA,A,3,07,08,09,11,18,23,26,28,29,,,,6.6,2.0,3.0*38
$GPGSV,3,1,09,07,29,18,44,08,22,09,42,09,30,23,44,11,07,07,3*75
$GPGSV,3,2,09,18,28,35,43,23,14,30,39,26,64,22,49,28,60,04,4*7E
$GPGSV,3,3,09,29,52,187,4*4E
$GPGLL,6027.8259,N,02225.6713,E,152926,V,S*48
$GPBOD,,T,,M,,*47
$PGRME,15.0,M,22.5,M,15.0,M*1B
$PGRMZ,147,f,3*19
$GPRTE,1,1,c,*37
$GPRMC,15228,V,6027.8319,N,025.6713,E,10.8,0.0,1903,5.9,E,S*29
```

Coding Example 5.2: Example data stream sent from the carried unit

```
22:20:03,0,-37.784569,175.30647,204
22:20:05,0,-37.784569,175.30647,345
22:20:07,0,-37.78458,175.30647,345
22:20:09,0,-37.784584,175.30647,345
22:20:11,0,-37.78458,175.30649,345
22:20:13,0,-37.784584,175.30649,345
22:20:17,0,-37.784607,175.30647,204
22:20:24,0,-37.784527,175.30652,345
```

are updated once every second by default on the Ublox Neo-6M GPS module, and are comma separated, to allow for easier parsing by microcontrollers. Utilizing the TinyGPS++ software library, the longitude, latitude, and time can easily be extracted from these sentences and used elsewhere in the software.

These sentences are gathered at a rate of once a second, and then parsed to extract the latitude, longitude, positional accuracy and time. These values along with the status of the button on the unit, with 1 being button held down and 0 being button released, are joined in a comma separated string in the format <*time, button state, latitude, longitude, accuracy*>, seen in Coding Example 5.2. This string is then converted into a byte format as this is the format the RFM69HW RF module requires the data it transmits to be in. This byte packet is then sent via the RF module to the in-cab unit. The library that interfaces with the radio frequency module also prepends the message

Coding Example 5.3: The notification activation on the carried unit

```
if (radio.receiveDone()) {
        digitalWrite(21, HIGH);
        delay(300);
        digitalWrite(21, LOW);
      }
```

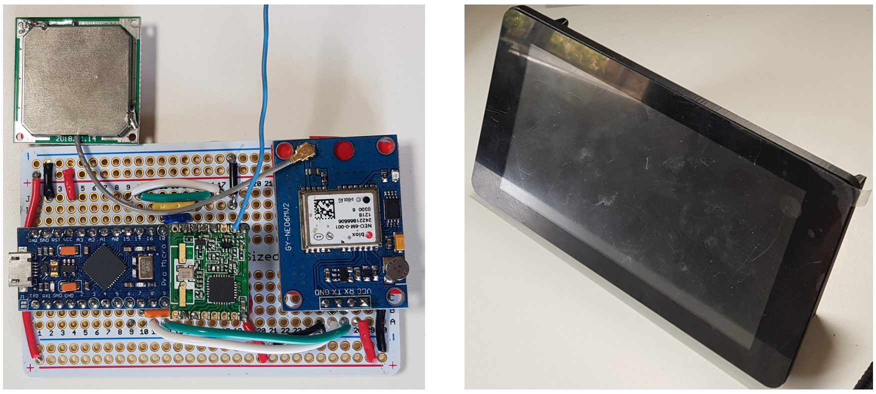
with the unit ID, thus allowing the receiving unit to identify which unit has sent the data. The unit ID is manually set for each unit, and is explained in more detail below.

When a breaker-out is setting a flag, feedback is required to notify the breaker-out that the flag has been set. Therefore the carried unit must also be able to receive messages from the in-cab unit. When the carried unit receives a message from the in-cab unit via RF, the unit will service the message as a notification, and consequently activate the notification device attached to one of the Arduino's Pins. As shown in Coding Example 5.3, this alert consists of a 300ms vibration caused by the vibration motor in the case.

Prior to the device beginning transmission, the RF module in each unit needs to be configured in order to transmit data to the correct unit. This is done by setting a network ID for the unit, a unit ID, and the destination unit ID for a unit on the same network. These are configured for the carried units to have their own unique unit ID, and destination ID of the in-cab unit. Another feature of the RF module is the ability to encrypt the data being sent, therefore if there were any malicious entities trying to gain access to the data, there would be an added level of security. The encryption uses a 16-byte key, defined by the user, and uses the AES encryption method.

5.2 In-cab unit

The in-cab unit consists of a receiver unit and a Raspberry Pi with display. The in-cab unit will be mounted in the hauler cab and receive the location data



(a) Receiver unit (b) Main unit

Figure 5.6: Complete in-cab unit

from the carried units. This data will then be shown on the display, showing the hauler operator where the breaker-outs are located. The geofence that the breaker-outs can configure with the carried units will also be calculated and generated on this unit, showing the machine operator whether a breaker-out is within the 'danger zone' or whether they are safe.

The in-cab unit is comprised of a receiver unit and a main unit. The receiver unit sends the location data of itself and the carried unit(s), via serial communication, to a Raspberry Pi with an attached 7" touchscreen display (the main unit). This allows the hauler operator to see a plot of where the hauler and breaker-out(s) are as the data is received, and to utilize the Raspberry Pi's processing power to perform manual geofencing, as described in Section 5.2.4.

5.2.1 Hardware

The hardware created for both the carried and in-cab units are very similar, due to both units requiring Radio Frequency (RF) connectivity and GPS location.

Fig. 5.6 shows the in-cab unit. The in-cab unit is comprised of two smaller units: a receiver unit (Fig. 5.6 left), and the main unit (Fig. 5.6 right). The receiver unit receives data from the carried unit and sends it to the main unit.

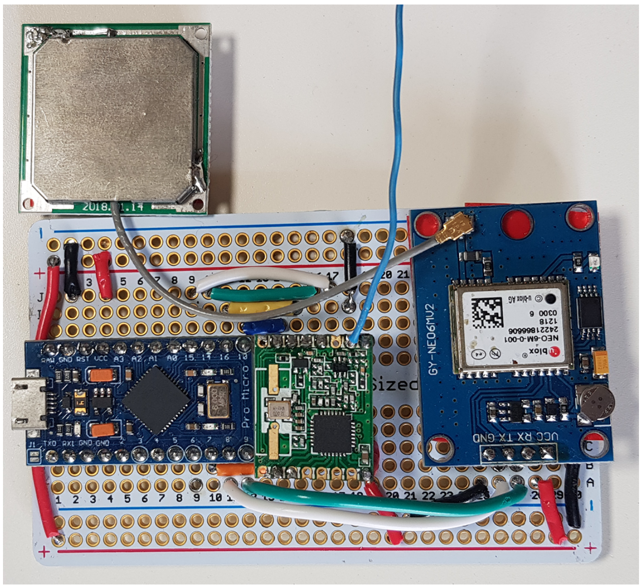


Figure 5.7: Prototype receiver board

It uses a micro-controller, a GPS module, and a radio frequency module. The specific components are outlined in more detail in Chapter 4 and are as follows.

- Micro-controller: Arduino Pro Micro
- Radio frequency module: RFM69HW RF module
- GPS module: Ublox NEO-6M

The main unit is comprised of a Raspberry Pi 3B+ and a touchscreen display. The receiver unit is connected to the main unit via USB. Again, the specific components are outlined in more detail in Chapter 4 and are as follows.

- Processor: Raspberry Pi 3B+
- Display: Raspberry Pi Official 7” Touch Screen Display

Like the carried unit, the in-cab unit could also have been mounted to a PCB. However, in the interest of time, the in-cab unit utilized a prototype board which included the necessary components to be plugged into another device in the cab. The prototype board, shown in Fig. 5.7, contains the GPS, RF module and Arduino to process the data, which is then sent via serial over

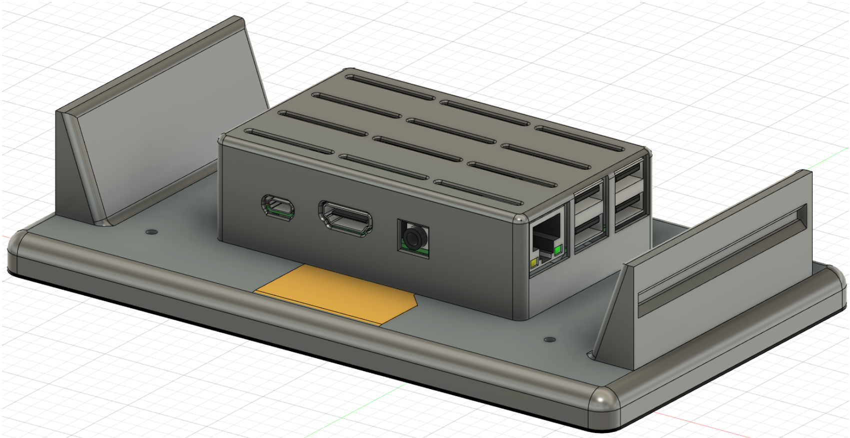


Figure 5.8: 3D model of the in-cab unit's case

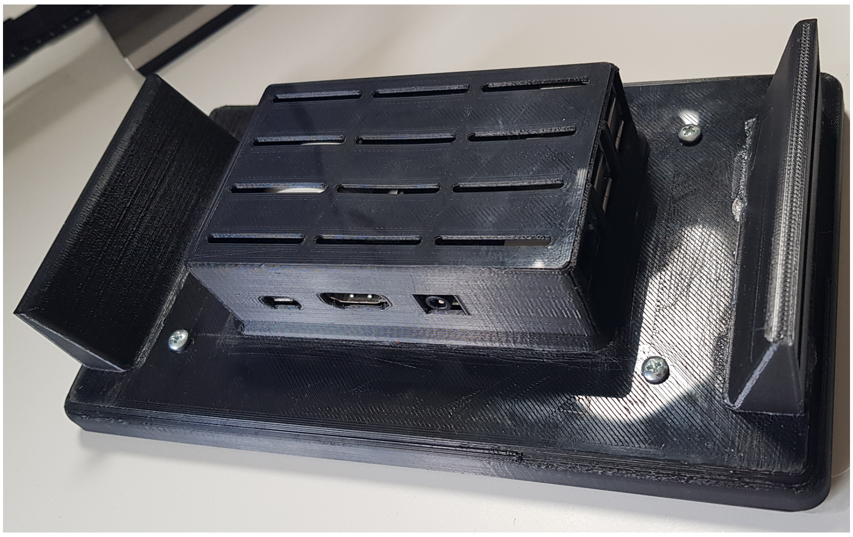


Figure 5.9: 3D printed in-cab unit case

USB cable to a Raspberry Pi 3B+ to be further processed and displayed to the hauler operator. As the in-cab unit did not have to be as robust as the carried unit, using the prototype board was sufficient for this stage in development.

