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Falcon Forestry Claw

Solving Performance Limitations for the Falcon Forestry Claw Motorised Grapple Carriage

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FUTURE FORESTS RESEARCH

DC REPAIRS LTD
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Abstract

Within the next ten years the New Zealand forestry sector will be faced with the task of harvesting a significant area of first rotation *Pinus radiata* that has been planted on steep and marginal terrain. Because of the location and the poor terrain on which the forests are planted, there will be increased infrastructure and harvest costs which will limit profitability of harvest operations. If efforts are not made to reduce harvesting costs, harvesting could potentially become non-economically viable and the valuable resource will be left to reach mortality. It has been identified that using cable harvesting systems which shot gun motorised grapple carriages could decrease the logging rate and increase worker safety. Moutere Logging and its subsidiary DC Repairs have developed a motorised grapple carriage to be shot gunned (i.e. out hauled by gravity). The process of grappling stems often results with the grapple colliding with the ground. The shock of this collision is transferred through the carriage and all its internal components. The shock loading can cause damage to components which results in downtime and lost profits. By providing the operator with real time range data that relates the carriages position to the cutover, it is predicted that the risk of collisions will reduce thus increasing the profitability of the system. An investigation into range finding methods, operation principles of the carriage and the working environment of the system was conducted. From the investigation it was determined that an ultrasonic range finding system could potentially fulfil the required design specifications. A field test was carried out with an ultrasonic sensor to determine if it could accurately range off the cutover. Experimental results show that ultrasonic sensors can effectively range off forest residues and show strong potential to be installed into carriages to provide real time range data to the operator.

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Introduction

During the 1980's and 1990's the New Zealand plantation forest industry grew significantly, as a result many areas of steep marginal terrain were planted in pine trees (Raymond, 2012). From analysis of the 2011 National Exotic Forest Estate statistics (Ministry of Agriculture and Forestry, 2011), there is an estimated area of 500,000ha of small, steep terrain forest that is due for harvest in the next ten years. This presents a challenge when considering that most of the small forests have little or no road infrastructure. The development of a forest road network in remote steep locations requires a significant amount of expenditure when compared to localised flat terrain due to increased earthworks.

The combination of steep topography, poor soils and environmental constraints associated with the oncoming harvest, means that cable harvest systems will be used extensively to harvest the timber. Although it is safer to harvest steep terrain with cable harvesting systems (Jarmer, 1992), it is still a hazardous procedure. Between 2005 and 2010, the industry wide injury database run by the Forest Owners Association recorded 18 fatalities in New Zealand. Tree Felling and breaking out contributed to 39% of these fatalities (Ministry of Business, 2012). When compared to cable harvest systems, it has been established that mechanised ground-based harvest systems are more cost effective in the order of 50-100% (Visser, 2011).

It is clear that the higher road and harvest costs that are associated with steep terrain harvesting will have a negative impact on the revenue earning capacity of the forestry sector. One of the best opportunities for reducing harvest costs whilst increasing productivity and worker safety is through developing improved cable extraction systems.

The main contributing factor which influences the productivity of cable harvest systems is the terrain, which in turn dictates what type of rigging configuration and equipment that can be utilised (Vissr, 1998). A rigging configuration which is regarded as being highly productive when used in areas that allow high deflection is the shot gun configuration. The shot gun rigging configuration consists of a simple two-rope system used for uphill yarding utilising a skyline and mainline (Studier, 1974). From a recent survey of experienced cable yarder operators and planners from within the New Zealand industry, it was found that 19% actively used this configuration as it is simple to configure and it maximises deflection and payloads (Harrill & Visser, 2011). The shot gun is a preferred configuration when deflection increases from medium to high; such instances occur during the transition from rolling to steep terrain. A typical shot gun system in displayed below in Figure 1.

