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# Introduction of Teleoperation to Steep Slope Harvesting: A Concept Design and Economic Feasibility Study

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# EXECUTIVE SUMMARY

The problem that Future Forests Research Ltd (FFR) is attempting to address is that harvesting plantation forests on steep terrain is challenging and expensive. Teleoperation, or the use of telecommunications to control equipment at a distance, has the potential to improve the safety, productivity and efficiency of harvesting operations on steep terrain.

This report combines earlier FFR work proposing two concept designs for the introduction of teleoperation to steep slope harvesting in New Zealand, with an economic feasibility study of one of those concept designs for machines that have the potential to achieve these aims.

A review of the use of teleoperated machines in other industries was undertaken. This review, combined with engineering experience at Scion, was used to propose the two concept designs. These concepts represent a proposed progression of the introduction of teleoperation to steep terrain harvesting in New Zealand.

The first of these concept designs is a teleoperated steep slope excavator tree harvester. The design includes full teleoperation, visual feedback from cameras on the excavator, and feedback from a range of sensors. This concept design should result in a commercial implementation within five years (i.e. within the life of FFR's PGP "Innovative Harvesting Solutions" programme).

The second concept design is a novel light-weight felling machine that uses an innovative mobility method to traverse forest terrain. As such it is more futuristic than the first concept design, and will require considerably more development.  It is expected that this concept design will result in commercial implementation within fifteen years.

The cost of retro-fitting an excavator for teleoperation once the detailed design and development has been completed has been estimated. A range of scenarios exploring the effect of teleoperation on productivity was considered, and the net present value of these scenarios was calculated.

The results indicated that an increase in harvesting rate of around 12 cubic metres per day (or 6% on current harvesting productivity) was required to make teleoperation feasible economically. This increase appears to be a realistic target for the programme.

# INTRODUCTION

Teleoperation describes the use of telecommunications for the wireless transmission of signals to initiate, modify, or terminate functions of equipment at a distance. In this report, the term teleoperation is used to describe a system where wireless communications allow an operator to control a machine out of direct line-of-sight. The term remote-control is used in this report to describe a system where wireless communications allow an operator to control a machine that is within sight of the operator. Semi-autonomous operation is where the machine itself controls some aspects of the operation to assist the operator, such as navigation and control or obstacle avoidance. In comparison, autonomous operation is where the machine can complete its tasks completely without human intervention.

Teleoperation has improved the efficiency of mechanical operations in many other industries. These applications include military, mining, crane work, and search and rescue. Developments in teleoperation are a natural progression in the technological advances from motor-manual tools and manually-operated machines towards semi-autonomous mechanisation.

Future Forests Research Limited (FFR) has developed a research project in its Mechanisation on Steep Terrain programme which seeks to apply teleoperation technology to improve the productivity and safety of steep terrain harvesting. This project is Task 1.2, Teleoperated Machine for Steep Country Harvesting.

It is proposed that teleoperation has the potential to improve efficiency in steep terrain harvesting in New Zealand in a number of ways:

- Improved safety of steep terrain harvesting through isolation of machine operators from hazards.
- Reduced physical and mental workload on the operator.
- Smaller more fuel efficient machinery.
- Lower emissions from smaller engines.
- Less ground disturbance through lighter weight equipment, possibly using different mobility systems.
- Improved machine utilisation through reduction in operator fatigue.
- Improved productivity, possibly through the adoption of elements of semi-autonomy.

A number of different machines for felling trees on steep slopes have been assessed in earlier FFR studies for their applicability to steep terrain harvesting in New Zealand, including both manned excavator harvesters (with traction winch systems) and remote-controlled and teleoperated processors and forwarders which are already operating in the forest industry overseas (Amishev, 2011[1]). Parker (2011) [2] also reviewed the human factors implications of teleoperation in harvesting.

The central hypothesis, which is the basis of further investigations presented in this report, is that teleoperation of excavator-based harvesters for felling and bunching stems in cable logging operations is a promising application. This report describes two proposed concept designs for teleoperation of a steep slope excavator-based harvester (Milliken and Parker, 2011[3]). An economic analysis of one of the concept designs was then undertaken. Although the effect of teleoperation on productivity cannot be assessed until such a teleoperated machine has been designed and built, the analysis presented in this report can be used to determine the feasibility of the project (i.e. whether the break-even increase in productivity is realistic).