5.2.2 Custom Casing

As already mentioned, the cases for both the carried and in-cab units were designed in Autodesk Fusion 360. While the dimensions for the carried unit case were based on the size of the physical hardware itself, the dimensions

Figure 5.10: In-cab unit mounted in the holder on a window

for the in-cab unit case are based on virtual measurements. This allows a virtual Raspberry Pi and touchscreen to be imported into Fusion 360 and used to model the case with the exact dimensions. Fig. 5.8 shows a sample of the schematics exported from Autodesk Fusion 360, while Fig. 5.9 shows the printed case. The case is approximately 110mm high, 200mm wide, and 50mm deep.

The in-cab unit case was designed to encase the main unit (the Raspberry Pi 3B+ and attached screen), while also allowing space for a suction cup mount that is designed to be used with a tablet. The ‘arms’ on the rear of the case were the solution to allowing the mount to grab the case and hold the device, as the mount would not have otherwise been able to do so. The case also allows space for the receiver unit to be mounted on the top of the back of the case, in a manner that would ensure the least obstruction to anyone using it. Fig. 5.10 shows the full in-cab unit, mounted onto a window.

Coding Example 5.4: Example data stream received from the carried unit

```
56,-27,2:51:19,0,-37.786522,175.31677,399
56,-26,2:51:20,0,-37.786518,175.31677,399
56,-27,2:51:21,0,-37.786518,175.31677,399
56,-26,2:51:22,0,-37.786518,175.31677,399
56,-27,2:51:23,0,-37.786518,175.31677,399
56,-26,2:51:24,0,-37.786518,175.31677,399
56,-27,2:51:25,0,-37.786518,175.31677,399
```

5.2.3 Software for the Receiving Unit

The software that is running on the receiving unit is written in Arduino C. As with the carried unit, Arduino C was chosen as there were libraries available to interface with the other hardware that it is connected to.

The receiving component of the in-cab unit has similar software to the carried unit, as it too locates itself using the GPS module and has the ability to send and receive data via the RF module. This part of the unit is controlled by the Raspberry Pi via serial and has a set of commands that it can carry out.

Whenever it receives a message from one of the carried units, this message will be converted back from byte form to a readable string. As seen in Coding Example 5.4, each message also includes a wrapper that the RF module places around it, allowing the ID of the unit that has sent the message to be easily identified. This allows the in-cab unit to know which unit the message was received from. Coding Example 5.5 shows the conversion that is completed.

Another purpose of the receiving component is to send alerts back to the carried units when they are in a 'dangerous' location. When a carried unit is deemed to be in a dangerous location, calculated by the Raspberry Pi, the Raspberry Pi will send the receiving unit the ID of the carried unit that needs to be alerted. This then triggers the receiving unit to send a series of five messages to the carried unit, each 200ms apart. These then trigger the alert as explained above in the description of the carried unit's software.

Coding Example 5.5: Conversion of received data from carried unit

```
if (radio.receiveDone()) // Received a message
  {
    lastNodeID = (int)radio.SENDERID;
    // Send Information to the Raspberry Pi via Serial
    Serial.print(radio.SENDERID, DEC);
    Serial.print(',');
    Serial.print(radio.RSSI);
    Serial.print(',');
    // The actual message is contained in the DATA array, and
        is DATALEN bytes in size:
    for (byte i = 0; i < radio.DATALEN; i++) {
      Serial.print((char)radio.DATA[i]);
    }
    Serial.println(); //Ends character for the Raspberry Pi is
        a newline
  }
```

5.2.4 Software for the Main Unit

The software running on the main unit was written in Python. Python was used because it has libraries that are required for this system, and is one of the languages that works well for data processing at a rapid pace.

The software running on the Raspberry Pi is where all of the calculation and geofencing occurs. Initially the software will get it's own location from the GPS module in the receiving component of the in-cab unit. This will then draw a plot with the location of the hauler as a black square. When the carried unit's data is received, each unit will be given it's own Worker object, with these being pre-configured to include the name of the worker for easier identification by the hauler operator. An example of this can be seen in Fig. 5.11.

The data received from the carried unit is read in via serial, in the format <*unit id, RSSI, time, latitude, longitude, button state, accuracy*>. This is then added to a reading object to make the data easier to handle. The reading is then saved for logging purposes, and is processed to display a point on the plot where the carried unit, which is being carried by a breaker-out, is.

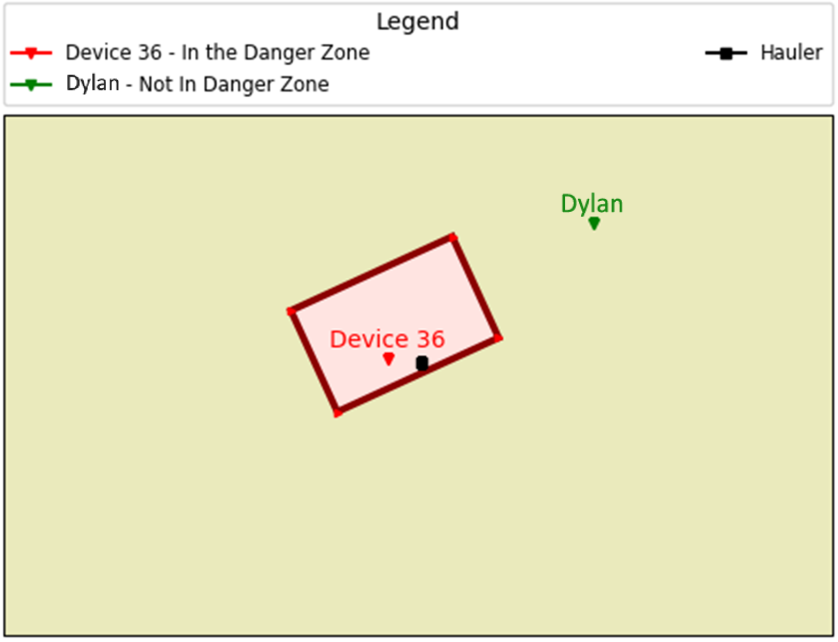


Figure 5.11: Example of hauler display with completed geofence

Coding Example 5.6: Three readings with the button held down

```
56,-80,2:56:51,1,-37.783841,175.316224,113
56,-77,2:56:53,1,-37.783841,175.316224,113
56,-84,2:56:55,1,-37.783841,175.316224,113
```

If the ‘button state’ value was set to 1 in each of the last three consecutive readings (i.e. the button was held down), then a flag is placed on the map. Coding Example 5.6 shows the three consecutive readings that are required in order to set a flag. This flag represents the physical flags that the breaker-out’s use as an indicator for where the safe retreat zone is. Once the two flags have been set by the breaker-outs, a rectangular geofence will be created and displayed on the screen for the hauler operator.

The geofence created relies heavily on geometric math, as it interpolates the line generated between the two flags that have been set, back to perpendicular with the hauler. This line is then translated across until one point is directly in front of the hauler, representing where the cable line is. A zone is then generated from these four vertices, giving the geofence of the danger zone

Coding Example 5.7: Calculation of the corners of a 20m wide geofence

```
grad = math.sqrt((flag2.Lat - flag1.Lat)**2 + (flag2.Lng -
   flag1.Lng)**2)
dLat = (0.000200/grad)*(flag2.Lng-flag1.Lng)
dLng = (0.000200/grad)*(flag2.Lat-flag1.Lat)
if slope >= 0:
    temp1Dist = math.sqrt((BSFlag.Lat-flag1.Lat+dLat)**2 + (
       BSFlag.Lng - flag1.Lng-dLng)**2)
    temp2Dist = math.sqrt((BSFlag.Lat-flag1.Lat-dLat)**2 + (
       BSFlag.Lng - flag1.Lng+dLng)**2)
    if temp1Dist > temp2Dist:
        Lat3 = flag2.Lat + dLat
        Lat4 = flag1.Lat + dLat
        Lng3 = flag2.Lng - dLng
        Lng4 = flag1.Lng - dLng
    else:
        Lat3 = flag2.Lat - dLat
        Lat4 = flag1.Lat - dLat
        Lng3 = flag2.Lng + dLng
        Lng4 = flag1.Lng + dLng
```

between the safe retreat line and the cables for the hauler. The geofenced area is calculated as follows.

$$Slope = \frac{F_{\text{1Lat}} - F_{\text{2Lat}}}{F_{\text{1Lng}} - F_{\text{2Lng}}}$$

where F_{1Lng} is Flag 1's longitude, F_{1Lat} is Flag 1's latitude, and F_{2Lng} is Flag 2's longitude, F_{2Lat} is Flag 2's latitude.

5.7 shows the calculation of a geofence, including interpolation of the points to elongate the geofence until it is at the hauler. When a breaker-out enters the geofence, the worker status is updated to “In the Danger Zone”, and when they are outside the geofence the status is changed to “Not In Danger Zone”, which is displayed to the hauler operator as a change in colour of both the label and icon of the worker on screen. A completed geofence with breaker-out displayed inside and outside can be seen in Fig. 5.11.

During the working day, there may be the occasion where the flags need to be moved as the tail block may be moved to retrieve stems in a different area than the cables are currently set up. This is accommodated for in the software, as when the breaker-out sets the next set of flags, the closest flag to their location will be moved, and the geofence recalculated to adjust for this.

