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IoT in forestry: Human-focused assistive safety technology

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ABSTRACT

Internet of Things (IoT) solutions are becoming increasingly prevalent in workplace safety. However, some industries are still in their infancy in adopting this technology. The New Zealand forestry industry is one such example. The forestry industry is one of the most dangerous industries in New Zealand (and internationally). Yet, while IoT solutions are being adopted in other industries, human-focused IoT systems for safety in forestry are lacking. The contribution of this paper is to highlight this, investigate whether IoT can be used as assistive safety technology in the New Zealand forestry industry, and highlight the challenges associated with it. To this end, this paper investigates feasible uses of technology for safety and injury prevention in the New Zealand forestry industry by introducing an IoT based system. This includes an outline of the generalised system, a proof-of-concept implementation, and an evaluation of its use within two forestry scenarios. Finally, this paper includes a discussion on how this system could be adapted for use in a variety of scenarios, provides a comparison with other existing approaches, and discusses the challenges involved in developing solutions for use in hazardous industries. This work is part of a larger project centred on the use of technology for safety and injury prevention in the New Zealand forestry industry.

1. Introduction

The New Zealand Forestry Industry is one of the most dangerous industries in New Zealand Worksafe (2017). Agriculture, Forestry, and Fishing Hunting and Trapping have been found to have the highest rate of workplace injuries and fatalities across all other industries in New Zealand Worksafe (2017). Within this group of industries, a worker is more likely to be killed in forestry than in either Agriculture or Fishing, Hunting, and Trapping (WorkSafe, 2021) (discussed further in Section 2.2).

While IoT solutions are being adopted in other hazardous and high-risk industries, human-focused IoT systems for safety in forestry are lacking. This is due, largely, to the nature of the forestry environment (particularly in New Zealand). The New Zealand forestry industry is remote. Work sites tend to have very little infrastructure and limited to no external connectivity (*e.g.* no wireless and cellular network communication). Yet, IoT systems often require this infrastructure, and when it is not available, result in high setup costs. This is not feasible within the forestry industry. Forestry worksites are transient. Using IoT solutions with high setup costs (whether that be monetary cost or cost in setup time) would not be sustainable.

To this end, our research investigates feasible uses of technology for safety and injury prevention in the New Zealand forestry industry, with the aim of answering the question *"can IoT be used as assistive safety technology in the New Zealand forestry industry"*. In order to answer this question, we have developed an assistive safety solution for forestry, trialed the solution on site in industry, and conducted a comparison between our solution and other solutions used in hazardous and high-risk industries.

Our proposed assistive safety technology uses radio frequency, location data, and geofencing to contextualise workers' locations in relation to hazards and dangerous areas on site. The system is light weight, portable, and low cost. It consists of two devices: a main unit and a carried unit. The main unit can be placed in a stationary position to provide context and location, while the carried units would be worn by forestry workers (in a pack or pouch that they carry with them). The two devices use radio frequency and GPS location data to tracker workers' locations and notify others if they come within range of dangerous areas or hazards.

The contribution of this paper centres on highlighting the lack of human-focused IoT systems for safety in forestry, investigating whether IoT can be used as assistive safety technology in the New Zealand

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forestry industry, and highlighting the challenges associated with it. In this paper, we first introduce background on the New Zealand forestry industry. Next, we discuss related work in other hazardous industries and highlight the lack of human-focused IoT systems for safety in forestry. After this, we introduce our IoT based system for use during forestry activities. This includes an outline of the generalised system, a proof-of-concept implementation, and an evaluation of its use within two forestry scenarios (geofencing for cable-hauling and proximity detection on a skidsite). Finally, this paper includes a discussion on how this system could be adapted for use in a variety of scenarios where proximity or closeness to a hazard poses a risk of injury, provides a comparison with other existing approaches, and discusses the challenges involved in developing solutions for use in hazardous industries.

2. Background

In this section we first introduce a series of forestry terms that will be used throughout the paper. After this we discuss forestry-based injury statistics and identify some of the more dangerous forestry activities within harvesting.

2.1. Forestry terms

- *Felling* is the process of cutting down a tree.
- *Stem* refers to a tree trunk, after it has been felled but before it has been processed.
- *Forest Area* is an area of managed forest where trees are felled and extracted (harvested)
- *Skid site* refers to the location where stems are processed and prepared for transport.
- *Harvesting* is the activity of extracting stems from a forest area. There are two main types of harvesting: ground-based harvesting and cable-hauling.
- *Ground-based harvesting* involves extracting stems from a forest area using a wheeled or tracked vehicle. This method is used when terrain is easily accessible.
- *Cable-hauling* involves extracting stems from a forest area using a hauler and cable system. This method is used when terrain is less accessible (*e.g.* steep and/or uneven).
- *Hauler* is a machine made up of a tower and a series of cables, winches, and breaks. Stems are attached to the cable system so that they can be dragged (hauled) out of the forest area and onto the skid site.
- *Breaker-outs* are the workers who attached the cable system to the stem during cable-hauling.

2.2. Forestry incidents and statistics

As touched on in Section 1, the forestry industry is one of the most dangerous industries, both internationally and in New Zealand. In 2017, the Agriculture, Forestry, and Fishing Hunting and Trapping industries were found to have the highest rate of workplace injuries and fatalities across all other industries in New Zealand Worksafe (2017). Since 2017, the New Zealand forestry industry has seen an average rate of 20 severe injuries per 1,000 workers per quarter, and a total of 21 fatalities (NZFOA, 2020). Forestry has a fatality rate of 64.23 when comparing the rates per 100,000 Full-Time Equivalent (FTE) workers. As a result, a worker is 3 times more likely to be killed in forestry than in Fishing, Hunting, and Trapping (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).

Within forestry, accidents, injuries, and fatalities (*i.e.* incidents) are broken down into causes, with "hit by object", "poor technique", and "loss of control" being the top three contributors. Between 2018 and 2021, "hit by object" was listed as the cause of 761 incidents; "poor technique" was listed as the cause of 760 incidents; and "loss of control" was listed as the cause of 638 incidents (FISC, 2018a,b,c,d, 2019a,b,c,d, 2020a,b,c,d, 2021). While both "hit by object" and "poor technique" could be mitigated through additional worker training, we propose that "hit by object" could also benefit from the use of human-focused assistive safety technology.

Incident rates can also be categorised into the activity and operation that was being performed when the incident occurred. In 2021, we conducted an analysis of 6584 forestry incidents that occurred over an eight year period between 2007 and 2016 (Hinze et al., 2021). During this analysis, we found "harvesting" to be the activity with the highest incident rate. Harvesting incidents accounted for almost 70% of all reported incidents within our dataset (4557/6584). The next most frequent activities were "distribution trucking" with 900 incidents (14%), and "silviculture and tending" with 611 incidents (9%). Within harvesting, manual and mechanical clearfell and hauler stem/logs were the most prevalent operation types, making up 94% of the harvesting incidents (4,293/4557).

2.3. Harvesting

Harvesting is the process of extracting stems from a forest area. This process involves felling a specified area of forest, moving the stems from that area down onto the skid site, processing the stems, and then loading them onto a truck for transportation off site (ForestryFocus, 2013).