# OBJECTIVES

Firstly to present two proposed concepts showing how teleoperation could be employed in steep slope harvesting; and secondly to conduct an economic feasibility study of the potential for improved productivity of a teleoperated steep country harvesting machine.

# METHODS

The methods used to meet the first objective were to:

1. Review the use of remote-control, teleoperation and semi-autonomous operation across a range of applications. This information was used to assess the feasibility of the technologies and how they might be applied to harvesting.
2. Consider a range of options for development of teleoperated machines. These development options fell into three categories:
    - off-the-shelf remote-controlled or teleoperated machines for harvesting:
    - retro-fitting existing harvesting machinery with remote-control or teleoperation equipment; and
    - custom-designed remote-controlled or teleoperated harvesting machines.
3. Develop two different concepts – one for immediate application (a teleoperated excavator) and a more futuristic design.
4. Conduct initial assessment of the advantages and disadvantages of the concept with immediate application, including preliminary recommendations.

The methods used to achieve the second objective were:

1. Estimate the cost of retro-fitting an excavator for teleoperation once the design has been developed.
2. Estimate the benefits of teleoperation of an excavator in a steep terrain harvesting application for a range of different scenarios.
3. Calculate the Net Present Value for each scenario.

Net Present Value was used to assess the value of the scenarios considered. The Net Present Value (summed over 25 years) is defined as:

$$N = \sum_{y=0}^{25} \frac{r_y - c_y}{(1+i)^y},$$

The notation used in this report is described in Table 1.

Table 1: Notation

| Variable | Description |
|---|---|
| $v_d$ | Increase in volume of wood cut per day due to tele-operation |
| $\rho$ | Revenue per cubic metre of wood cut |
| $r_y$ | Additional revenue in year $y$ due to tele-operation |
| $c_y$ | The additional cost in year $y$ due to tele-operation |
| $w$ | Days per year that the excavator is operating |
| $i$ | Discount rate for Net Present Value calculations |
| $N$ | Net Present Value |
| $y$ | Years since purchase of tele-operation equipment |

# RESULTS

# 1. A REVIEW OF EXISTING TELEOPERATION

A review of remote-controlled, teleoperated and semi-autonomous machines provides a useful comparison with harvesting operations. This information was used for two purposes: firstly, to determine what was possible, and secondly, to allow the concept design to make use of standard, open components and systems to ensure a rapid, cost-effective deployment. The latter point is particularly relevant to teleoperation in harvesting, as whatever system is developed will have a low volume of sales, and therefore design costs will be amortised over only a few units.

This review covers the following:

- The relatively recent adoption of teleoperated machines by the US military.
- The use of teleoperation in surgical operations that require a lot of dexterity
- The mining sector which probably has the most advanced teleoperated and semi-autonomous equipment outside the military.

## Teleoperation in the U.S. Military

The military is the sector that is most advanced in terms of its adoption of teleoperation. The U.S. military makes extensive use of ground-based and unmanned aircraft systems. The iRobot 510 Packbot is a small teleoperated robot that can be used for search, reconnaissance and bomb-disposal as shown in the left image of Figure 1. Communications operate on frequencies of 2.4 and 4.9 GHz with video and two-way audio (iRobot, 2011[4]). The US Army has been using unmanned aerial vehicles (UAVs) in combat operations for the past decade. They now have over 4,000 unmanned aircraft systems (Army UAS CoE Staff, 2010[5]). A Shadow unmanned aircraft is shown in the right image of Figure 1.

**Figure 1: Images of iRobot 510 Packbot (left) and Shadow unmanned aircraft (right). (From Army UAS CoE Staff (2010)[5])**

## Medical Robotic Technology

Surgical robotics was little more than a medical curiosity until Intuitive Surgical introduced the *da Vinci®* Surgical System in 1999. The da Vinci Surgical System[6] (Figure 2), is a robotic surgical tool that allows the surgeon to control surgical tools from a console.

The original prototype for Intuitive Surgical's da Vinci System was developed in the late 1980s at the former Stanford Research Institute under contract to the U.S. Army. While initial work was funded in the interest of developing a system for performing battlefield surgery remotely, possible commercial applications were even more compelling. Similarly, applications in harvesting are equally compelling.