Finally, the readings are saved in a CSV file in batches, allowing historical data to be obtained in the event of an incident. The CSV does not show names, only the ID of the unit that sent the reading, therefore the data is already anonymous if studies were to use the data. Optimizing when the data is saved was another aspect that had to be considered. Saving the data is important. However, the main function of receiving, processing and displaying the data must not be compromised. Saving the data each time it is read could potentially bottleneck the system, resulting in the loss or delay of data display, as reading and writing data is typically a more intensive task. Therefore saving in batches was implemented, with a batch size of 25, resulting in an average of 2 saves each minute with one unit, and 4 saves each minute with two units.

Chapter 6

Evaluation

Both the carried unit and in-cab unit have been subjected to a series of tests to evaluate their validity. The units were tested both in-house and in a field test in a forestry setting. The in-house test focused on testing the technical aspects of the units, to ensure they would meet the requirements (under ideal conditions) to prove a system like this could be feasible. The field test involved taking the units into a real forestry setting and letting the workers use them. The test was used primarily to evaluate the robustness of the units, whether the forestry workers would use them, and whether the units would improve the safety of the workers on the ground. The results of these tests would then be used to suggest improvements to the units, as well as the software and other applications that the same or similar technology can be applied to.

6.1 In-House Test

In-house testing was used to evaluate the technical capabilities of the units, ensuring that they could meet the requirements under ideal conditions. These ideal conditions consisted of a flat field, with line-of-sight between units, and clear weather, which aids the GPS in locating the units accurately. This was conducted at The University of Waikato, on one of the sports field. This provided enough space to test the devices to the distances stated in the technical requirements (Section 4.2.1), whilst also being flat and having good vision to the sky for the GPS modules.

6.1.1 Methodology

To test the units, two carried units and one in-cab unit were used to simulate multiple breaker-out's and the hauler. The in-cab unit was placed at one side of the sports field, and the two carried units were carried around the field. The following tests were used to verify the technical requirements of the system:

- Test 1.1: Accuracy of the units
- Test 1.2: Setting flags and alert feedback
- Test 1.3: Creating a geofence
- Test 1.4: Moving flags
- Test 1.5: Different geofence orientations
- Test 1.6: Range and reliability of communication
- Test 1.7: Display shows correct status
- Test 1.8: Multiple carried units
- Test 1.9: Battery life
- Test 1.10: Charging Time

Test 1.1 aimed to verify both the in-cab unit and the carried units were reporting an accurate GPS location. A smartphone was used to compare the longitude and latitude of the units. Only when this was verified, were the following tests conducted.

Test 1.2 was used to test the basic functionality of the carried unit. A coned area was set up with one cone at each corner of a 20m x 20m area, as seen in Fig. 6.1. Within the software, the default width of the geofenced area created was set to 20m. The in-cab unit was then placed at cone A, whilst the carried unit was placed at cone B. The button on the carried unit was held

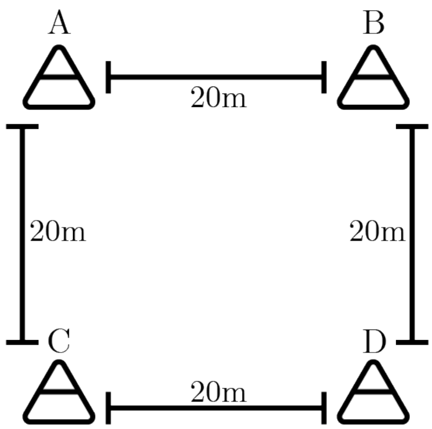


Figure 6.1: Layout of the cones for the 20m x 20m test

until a flag was set. This was used to verify that the carried unit could set a flag. The carried unit was also tested to ensure there was a vibration feedback given to the user when a flag was set.

Test 1.3 then moved the carried unit to cone D, and the button held until the second flag was set. This would then show on the in-cab unit as a geofence across the 20m x 20m zone.

Test 1.4 aimed to test the movement of the flags. To do this, the carried unit was moved further outside to ensure that the unit could move the flag from cone A to outside of the coned zone and back again. This was then repeated with the other flag at cone B to ensure that the closest flag to the unit's position was being moved each time.

Test 1.5 aimed to verify that the geofence would correctly generate at various coned areas. Different combinations of flag and in-cab unit placements were used to ensure that the software would correctly display the geofence on various orientations of longitude and latitude. The various combinations of the placements can be seen in Fig. 6.2.

The coned out area was then extended to be approximately 200m long, and 20m wide, to more closely simulate the conditions that the units would be used in, as the zone flagged out in a typical hauler forestry operation would be between 100m and 500m long. The above tests were then repeated with the

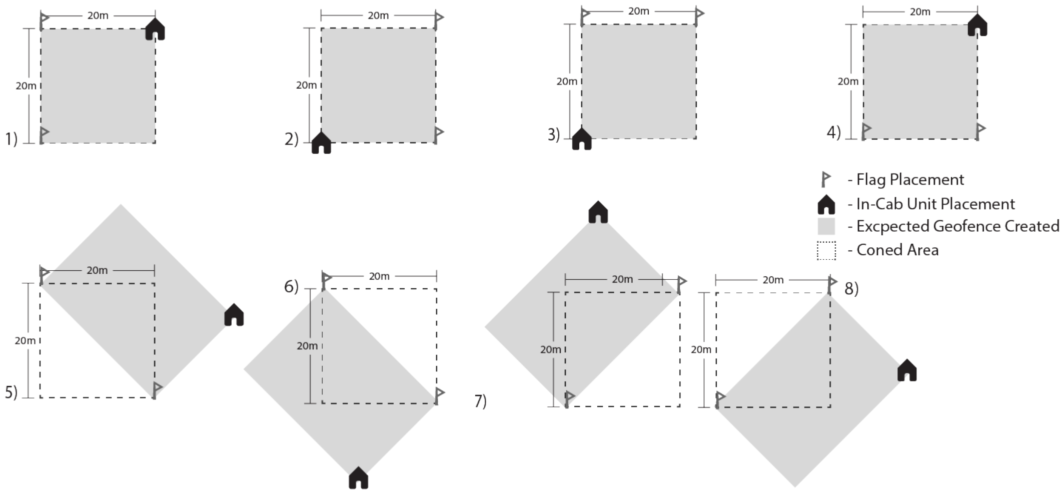


Figure 6.2: All the different combinations of flag/in-cab unit layouts

new zone sizes to ensure that the software worked at scale also.

Test 1.6 aimed to verify the range of communication. The carried unit was walked out to different distances, where a 100 second timer was started and the number of received data packets were counted. This would then be used to determine how many data packets were lost. The distances measured were 100m, 200m, 300m, 400m, and 500m, with the in-cab unit being stationary and with line-of-sight between the two units at all times. This was tested with one carried unit, then repeated with two carried units to ensure that they would not interfere with one another and would provide reliable transmission at the distances above.

Test 1.7 was used to verify the display on the hauler changed correctly when the carried units were located within or outside the “danger zone”. This test involved taking a carried unit and moving it inside the geofenced zone, ensuring that when the line was crossed the display changed accordingly. This also evaluated the status of the carried units, ensuring that the unit was deemed safe when outside of the geofence and in danger when inside.

Test 1.8 used the following set of tests to test whether the system would function correctly with multiple carried units sending data to one in-cab unit, closely representing how they would be used in the forestry industry. This used two carried units and one in-cab unit and were aimed to evaluate whether:

- each of the carried devices data is received by the in-cab unit at least once every 5 seconds
- that the carried unit's statuses are correct when one crosses over the boundary
- that the carried unit's statuses are correct when both cross over the boundary
- that both units can set flags
- that both units can move flags
- that both units can move flags set by the other unit

Test 1.9 was used to verify that the battery life was sufficient to last an entire working day. This was done by taking the fully charged carried units and running them until they had fully discharged. By taking the first and last timestamps of the data sent from the carried units to the in-cab unit, the battery life could be calculated.

Test 1.10 aimed to ensure the charge time of the units met the requirement of less than 8 hours. This was conducted by ensuring the carried unit's batteries were flat, and then charging them, taking note of start time. By checking on the units every 15 minutes, a good estimation of charge time can be obtained.

6.1.2 Results

Test 1.1, which tested whether the GPS modules were reporting the correct longitude and latitude, was a success. The GPS modules reported a longitude and latitude within 0.00002 degrees of what the smartphone was reporting, as seen in Table 6.1. This is the equivalent to 2.22m difference, which is within the accuracy requirement of 5m.

Test 1.2 resulted in the flags being set correctly. Shown in Coding Example

Table 6.1: Comparison of carried unit and smartphone longitude and latitude

Carried Unit Position	Smartphone Position	Difference (Degrees)
-37.775544, 175.32377	-37.775529, 175.323772	0.00002

Coding Example 6.1: Three consecutive readings showing a flag being set

```
56,-90,2:59:59,1,-37.782997,175.3183,113
56,-92,3:00:01,1,-37.782997,175.3183,113
56,-85,3:00:04,1,-37.782997,175.3183,113
```

6.1, the time to set the flag took the expected 3 seconds, as it requires three readings from the same unit with the button pressed to trigger a flag to be set within the software. This also triggered a vibration in the carried unit, letting the user know that they can release the button as the flag has successfully been set.

Test 1.3, which involved setting the second flag at cone B, showed that the geofence was being created correctly and that the correct size was configured. This was verified by walking the carried unit from edge to edge and verifying that the unit's position on the in-cab device was on the edge of the zone as it got to the edge of the coned area, as seen in Fig. 6.3. Moving the carried unit in and out of the coned area also showed that the status and icon displayed on the in-cab device changed correctly and accurately as the unit passed over the boundary.

Test 1.4 showed that moving the flags from cone A and cone B were also a success. The correct flag was moved each time, and was able to be set back at the cone once moved. The geofenced area that is generated also correctly updated each time a flag was moved, which also continued to be the correct shape and size.

