HARVESTING
TECHNICAL NOTE

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Teleoperation for Steep Country Harvesting: A Literature Review of the State of the Art

Summary

It is desirable that machine operators are removed from the harvester site, not only for the safety of forestry workers but also to reduce workload and make the job more attractive. The early phase of the FFR Project Task 1.2 Teleoperated Felling Machine involved a summary of the state-of-the-art of teleoperation that is applicable to forest harvesting. This review is a necessary first step towards development of a teleoperated tree felling machine for the New Zealand forest industry.

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Introduction

Mechanisation of tasks such as tree felling, log forwarding and log sorting has shown great benefits for productivity of forest harvesting operations. In New Zealand, forest harvesting on steep slopes with large trees is common. Felling trees in these conditions is presently done manually under hazardous conditions. Where mechanised harvesting is possible it has improved productivity but it also presents hazards on steep slopes. A teleoperated felling machine will isolate the operator from the steep slope hazard and can improve working conditions, reduce work load and potentially improve productivity.

This report builds on previous Future Forests Limited research introducing robotics for steep country tree felling [1]. It is a necessary first step towards development of a teleoperated tree felling machine for the New Zealand forest industry.

Machine Teleoperation

Teleoperation is similar in concept to remote control. Unlike remote control, teleoperation is designed for control of the machine without direct line of sight. All the information the operator needs comes from sensors on the machine and mathematical models. The amount of sensing and processing is dependent on the operating environment. Advances in computing power, sensing and communications have made teleoperation feasible in unstructured operating environments such as forest harvesting.

Effective teleoperation in this environment requires appropriate sensing and modeling combined with a good operator interface. Good feedback and controls creates *telepresence*. An operator with telepresence can operate a machine as well as if they were controlling it directly. Examples of some types of feedback include haptic (touch-force), orientation, audio, 3D mapping and binocular vision.

Applications of teleoperation in horticulture [2], mining [3], and multi rotor helicopters [4] are also relevant to steep-slope harvesting. In military applications, the US Army 2010-2035 roadmap lays out many fundamentals of teleoperation [5].

One example in horticulture includes a teleoperated manure spreader developed in Japan (Figure 1). The teleoperation is done over the internet, so the control computer can be located anywhere with internet access. The machine operator gets all the required position information from the GPS and omni-directional camera. The operator interface also relays

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information about fuel levels and operating temperature.

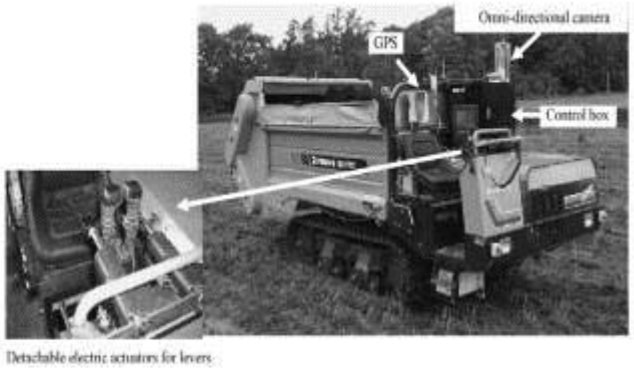

Figure 1: Teleoperated manure spreader [2].

The manure spreader can be run in autonomous ‘supervisory’ mode, where the operator issues commands but does not have direct real-time control over the manure spreader. Supervisory mode allows the operator to control multiple machines at once. It was found the manure spreader had better positioning accuracy in supervisory mode than under direct operator control.

Teleoperated machines have been used for many years in mining. Rio Tinto has several different types of teleoperated machines in use, including autonomous load-dump-haul (LDH) trucks and mining plant equipment [6, 7, 8]. Teleoperation can be used over very long distances to perform non-trivial tasks. Rio Tinto has a teleoperated ore crusher at West Angelas mine in Western Australia being controlled from over 1000 km away in Perth.

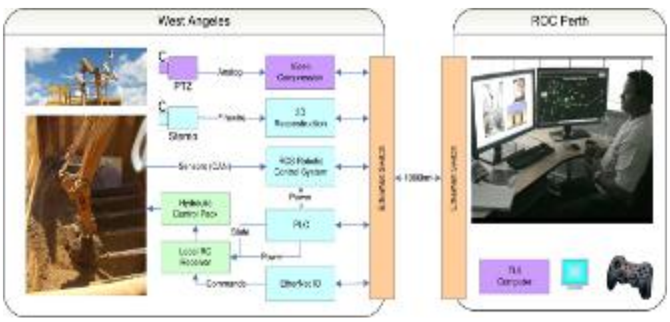

Figure 2: Long distance teleoperation control system for a rock crusher [7].