**Figure 2: The da Vinci Surgical system (http://www.intuitivesurgical.com)**

The surgeon can see a binocular (3-D high definition) video stream of the surgical site and the surgeon's movements are scaled and filtered to allow very precise movement of the surgical instruments. The system provides haptic feedback so the surgeon can "feel" the forces that are being exerted by the surgical tools.

Binocular vision and haptic feedback would also enhance the productivity of a teleoperated excavator harvester. However, to allow rapid development of the first teleoperated machine, it is recommended that the first prototype teleoperated excavator be built without these features. The addition of haptic feedback and binocular vision can be investigated at a later stage.

## Caterpillar Detect System for Mining Vehicles

Caterpillar's in-cab object detection system, called Object Detection, uses a combination of radars, an in-cab display, and multiple cameras, to provide equipment operators with enhanced awareness for increased site safety.

At start up, during slow speed operation or whenever a machine stops for a set period of time, the touch screen display alerts the operator when objects have entered critical areas around the equipment. The radar view provides a visual indication of where the objects are relative to the machine.

The system can be configured for distance-based or speed-based standby mode. The radars remain active through 20 metres of start up travel while in distance-based mode. When configured for speed-based mode, the radars remain active until the machine exceeds the maximum speed threshold and exits standby mode when machine speed decreases below the minimum threshold. Cameras always remain active. Both visual and audible warnings are provided when an object has been detected while the machine is in gear and attempts to move towards the object.

Object Detection works on most types of Caterpillar equipment, including off-highway trucks, wheel loaders, motor graders, wheel dozers and track-type tractors. The system will soon be available for equipment from other manufacturers (Caterpillar Inc., 2011[7]).

It is recommended that an object detection system such as Caterpillar's Detect be investigated at a later stage, after the first prototype teleoperated excavator is operational.

## Remote Control Technologies' Teleoperation Systems

Remote Control Technologies Pty. Ltd. (RCT) is a leading provider of remote-control and teleoperation solutions for mining machines. Furthermore, RCT has retrofitted remote control units to "hundreds of underground and surface machines" (Buchanan, 2010[8]), including at least 17 different types of bulldozer. RCT offers integration of pitch and roll feedback into the visual displays, which could be useful when operating a teleoperated excavator on steep terrain.

A frequency range of 550MHz to 680MHz is used for video communications, such as broadcast UHF television (Remote Control Technologies Pty. Limited, 2011[9]) and 470 to 490 MHz is used for the CM2000D Remote Control Transmitter (Remote Control Technologies Pty. Limited, 2011[10]). These frequencies are similar to those designated for telecommand and telemetry in New Zealand (MED 2010 [11]). Price estimates were requested from RCT to install a remote-control and/or teleoperation system on an excavator and these estimates were used to define future direction of the project.

## Nautilus Automation's Remote-control and Teleoperation Systems

Nautilus Automation provides remote-control and teleoperation equipment that can be retro-fitted to existing vehicles. The Nautilus system has an optional Proximity Detection Control System that uses signal strength to estimate the proximity of the machine to the operator and will warn the operator if the Load-Haul-Dump loader (LHD) gets close to the operator and then shut down the LHD when it reaches a pre-set distance (Nautilus Automation, 2011[12]). This type of proximity-estimation system will enhance the safety of the excavator being developed for this project. The wireless communication for the Nautilus system operates between 406 and 520 MHz.

## Caterpillar Command System for Teleoperation of Mining Vehicles

The Caterpillar Command system includes a remote-control option for line-of-sight control of a bulldozer (Caterpillar Inc., 2011[13]; Buchanan, 2010[8]) and a teleoperation and semi-autonomous option for underground mining vehicles. The latter system is called Command for Underground. Command for Underground is built for Caterpillar Load-Haul-Dump loaders in underground mining (Cat® LHD machines). The system is fully integrated and can be installed at the factory or as retrofit in the field to maximize machine performance (Caterpillar Inc. 2011[14]).

Caterpillar's system is based in a remotely located control station, where the operator loads and dumps the material via remote control (Figure 3).

**Figure 3: Underground mining vehicle using Caterpillar's Command for Underground teleoperation system. (Image: Caterpillar Inc. Cat Minestar System Command, [http://www.cat.com](http://www.cat.com) 2011)**

A combination of on-board computers, cameras, lasers, and operator station software enables the system to steer the machine autonomously during hauling. This improves accuracy of tunnel navigation, enhancing productivity and reducing machine damage from contact with tunnel walls. Ergonomic controls allow operation of the machine using familiar components, reducing training time to get accustomed to new equipment, while also providing a safe environment for the operator. Machines are prohibited from leaving the work zone, and personnel are prohibited from entering secured areas during remote operation of the Command for Underground system. Additional safety features can be configured for avoidance of hazardous areas and full system shut down in the event that one part of the system is not functioning properly.