Test 1.5 involved setting the flags in a series of different 20m x 20m configurations. All eight of the configurations in Fig. 6.2 worked correctly and generated the expected geofenced area. Seen in Fig. 6.4 and Fig. 6.5, the software that automatically generates the geofence from the flags set by the

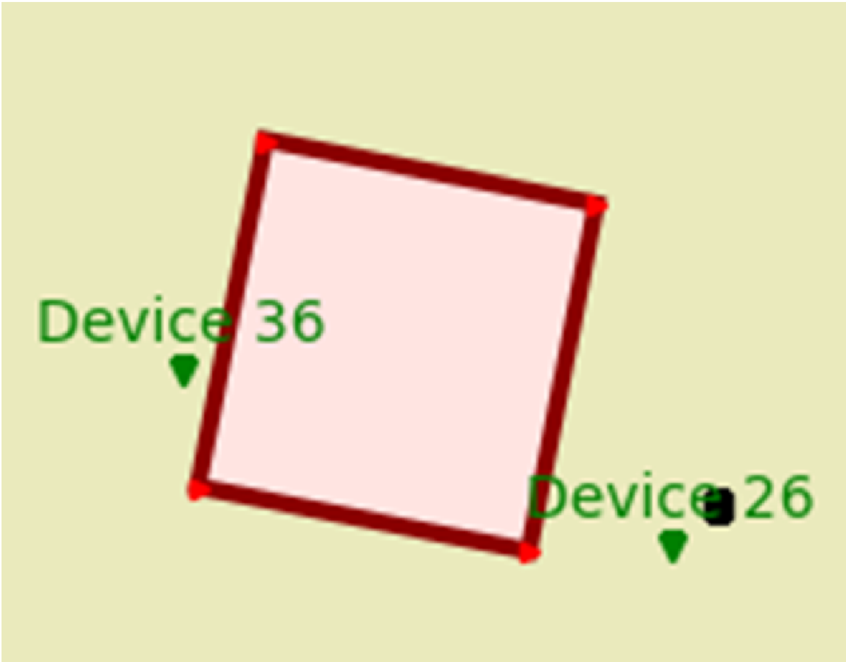


Figure 6.3: Unit on edge of zone

carried unit can therefore be deemed successful and working. This can also be seen in Fig. 6.6, when repeating this test at 200m.

Test 1.6 was centered around the range and reliability of communication between the carried and in-cab devices. As shown in Table 6.2, the range testing showed that at the distances from 100m to 300m there were no lost data packets, with 100 of 100 being successfully received by the in-cab unit. At 400m there were 12 lost data packets giving a total of 88 out of 100, and at 500m there were 18 lost data packets totalling 82 of 100 received by the in-cab unit. When repeated with the second unit, to test for interference, a similar trend occurred, as seen in Table 6.2. The elevated number of dropped data packets suggest that interference may be present between the two units.

Test 1.7 showed that the in-cab device was correctly and accurately updating the status of the carried units on entry and exit of a geofence. Fig. 6.7 shows one carried unit inside and one carried unit outside of the geofence, with the statuses and colors of the icons updated correctly. This ensures that the

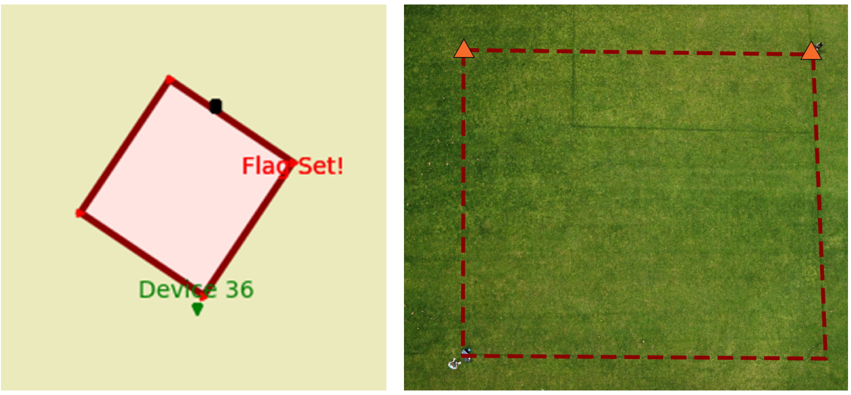


Figure 6.4: Correctly generated square geofence

Figure 6.5: Geofence at a 45-degree angle

display for the hauler operator will be accurate and ensures that each of the units can be easily identified as inside or outside the geofence.

Test 1.8 repeated the geofence testing with two carried units. As shown in Fig. 6.8, the carried units can both set flags, and move flags set by themselves and the other unit, as each unit has set the flag that they are closest to. This worked as planned and also showed that the two units could be displayed independent of one another, with separate statuses for whether they are inside or outside the geofence, as seen in Fig. 6.7. As shown in Test 1.6, introducing another carried unit to the system has a minor impact on the reliability of

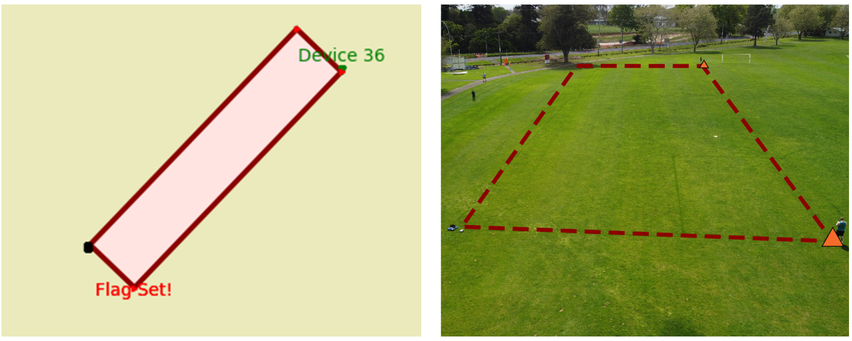


Figure 6.6: Geofence at 200m

Table 6.2: Number of packets received (out of 100)

Distance (m)	Packets Received (One Unit)	Packets Received (Two Units)
100m	100	100
200m	100	100
300m	100	95
400m	88	89
500m	82	79

the communication for the carried and in-cab units, reducing the number of packets received by 3% at 500m.

Test 1.9 showed that the battery life of the carried devices was sufficient to last an entire working day. The battery test was run six time, as shown in Table 6.3. From the tests run, an average battery life of 12 hours and 43 minutes was calculated.

Test 1.10 was used to obtain the charging time of the carried units. As seen in Table 6.4, the approximate charging times were between 6 hours and 15 minutes and 6 hours and 45 minutes, with an average charging time of 6 hours and 32 minutes.

6.1.3 Discussion

Six of the design requirements have been tested during the in-house testing of the GPS tracking system: (1) accuracy, (2) range, (3) reliability (4) battery life, (5) charging time, and (6) notifications (each of these requirements is

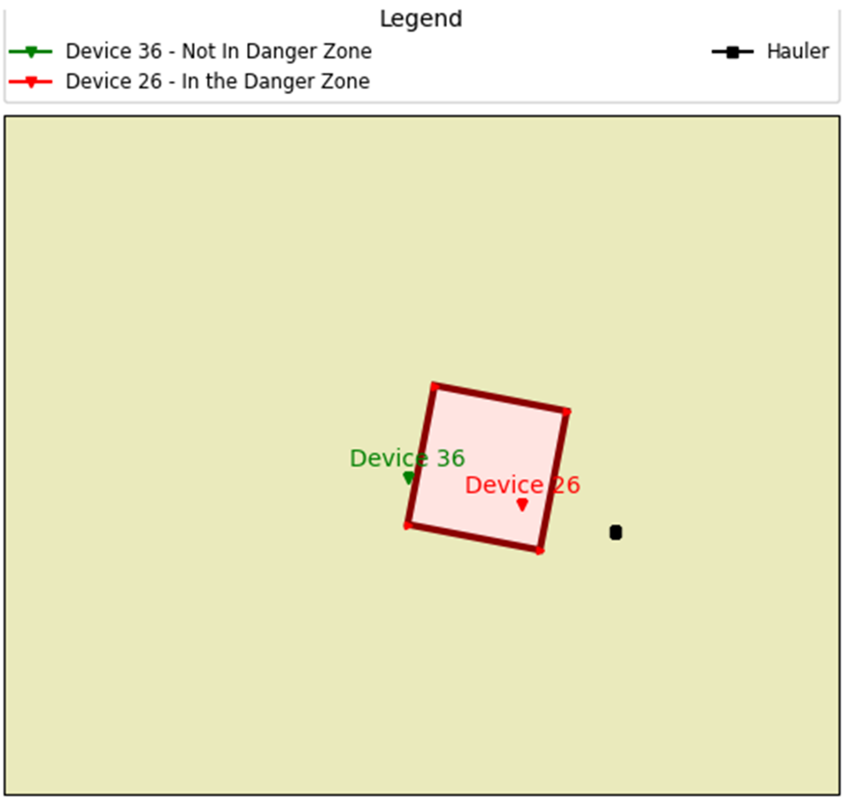


Figure 6.7: Unit inside and outside the geofence

described in more detail in Section 4.2).

To meet the ‘accuracy’ design requirement, the system must locate the worker within 5m of the actual position. This was met as Test 1.1 shows that when compared to a smartphone, which is generally considered accurate, the unit was located 2.22m away from where the smartphone was placing it. This illustrates that the ‘accuracy’ design requirement has been met.