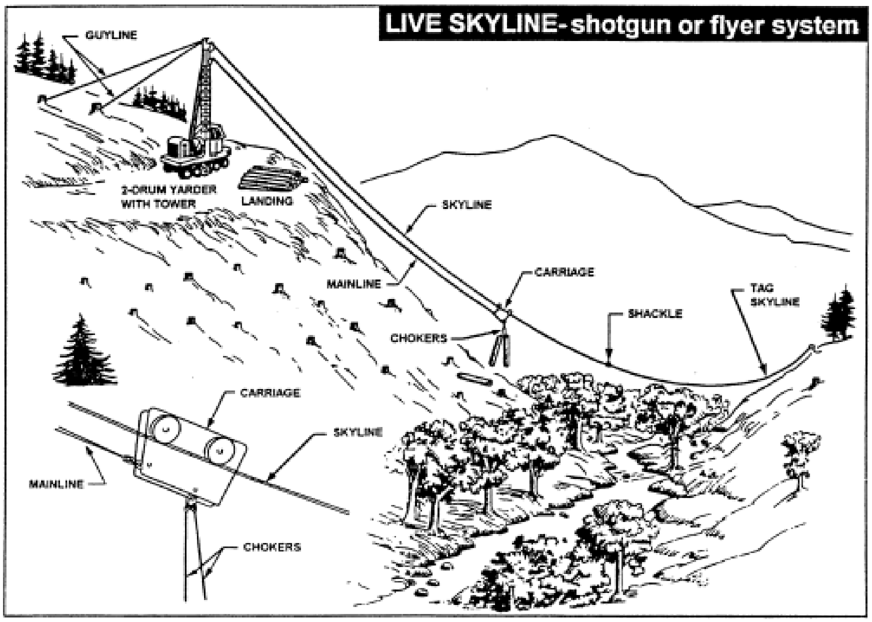

Figure 1: Live Skyline-Shotgun system (WAC, Department of Labor and Industries)

Advanced yarding equipment such as motorised carriages, are viewed as productive, versatile devices and are the most preferred in high to extreme deflection scenarios. Despite this belief, only 25% of survey participants had used any rigging configurations that included motorised carriages, mechanical slack pulling carriages or grapples within the last five years (Harrill & Visser, 2011). This can somewhat be attributed to the fact that the survey participants are not willing to make the capital investment. It is perceived that their investment in a motorised carriage will not provide the desired return because it is likely to be damaged during operations and require additional maintenance.

An alternative that is favoured over the motorised carriage is the mechanical grapple. Favoured for its simplicity and robustness, mechanical grapples are perceived to be very productive and good for short hauling distances (Harril & Visser, 2012). The primary advantage associated with mechanical grapples is that workers are removed from the cutover during stem extraction. Removing workers from the cutover improves worker safety and reduces crew size which also reduces operational costs. Mechanical grapples are commonly used on running skyline configurations, requiring an additional line to open and close the grapple.

Advances in grapple technology have resulted in grapples which do not require mechanical control from an additional line, but rather they use a power supply that enables them to be radio controlled. This advancement is known as the motorised grapple carriage. As the motorised grapple carriage does not require an additional line to control grapple functions, it can be used on simplistic rigging configurations such as the shot gun.

The combination of a motorised grapple carriage coupled with a shot gun rigging configuration is a very attractive option when considering the possibility of increased production and fuel savings. It is clear from Harrill & Visser's (2012) research that this configuration will not be widely adopted by cable yarder owners and operators because the risk is perceived to be too high. The process of shot gunning exposes the motorised grapple carriage to the risk of damage from collision with the cutover (i.e. the clear felled harvest area comprised of exposed ground and branches) during each extraction cycle. If contractors are not willing to invest in a motorised slack pulling carriage which are predominately used on live skyline systems, where the carriage is clear of the cutover at all times, it is unlikely they will invest in a carriage that frequently comes into close contact with the cutover.

Despite research suggesting that a motorised grapple carriage that is designed to run on a shot gun rigging configuration will not be accepted by industry, Moutere Logging and its subsidiary DC repairs have been developing the Forestry Falcon Carriage (FFC) to do so. In order for the FFC be successfully accepted by industry, owners must feel that their investment is going to return a profit and not be damaged during stem extraction.

During a site visit to Nelson to watch the FFC in operation, it was apparent that shot gunning the FFC was a high risk procedure. Frequent collisions with the cutover were observed, some collisions resulted in downtime to repair damage. An investigation was undertaken into how to improve control of the grapple carriage so that collisions could be avoided. It was determined that providing the operator with real time range data that related the FFC's proximity to the cutover could possibly reduce the frequency of collisions.

This report was commissioned by Future Forest Research (FFR) to investigate and explore opportunities to improve the control system on the Falcon forestry claw. It has been concluded that carriage control can be improved if the operator is provided with real time range data that relates the position of the FFC to the ground. It is predicted that the operator will be able to act on the range data so the frequency of collisions will reduce. From literature review it is understood that there are no grapple systems in existence that utilise range finding systems. The report covers an investigation into current range finding technology, operating function and environment of the FFC and a field trial of a range finding sensor. Conclusions are drawn on the applicability of range finding technology to the FFC finding technologies that could be implemented to the FFC, for the purpose of warning the operator of an imminent collision.