If the Command teleoperation system were available for excavators, it is likely that it would provide a suitable solution for forestry steep terrain harvesting, with the addition of inertial measurement unit signals to indicate the pitch and roll of the machine.

# 2. CONCEPT DESIGN: A TELEOPERATED EXCAVATOR

Development of a teleoperated excavator harvester is the preferred option for rapid deployment of teleoperation for steep slope harvesting within five years. Initially, the reasons that this solution is preferred are:

- excavators are already widely used in harvesting operations so the ability to retrofit a teleoperation solution is desirable;
- there are already two manned cable-assisted excavators operating in steep slope harvesting operations in New Zealand and a third in construction by an innovative engineering firm in Nelson (Trinder [15]);
- the technical challenges associated with retro-fitting an existing machine are considerably less than designing a new teleoperated machine for steep slope harvesting; and
- no commercial off-the-shelf teleoperated excavators were available at the time of writing (2011).

Two development options were initially under consideration to proceed with this task;

- Firstly, to retro-fit an excavator for teleoperation, a price estimate was requested from Remote Control Technologies Pty. Limited (RCT).
- Secondly, there is an option for customised development of teleoperation by configuring commercial off-the-shelf components for wireless communication, actuation and video/audio streaming.

A price estimate of approximately A$136,000 (NZ$180,000) was gained from RCT for a remote control unit. As this option did not offer the opportunity for further development, the second option is described in more detail. Further information regarding the performance standards for in-house customisation, documentation of the detailed design including cost of componentry (bill of materials) will be prepared in a subsequent report to determine which development option will be recommended for the next stage of the project.

Since remote-control will be part of the solution for a teleoperated excavator, it is proposed that the development be done in two stages: firstly, to design and build a remote-controlled excavator and secondly, to add video and audio feedback to permit teleoperation. The earlier human factors study documented by Parker (2011) [2] underpins the requirements for the concept design.

There are currently two options for the concept design for the remote-controlled excavator, presented in Figures 4 and 5. The option shown in Figure 4 does not have actuators that allow haptic feedback to the operator. However, this is a simpler solution which should allow more rapid deployment of the teleoperated system. This option is preferred for the first prototype for this reason.