The ‘range’ design requirement states the carried and in-cab unit must be able to communicate over at least 500m. Test 1.6 showed that this system could send data across 500m, with a good level of reliability. This also showed that the ‘reliability’ design requirement was met, as at 500m, 82% of the data packets that were sent by the carried unit were received by the in-cab unit. This results in the equivalent of 1 reading every 1.8 seconds, which far exceeds the requirement of 1 reading every 5 seconds. Even with two carried units

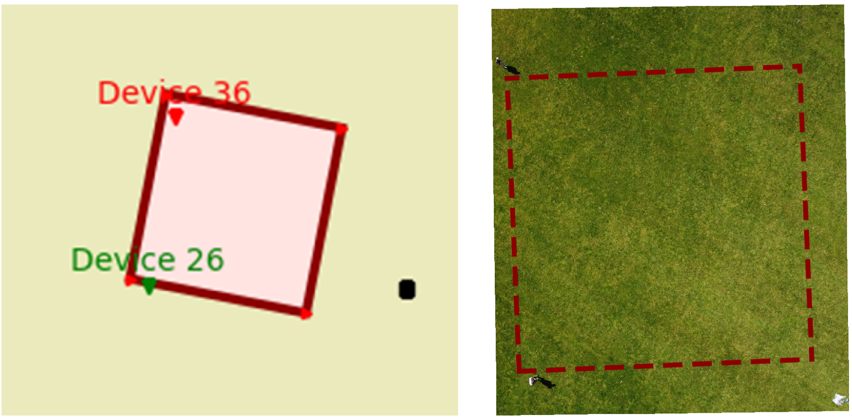


Figure 6.8: Flags set by different units

Table 6.3: Battery life testing results of the carried unit

Test Number	Start Time	End Time	Time Running
Test 1	08:03	20:46	12:43
Test 2	08:14	21:05	12:51
Test 3	07:56	20:25	12:29
Test 4	08:07	20:38	12:31
Test 5	08:11	20:18	13:07
Test 6	08:01	20:41	12:40

this only dropped to 79% reliability. This shows that both the ‘range’ and ‘reliability’ design requirements have been met.

To meet the ‘battery life’ design requirement, the carried devices must be able to run for a 12 hour period continuously. Test 1.9 ran the devices for an average of 12 hours and 43 minutes, with a maximum run time of 13 hours and 7 minutes and a minimum run time of 12 hours and 29 minutes. This illustrates that the ‘battery life’ design requirement has been met. The ‘charging time’ design requirement requires the carried units to be able to be fully charged from flat in under 8 hours, as they will need to be charged overnight for use the following day. This was shown in Test 1.10, as the average charging time of the carries units was 6 hours and 32 minutes, with a maximum charge time of 6 hours and 45 minutes and minimum charging time of 6 hours and 15 minutes. This shows that the ‘charging time’ design requirement has been met.

Table 6.4: Charging time testing results of the carried unit

Test Number	Start Time	End Time	Time to Charge
Test 1	07:30	14:00	06:30
Test 2	07:30	14:15	06:45
Test 3	07:30	13:45	06:15
Test 4	07:30	14:00	06:30
Test 5	07:30	14:15	06:45
Test 6	07:30	14:00	06:30

To meet the 'notifications' design requirement, the system must notify the worker where appropriate to ensure they stay out of harm. In this testing the notification system is used to notify the carried unit when a flag is set. Test 1.2 showed this working, with the carried unit receiving notifications when a flag was set. This illustrates that the 'notifications' design requirement has been met.

Test 1.3, 1.4, 1.5, 1.7, and 1.8 were not directly tied to a design requirement, but were instead carried out to ensure the system performed as expected when creating, manipulating, and using the geofence. These were targeted at ensuring that the geofence was accurate and that the flags were set correctly. As Test 1.3 shows, the geofence was able to be created successfully, with a 20m x 20m box created that matched the one that was marked out. Test 1.4 demonstrated that the flags could be moved successfully and that the zone created by the moved flags was updated successfully to accommodate the moved flag. This also verified that the closest flag to the carried unit was the flag selected to move. Test 1.5 illustrated that the system would work with all orientations of geofences. Eight typical configurations that the system would expect to generate were tested to ensure that the system would work regardless of orientation, all of which were successful. Test 1.7 was used to evaluate whether the display for the in-cab unit was showing the status of the units correctly, as this is how the hauler operator would be able to tell whether a breaker-out is within the danger zone or not. This was validated by confirming that the status of a unit changed when it crossed the geofenced area's boundary. Test 1.8 was designed to test the system as it created, manipulated, and used the geofence, with multiple carried units. This set of tests allowed the evaluation of different scenarios that may occur in a forestry setting, such as different units setting and/or moving flags set by other units, multiple units with different statuses, and the reliability of the data transmission with multiple carried units in close proximity to one another. These were all successful, with the system showing flexibility in relation to setting and manipulating flags.

Overall, the system performed well, meeting all of the design requirements that the in-house test was aimed at validating, and showing that it can be used in a wide number of configurations, with one or multiple carried units.

6.2 Forestry test

While in-house testing allowed for a set of systematic tests to be conducted in a controlled environment, a second test – the forestry test – was also developed to evaluate the devices on-site in the forestry industry. This test was used to determine whether this IoT solution would be a feasible solution when deployed in a real world setting. While the controlled in-house test was used to evaluate the technical requirements of the system, the forestry test was used to evaluate the usability and durability of the system, and to identify any issues that were not raised during the in-house testing. As this test involved human participants (the forestry workers), ethical consents was obtained from the Faculty of Computing and Mathematical Sciences Ethics Committee at The University of Waikato. See Appendix A.

6.2.1 Methodology

One in-cab unit and two carried units were taken to an active forestry harvesting location to be tested in a real forestry environment. The in-cab unit was placed inside the cab of the hauler. It was mounted using a suction cup, as shown in Chapter 5, Fig. 5.10. The carried units were given to one breaker-out and one tree feller to carry with them around the work site. The breaker-out was instructed to set the flags for the safe retreat zone to create a geofenced area. The workers then continued as they would on a normal work day, with the carried units in a pouch or pack with them. While the workers were using the units, the in-cab unit would record data logs of the data being sent from the carried units for post test analysis if required. At the conclusion of the day, the devices were collected, and the workers were queried about their experience with the system.

As already mentioned, the purpose of the forestry test was to evaluate the usability and durability of the system, and to identify any issues that were not raised during the in-house testing. As such, there were four main areas of interest:

1. Durability: investigate whether the units could stand up to the conditions of the forestry environment
2. Usability: determine whether the workers found the units easy to use
3. Limitations: find potential flaws in the current design
4. Functionality: testing the functionality of the system

6.2.2 Results

First, the ‘durability’ of the devices was tested by the condition that they were in at the end of the work day. At the end of the day, both carried units came back undamaged. Both were dirty, which was to be expected given the nature of felling and breaking-out, but no damage was sustained by either carried unit. This can be seen in Fig. 6.9, with the image on the left showing the unit prior to testing, and the image on the right showing the unit after one day in the breaker-out’s possession.

(a) Carried unit before test (b) Carried unit after test

Figure 6.9: Carried unit before and after forestry test

Second, 'usability' was evaluated based on feedback that was given by the workers. Table 6.5 outlines the questions and answers that were given when talking to the hauler operator about the in-cab device. The usability of the device was reported as being good, as it is only required to be turned on and setup once in the morning. The display was a good size and the icons were easy to see on the screen. The hauler operator does currently prefer the current system in place, due to the limited use of the proposed IoT system, which is addressed later in this section. Similarly, Table 6.6 outlines the questions and answers that were given by the breaker-out about the carried device. The breaker-out liked that the interaction with the device was limited to short intervals when moving flags, as this would not add any extra work. The device was easy to carry, the small size meant it was easy to place in a backpack or jacket pocket. They had no opinion on whether they preferred this system to the current one as it does not add any extra work, but could be very beneficial for instances where the hauler operator cannot see the breaker-out. In general, when asked about their feelings around having their locations tracked while on-site, the breaker-out and feller were happy with this as they are typically communicating their locations via radio during the day.

[1]The current system consist of using a combination of the 2-way radios and a beeper to communicate between the breaker-outs and hauler operator. The beeper is used via a system similar to Morse code to tell the hauler operator where to move the cables, with the radios as a way to talk with one another.

Table 6.5: Questions and responses from hauler operator

Was the device easy to use?	Yes, as the setup was only required to do once then use it throughout the day.
The workers were easy to see on the screen?	Yes, the labels and icons were large enough to be seen easily, but not too large that the screen feels crowded.
Do you prefer the current system?[1]	Yes, the current system works well and this could be useful. The primary use for this type of system would be when I cannot see the breaker-out, which currently it cannot help with.

Table 6.6: Questions and responses from breaker-out

Was the device easy to use?	Yes, the device was easy as most of the interaction with the device was short while setting up flags, but then I could put the device in a pack and forget about it.
Was the device easy to carry?	Yes, it was small enough to fit easily in my pack or one of the pockets of the wet weather jacket.
Do you prefer the current system?[1]	Neutral, this system does not add much work and I can see how this could help in cases where the hauler operator cannot see us.

Third, it was discovered that there was a significant 'limitation' in the current system. With the in-cab unit mounted in the hauler cab, the radio frequency module was not powerful enough to enable the system to work without line of sight to the carried unit. This was further compounded as the radio frequency module was not able to penetrate the cab of the hauler. This resulted in the in-cab device receiving no data packets from the carried device that the breaker-out was carrying, even when line-of-sight was established. To verify it was the hauler cab that was blocking the signals, the in-cab unit was removed

Coding Example 6.2: Log of packets received from carried unit

```
26,-84,21:31:03,0,-38.169327,175.91551,91
26,-86,21:31:05,0,-38.169327,175.91551,80
26,-86,21:31:07,0,-38.169323,175.91551,93
26,-88,21:31:09,0,-38.169323,175.91553,80
26,-95,21:32:35,0,-38.169567,175.91545,82
26,-84,21:32:37,0,-38.169563,175.91545,82
26,-84,21:32:40,0,-38.169563,175.91544,82
26,-94,21:32:45,0,-38.169563,175.91544,82
26,-95,21:32:47,0,-38.169563,175.91544,77
26,-84,21:34:14,0,-38.16946,175.91547,80
26,-94,21:34:17,0,-38.169472,175.91548,89
26,-98,21:34:23,0,-38.169483,175.91551,89
26,-92,21:34:26,0,-38.169472,175.91554,102
26,-79,21:34:58,0,-38.169476,175.9155,80
26,-90,21:35:01,0,-38.169483,175.91548,80
26,-93,21:35:08,0,-38.169491,175.91548,80
26,-92,21:35:14,0,-38.169483,175.91547,80
```

from the cab, and the data packets started to be received. This limitation is further addressed in Chapter 8 (Section 8.1 and Section 8.2).

Finally, to test the 'functionality' of the system as extensively as possible, the in-cab unit was removed from the hauler cab and used as a handheld device. This then saw the carried unit reliably send it's location from approximately 300m away. As the in-cab device was no longer located within the cab of the hauler, the flag setting and geofence testing could not be tested correctly, but the functionality of sending and receiving packets could be tested.