Range finding technology

Range finder technology, developed primarily for range determination in industrial applications such as surveying or examination of objects, now is a widespread mature technology (Herbet, 2000). A range finder, as the name suggests, is an instrument that provides a non contact measurement distance between the instrument and an object. Range finders are classed broadly as passive or active and on the other hand into monocular and binocular methods (Jarvis, 1983).

Passive range finding

The passive monocular approach includes such techniques as, shape from texture, shape from shading, shape from contours and other shape principles. Electronic methods gather the 3-D information about the scene from the brightness and intensity of the captured image. Passive binocular ranging methods, known as stereo vision, work on the same principle as human's vision. A targets 3-D location is found by viewing the object from two different positions. Stereo vision is constrained by the correspondence problem, the matching of scene features in the two images. The process of matching is computationally expensive (Jarvis, 1983), and cannot be justified for real time applications. Passive ranging techniques suffer from environment factors, such as scene illumination, surface reflectance and camera hardware characteristics (Moring, 1989). Because environmental factors have a large influence over passive ranging performance, such techniques are poorly suited to outdoor environments (Wagner, 2004).

Active range finding

Active ranging techniques involve some form of controlled energy, where a beam is directed at the target and the reflected energy is detected. Active binocular techniques are based on triangulation, which differs from stereo as one of the cameras is replaced with a controlled light source (Moring, 1989), see Figure 2. The controlled light source illuminates a light pattern on the target; the pattern is then detected by a camera which is positioned parallel at a certain lateral distance (baseline) from the source. The image is processed by using the principle of triangulation to determine the location of the target. Compared to passive techniques, active triangulation methods greatly simplify the signal processing to be done to recover distance information (Rioux, 1984). The simplicity of active range finding is an attractive feature; however the technique has several critical drawbacks when used in a dynamic outdoor environment. The first problem relates to the depth of field over which the system can effectively range. The length of the 'baseline' directly affects the resolution relative to depth ratio of the system. To determine the range of distant targets, the system is required to have a large baseline. Increasing the base line increases the occurrence of occlusions and missing data, which limits the system to short range applications (Herbet, 2000). There are a limited number of commercially available active triangulation rage finders, available systems are primarily used for ranging targets less than 10m away (Beraldin, 2003). The second problem is detecting the illuminated light pattern on the target in the camera image. External sources of energy can add a non-negligible contribution to the irradiance introduced by the controlled light source on the target (Ilstrup, 2010). A simple way to combat this problem is to increase the power of the light energy source. This however causes eye safety concerns; established regulations such as the American National Standards Institute (ANSI) pose limits on the amount of energy that is allowed to be emitted in a laser pulse.

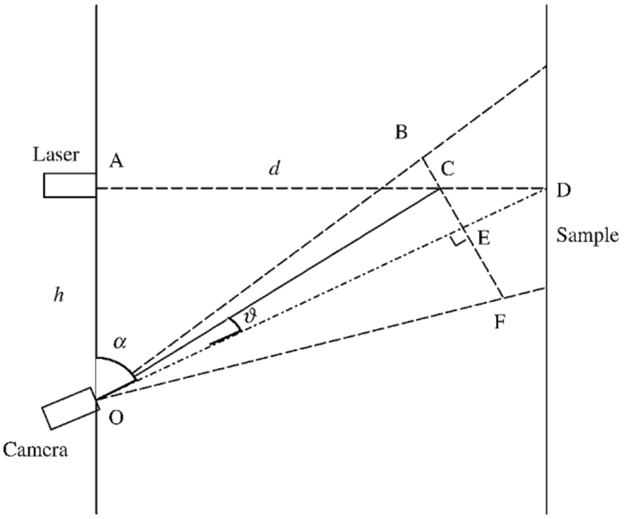

Figure 2: Simple active triangulation instrument (emeraldinsight.com)

Active monocular methods determine the range of an object by measuring the time taken for the emitted energy to travel from the transmitter to the target and reflected back (Gokturk, Yalcin et al. 2004), refer to Figure 3. These sensors are typically referred to as Time Of Flight (TOF) sensors. TOF sensors directly produce range information that does not require any further computation (I. Moring, 1989). Two common TOF ranging sensors are commercially available, laser and ultrasonic or sonar. They differ in the form of energy that they emit to establish the range of targets.