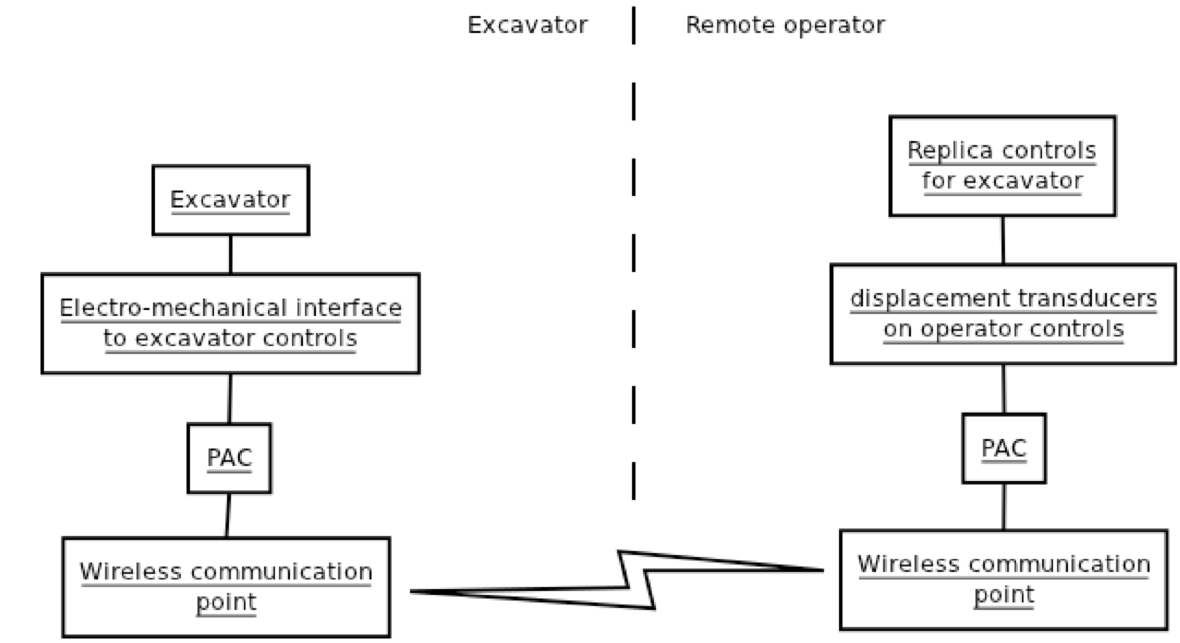


**Figure 4: Components of remote control system without haptic feedback.**

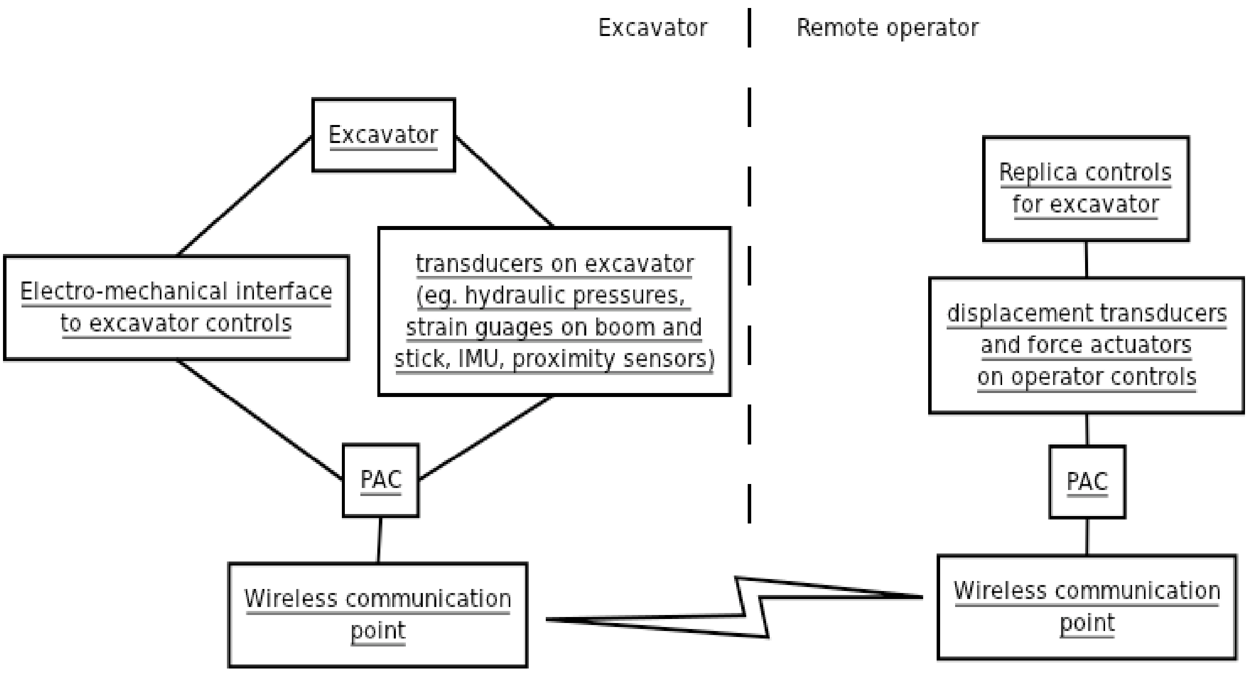


**Figure 5: Components of remote control system with haptic feedback**.

There are several options for the wireless communications. Lower frequencies have lower requirements for line-of-sight but are more susceptible to noise and cannot transmit data as quickly. Remote control of an excavator will have similar data-rate requirements to model aircraft, which typically operate at frequencies between 35 MHz and 41MHz (e.g. VHF Band F frequencies for aeronautical model control range only from 40.510 to 40.770 MHz [11]). However, video feedback would benefit from the increased data rates offered by the 802.11g standard for wireless local area networks (Wi-Fi) which operates in the 2.4GHz band. Therefore, a system using the 802.11g standard is preferred. An 802.11g link can provide up to 22Mbps of data throughput, excluding overhead (Hacker Friendly LLC, 2007 [16]). This type of system has the added advantage that components are readily available.