Figure 2 shows the teleoperation system architecture for the West Angelas mine rock crusher. Rio Tinto is also operating a fleet of autonomous Komatsu dump trucks and autonomous drilling equipment.

As part of a NASA-sponsored study into excavation for lunar missions, CSIRO in Australia developed a teleoperated drag line. The dragline, an excavator with a cable-operated bucket, was set up in Redbank, Queensland. It was then successfully teleoperated over the internet from as far away as Boston in the United States [9]. The drag line was autonomous, using a “click and dig” style interface.

In the forest industry, remote controlled tree harvesters such as the Besten have been developed [10, 11] and reported previously [1]. While it is not envisaged that multiple tree felling machines will be controlled at once, autonomy makes it possible to implement a “click and fell” style interface [9]. Such an interface could be useful for reducing operator workload, and can reduce bandwidth requirements and sensitivity to communication delay.

Wireless Communications

Wireless communications are useful when maximum mobility is required and damage to a communications cable is likely. Wireless communication system using internet protocol (TCP/IP) is a good starting point due to its widespread use. TCP/IP is a “packet switched” protocol. The data content is separate from the medium it is carried on. This allows development to be done with wired or different wireless equipment first [8-12]. TCP/IP allows off-the-shelf wireless equipment to be chosen that meets the required performance without having to implement customized communication and error correction protocols in the sender and receiver.

The target operating range for the project is 300 m. Wi-Fi will struggle with this distance, but other wireless communication protocols can be

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used [13]. Detailed comparisons of individual wireless communication protocols and methods [14] are beyond the scope of this report, but there is a general three-way tradeoff between speed, range and packet error rate. Packet errors are manifested as slow speeds and large and unpredictable delays.

Figure 3 shows the architecture of a prototype control system for autonomous log forwarders [15]. The motives for using autonomous log forwarders are similar to using autonomous dump trucks in mining: a single operator can manage multiple vehicles at once. The log forwarder can use more sophisticated control methods to load and unload logs faster.

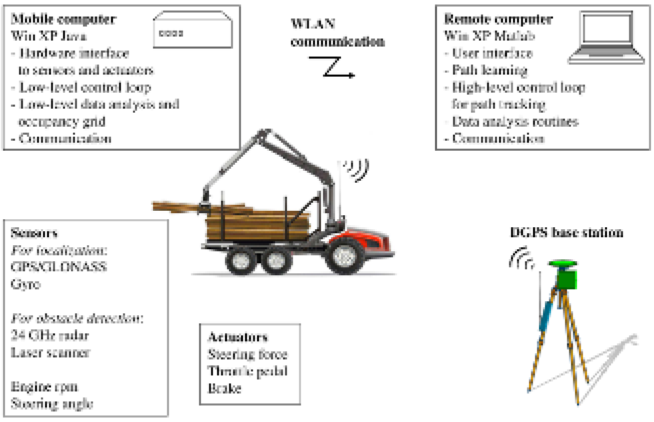

Figure 3: Teleoperation architecture for autonomous log forwarders [15].

Operator Vision Systems

Most human perception is visual. Therefore a good vision system is vital to achieving telepresence. At 300 m distance control by direct observation while expecting productivity improvements is not feasible. A system of cameras needs to be fitted to the harvester to gather visual information for the operator. The information then needs to be presented to the operator. The main methods of showing the images are to use monitors (Figure 4), projections [16, 17] and visors. Systems that have a larger field of view are more immersive than systems with a large number of cameras from disparate viewpoints.

2D visual interfaces are simple to implement but the lack of 3D information makes depth perception difficult. It is difficult for the operator to reconcile multiple different camera viewpoints.

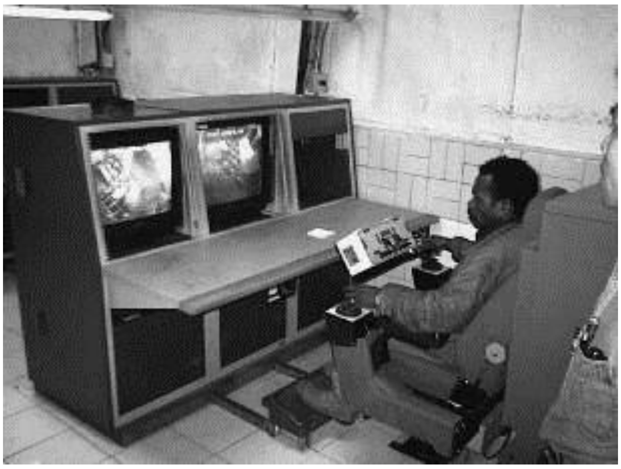

Figure 4: RCT (Remote Control Technologies) mining teleoperation interface [2].