Tree felling (clearfell) is the process of cutting down a tree. This can be done, either manually or with a machine. If done manually, which is often the case on steep or uneven ground, this involves a worker using a chainsaw to fell the trees. In contrast, mechanical felling uses a mechanical felling attachment which grapples the tree, cuts the base, and positions the stem in a safe direction. Both scenarios pose risks to forestry workers. The former involves working on uneven terrain with chainsaws and falling stems. This can cause incidents such as "slip, trip, and falls" and "hit by object". The latter involves working around heavy machinery, which often have blind spots and can be difficult to see out of.

Once an area has been clearfelled and the stems are on the ground, these stems must be extracted from the area and moved onto the skidsite. There are two main methods for extracting the stems: ground-based harvesting and cable-hauling. Ground-based harvesting involves extracting stems from a forest area using a wheeled or tracked vehicle. This method is used when terrain is easily accessible. In contrast, cable-hauling involves extracting stems from a forest area using a hauler and cable system. This method is used when terrain is less accessible (*e.g.* steep and/or uneven).

A hauler is a machine made up of a tower and a series of cables, winches, and breaks. The hauler is set up near the skidsite, with a cable attached to an anchor at the other end, spanning a valley or hill. The system then uses choker cables to attach felled stems to the cable system and haul the stems down to the skidsite. The choker cables are attached to stems by forestry workers called "breaker-outs" (Visser, 2016).

Breaking-out is one of the most dangerous jobs within harvesting. These workers typically spend their day on the hill, moving in and out of range of the hauler cables to attach choker cables to each of the stems before they can be hauled down to the skidsite. This places them closest to the stems when the hauler is in operation (PFOlsen, 2016).

3. Related work

In this section we first discuss existing IoT systems for safety in the forestry industry, and highlight a lack of these systems in the current environment. After that we discuss IoT based safety systems for other hazardous industries.

3.1. Human-focused IoT in forestry

IoT has not yet been widely adopted for safety in the forestry industry, either in New Zealand or internationally. Nevertheless, there are some applications that have been trialed and used (outside of New Zealand), namely the man-down system and geofencing applications.

Man-down systems use accelerometer data to detect changes in position, lack of movement, or a sudden jolt/impact. When an impact is detected, man-down systems can inform other workers that a fall or impact has occurred. Man-down systems are typically employed for lone employees who are located far from other workers and who perform their task alone (Guilbeault-Sauvé et al., 2021).

Geofencing applications use GPS co-ordinates to map a virtual location boundary. One concept that has been trialed used handheld GPS devices to detect when fellers came into close proximity to one another (Zimbelman et al., 2017). Researchers used handheld Radio Frequency (RF) devices with a screen and GPS capabilities to create a mobile geofence around each feller. When the geofences of two or more fellers overlap, an alert is sent to each worker via the radio device. This is particularly beneficial when the workers are not within visual range of each other, or if their vision of each other is obstructed by trees within the forested area. The study investigated the accuracy of the system when different angles of approach were used, and although they found that the raw geofence data was not fine-grained enough for sufficient accuracy, the authors of the study suggest that a correction method could be used to improve the application.

The lack of human-focused IoT for safety in forestry is, in part, due to the remote nature of the industry. The rugged nature of the work means that any equipment used in the field must be designed to withstand harsh outdoor conditions and high manual workloads. In addition, forestry worksites tend to be remote, resulting in little to no existing infrastructure. This includes limited power, internet access, and cellular signal. This is evident in the few human-focused IoT applications that do exist in forestry, mainly through their use of Radio Frequency, rather then other communication approaches. Zimbelman et al. (2017) for example, rely on Radio Frequency as their primary form of data transfer. This is because many forestry sites are outside of cellular or wireless range. Finally, while other hazardous and high-risk industries can build infrastructure into their IoT solutions to mitigate the challenges associated with limited wireless or cellular access (as discussed further in Section 7), this is not feasible in the forestry industry. Forestry worksites are transient. Using IoT solutions with high setup costs (whether that be monetary cost or cost in setup time) would not be sustainable. A forestry worksite is set up at one location for a limited period of time before moving on to the next location. Often the only infrastructure seen on a New Zealand forestry worksite is a shipping container, which is used as additional storage and/or an on-site office space (Worksafe, 2023). Shipping containers are used because they are low-cost, portable, and have little setup and breakdown time. This allows them to be moved from one site to another with minimal effort. In contrast, setting up a network of transmitters and receivers for data transfer across a forestry worksite would be infeasible.

3.2. Human-focused IoT in other industries

While the application of IoT for safety in forestry is currently limited, the investigation of IoT for safety in other industries is much more common. Three such industries are mining, oil and gas, and construction.

The primary risks for the mining industry include natural gas, explosions, and mine collapse (Donoghue, 2004). As such, majority of research into IoT for safety in the mining industry centres on the adoption of gas sensors and relative location detection. One such example involved the development of a helmet which contains sensors to measure air quality (CO and CO^2) and Radio Frequency (RF) technology to locate the worker within the mine using localised units (*i.e.* beacons). The helmet used an audio alarm to alert workers when conditions became dangerous, and an LCD screen to display the data being gathered (Shabina, 2014). The Radio Frequency also allowed data to be transmitted back through the mine to the control room for real-time updates.

Similarly, the primary risk for the oil and gas industry centres on toxic gas exposure and the state of workers in such events. As such, majority of research into IoT for safety in the oil and gas industry centres on the adoption of gas sensors and the physiological monitoring of workers. One such example leverages multiple layers of smart clothing, *i.e.* an under-vest, and outer jacket, a pair of shoes, and a carabiner with embedded hardware (Thibaud et al., 2018). The smart clothing system monitors physiological (*e.g.* heart rate and respiration) and environmental variables (*e.g.* gas levels) which are sent via a mesh network to a dashboard for monitoring. This allows the workers' to be alerted should their physiological stats and/or exposure to hazardous chemicals begin approaching unsafe levels.

Finally, a primary risk within the construction industry centres on working in close proximity to heavy machinery. As such, research is being conducted to develop IoT systems to help mitigate this risk. One such example utilises radio frequency to alert workers who are within close proximity to a machine. The system consists of a collection of ultrasound distance sensors and a directional radio frequency antenna which are mounted to the back of a machine, as well as a wearable radio frequency device. This allows workers (who are wearing the radio frequency device) to be alerted when they come too close to the machine (Kanan et al., 2018). The researchers also suggest a secondary application for this technology — placing the machine-based device close to areas where workers may be at risk of falling, such as the edge of a hole or building. This would allow workers to be alerted when they get too close and could reduce the risk of falling.

4. Designing an IoT solution for forestry

As already mentioned, the forestry industry is one of the most dangerous industries in New Zealand, and as discussed in Section 2.2, the leading cause of injury in the New Zealand forestry industry is "hit by object". This type of injury can occur while moving around machines on the skidsite, while felling trees, while removing stems from forested areas, and in many other forestry scenarios. The forestry industry has several safety protocols in place to help mitigate these risks. However, we suggest that the use of safety technology could also assist in reducing risk. To this end, we have designed an IoT system for safety in forestry, with the main focus of mitigating "hit by object" incidents. Similar to some of the applications discussed in Section 3, our system uses geofencing technology to mark out a hazard or hazardous area (*e.g.* the area around a tree being felled, or the area around a machine) and uses location data to track when workers come within close proximity to the area. The main advantage of our system is that it does not require any additional infrastructure, thereby providing a well-suited solution for the remote and transient nature of the forestry industry.