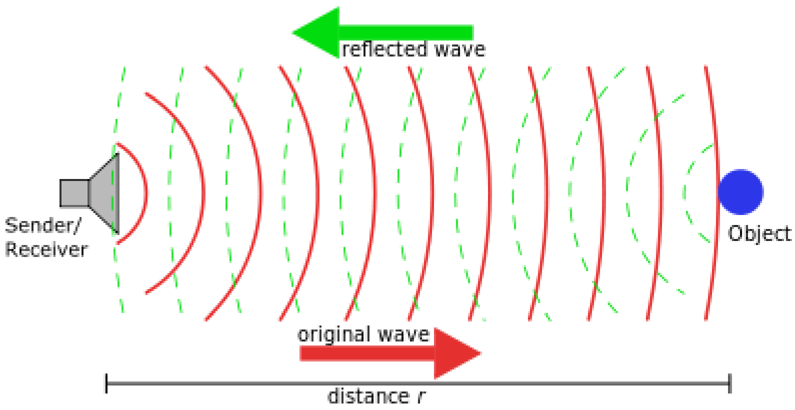

Figure 3: Ultrasonic Time of Flight Principle (Wikipedia)

Ultrasonic sensors transmit a short burst of ultrasonic sound waves toward the target. By emitting sound, ultrasonic sensors are not affected by ambient light or the colour of the target. There are a wide range of available sensors on the market; they vary from one another in their features, protective housings and mounting configurations. More importantly, they operate at different frequencies and produce different wave radiation patterns. The ranging environment combined the sensors acoustic characteristics can have a great effect on how the sensor operates and the measurement generated (Massa, 1999). The sensors operating range and spatial resolution is directly influenced by the sensors operating frequency and power, impedance of the propagation medium, the sensitivity of the receiver and target reflectivity. Therefore, it is essential to stipulate the desired performance of the sensor and tailor the system to work within the environmental parameters (Canali, 1982). Ultrasonic sensors have been successfully used in outdoor environments since the late 1980's, where they have been used to measure the height of tree canopies so that biomass could be estimated (Lee, 2010). More recently, Thomas Fricke-(2011) attached an ultrasonic range finder to a mobile tractor and successfully determined the height of legume grass over a paddock. Thomas's work demonstrated that an ultrasonic sensor can be used effectively in a dynamic outdoor environment. Ultrasonic sensors are well suited to use in industrial environments as they are robust and unaffected by dirt and grease (Sains, 1964). In addition, ultrasonic sensors are inexpensive, compact, have simple circuitry and are easy to interface with computers (Tanzawa, 1995). A concern with ultrasonic sensors is that the majority of commercially available sensors have a less than 10m operating range. From investigation into product lists, it was found that there are cost effective ultrasonic sensors that can range out to 25m.

Laser Range Finders (LRF's) differ to ultrasonic in that they emit energy in the form of light. LRF's are used in a large range of industrial applications, ranging sub meter to kilometer distances in some applications. Although TOF LRF's are thought to be well suited for long range applications in outdoor settings (Herbet, 2000), they operate poorly in low visibility conditions (Luo, 2004). Atmospheric conditions such as fog, smoke or rain can cause the emitted light to scatter, resulting in invalid range data. In addition to atmospheric conditions, a LRF's performance is limited by a targets reflective property (Sabatini, 2010). The reflectivity of a target can be expressed by two components, the specular and diffuse component, displayed in Figure 4 below. The energy that reflects away from the target at the opposite angle of incidence is referred to as the specular component. The diffuse component refers to the energy which is reflected off in all directions. Natural broken terrain, such as soil, has low reflectance and is highly diffuse. SICK Sensors sales engineer, Simon Bennetto said that bare soil in some cases can be comparable to coal in terms of reflectance. Acuity, a laser sensor supplier, state that when ranging off coal, the maximum range and depth of field of a LRF could possibly be limited to 1/5 of what is possible from light-coloured targets (Schmitt Industries, 2012).

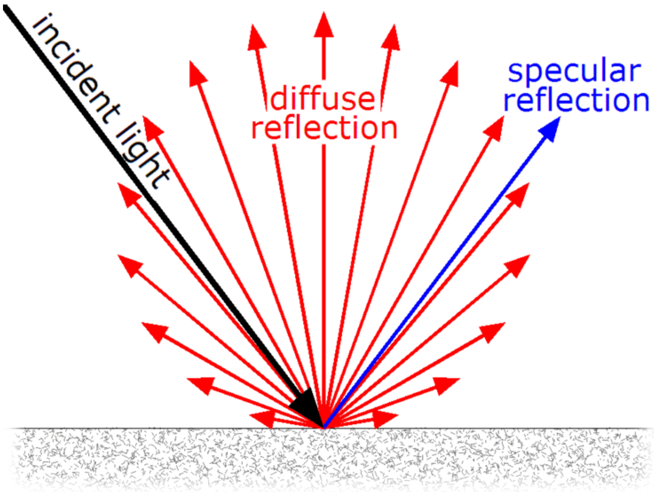

Figure 4: Different modes of reflection depend on surface characteristics (Wikipedia)

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Many turnkey systems are now available and have been demonstrated in robotics research (Herbet, 2000) but they are costly when compared to other solutions such as ultrasonic. Unlike ultrasonic systems, LRF systems are viewed as a less durable option and are not recommended to be exposed to shock loading (Bennetto, 2012).