The data packets from the carried unit located on the breaker out were received by the in-cab unit with reduced reliability to the in-house tests. This can be seen in Coding Example 6.2 where the data packets are not coming through consistently each second as they should. The communication from carried unit to in-cab unit averaged one packet every 2-3 seconds, with gaps of up to 3 minutes in places where the communication was interrupted. One factor that could have influenced the performance of the units is the weather. On the day, the weather was foggy and raining all day. This is detrimental to the signal quality from the carried unit to the in-cab unit.

Figure 6.10: Weather conditions for the forestry test

6.2.3 Discussion

As already mentioned, the in-house tests evaluated majority of the technical requirements and one of the usability requirements that were outlined in Chapter 4 (accuracy, range, reliability, notifications, battery life, and charging time). The forestry test aimed to evaluate the remaining requirements: durability, ease of use, size.

The ‘durability’ design requirement for the devices was met. This was shown as the carried devices withstood a full working day whilst being carried with a breaker out with no damage. The devices were dirty, but this was to be expected. The weather throughout the day was not ideal, as the site was foggy for most of the morning and then began raining for the final 4 hours of the test, as seen in Fig. 6.10. This also showed that under these poor conditions, a breaker-out can carry the carried units with them without them being damaged.

The ‘ease of use’ design requirement was also met. The response from the hauler operator on the usability of the device was generally positive. The setup and display of the in-cab device being good, with short setup times and the display size and contrast being easy to see. The only negative feedback was that the hauler operator would not use this system over the current system as the only time they would use it is when there is no line-of-sight to the breaker-out, which currently the system cannot support. Again, this limitation is addressed in Chapter 8 (Section 8.1 and Section 8.2). The response from the breaker-out was also positive. The device setup was easy, as the interaction to setup the flags is short and easy to perform. They had no opinion on whether they preferred the current system to this one. However, they did state that if the hauler operator could not see them, or the visibility was less-than-ideal, this system would be preferred as it would show their location to the hauler operator.

The 'size' design requirement was aldo met. The response from the breaker-out, in response to size, was positive. They stated that the unit was easy to carry, and once they had performed the steps to set up a geofence, the unit was stored in their backpack all day.

Although all of the design requirements were met, as discussed earlier, one significant limitation was discovered during the forestry testing. The radio frequency module was not powerful enough to get a signal through the front window glass and the metal bars of the hauler. This limitation meant that the testing that would be done from inside the cab could not be undertaken as the carried unit could not transmit the data to the in-cab device. Addressing this issue is the top priority in the future work on this system.

While the device did not perform as well as first hoped, the durability, size, and usability of a system like this was shown to work successfully within a forestry testing. This illustrates that a system such as the one implemented here would be a feasible solution to help mitigate the risks the breaker-outs undergo each day. In addition to this, I propose that the hardware used for this system can also be applied in other areas of the forestry industry. One example of this is using it as a proximity detection system for workers around the skid site.

Chapter 7

Additional applications

Up until this point, this thesis has focused primarily on developing an IoT solution that can be used in the forestry industry during 'breaking-out'. However, this technology can be applied to different situations. For example, it can be leveraged for use in proximity detection (Teizer et al., 2010). While talking with a forestry group manager, it was brought to my attention that a proximity detection system that tracks workers on the skid site could be of use to them.

Currently, when a worker moves across a skid site, around the machines, they must communicate with each of the machine operators to let them know they want to move past. The operator must then stop working, acknowledge that the worker is coming past and wait until they are at a safe distance again before resuming the work they were doing. This could easily be forgotten, or the worker on foot could unknowingly walk too close to the machine before the operator is aware of them. This could potentially cause an incident or put the on-foot worker in unnecessary danger. A proximity detection system could mitigate this and alert the operator and worker before an incident occurs. This system could be built into the carried and in-cab units to make the current devices multipurpose. This section outlines the design, implementation, and evaluation of such a system.

7.1 Design

First, based on discussions with a forestry-industry expert, and existing research in the field of IoT and proximity detection (see Chapter 3), I have outlined four design requirements that should be met. They are as follows.

1. Accuracy: The system must locate the worker on foot within 3m of their actual position. This is more strict than the GPS system as the location of the workers needs to be more accurate in a proximity detection application.
2. Range: The range of communication should be at least 50m, to ensure there is plenty of time for an early warning.
3. Reliability: The system must transmit at least one reading every 3 seconds to ensure that there is an up-to-date position of the worker at all times. This is more strict than the GPS system due to the reduced time for a worker to enter a dangerous area in a proximity detection application.
4. Notifications: The alerts that the units provide should trigger when expected and provide adequate feedback to gain the attention of the worker using it.

The system will be comprised of two units, the existing carried unit and the existing in-cab unit. Both the carried and in-cab units will use GPS location data gained from their GPS modules to locate themselves. They will also use their radio frequency modules to transmit and receive data to each other. This hardware and communication is unchanged from that of the original devices that were outlined in Chapter 5.

In-cab units will be placed in each of the machines on the skid site. Once they are set up, they will each generate a circular geofence that represents an 'unsafe'/'safe' zone. If a worker comes close to or within the zone, an alert will be served to the worker on the ground and to the machine operator to ensure both parties are aware of one another. The radius of each geofence will be configured in the in-cab device when it is mounted, allowing for the radius to be altered depending on the machine type, reach, etc. This could also allow for a connected work site where each machines knows the position of all other machines and their geofences, as well as the positions of all workers in the skid site.

The in-cab unit will be responsible for monitoring the geofenced area and for generating the alerts for both the carried and in-cab units. The alerts for the worker on the ground will be serviced by a vibration motor, as this should be felt by the worker. The alerts for the machine operator will be an audible alarm tone, to let them know that there is someone on foot inside the safe zone. This audio alert will also be accompanied by a screen to show the operator where the worker is, assisting if the worker is in the operator's blind spot.

7.2 Implementation

The existing carried and in-cab units were used to implement this system. They already contain all of the hardware components that are required. The data flow diagram outlined earlier in Chapter 4 (Fig. 4.5), illustrates the flow of data around the original system. This data flow has not changed, and therefore also represents the data flow around the proximity detection system. The main difference between the original system and the proximity detection system centers on the software stored in the Raspberry Pi in the in-cab unit. Changes have been made to this software to create a radial geofence around the in-cab unit, and to service alerts to the carried unit.

As shown in Fig. 7.1, the in-cab unit gathers it's own location when it is launched, and updates it's own location once every 30 seconds to ensure that if the machine has moved, the geofence that is created is also moving with it. Each time it receives data from a carried unit, the icon and status of the

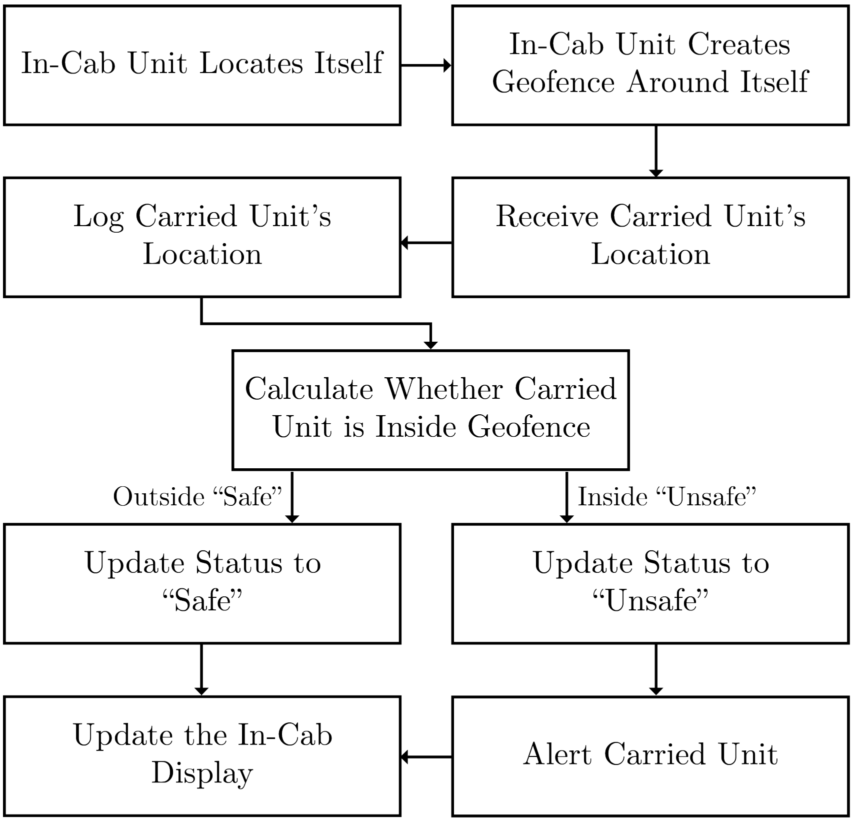


Figure 7.1: Event diagram for the proximity detection system

corresponding unit are updated and shown on the display. If the unit is within the geofence, meaning the worker with the unit is too close to the machine, then an alert in the form of an audio alarm sounds for the operator, and the icon changes color. The carried unit then sends an alert each second that it is detected within the geofenced area, with each alert causing the unit to vibrate. The in-cab unit will also sound an alert every 5 seconds. Coding Example 7.1 illustrates generating the radial geofence, while Coding Example 7.2 shows the distance to unit calculation.

7.3 Evaluation

This section describes three tests that were designed to verify the technical requirements of the proximity detection system. Each of these tests were

Coding Example 7.1: The creation of a radial geofence

```
ax = plt.axes(projection=ccrs.PlateCarree())
ax.set_extent(extents,crs=None)
c20m = plt.Circle((BSFlag.Lng, BSFlag.Lat), r20m , color='
   orange', alpha = 0.25)
ax.add_patch(c20m)
```

Coding Example 7.2: The calculation to determine distance to a unit

```
dWorker = ((BSLng-unitLng)**2 + (BSLat - unitLat)**2)
                d10m = r10m**2 - dWorker
                d20m = r20m**2 - dWorker
                d30m = r30m**2 - dWorker
                d40m = r40m**2 - dWorker
                d50m = r50m**2 - dWorker
    #If any of the dXXm values are greater than zero, the unit
       is within the corresponding distance
```

conducted in-house.