4.1. An overview of our IoT system

Fig. 1 illustrates our system. As shown in the figure, there are two types of devices: a main unit and a carried unit. The main unit includes an LCD screen for visual updates. It can be used to create a geofence around a hazard or hazardous area, which is then displayed on the screen. The carried unit is worn by forestry workers, either in a pocket or backpack. It sends location data to the main unit to track workers' locations relative to the geofenced area. The main unit displays the workers' locations and provides information about whether they are safe, or whether they are unsafe (*i.e.* inside the geofenced area). The carried unit produces a vibration any time the worker moves within the hazardous area.

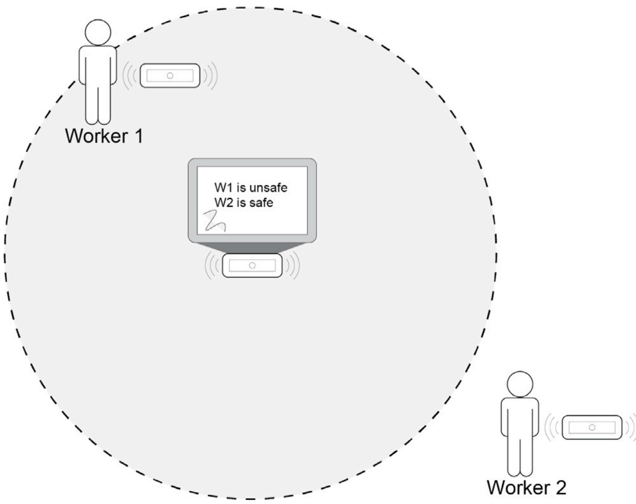


Fig. 1. Our IoT system for safety in forestry.

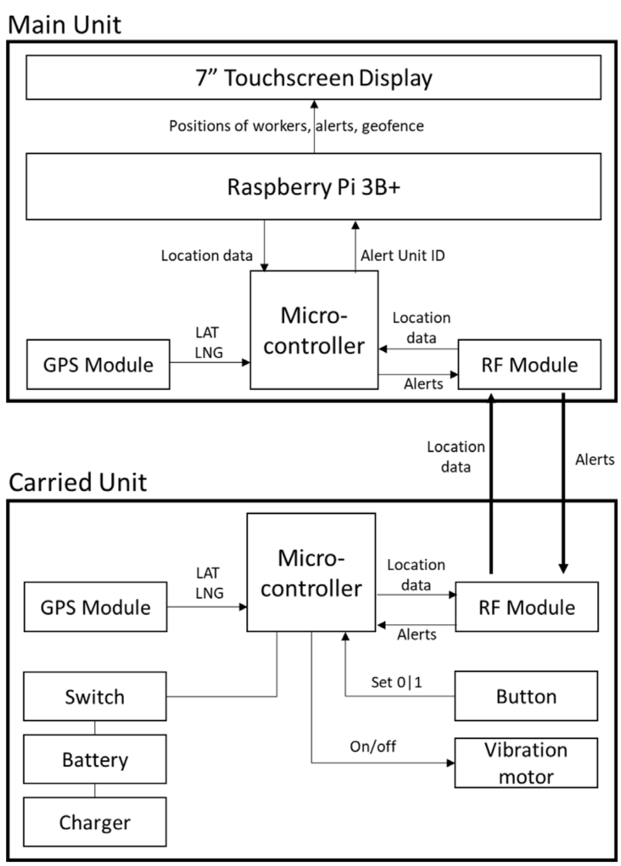


Fig. 2. Data flow diagram, communication between the carried unit and the main unit.

Fig. 2 shows the components within the main unit and the carried unit, including the data flow between components, and the communication between the two devices. As shown in the figure, both the carried unit and the main unit use Radio Frequency (RF) connectivity and GPS location. The carried unit receives latitude and longitude data via the GPS Module and sends this location data to the main unit via radio frequency. In return, the main unit sends alert information, via radio frequency, back to the carried unit. This allows the workers to feel a small vibration on the carried unit when they cross the threshold into the geofenced area.

As also illustrated in Fig. 2, the hardware for each of the devices is similar. The carried unit contains a micro-controller, a GPS module, a radio frequency module, a battery charger module, a button, a power switch, and a battery, as follows.

- Micro-controller: Arduino Pro Micro
- Radio frequency module: RFM69HW RF module
- GPS module: Ublox NEO-6M
- Button: Momentary push button
- Vibration motor: Vibration ERM Motor 3 V
- Power switch: SP/DT switch
- Battery: 2000 mAh 3.7v Li-Po battery
- Battery charger module: 5 V 1 A TP4056 lithium battery charger

The main unit consists of two components: a receiver unit and a visual display unit. The receiver unit receives data from the carried unit and sends it to the visual display unit. It uses a micro-controller, a GPS module, and a radio frequency module, as follows.

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

The visual display unit consists of a processor and a display, as shown below. The receiver unit is connected to the visual display unit via USB. The visual display unit processes the data that is sent by the receiver unit and displays the data as a visual map for workers to view.

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

The cases for both the carried unit and the main unit were designed in Autodesk Fusion 360 and 3D printed. The case for the carried unit is approximately 30 mm high, 75 mm wide, and 60 mm deep, while the case for the main unit is approximately 110 mm high, 200 mm wide, and 50 mm deep (excluding the touch display screen and suction cup mount). Figs. 3(a) and 3(b) shows the completed devices.

4.2. Setting the geofence

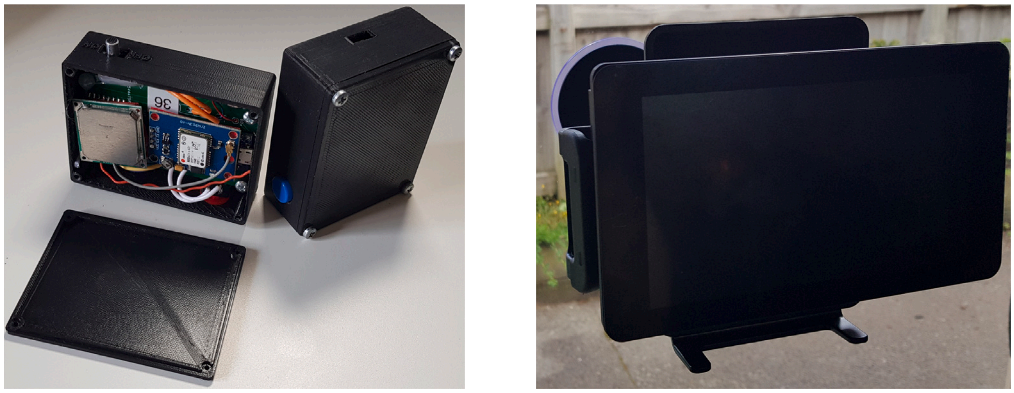
As discussed earlier and shown in Fig. 1, we have developed an IoT system that sets a geofenced "danger zone" and tracks workers' locations in and around that danger zone. In the forestry industry, this danger zone can take on a variety of forms, depending on the scenario it is used for. When moving around the skidsite for example, the geofence may be circular, with the main unit at its centre representing a machine or piece of equipment that acts as a hazard. In cable-hauling, the geofence may be rectangular, to span a pre-defined portion of the forested area.