Falcon Forestry Claw function and principles of operation

The Falcon forestry claw carriage is equipped with an internal combustion engine which powers a hydraulic grapple and rotator unit, the FFC provides flexibility during extraction operations. The flexibility over traditional mechanical grapple stems from the utilisation of a hydraulic power supply. Unlike mechanical grapples which are fixed on a single axis and use a cable and gravity to operate the grapple, the remotely operated hydraulic grapple and rotator unit allows the operator to have full control over grapple functions. As a result, stems that would have been previously un-accessible to a mechanical grapple can be extracted with the FFC. Recently, mechanical grapples have been fitted with camera vision systems to eliminate the need for spotters. The FFC has also been fitted with a video camera so the carriage can be operated if the operator doesn't have good vision of the stems. The video camera is mounted on the carriage in the downward position to capture the grapple and cutover. The video data is transmitted via a wireless radio frequency data link to the operator who views the live data stream on a LCD monitor. From the live video footage, the operator is able to locate stems on the cutover and determine where the grapple is relative to the stems. Through using wireless radio frequency links to transmit data, the FFC can be shotgunned out to distances in excess of 600m from the hauler. The operating principles behind the FFC allows the carriage be utilised in scenarios where breaker outs and strops would previously have been favoured over a mechanical grapple. This is the primary advantage of the FFC, as it is vastly improves worker safety because workers are removed from the cutover. This eliminates the risk that is associated with performing the inherently dangerous task of "breaking out".

Working Environment of the sensor and carriage

Location of the sensor

It is vital that the sensor is mounted within the carriage housing; this is to shield it from direct impact from objects such as branches or the ground. Modern electronic range finding equipment, which is widely used in industrial applications, must be able to survive the harsh environmental conditions within the carriage for the life cycle of approximately 15 years. The hostile environment within the carriage can be mainly attributed to the internal combustion (IC) engine. Internal combustion engines generate power using the extremely rapid pressure pulse from igniting fuel and oxygen above the piston. The explosive pulses of combustion contribute negatively to the mounting environment of electrical components in two ways. Firstly, the pulses cause the engine to vibrate in response and then engine force is transmitted to the chassis by vibration isolators. Traditionally designed vibration isolators are often insufficient for maintaining a failsafe vibration environment for electronic equipment (Veprik, 2003). Insufficient isolation can result in serve vibration which can critically affect the endurance of mounted components, soldered joints, connectors etc. Secondly, IC engines produce waste energy in the form of heat, from the conversion of primary energy to mechanical energy. Compression engines, such as diesel engines, typically loose 38-70% of the fuel heating value through cooling of the engine and spent exhaust gasses (Haidar, 2001). Whilst the exhaust is directed outside of the carriage, the other radiant energy from the engine is dissipated into the carriage. This leads to temperature rises within the carriage, which can induce temperature related failure modes for electrical components. Research conducted by Mattila(2006) in the field of on the failure modes of solder interconnections, found that the average number of drops and vibrations that component boards could withstand decreased by 40% when the temperature was elevated up to 70°C from room temperature. Additional to the vibratory forces that are transferred through the carriage, shock loads are prominent too. The process of grappling stems often results with the grapple colliding with the ground. The shock of this collision is transferred through the carriage and all its internal components. Therefore it is vital that the range finding technology that is chosen is of quality construction, well isolated and has strong vibration and shock resistance. Supplementary to IC engine, the carriage is not water tight, therefore the range finder system must be sealed as to avoid any precipitation damage. Figure 5 below displays the internal environment within the FFC.

Figure 5: Falcon forestry claw with engine exposed

Environment of the carriage

The range finding technology must be able to withstand and function properly within the carriage, in addition, it must effectively range find in the environment from which the carriage operates. The FFC operates exposed in the outdoor environment of the cutover, example of a typical working environment of the FFC is shown in Figure 6. This introduces non controllable factors into the system. Factors such as varied ambient illumination, changeable atmospheric conditions and temperature fluctuations can have a profound effect on the performance on range finding systems. Another factor that has a large effect on the performance of a range finder is the surface that it ranges from. In this application, the cutover is the surface from which we which range measurement are taken from. The surface is irregular, highly diffuse, has low reflectivity and has multiple objects arranged in various orientations (branches, needles etc). To perform to an acceptable standard, the range finder must be able to effectively range over a variety of light and weather conditions. Additionally, the range finder system must be able to range off the highly variable terrain that is the forest cutover.