The conversion of the remote-controlled excavator to teleoperation will require a video and audio feedback system that could be developed in parallel with the remote-control hardware. A diagram of the components of this system is shown in Figure 6. Note that the communication protocol has been specified as 802.11g or 802.11n due to the high data-rate requirement for streaming video. The disadvantage of a high frequency is that line-of-sight will be required because forest is relatively opaque to high-frequency communications (Hacker Friendly LLC, 2007[16]).

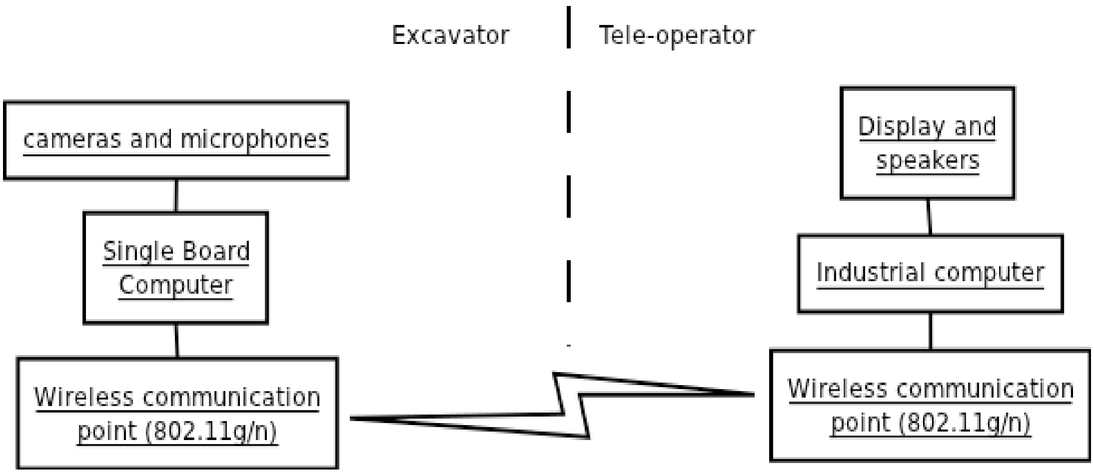


**Figure 6: Components of camera and audio feedback system to enable teleoperation**

It is recommended that the base machine for the first prototype teleoperated excavator be approximately 2 tonnes without a felling head. This will reduce the cost, while the design should be applicable to a larger machine with very little modification.

Once the teleoperated machine is operational it will serve as a platform for further development that will make the machine more efficient, safer and easier to operate. These developments will include:

- improving the human-machine interface including assessing different hand controls, including haptic feedback;
- testing additional transducers on the excavator such as proximity sensors, inertial measurement units and laser-range-finders; and
- examining the potential of semi-autonomous operation such as collision prevention.

# 3. RECOMMENDATIONS FOR A SECOND CONCEPT DESIGN

Although the concept described in the previous section is expected to provide a good solution for steep slope harvesting in New Zealand for the next couple of decades, a teleoperated cable-assisted excavator will be a solution that requires an approximately 30-tonne machine and a substantial anchor. This contrasts with the manual tree faller carrying a chainsaw with a combined weight of about 100 kilograms. Scion has been developing a light-weight concept machine that is expected to provide a good solution for steep slope harvesting in New Zealand.

# 4. ECONOMIC FEASIBILITY OF TELEOPERATED EXCAVATOR

## Cost Estimates

Estimates of the major costs that will be involved to retrofit an excavator for teleoperation were obtained from a range of industry sources (Table 2).

Table 2: Table of rough cost estimates for retro-fitting one excavator for tele-operation once the development has been completed.