For a circular geofence, the centre point can be calculated automatically by the GPS module inside the main unit. A geofence can then be calculated at a given radius out from the centre point (*e.g.* 50 metres). Fig. 4(a) shows an example, creating geofences that radiate out from a centre point at 10 metre intervals.

For a rectangular geofence, the main unit can be used as one GPS point in the rectangle. Workers would then need to set two other points to fill out the rectangle. The minimum number of GPS points that are needed in order to calculate a rectangular geofence are as follows.

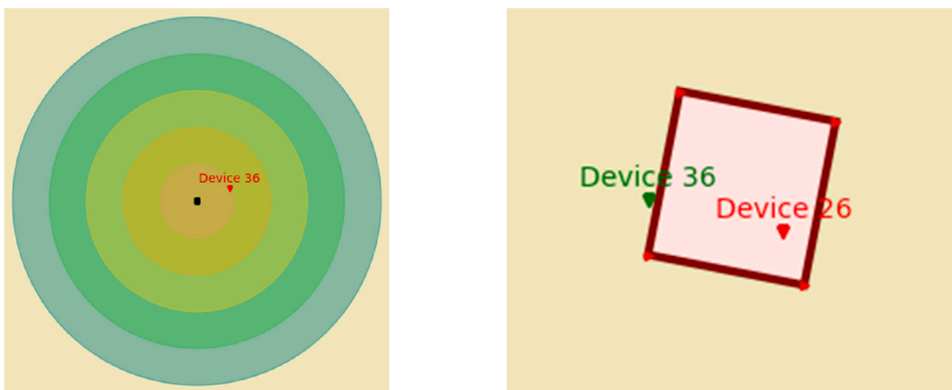
1. Main unit location, used as the starting point of the geofence
2. Point 1, used to calculate the width of the geofence
3. Point 2, used to calculate the length and direction of the geofence

As shown earlier in Fig. 2, the carried unit includes a button. This button can be used to set the GPS locations for the geofence (*i.e.* point 1 and point 2). When the button is held down for three or more seconds,



(a) Carried unit (b) Main unit, mounted

Fig. 3. The human-focused IoT system.



(a) A circular geofence (b) A rectangular geofence

Fig. 4. Setting a geofence.

the carried unit sends a series of message to the main unit with the current location and a request to set a geofence point. The main unit stores this location and sends a message back to the carried unit to inform that the point has been set successfully, which is portrayed to the worker as a vibration. The two points can be set in any order. The point with the closest location to the main unit is then assumed to be point 1, and the point furthest from the main-unit as point 2. Once both points are set, and the main unit's location has been retrieved, the main unit can then calculate and set the geofence. Fig. 4(b) shows an example of a rectangular geofence.

4.3. Tracking workers

In order to determine when workers are in a hazardous location, the system must track the workers' locations. As described, the carried unit contains a GPS module and an RF module. 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. These sentences are gathered at a rate of once per second, and then parsed to extract the latitude, longitude, positional accuracy and time. The carried unit then sends this information, along with a worker ID, formatted as a byte packet, via the RF module to the main unit. This allows the main unit to receive updated GPS location data for each of the workers at a rate of once every second.

4.4. Map visualisation

Once a geofenced danger zone has been calculated, and the workers positions are being received, the main unit can begin displaying the information in real time. Fig. 5 shows an example of the screen that is displayed on the main unit (when a rectangular geofence is used). The red box represents the geofenced danger zone, and the device markers

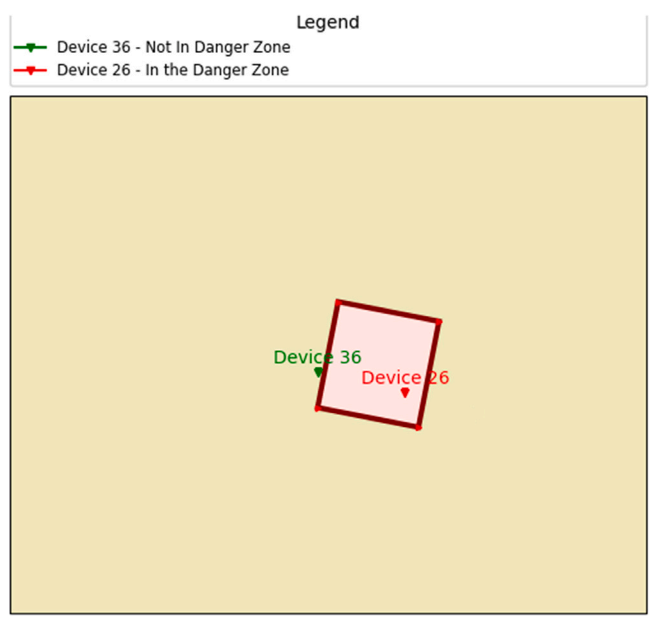


Fig. 5. Map visualisation example from the main unit.

represent two workers. Device 36 is green because the worker is outside of the danger zone and is safe. Device 26 is red because the worker is inside the danger zone and is unsafe. The screen also shows a legend in the top left. This can be customised to include names or nicknames for workers if desired.

5. Evaluation

As discussed in Section 3.1, while other hazardous and high-risk industries can build infrastructure into their IoT solutions to mitigate the challenges associated with limited wireless or cellular access and limited power supply, this is not feasible in the forestry industry. As such, our system has one main requirement — it must not depend on new or existing infrastructure. To this end, out system must meet the following criteria.

1. The system must rely on RF only. Therefore, RF range and reliability must be stable.
2. The system cannot rely on an on-site power source. Therefore, the battery life of the devices must last a full day, and the charge time should not exceed that which can be charged overnight.

To this end, both the main unit and the carried unit have been tested for range and reliability of communication, and the battery life and charging time of the devices.

5.1. Methodology

The first test centred on the range and reliability of communication between the main unit and the carried units. The carried unit sends location data to the main unit once every second. In ideal conditions, this means that the main unit would receive location data, and update the workers' locations, once every second. However, this data transfer can be interrupted by interference from other devices. In extreme cases, *i.e.* if communication were interrupted for an extended period of time, this could result in the main unit not receiving an update on workers' locations for seconds or minutes. If workers were to move into the dangerous area during that time, this would result in the main unit reporting that workers are safe when they are not. As such, the communication between the main and carried units should be sent at an average rate of at least once every 2 s, with a prolonged interruption period of no more than 5 s.

The range and reliability test involved periodically increasing the distance between the main unit and the carried units, recording the number of packets that were receive at each distance. The distances measured were 100 m, 200 m, 300 m, 400 m, and 500 m. The carried units were held at each distance for 100 s, therefore expecting the transmission of 100 packets (one per second). This was repeated, once with a single carried unit, and once with two carried units. This allowed us to test both the reliability of a single device, and whether there was any interference when two devices were used at the same time.

The second test centred on the battery life of the devices. For these devices to be viable out in industry, they would need to last a full workday. For the forestry industry, this can be up to 10 h including travel. To test this, one of the devices was left on, sending packets once every second until the battery died. This was repeated five times, with the time the device was turned on and the time the device ran out of battery being recorded.