Figure 6: Typical working environment for the FFC

Range finder performance requirements

A set of performance requirements were established for the range finding system, the system must meet these requirements during all operating conditions of the FFC. It is believed that these are the base line requirements that must be satisfied, so that the operator is supplied with sufficient information to avoid collisions.

Depth of field

The minimum depth of field of the system, defined by the distance over which the sensor will be able to reliably measure displacement, is specified as 1.5 to 15m. This range was chosen for two reasons. Firstly, there is no perceived advantage in having a smaller minimum range as the grapple extends down past the carriage. Therefore the grapple is the first part of the FFC that will collide with the cutover; any range data below this point is redundant. A maximum range of at least 15m is required. With this span, if the carriage is falling at a very rapid rate of 3m/s, the operator has 4.5 seconds to react from when the ground is first ranged to the point of collision.

Resolution

Resolution is defined as the smallest increment of change in distance that the range finder system can detect. It is directly affected by the vertical speed of the FFC. Because the target is moving rapidly, the sampling frequency needs to be increased to reduce error. For the falling rate of 3m/s, the minimum allowed resolution is 3.7% or 0.5m.

Accuracy

The measurement of the difference that can be expected between a sensor's reading and the actual distance measured is defined as the accuracy of the sensor. The lowest acceptable accuracy for the system is specified at 0.5m.

Sensor system suitability

A weighted decision matrix seen in Table 2 was used to determine which range finding system was best suited for the Falcon Forestry Claw. Three active range finding methods were chosen for analysis, active triangulation, ultrasonic and laser range finding. Passive range finding techniques were omitted on the basis that literature states that they do not perform strongly in outdoor environments. The weighted matrix is built on the attributes that have been identified as key components which will ultimately define the performance of the range finding system. Many of the attributes were ranked with the maximum weight of 1 because they were seen as critical to the systems performance.

From using knowledge gained from literature and relating it the FFC’s operating environment, the performance of each individual ranging system was scaled from 1-5 in each category. An ascending scale from 1-5 was used, 1 representing very poor performance and 5 representing excellent performance within the category. The scores were then weighted on how important the attribute is to the function of the system.

Table 1: Attribute rating scale for decision matrix

Rating				
Excellent (5)	Good (4)	OK (3)	Poor (2)	Very Poor (1)

Table 2: Range finder decision matrix

		Active triangulation		Ultrasonic		Laser range Finder	
Selection criteria	Importance	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score
Operational Range	1	1	1	3	3	5	5
Low Light Performance	1	5	5	5	5	5	5
Bright Light Performance	1	1	1	5	5	5	5
Diffuse Target performance	1	3	3	5	5	3	3
Durability	1	1	1	5	5	2	2
Accuracy	1	5	5	5	5	5	5
Cost	0.5	1	0.5	5	2.5	2	1
Resolution	0.5	5	2.5	4	2	5	2.5
Ease to mount	0.4	2	0.8	5	2	5	2
All Weather Performance	1	2	2	4	4	2	2
Total		21.8		38.5		32.5	

From the weighted decision matrix, it was concluded that ultrasonic sensors were the best candidate for further investigation. Although literature indicates that ultrasonic sensors perform well when ranging off natural continuous surfaces such as legume grass, there was no research found on range performance over forest residues. The clear felled landscape consists of a variety of reflective surfaces such as rocks, bare earth, grass and tree residues. Measured ranges could potentially vary between the changeable surfaces, it was necessary to establish a field trial to determine how an ultrasonic sensor performs over the cutover.

Ultrasonic rage finder field trial

Material and methods

Technical description of the ultrasonic sensor

Measurements were recorded using an UM30-15113, manufactured by SICK Sensors. The sensor used in this study was single headed having one sonic transducer (frequency 80kHz) that acts both as a transmitter and receiver. The operating scanning distance is specified as 6m. The sensing range was checked using a horizontal concrete wall. The sensor was supplied with power from a 12V from an automotive battery and the ultrasonic echo was converted into an output voltage that increased linearly with distance. A volt meter was used to display the voltage and results were manually recorded.

Field experiment for static measurements

The experiment was conducted on 20th of August on a recent clear fell site in Moutere, Nelson New Zealand. Tests were conducted over bare, surface wet undulating clay and over dense forest residues. Residues consisted of branches, needles and bare top soil. The sensor was mounted to a rope which was strung over the harvest site. The use of a rope assured that the sensor was not taking obstructed readings from a mounting frame, instead only taking reading from the cutover surface. The rope was raised and lowered in intervals, a survey staff was used to measure the height from the surface residues to the sensor.