7.3.1 Methodology

To test the technical requirements, one carried unit and one in-cab unit were used. The testing took place in two locations at the University of Waikato, once on a sports field, and once in a car park. The first location provided ideal conditions, while the second location provided conditions with potentially more interference and metallic objects (i.e. simulating forestry machines on-site in the forestry industry).

For the first location, the in-cab unit was set up in the middle of a sports field where an increasing radius, from 10m to 50m, was coned out in one direction. This is shown in Fig. 7.2. This evaluation included three tests to verify the requirements of the system, these were:

- Test 1.1: Accuracy of the units
- Test 1.2: Data transmission reliability
- Test 1.3: Notification system

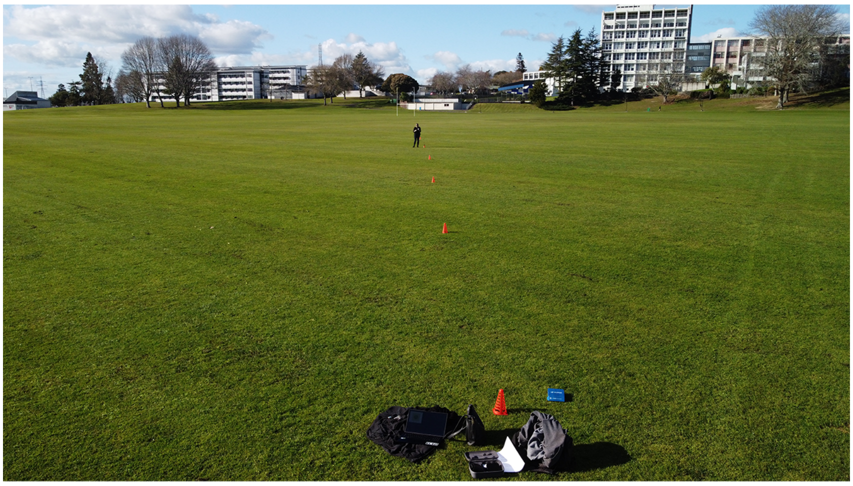


Figure 7.2: Layout of the cones spaced 10m apart

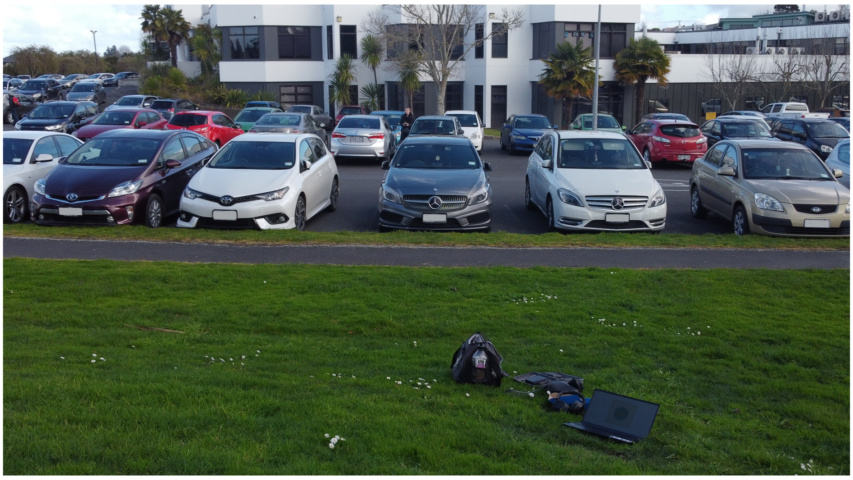


Figure 7.3: University car park testing site

Test 1.1 was used to verify the accuracy of the device's GPS location. The longitude and latitude collected by the carried unit was compared against the longitude and latitude generated by a smart phone. Test 1.2 was used to validate data transmission between the carried unit and the in-cab unit. The carried device was taken beyond the 50m cone, to approximately 75m, and kept there for 100 seconds. The number of readings that were received by the in-cab unit over the time frame was recorded. Test 1.3 was used to evaluate the alert system. The carried unit was placed outside the boundary of the geofence, where no alerts were expected. It was then moved inside the

Table 7.1: Comparison of carried unit and smartphone longitude and latitude

Carried Unit Position	Smartphone Position	Difference (Degrees)
-37.780544, 175.31677	-37.780529, 175.316772	0.00002

Table 7.2: Number of received packets, tested at a distance of 75m

Test Number	Number of Packets Received (per 100s)
Test 1	98
Test 2	100
Test 3	99

Table 7.3: Alerts felt at each distance

Distance	Test 1 Alert Felt	Test 2 Alert Felt	Test 3 Alert Felt
10m	Yes	Yes	Yes
20m	Yes	Yes	Yes
30m	No	No	No
40m	No	No	No
50m	No	No	No

boundary and into the geofence, where alerts are expected.

The second testing location, seen in Fig. 7.3, in the University of Waikato car park was used to test whether the data transmission between the carried and in-cab unit would degrade when vehicles were placed between them. This test was carried out by checking how many packets were lost out of 100 when behind and not behind a vehicle at 10m, 20m, 30m, 40m, and 50m.

7.3.2 Results

First, Table 7.1 shows the results of Test 1.1. When the longitude and latitude of the carried unit was compared against the longitude and latitude of a smart phone, there was a difference of 0.00002. This is the equivalent of 2.22m, which is within the design requirement of 3m. Next, Table 7.2 shows the results of Test 1.2. Test 1.2 was conducted with the carried unit placed 75m away from the in-cab unit. The test was repeated three times, where the number of data packets received in 100 seconds was recorded. On average, 99 out of the 100

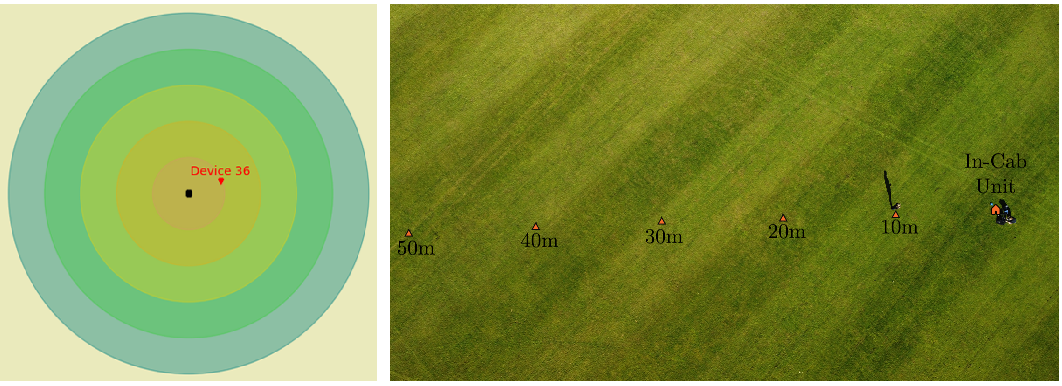


Figure 7.4: Screenshot and image of proximity detection testing at 10m

Table 7.4: Car park test results

Distance	Number of Packets Received (No Obstruction per 100s)	Number of Packets Received (Obstruction per 100s)
10m	100	95
20m	100	95
30m	99	94
40m	99	92
50m	99	89

expected packets were received. Table 7.3 shows the results of Test 1.3. As can be seen, alerts were sent consistently while the carried unit was located inside of the geofence, which was set at 20m. Fig. 7.4 illustrates this when the carried unit was placed 10m from the in-cab unit. Each ring in the screenshot represents 10m on the ground. The alerts were registered each second by both the carried and in-cab units.

The car park field test results, seen in Table 7.4, having a vehicle between the carried and in-cab unit's has a small impact on the reliability of the signal. This degradation of signal was only slight, as still within the 1 reading every 3 seconds from the technical requirements.

7.4 Discussion

Four design requirements have been outlined for the proximity detection system: (1) accuracy, (2) range, (3) reliability, and (4) notifications (described in more detail in Section 7.1).

To meet the 'accuracy' design requirement, the units GPS location must be within 3m of the same GPS location, generated by a smartphone. As shown in Test 1.1, the units were 2.22m from where the smartphone was locating the units. This shows that the 'accuracy' design requirement has been met. To meet the 'range' design requirement, communication between the in-cab and carried units should reach at least 50 metres. As shown in Test 1.2, at a range of 75 metres, 99% of packages were received. This illustrates that the 'range' requirement has been met, and that the devices work at a range greater than what is required. To meet the 'reliability' design requirement, an average of 1 packet every three seconds is required. Test 1.3 showed an average of 99% of data packets were received at 75m, therefore the 'transmission reliability' design requirement is met. To meet the 'notifications' design requirement, notifications must be served to both units when a carried unit crosses the geofence boundary. As shown in Test 1.3, the alerts were registered by both the in-cab and carried units each second as expected. This illustrates that the 'notification' design requirement is met. Finally, as shown in Figure 7.4, the proximity detection system can be used, not only to detect when a worker is within a pre-defined danger zone, but also to locate them in relation to the centre of that zone. This can help immensely for the operators of the machines as the display could show the operator where the worker on foot is, especially if they are in a blind spot.

The car park testing showed that even with a vehicle between the carried unit and the in-cab unit, the signal is only slightly affected and still meets the reliability technical requirement.

Although this system has not been tested in a forestry situation, the hardware itself has. This was shown in Section 6.2, with the in-cab unit being placed in the hauler cab, and a breaker-out and tree feller carrying one of the carried units each. In these tests, the units were shown to be durable enough for the forestry industry, but the radio frequency could not transmit through the cab. Therefore, for the proximity devices to work correctly in the forest, changes would need to be made to the hardware to ensure the transmission of data between the in-cab and carried units is reliable in all situations (described later in more detail in Section 8.2).