The third test centred on the charging capacity of the devices. As well as battery life, the amount of time it takes to charge the devices must also be considered. When out in industry, it is assumed that each of the devices would be taken home at the end of the day and need to be charged overnight for use the following morning. As such, the charge time for each of the devices would ideally be less than 8 h (*i.e.* charging overnight). To test this, one of the devices was put on charge from empty, and left on charge until full (the device was checked every 15 min and considered fully charged when the orange charging light had turned green). This was repeated five times, with the time the device was put on charge and the time the device was found to be fully charged being recorded.

Table 1
Number of packets received (out of 100).

Distance (m)	Packets received (one device)	Packets received (two devices)
100 m	100	100
200 m	100	100
300 m	100	95
400 m	88	89
500 m	82	79

Table 2
Battery life testing results of the carried unit.

Test number	Start time	End time	Time running
Test 1	08:03	20:46	12 h 43 min
Test 2	08:14	21:05	12 h 51 min
Test 3	07:56	20:25	12 h 29 min
Test 4	08:07	20:38	12 h 31 min
Test 5	08:11	20:18	13 h 07 min
Average			12 h 44 min

Table 3
Charging time testing results of the carried unit.

Test number	Start time	End time	Time to charge
Test 1	07:30	14:00	6 h 30 min
Test 2	07:30	14:15	6 h 45 min
Test 3	07:30	13:45	6 h 15 min
Test 4	07:30	14:00	6 h 30 min
Test 5	07:30	14:15	6 h 45 min
Average			6 h 33 min

5.2. Results

Table 1 shows the results from the range and reliability test. As can be seen in the table, at a distance of 100 m to 300 m there were no lost data packets for a single device, with 100 of 100 being successfully received by the main unit. At 400 m there were 12 lost data packets giving a total of 88 out of 100, and at 500 m there were 18 lost data packets totalling 82 of 100 received by the main unit. When repeated with the second device, to test for interference, a similar trend occurred. No data packets were lost at a distance of 100 to 200 m. 5 data packets were lost at 300 m, 11 were lost at 400 m, and 21 were lost at 500 m. This shows that the devices are slightly less reliable at further distances, and that multiple devices may interfere with each other. However, even at their lowest reliability, the devices were still sending 47 packets per minute (79/100∗60), or an average of one packet every 1.26 s.

Table 2 shows the results from the battery life test. As shown in the table, the battery of the device lasted more than 12 h in each trial. The shortest time was 12 h and 31 min, while the longest time was 13 h and 7 min. This gave an average battery life of 12 h and 44 min, well within the range needed (minimum 10 h) for the device to be viable for use in industry.

Table 3 shows the results from the battery charging test. As shown in the table, the charging time sat below 7 h for each trial. The shortest time was 6 h and 15 min, while the longest time was 6 h and 45 min. This gave an average charging time of 6 h and 33 min, well within the range needed (maximum 8 h) for the device to be viable for use in industry.

6. Applying our system to real-world forestry scenarios

Our IoT system uses geofencing technology to mark out a hazard or hazardous area (*i.e.* the area around a tree being felled, or the area

Fig. 6. A breaker-out waiting for the hauler cables to be lowered.

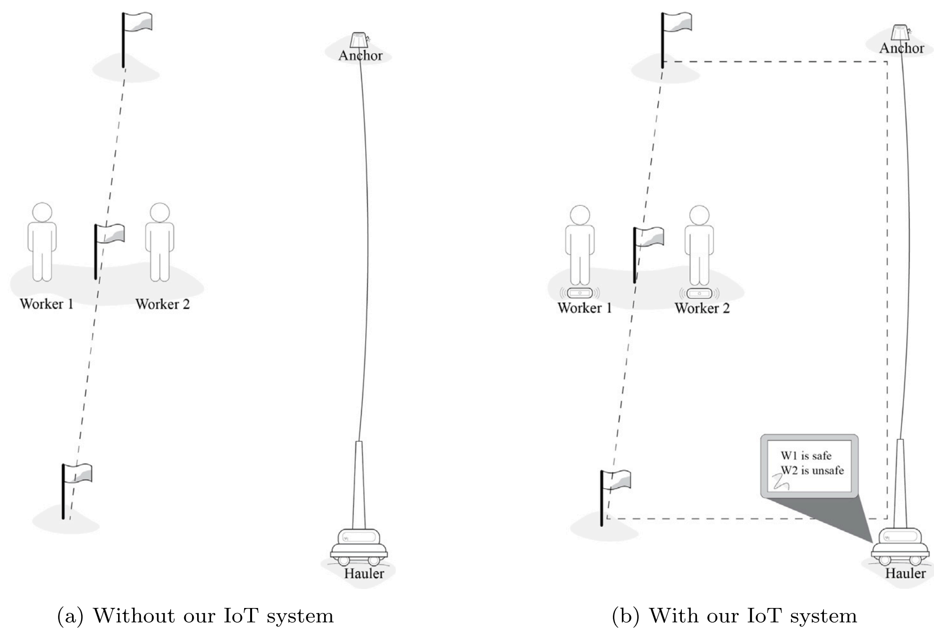


Fig. 7. A typical breaking-out setup, with and without our IoT system.

around a machine) and uses location data to track when workers come within close proximity to the area. The development of this system was inspired by the hazardous environment that breaker-outs experience while cable-hauling. However, we recognise that cable-hauling is not the only hazardous environment within forestry, and that forestry is not the only hazardous industry. As such, rather than developing a system that was configured for one specific scenario, we developed a system that can be configured differently dependant on the scenario in which it is used. As such, while we have already described our system as a whole, this section illustrates how it can be adapted to two specific forestry scenarios: cable-hauling, and proximity detection around the skidsite.

6.1. Geofencing for cable-haulers

As discussed in Section 2.3, breaking-out is one of the most dangerous jobs within harvesting. These workers typically spend their day on the hill, moving in and out of range of the hauler cables to attach choker cables to each of the stems before they can be hauled down to the skidsite. This places them closest to the stems when the hauler is in operation (PFOlsen, 2016). Fig. 6 shows a breaker-out waiting on a slope for the cables to be lowered. Once the cables are lowered, the breaker-out must attach the choker cables to the felled stems and retreat to a safe distance before the cable-hauler can start moving the stems.

Fig. 7(a) shows a typical cable-hauling setup. The hauler is placed near the skidsite, with cables spanning the length of the forested area. Breaker-outs place high visibility flags parallel to the main cables to indicate their "safe retreat" distance, typically two times the average height of the trees. Any area between the flags and the hauler is considered the "danger zone". As an example, in Fig. 7(a), Worker 1 is beyond the safe retreat distance and is considered safe. Worker 2 is within the danger zone and is therefore considered unsafe. Workers move into the danger zone to attached the choker cables to stems, they then retreat out of the danger zone, passed the safe retreat distance and sound a manual horn (carried by the workers) to alert the hauler operator that they are out of harms way. Once the breaker-outs have sounded the horn, the hauler operator begins hauling the stems out of the forested area and down onto the skidsite. For the duration of the hauler moving the cables, the breaker-outs must stay beyond the safe retreat line. One known issue with this process is that workers will sound their horn as they move away from the stem, before they