| Item | Qty | Unit price | Cost |
|---|---|---|---|
| IMU (eg Landmark Gladiator) | 1 | 5,000 | 5,000 |
| TCP/IP Camera and mouting accessories | 4 | 2,000 | 8,000 |
| Laser Range finder | 2 | 6,000 | 12,000 |
| 802.11g access point | 2 | 50 | 100 |
| PAC (eg. Artila Matrix 504) | 2 | 700 | 1,400 |
| DC servo Motor (eg. SM23165DT) | 6 | 1,500 | 9,000 |
| Cabling for DC servo | 6 | 300 | 1,800 |
| Screens and speakers | 1 | 600 | 600 |
| Replica Controls | 1 | 3,000 | 3,000 |
| Potentiometers | 6 | 300 | 1,800 |
| Microphones | 4 | 80 | 320 |
| Mechanism to interface with controls | 6 | 400 | 2,400 |
| Power interface with excavator | 1 | 300 | 300 |
| Power supply to operator console | 1 | 500 | 500 |
| Wiring/fuses/wireways etc. | 1 | 1,500 | 1,500 |
| Single-board Computer | 1 | 1,000 | 1,000 |
| Industrial computer | 1 | 1,000 | 1,000 |
| Watchdog kill function | 1 | 500 | 500 |
| wireless kill mechanism | 1 | 3,000 | 3,000 |
| Physical installation and configuration | 1 | 20,000 | 20,000 |
| Commissioning/customising/testing/tuning | 1 | 10,000 | 10,000 |

The direct costs in Table 2 totalled $83,220. Therefore it was assumed that the system will cost around $150,000 (using a 45 per cent margin) and will cost $15,000 per year (for years 1 to 25) to maintain. Equivalently,

$$c_0 = 150,000, \quad (1)$$

$$c_y = 15,000, \quad (2)$$

for years $y : 1 \leq y \leq 25$.

## Estimates of Benefits

It is expected that the benefits of teleoperation will include the following:

- a better view of the excavator and the working area for the operator;
- efficiency due to semi-automation and operator assistance such as alarms and on-screen displays;
- less fatigue;
- less mental stress due to being situated in a safe environment; and
- very rapid change-over of operators will be possible at breaks and at the start and end of the day.

The benefits of teleoperation cannot be quantified until the machine is operational, so the benefits were estimated. Amishev (2011)[1] suggested a harvesting rate of 352 cubic metres per day is realistic for manned felling and up to 519 cubic metres per day is possible with a cable-assisted excavator-based harvester. Teleoperation could allow a further increase in the harvesting production rate.

The additional revenue in year *y* is

$$r_y = v_d \rho w \qquad (3)$$

The results of Amishev (2011)[1] were used to make a conservative estimate of the revenue per cubic metre of wood. A value of $\rho$=25 dollars per cubic metre was used for the analysis presented here.

## Scenarios

Scenarios 1, 2 and 3 covered a range of situations with different productivity implications for teleoperation.

**Scenario 1:** In this pessimistic scenario, it is assumed that teleoperation does not perform as hoped so there is no increase in productivity compared with a manned machine. Thus, $v_d = 0$ and therefore $r_y$ =0. Teleoperation is employed for 25 years in the hope that productivity will increase as operators develop skills in remote operation.

**Scenario 2:** In this moderate scenario, it is assumed teleoperation results in an increase of $v_d$ = 12.6 cubic metres per day and the machine works for $w$ = 100 days per year.

**Scenario 3:** In this extreme scenario, teleoperated machines are mandated for all mechanised felling on steep terrain. Also it is assumed that the difference between a manual tree faller and an excavator-based harvester is $v_d$ = 100 cubic metres per day. Given measured productivity of an excavator-based harvester in steep terrain of 33 trees per productive machine hour versus 11 trees per hour for manual felling this assumption is conservative (Evanson and Amishev,2010 [17]).

Scenarios 4 and 5 examined the effect of different values for the revenue per cubic metre of wood harvested (logging rate) and the effect of raising the discount rate.

**Scenario 4:** The same assumptions are made as in Scenario 2 (an increase of $v_d$ = 12.6 cubic metres per day and the machine works for $w$ = 100 days per year), plus the logging rate (revenue) per cubic metre harvested is increased from $25 to $36. This represents more difficult logging conditions.

**Scenario 5:** This scenario examines the effect of different values for the revenue per cubic metre of wood harvested and the discount rate. That is, the same assumptions as in Scenario 4 (an increase of $v_d$ = 12.6 cubic metres per day, the machine works for $w$ = 100 days per year, and the logging rate per cubic metre harvested is increased from $25 to $36), plus the discount rate is assumed to be increased from 10% to 20%.

## Calculation of Net Present Value

Net Present Value was used to assess the value of the scenarios considered in this document. The Net Present Value (summed over 25 years) is defined as

$$N = \sum_{y=0}^{25} \frac{r_y - c_y}{(1+i)^y}, \tag{4}$$

where $r_y$, $c_y$, $y$ and $i$ are defined in Table 1.