While this is one additional application for these devices, I propose that they can be re-purposed for many other applications. The devices are capable of GPS location, alerting the carried unit and displaying the location of the carried units on the in-cab unit's screen, therefore any application where hazardous locations are present could adopt this system. This system can mitigate the risk of workers moving into any type of hazardous area by alerting them and ensuring that worker's are not entering these zones unknowingly.

Chapter 8

Conclusion

This thesis has illustrated the design and implementation of IoT devices for use in the forestry industry to improve the safety of the workers. The devices were tested in-house to verify the technical requirements, then tested again in a forestry setting. This section outlines some limitations that the system has, and the future work that could be undertaken to further the system and improve on it.

8.1 Limitations

Two devices were developed for this thesis; a carried unit that was designed to be carried around by a breaker-out to track their location, and an in-cab unit which was designed to be placed in a hauler cab to display the location of the breaker-outs. These devices have been evaluated as a proof-of-concept. However, as with any system there are always limitations. For this system, the limitations include: some of the hardware components used, the environment for intended use, and the cost considerations for the devices.

One of the most significant limitations stems for the type of hardware used to develop the system. The radio frequency module that was used was a low-power model, designed for use in homes and spaces where the distance is short, and there is mostly line-of-sight from one device to another. This module performed well under ideal conditions, and then again whilst in the forest with line-of-sight. However, as soon as the line-of-sight was lost, or the in-cab unit was placed in the hauler cab, the communication between the devices ceased. This limitation results in a significant performance deficit. One of the most high-risk situations when breaking-out, is when the hauler cab does not have line-of-sight to the workers. As such, while the proof-of-concept has been validated, it is important that this limitation be resolved before the devices are used on site in the forestry industry. One solution is to utilize a higher-power radio frequency module and antenna external to the hauler cab. This solution is discussed in more detail in Section 8.2 Future Work.

Another limitation centers on the environment that the devices will be used in. The forestry environment is another limitation of this project, as it involves a forestry harvesting area which is typically remote and without reliable mobile network coverage. This type of environment introduces limitations to the requirements of the project. For example, the way in which the devices can communicate with one another, and the types of IoT components that can be used. Generic IoT devices would easily be damaged by the workers or the conditions that are faced by them as part of their occupation. This limitation results in a more restricted components selection and increased scrutiny on the build quality. One way to mitigate this is to build robust devices with as few points of failure as possible.

One last limitation centers on the cost of developing the devices. In order for these devices to be viable for use in forestry, they must be developed as cost effectively as possible. This is especially true if the devices are optional, rather than mandated by health and safety. For example, we can imagine that forestry companies would be more likely to adopt this solution if the devices cost hundreds of dollars, rather then if they cost thousands. This consideration was taken into account from the requirements phase, through to implementation. While this is an important consideration, it does introduce challenges. The use of lower-cost hardware, for example, has introduced issues such as using components that are not designed for these applications, and the general quality and performance loss with using cheaper components. While this could have been avoided through the use of more expensive hardware, the additional cost would be detrimental to the adoption of the project in the long term.

8.2 Future Work

This thesis outlines the design and implementation of a novel IoT solution for safety in the forestry industry. This solution can be used to mitigate the risk of an incident occurring, specifically around breaking-out. While the devices the thesis outlines and evaluates are proof-of-concept, there are various additional steps that can be taken to further this project. Some of these steps include replacing under-powered and unreliable hardware, continuing to test features of the devices, and applying the technology to other relevant industries.

Firstly, the radio frequency module used for the communication between the carried and in-cab units was a low-power model. This lead to the units not being able to communicate when line-of-sight was lost and when the in-cab unit was located within the cab of the hauler, as discussed in Section 6.2. Replacing this with a more powerful module with an antenna external to the cab would help to increase the likelihood of the data being received with no line-of-sight. The external positioning of the antenna on the hauler cab would need to be placed in a position that is primarily facing the direction the breaker-outs are working, but also in a place where it is unlikely to get damaged by a stem or the hauler cables. The cost of replacing the antenna and radio frequency module with a more powerful one and external antenna could increase significantly. As this is quite a large issue as the case where this system would be most useful is when there is no line-of-sight to the breaker-outs, this cost increase would be justified, though may make the system less attractive in industry.

Second, Chapter 7 outlined an additional use for the carried and in-cab devices, in the form of proximity detection. This application has undergone preliminary testing, as outlined in Section 7.3. However the proximity detection testing needs to be formally conducted in a forestry setting. Current testing was limited to in-house testing. While the technical requirements have been met via the in-house testing, testing within a forestry setting may uncover some more work that is required for the system to be considered fully operational and successful.

Finally, this system could be utilized in other industries, such as construction and mining. As discussed earlier in Chapter 7, similar systems have been designed and evaluated. Teizer (2015) outlines a solutions that could utilize a similar system to the one outlined in this thesis for use in construction. Similarly, Roja and Srihari (2018), outlined an IoT solution that could be applied in a similar way to assist the safety of the workers in the mining industry.

8.3 Conclusion

The New Zealand forestry industry is one of the most dangerous industries in New Zealand. The industry's fatality rate is over three times higher than any other industry in the country. One of the causes of these fatalities is workers being hit by an object, typically when breaking-out or felling trees. Since 2017, there have been 21 fatalities within the forestry industry and an average of 20 severe injuries each quarter, per 1,000 workers (NZFOA, 2020).

The solution detailed in this thesis was created to assist in the safety of the workers in this industry, in particular the breaker-outs. This system uses IoT to track the locations of breaker-outs, and allows them to set a virtual boundary at the safe retreat zone that can be seen by the hauler operator on a display in the cab.

This system was comprised of two separate units, a carried unit which the breaker-out carries with them, and an in-cab unit, which was mounted in the hauler cab. These units would then use GPS positioning to gather their own locations, and the carried unit would transmit it's location each second to the in-cab unit. The in-cab unit displays it's own position and the position of each of the carried units on a display for the hauler operator to see. The carried units have a button on them, which allow the breaker-outs to set up a virtual geofence. This allows them to create an area between the cables from the hauler and the safe retreat line. The geofence that is created allows the hauler operator to visually see where the breaker-out's are in relation to the "danger zone". The hauler operator can also see the status of each of the breaker-out's, with the two statuses being "safe" and "in danger". These relate to whether the breaker-out is located outside or withing the geofence respectively.

The units were tested under ideal conditions in-house, and then again in a forestry setting. The in-house testing was designed to test the technical requirements and limitations of the system. While the forestry tests were used to evaluate the robustness of the units and the attitudes of the workers towards them. The in-house testing showed that the accuracy of the GPS units were within 2.22m, and could set flags in a timely manner of approximately 3 seconds. The range at which the two units could communicate was 500m, with 82% reliability at that range. The system could also successfully create a geofenced area by setting two flags under all the expected layouts at both 20m and 200m from the in-cab unit, seen in Chapter 6, Fig. 6.6. Bringing in another carried unit to simulate multiple breaker-outs showed that there was minimal interference between the units. They were also able to set and move flags, including the flags set by the other unit, with the geofenced area updating correctly each time a flag was moved. In the forestry test, a carried unit was given to the breaker-out, with the in-cab device being mounted in the cab of the hauler. Both units were undamaged at the end of the working day, therefore the durability requirement was met. The radio frequency module was not powerful enough to penetrate the cab of the hauler, so the in-cab unit was removed and used as a handheld device external to the cab. Once this change was made, the system worked as expected over a range of approximately 300m in rain and fog. From the feedback given by the breaker-out, the device was easy to use and easy to carry around, therefore the usability requirement for the carried unit was met. Feedback from the hauler operator was that the device would be useful if the location of the breaker-out could be shown when there is no line-of-sight. This is a known current limitation of the hardware used, but still shows merit for a system such as this one.

Finally, by utilising the same hardware, these two units can be re-purposed to function as a proximity detection system. This was implemented by altering the software running on the Raspberry Pi in the in-cab unit to generate a geofence around the unit's location. The in-cab unit also served alerts to any carried unit that was within the zone and also alerting the operator by means of an on-screen alert. This was tested in-house, to confirm the technical requirements of the system, which can be seen in Chapter 7. This included range and reliability testing, and ensuring the location of the units was accurate and that the alerts were served correctly. The units could reliably send data over the 50m required distance, dropping an average of 1% of the packets sent at a range of 75m. The accuracy of the units met the ¡3m requirement, in comparison to a smartphone the difference in longitude and latitude was 0.00002 degrees, or 2.22m. When the carried unit was bought within the geofenced area around the in-cab unit, the device was served an alert each second. This illustrates that these devices have the potential to be used, not just within breaking-out, but in the other high-risk operations within the forestry industry.

Systems such as the ones outlined in this thesis could be used by the forestry industry to improve the safety of it's workers. Tracking their location in relation to geofenced areas that are considered dangerous could reduce the risk of incidents occurring. These devices have been focused on mitigating the risk of breaker-outs being ht by stems as they are being hauled in. However, these could also be used in other high-risk applications within the forestry industry, and with some minor alterations, they could be utilized by other hazardous industries such as construction or mining.

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Appendix A

Ethical Consent Approval

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HECS Human Ethics Committee
Brett Langley
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THE UNIVERSITY OF
WAIKATO
Te Whare Wānanga o Waikato

11 May 2021

Dylan Exton
Jemma Konig

Re: HECS Ethics Approval of Application HREC(HECS)2021#18 "Field Testing IoT Devices with Forestry Workers"

Dear Dylan:

Thank you for submitting your amended application HREC(HECS)2021#18 for ethical approval.

We are pleased to provide formal approval for your project, including the following activities:

- Field-test hardware for tracking forestry workers locations during their working day, as a part of the overall goal of the Tini o te Hakituri project to improve their workplace safety.
- GPS devices will be tested over a week-long period with a group of forestry workers, to assess the information the devices can gather, and their durability under these circumstances.
- Complete a questionnaire at the end of the study by workers involved.

Please contact the committee by email (hecs-ethics@waikato.ac.nz) if you wish to make changes to your project as it unfolds, quoting your application number with your future correspondence. Any minor changes or additions to the approved research activities can be handled outside the monthly application cycle.

We wish you all the best with your research.

Kind regards,

Brett Langley, PhD
Chairperson
HECS Human Ethics Committee
University of Waikato