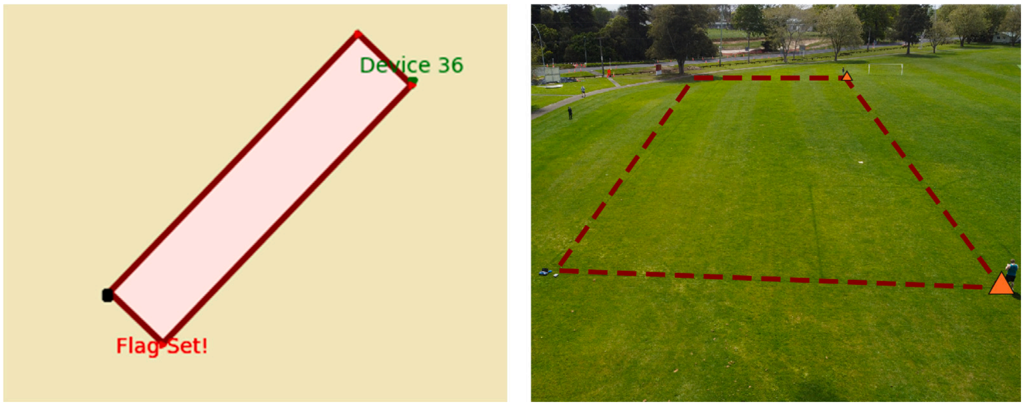


Fig. 8. Setting a geofence for breaking-out.

Fig. 9. The terrain and weather conditions while on-site.

reach the safe retreat line. The assumption is that by the time the hauler operator responds to the horn and starts the cable they will be in the safe zone.

This is one such scenario where our IoT system could provide additional safety and help mitigate the risk of incident. Fig. 7(b) shows how our IoT system could be applied to this scenario. In this case, the carried units would be held by the breaker-outs. The breaker-outs would then use the carried units to set geofence points for the top and bottom flags to create a rectangular geofence around the danger zone (as shown by a dotted lined in Fig. 7(b)). The system would then track the workers' location in and around the danger zone. The main unit would be placed in the cab of the hauler, providing the hauler operator with a graphical map of the danger zone and the workers' locations in and around it (as shown in Fig. 8).

A test has been conducted, on-site in industry, to illustrate the feasibility of our IoT system when deployed in a real world setting, *i.e.* to evaluate the usability, durability, and communication capabilities of the system. One main unit and two carried units were taken out onto an active cable-hauling site. Fig. 9 shows the terrain and weather conditions on-site during the study. As can be seen in the image, the forested area started on the top of a valley and moved down into a gorge. The weather was overcast and foggy, with a little drizzle falling throughout the day.

Once on site, the main unit was placed inside the cab of the hauler, mounted to the window using the suction mount shown earlier in Fig. 3(b). The carried units were passed out to one breaker-out and one feller. At the start of the day the breaker-out was asked to set the virtual flags to create the geofenced danger zone. After this, the breaker-out and the feller were asked to continue on as they would on any normal day, with the carried units placed in a pouch that they carried with them. At the end of the day, the carried units were collected, and the workers were asked about their experience with the system.

First, the durability of the devices was evaluated by observing the condition that they were in at the end of the day. Fig. 10 shows one of the carried units, both at the start of the day, and at the end of the day when it was collected back from one of the workers. As can be seen in the image, the device came back dirty, but undamaged. While both devices came back dirty, this was to be expected given the nature of harvesting in the New Zealand forestry industry. Regardless of surface condition, no damage was sustained by either of the carried units.

Next, the usability of the system was evaluated. At the end of the day, the carried units were collected, and the workers were asked about their experience with the system. Here, it should be noted that this evaluation was conducted on-site at an active forestry worksite. As such, any questions that were asked had to be brief and formed as a discussion. Even then, only two of the three workers were available to participate (the hauler operator and the breaker-out). The questions asked were as follows.

1. Was the device easy to use?
2. Were the workers easy to see on the screen? (Asked of the hauler operator)
3. Was the device easy to carry? (Asked of the breaker-out)
4. Do you prefer the current system?

Tables 4 and 5 show these questions and responses. Table 4 shows the responses from the hauler operator, in relation to the usability of the main unit. The hauler operator's response to the usability of the device was positive. He recognised the benefit to only having to set up the device once in the morning and then being able to use it throughout

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

Fig. 10. Durability tests: carried unit before and after forestry test.

Table 4
Questions and responses from hauler operator.

Question	Response
Was the device easy to use?	Yes, as the setup was only required to do once then use it throughout the day.
Were the workers 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?	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 5
Questions and responses from breaker-out.

Question	Response
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?	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.

the day. He also commented that the display was a good size and that the icons were easy to see on the screen. The hauler operator stated that he preferred their current system over the new IoT system. However, this may be due to his use of the system being limited by complications on the day of the study (this is discussed in more detail later in this section). Even while preferring the current system, the hauler operator did note that this type of system would be useful in cases where he cannot physically see the breaker-outs.

Table 5 shows the responses from the breaker-out in relation to the usability of the carried unit. The breaker-out's response to the usability of the device was also positive. He recognised the benefit to only having to set up the flags and then being able to forget about it for the rest of the day. He also commented that the device was small enough to fit into his pack to carry around with him. The breaker-out stated that he did not feel strongly one way or the other about using the existing system or using the IoT device. However, he did say that he could see the benefit in using the IoT system in cases where the hauler operator cannot physically see the breaker-outs.

Finally, the third condition aimed to evaluate the reliability of communication between the main unit and the carried units when on-site in industry. When the main unit was mounted in the cab of the hauler, it was discovered that the radio frequency was not powerful enough to penetrate the cab to send and receive data packets. This resulted in the main device receiving no data packets from the carried unit that the breaker-out was carrying. To confirm that it was the hauler cab that was blocking the signals, the main unit was removed from the cab, and the data packets began sending and receiving reliably. In order to continue with the on-site study, the main unit was moved outside of the hauler cab and instead used as a handheld device. This then saw the main unit successfully receive location data from the carried units at a distance of up to 300 metres away. Table 6 shows an example of the packet rates. As shown in the table, the communication from carried unit to main unit averaged one packet every 14 s. We attribute this to the poor weather conditions and steep terrain and suggest that further work be done to increase the strength of the radio frequency. While some improvements may need to be made to the system in order to

Table 6
Example of packets received by the in-cab unit while on-site in industry.

Device ID	Time	Lat	Long
26	09:31:03	−38.169327	175.91551
26	09:31:05	−38.169327	175.91551
26	09:31:07	−38.169323	175.91551
26	09:31:09	−38.169323	175.91553
26	09:32:35	−38.169567	175.91545
26	09:32:37	−38.169563	175.91545
26	09:32:40	−38.169563	175.91544
26	09:32:45	−38.169563	175.91544
26	09:32:47	−38.169563	175.91544
26	09:34:14	−38.16946	175.91547
26	09:34:17	−38.169472	175.91548
26	09:34:23	−38.169483	175.91551
26	09:34:26	−38.169472	175.91554
26	09:34:58	−38.169476	175.9155
26	09:35:01	−38.169483	175.91548
26	09:35:08	−38.169491	175.91548
26	09:35:14	−38.169483	175.91547

Fig. 11. An example of a forestry skidsite.