Results

The specified operating scanning distance was not realised during any of the tests. The maximum range over which the sensor generated outputs was 4m. This value was obtained for the concrete wall as well as the clay residue. Due to limitations in rope length, it was not possible to extend the sensor out to find a maximum range while testing over the residues. From Figure 5, as expected, the sensor provided a solid linear relationship between voltage and distance when ranging off the concrete wall. Testing of the clay soil produced an overlapping linear trend over the concrete wall data. The forest residues also produced a solid linear trend. When comparing the residue results to the concrete wall results, there is slight variation but is negligible and falls well within the accuracy tolerance of 0.5m

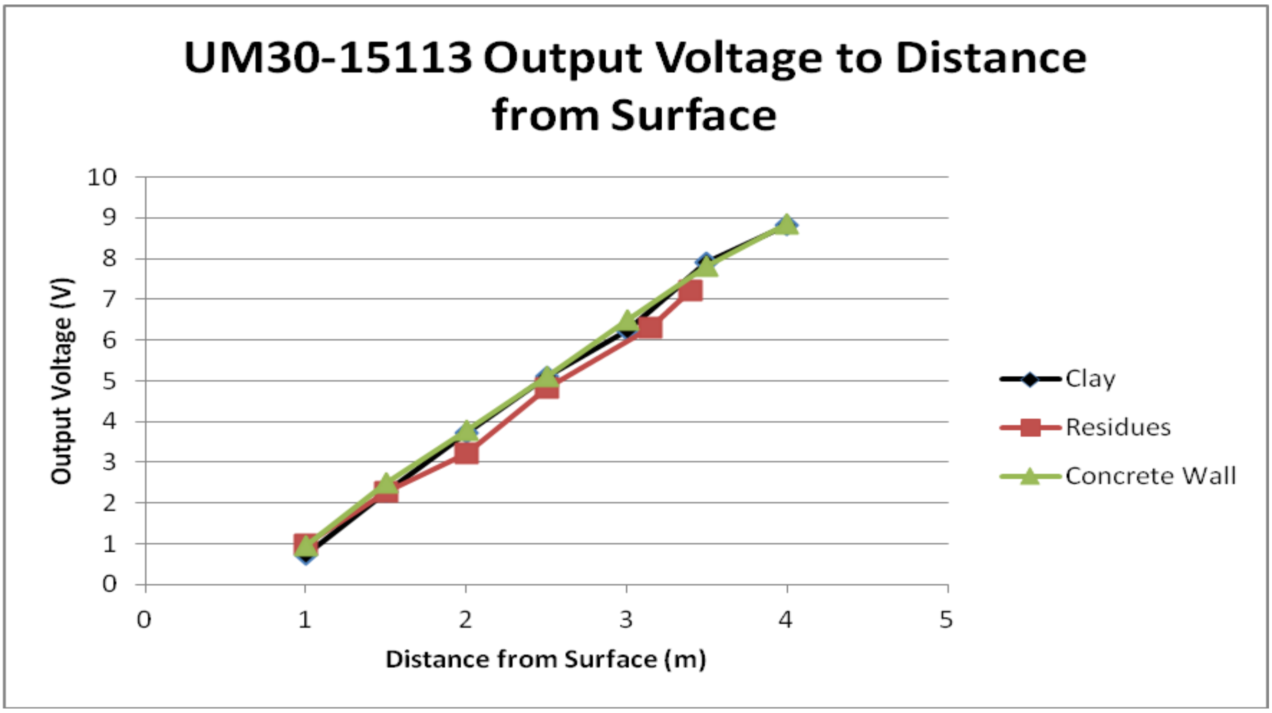

Figure 7: UM30-15113 field test results

Discussion

There are clear limitations with this field test, primarily associated with the lack of data points and that the test was done in static conditions. Although the test has limited data points, it clearly indicates that ultrasonic sensors can accurately range over forest residues in static conditions. With more time, further tests could be undertaken to prove the validity of the results. The test performed does not replicate the dynamic system in which the FFC operates. An improvement on the test would be to simulate the operation of the FFC by moving the sensor along on a known profile over the cutover and record the output voltage. Although a maximum distance value was not obtained over the forest residues when the sensor was attached to the rope, a maximum reading was obtained by rigging the sensor onto the survey staff. It was found that the sensors maximum range was 4m over residues when attached to the staff. Attaching the sensor to the staff is not constant with the test procedure, but it indicates that the sensors range is not limited by the residues. An area of concern is that the sensor did not meet its maximum specified range, falling 2m short. This is likely attributed to the fact that the sensor was second hand and had previously been programmed for other tasks. Time was taken to re-calibrate the sensor but is believed to have been unsuccessful. If further trails are going to be conducted to replicate the dynamic environment of the FFC, it is suggested that a brand new sensor with an operating range of at least 15m is trailed.