Combining equations 1, 2, 3 and 4 resulted in net present values for each scenario as presented in Table 3.

**Table 3: Calculation of NPV**

| Scenario | Net Present Value ($ NPV) |
|---|---|
| 1 | -$290,000 |
| 2 | $0 |
| 3 | +$2,000,000 |
| 4 | +$126,000 |
| 5 | $0 |

## Discussion of Net Present Value results

In Scenario 1, as shown in Table 3, the net present value is -$290,000. This means if there is no increase in volume production (and hence revenue) then the investment in teleoperation is a poor one.

Scenario 2 resulted in a net present value of $0. This means teleoperation becomes worthwhile only if it results in the extraction of more than an additional 12.6 cubic metres per day. Given that current average cable logging productivity exceeds 200 cubic metres per day an increase of 6% (12 cubic metres) seems realistic. Scenario 2 appears to be achievable, in which case it would be worthwhile for harvesting crews to utilise teleoperated cable-assisted excavators for yarding operations on steep terrain.

In Scenario 3, the net present value would be almost $2,000,000, the payback period would be less than one year and the Internal Rate of Return would be more than 150 per cent. Although Scenario 3 is an extreme situation, it illustrates the value of any technology that can make a major improvement in productivity. Examples of technologies that might improve the productivity of a teleoperated excavator include additional transducers for improved situational awareness and semi-autonomous operation.

Scenario 4 examines the effect of an increase in the logging rate (revenue per cubic metre) from $25 to $36 (i.e. from low cost cable logging to high cost cable logging). This higher logging rate represents the upper range of current cable logging rates. This resulted in a net present value of $126,000. This showed the combined impact of the additional 12.6 cubic metres per day production at an increased logging rate (i.e. even higher revenue).

In Scenario 5, the resulting net present value is $0. As there is an inverse relationship between NPV and discount rate, the effect of raising the discount rate is to reduce the NPV, in this case to zero. This higher discount rate may be more appropriate for a business with tight cash-flow or for a decision that is considered risky. This means in conditions of higher risk (higher discount rate) and more difficult logging conditions (higher logging rate) the additional volume harvested per day due to teleoperation would need to exceed 12.6 cubic metres for teleoperation to be feasible economically.

# RECOMMENDATIONS AND CONCLUSION

1. The preferred near-term concept for a teleoperated machine for steep terrain harvesting was determined to be a cable-assisted excavator-based harvester of around 30 tonnes machine weight with a felling/bunching head. This concept design should result in a commercial implementation within five years (i.e. within the life of the PGP “Innovative Harvesting Solutions” programme).

2. Binocular vision and haptic feedback would enhance the productivity of a teleoperated excavator in harvesting. However, it is recommended that the first prototype teleoperated excavator be built *without* these features to allow rapid early development. The addition of haptic feedback and binocular vision can be investigated at a later stage.

3. For the first prototype, the simpler solution does not have actuators that allow haptic feedback to the operator. This should allow more rapid deployment of the teleoperated system, and is therefore preferred for this reason.

4. Video feedback would benefit from the increased data rates offered by the 802.11g standard for wireless local area networks (Wi-Fi) which operate in the 2.4GHz band. Therefore a system using the 802.11g standard is preferred.

5. It is recommended that an object detection system (similar to Caterpillar’s Detect system), or a proximity-estimation system (such as the Nautilus system) be investigated at a later stage, after the first prototype teleoperated excavator is operational. Likewise consideration should be given to the integration of pitch and roll feedback into the visual displays, which could be useful when operating a teleoperated excavator on steep terrain.

6. It is recommended that a base hydraulic platform be designed for the first prototype teleoperated excavator. This will reduce the cost, while the design should be applicable to a larger machine with very little modification. Subsequent work will design this development platform, and an alpha prototype development plan that specifies the operational parameters and performance standards will be completed.

The economic analysis in this report has indicated that once retro-fittable teleoperation for excavators has been developed, it is estimated that it will cost $150,000 to convert an excavator to teleoperation, and that it will cost $15,000 per annum to maintain the system. Given these estimated costs, the required increased productivity for a cable yarding operation would be around 12 cubic metres per day for the investment to be feasible economically. Since current average cable logging productivity is around 200 tonnes per day, this represents an increase of 6% in daily productivity, and appears to be an achievable target.

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