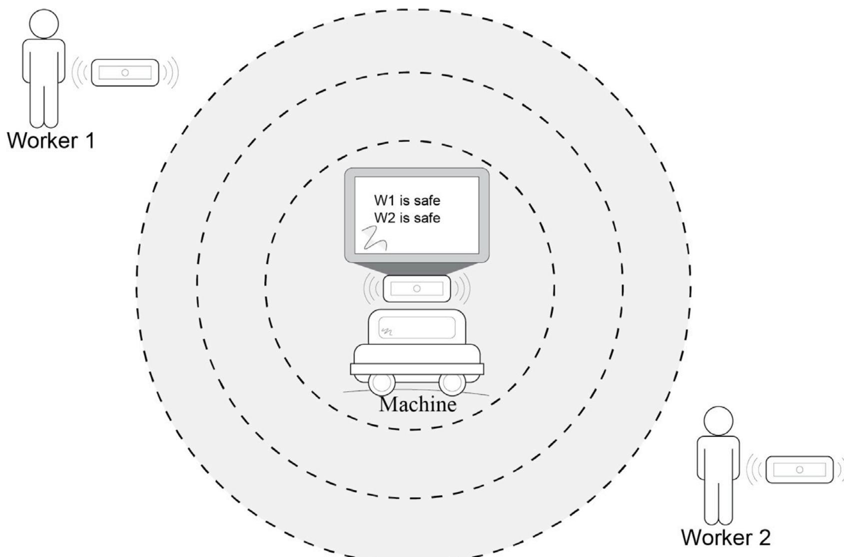


Fig. 12. Using the IoT system for proximity detection on the skidsite.

increase communication reliability, this on-site study has allowed us to test the system on-site in industry and has illustrated that it can be adapted to suit specific forestry scenarios.

6.2. Proximity detection around the skidsite

Cable-hauling is not the only dangerous activity in the forestry industry. Incidents have also been known to occur on the skidsite when workers are moving in and around large forestry machines. Fig. 11 shows a typical forestry skidsite. A skidsite is a flat piece of land where forestry machines are used to process felled stems and prepared them for transport. 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.

Fig. 12 illustrates how our IoT system could be adapted for use around the skidsite. In this case, the main unit is placed within one of the machines on the skidsite. The visual display then shows radial distances expanding out at 10 metre increments. The carried units can then be placed in a pack to be carried by forestry workers who are moving around the machines. The system would then display the workers' locations on the screen and mark them as red (unsafe) if they move too close to the centre (as shown in Fig. 13). The workers would also receive a vibration on the carried unit when they get within a predefined dangerous range of the machine.

We have not yet conducted an on-site evaluation for this scenario. However, we have evaluated the system in an off-site environment. For this evaluation we focused on the communication between the main unit and the carried unit, both with line-of-sight, and when line-of-site was obstructed (as would likely be the case at a skidsite). For this evaluation, we measured the number of packets that were being received by the main unit over a period of 100 s at five distances (10 m, 20 m, 30 m, 40 m, 50 m). We repeated this twice, once with vehicles placed between the main unit and the carried unit, but with line-of-sight remaining (*i.e.* no obstruction), and once with vehicles directly obstructing the line-of-site (*i.e.* obstruction) (the off-site environment can be seen in Fig. 14).

As shown in Table 7, having the line-of-site obstructed affected the number of packets that were lost. However, in this environment, even at the furthest distance (50 m) and with obstruction, the main unit was still receiving 53 packets per minute (89/100∗60), or an average of one packet every 1.13 s. While this application has not yet been tested on-site in industry, this gives a good indication of how our system can be adapted to different hazardous scenarios.

7. Discussion

This paper introduces a human-focused IoT system as an assistive safety technology for the New Zealand forestry industry. The IoT system

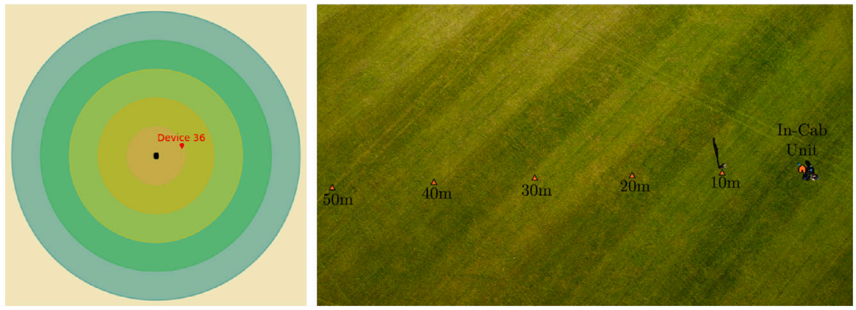


Fig. 13. Setting a geofencing for proximity detection.

Fig. 14. Conducting an off-site evaluation.

Table 7
Off-site test results.

Distance	Number of packets received (no obstruction) (per 100 s)	Number of packets received (obstruction) (per 100 s)
10 m	100	95
20 m	100	95
30 m	99	94
40 m	99	92
50 m	99	89

is made up of two devices: a main unit and a carried unit. The main unit calculates a geofence representing a dangerous area and allows workers to get a visual confirmation (via a screen) when people near the area. The carried units are worn by forestry workers (in a pack or pouch that they carry with them) and send the workers' locations to the main unit so that the main unit can display the workers' locations relative to the geofenced area. The main unit can then determine whether or not the workers are safe and update their status accordingly. This system would be of particular interest when weather and terrain conditions make it difficult to see the workers on the ground, or when people are working around large machinery that are difficult to see out of.

7.1. A comparison with existing approaches

Section 3 discussed existing IoT systems for safety, both within the forestry industry, and in three other hazardous environments: mining, oil and gas, and construction. Table 8 provides a comparison between each of these systems (rows 1–4) and our system (row 5). As discussed in Section 3.1, in order to develop a system for use in forestry, that system needs to be low cost and portable (*e.g.* no infrastructure required). This is reflected in Table 8, where neither our solution (row 5) nor the existing forestry solution (Zimbelman et al., 2017) (row 1) rely on any off-site (wireless or cellular range) (column 5) or on-site (column 6) infrastructure. Instead, both solutions rely on Radio Frequency alone for data transfer. In contrast, all other systems (rows 2–4) rely on either wireless or cellular range or a custom built, localised mesh network.

Both the mining (Shabina, 2014) and oil and gas (Thibaud et al., 2018) solutions include a custom built, localised mesh network for data transfer. This provides the advantage of being able to transfer data across longer distances, which can be a disadvantage of the shorter-range forestry systems. However, both mining and oil and gas sit within environments that make this more feasible. Mesh networks can be setup inside the mine, and easily repositioned when the active area of the mine changes. Similar can be done in the oil and gas industry. In contrast, as already discussed, the forestry industry is transient. The active part of the worksite can move as frequently as daily, and the worksites themselves are located all over the country, with crews moving from one to another regularly. The construction system (Kanan et al., 2018) is the only one that relies on external infrastructure (wireless or cellular communication). This is understandable, as construction worksites tend to be based in cities and urban areas where wireless and cellular range is readily available.

Finally, Table 8 also provides a comparison of the scope of each system. As shown in the table, the scope of each system directly reflects areas of risk in each industry. Mining and Oil and Gas both have risk of toxic gas exposure. As such, both systems measure air quality (CO and CO^2). The oil and gas system also measures the physiological state of the workers.