Conclusions

Research was conducted into the area of range finding technologies to determine the potential application of a range finding system for Forestry Falcon Carriage, with the aim of providing the carriage operator with real time proximity data that relates the carriage to the cutover. The working environment and performance requirements for a potential ranging system were clearly defined. Active and passive forms of sensing were investigated and it was determined that an ultrasonic time of flight range finding sensor had the greatest potential to provide accurate real time range measurements within the harsh working environment in which the FFC operates.

A static condition field trial of a UM30-15113 ultrasonic sensor was conducted over clay soil and forest residues. Results showed that the ultrasonic sensor provided accurate range methods over both surfaces but the maximum specified operating range of 6m was not achieved. The reduction in operating range has been attributed to the fact that the sensor was second hand and had been previously calibrated for other uses. Further sensor trials are required to simulate the dynamic operation of the FFC, preferably with a sensor that has a range of at least 15m.

From this study, it predicted that ultrasonic sensors will be fit for the purpose of ranging from the carriage to the cutover and will endure the harsh environment with the carriage for the service period of 15 years.

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Appendix

Below in Figure 8 is the radiation pattern for SICK sensors UM 30-15113 ultrasonic range finder that was used for the field test.

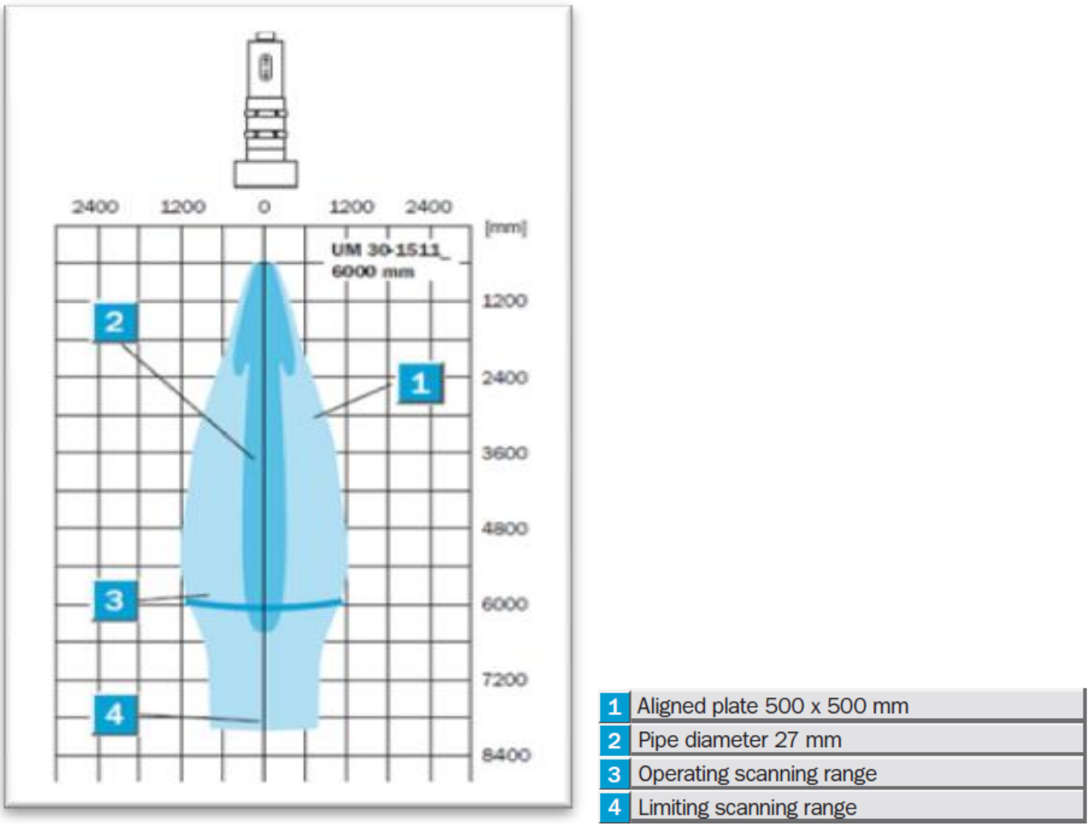

Figure 8: Radiation pattern of the UM 30 -15113