In contrast, one of the highest risks in both forestry and construction centres on interaction with hazards such as heavy machinery. As such, all three systems (row 1, 4, and 5) focus on proximity detection. Yet, while each system uses proximity detection, each is interested in a

Table 8
A comparison of approaches.

Scope	Industry	Types of data	Communication	Off-site infrastructure	On-site infrastructure	Estimated cost
Proximity detection: two workers	Forestry (Zimbelman et al., 2017)	GPS location data	RF	No	No	Low
Atmospheric detection	Mining (Shabina, 2014)	Air quality (CO and CO^2)	RF	No	Yes, a localised mesh network	High
Atmospheric detection + physiological state	Oil and Gas (Thibaud et al., 2018)	Heart rate, respiration rate, and air quality	RF	No	Yes, a localised mesh network	High
Proximity detection: worker + machine	Construction (Kanan et al., 2018)	Distance (ultrasound)	RF, Bluetooth, GPRS	Yes, internet access (GPRS)	No	High
Proximity detection: worker + hazard	Forestry	GPS location data	RF	No	No	Low

different aspect. The existing forestry system centres on a set of mobile geofences which allow workers to become aware of each other while felling trees. The construction system focuses on proximity detection directly behind heavy machinery. Our system centres on geofencing for cable-hauling and proximity detection on a skidsite. This illustrates the importance of (and many uses for) proximity detection within hazardous and high-risk industries.

7.2. Challenges

When developing an IoT-based assistive safety solution for use within the forestry industry, there are two main challenges that we encountered: the lack of infrastructure, and the limited range of RF.

First, as discussed in Sections 3.1 and 7.1, due to the remote and transient environment, technology used in the forestry industry must not include any reliance on either off-site or on-site infrastructure. This makes developing IoT solutions for forestry difficult, and the technology and data transfer protocols limited. Here, it should be noted that forestry-based IoT solutions could include cloud-based data. However, this data would need to be stored locally on-site and uploaded later when the equipment has been moved off site and back within wireless and cellular range. While on-site, the most feasible data transfer protocol is via RF, as illustrated by our solution and that of Zimbelman et al. (2017).

Second, while RF is the most feasible form of data transfer/communi cation for forestry environments, it tends to be best suited to shorter-ranged, line-of-site communication, which is not the typical use case within forestry. As discussed in Section 6.1, our preliminary on-site testing highlighted some of these challenges, namely the communication when the RF antenna is mounted inside the cab of heavy machinery, and the communication across long ranges in less than ideal conditions.

While our main unit uses a RF module which is placed inside the device and is mounted to the inside of a cab, Kanan et al. (2018) use a RF antenna, which is mounted to the back of the heavy machinery. The use of a RF antenna which is mounted outside the machinery, rather than a smaller RF module mounted inside, would make setup more costly and more complex. However, it could aid in strengthening our RF signal. This could, in turn, allow for better transmission between the main unit and the carried unit, and less interference across longer ranges.

7.3. Future work

Our IoT system is a stand alone system that used RF and location data to track workers in and around hazardous areas within the forestry industry. This system could be expanded and/or adapted in a miriad of ways, including the addition of mobile geofencing, and the inclusion of Context History and Context Prediction.

First, other researchers (Zimbelman et al., 2017) have investigated the use of mobile geofencing, *i.e.* a geofence that moves with a worker when they move. As discussed in Section 3, Zimbelman et al. (2017) focused on one forestry scenario, that of tree felling, where workers move in and around a forestry area cutting down trees. While a mobile geofence is well suited to this scenario, we can imagine other scenarios both within forestry and in other hazardous industries where a mobile geofence could also be beneficial (*e.g.* any scenario that involves two or more moving hazards, such as a moving machine and a moving worker). This highlights a challenge within both the forestry industry and other hazardous industries — developing IoT solutions for safety in industries where hazards may be of any shape or size and may be stationary or moving.

While we have not yet investigated the use of a mobile geofence, we have developed our system to create two different forms of geofence: a circular geofence and a rectangular one. We have also developed the ability to set the parameters of the geofence using a button on the carried unit. With a little adaption, this would allow the creation of irregular geofences of any shape or size, which in turn allows the system to be adapted to a variety of different scenarios – *i.e.* any scenario where proximity or closeness to a hazard poses a risk of injury.

Second, our system uses geolocation to track workers in real time. However, it does not take workers' previous locations (*e.g.* context history) into account. Context History refers to the use of not just a user's current context (*i.e.* the present), but also their past context within a specified time period (*i.e.* the past). This consideration of past context is referred to as Context History (Rosa et al., 2015). Context History can be used to develop Context Predictions (*i.e.* the future). Context Prediction uses models and algorithms to predict future scenarios. In general, this can include both location data and more general context information. While the variability in scenarios can make Context Prediction challenging, researchers are developing models that decide the best prediction model for individual situations (da Rosa et al., 2016; Dupont et al., 2020). In our scenario, the use of Context History and Context prediction could allow us to use the past context (*e.g.* location and environmental variables) of workers and machinery to identify a potential incident before it happens. While this is outside of the current work, future work could include incorporating Context History and Context Prediction to develop a more intuitive solution.

8. Conclusion

The New Zealand Forestry Industry is one of the most dangerous industries in New Zealand and internationally. Yet the NZ forestry industry has not yet widely adopted human-focused IoT systems for worker safety. The main contribution of this paper was to highlight this lack of human-focused IoT systems for safety in forestry, investigate whether IoT can be used as assistive safety technology in the New Zealand forestry industry, and highlight the challenges associated with it. First, we identified the main cause of low adoption of technology in the forestry industry — that of the remote and transient environment. Most IoT systems rely on new or existing infrastructure. This is obtainable in other hazardous industries (*e.g.* Mining, Oil and Gas, and Construction). However, the nature of the forestry environment and lack of infrastructure makes IoT system adoption difficult.

To this end, we have suggested the use of human-focused IoT systems that do not require any new or existing infrastructure. As an example, we introduced our IoT system, which uses radio frequency and GPS location data to track workers' locations in and around a geofenced area. This system has been shown to provide adequate range and reliability for RF communication, and the battery life of the devices have been shown to be adequate for working onsite where there is no power source. We have also illustrated how this system can be applied to two specific scenarios within the forestry industry: cable-hauling, and proximity around machines on the skidsite. For the former, forestry workers highlighted the usefulness of the system during bad weather or on steep terrain when visibility is poor.

This system has been compared against other systems that are in use, both within forestry and in other hazardous industries. This has allowed us to further highlight the importance of working without infrastructure for the forestry industry, and how other hazardous industries have built their own custom infrastructure such as RF mesh networks. Finally, we have discussed future work, including the possibility of incorporating Context Histories and Context Predictions to create a more intuitive system. The system could then predict incidents and injuries and notify workers of the risk before any incidents occur.

Ethics approval

For the forestry study, ethics was applied for and approved by the University of Waikato Human Research Ethics Committee on 11th May 2021 (HREC(HECS)2021#18).

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CRediT authorship contribution statement

Jemma L. König: Writing – original draft, Validation, Supervision, Methodology, Formal analysis. **Judy Bowen:** Writing – original draft, Supervision, Methodology, Funding acquisition, Conceptualization. **Annika Hinze:** Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Dylan Exton:** Validation, Software, Methodology, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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