Telepresence can be improved by having a larger screen. Figure 5 shows the interface for a harvester simulator developed by Skogforsk in Sweden [17].

Figure 5: Skogforsk Simulator using a projection screen [17].

Projector systems have the advantage of unlimited screen size and not being restricted to a flat screen. Curved screens allow a larger field of view [16, 18]. Figure 6 shows a jet simulator developed by the Defence Technology and Science Organisation in Australia using a wrap-around screen. The screen has a field of view of 200° horizontal and 100° vertical (70° up and 30° down).

Figure 6: Jet fighter simulator with dome screen [16].

Figure 7 shows a curved screen for a mining simulator [18]. Unlike the fighter simulator the screen is vertical rather than horizontal. The projector is situated at the bottom and uses a mirror.

Figure 7: CSIRO Mining Simulator Concept Screen [18].

The main disadvantages of curved screens are the more complex visual processing and uneven resolution. Any screen or projector system can be used to provide 3D images with combinations of polarized light and 3D glasses [19]. The frame rate should be at least 10 frames per second for the operator to maintain effective control [20].

Operator Control Systems

Excavators use a two-joystick system to control the position of the boom. The joysticks move the arm around by directly controlling the length of the hydraulic rams. This system is very simple mechanically but has a complex relationship between arm position and ram length. Alternative control methods can be used to increase productivity and reduce operator fatigue. Some approaches include goal-based control [2, 17], and haptic feedback [21,22] and direct control using sensors on the operator's arm [23]. As the original control system will be modified any alternative control method implies a degree of autonomy.

Skogforsk of Sweden have built a forestry harvester simulator to test various control algorithms and their effect on operator productivity [17]. The semi-autonomous mode has the operator controlling the position of the harvester head directly. A kinematic solver determines the required lengths of the hydraulic rams in real time. A similar system can be implemented in the steep slope harvester in this project.

Skogforsk noted that using the simulator semi-autonomously increased the productivity of inexperienced operators from 25% to 80% of an experienced operator. It is important to note performance of the Skogforsk simulator was not limited by problems with communications delays and processing of input data. However, it does show how different control methods can improve productivity of inexperienced operators.

Given the potential productivity benefits it is worth considering alternative control methods. Conventional excavator joystick controls with modified functions have been combined with

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haptic feedback [21, 24]. Custom haptic devices have been developed for excavator control [22]. Semi-autonomy can be used to provide an improved control interface and reduce bandwidth requirements, as well as reducing sensitivity to transmission delays and packet loss.

Harvester Hardware

The harvester hardware consists of sensors, actuators and wireless communications hardware. Some example sensors are orientation sensors (e.g. inertial measurement units/IMU), GPS, cameras, audio sensors and machine instrumentation (e.g. engine temperature).

Orientation sensors can be used to provide input to kinematic models of the harvester for stability calculation. Cameras are important as the main feedback for the operator is visual. There are various means of achieving this feedback including: (1) individual cameras the operator can choose as required [3]; (2) cameras with an omnidirectional mirror to achieve a large horizontal field of view [2, 25]; (3) an array of cameras similar to those used with Google Street View for synthesising a larger image. The exact camera setup affects processing requirements and bandwidth requirements.

Figure 8: Rock crusher instrumentation [10].

Figure 8 shows the hardware fitted to the rock crusher at Rio Tinto's West Angelas mine [7, 8]. The hardware consists of monocular and 3D cameras and tilt sensors on the breaker boom.

Autonomous and semi-autonomous teleoperation has been researched for manipulator arms [26]. Fully autonomous operation is not a goal for the steep slope harvester. The harvester hardware for the steep slope harvester can be developed and set up for non-autonomous or semi-autonomous operation. Increased autonomy comes at the cost of increased hardware complexity at the remote harvester end. There will always be a certain degree of autonomy because protective functions like over pressure and over temperature cutouts will be present.

Haptic Feedback

Haptic (touch force) feedback has not been used in forestry harvesting to date. Haptic feedback can be used to provide supplementary information about the state of the machine and its ability to respond to a command. The level of force to apply is entirely algorithm dependent. Haptic feedback can be used to amplify or attenuate forces, or even generate forces that do not physically exist. Haptic feedback has been used in conjunction with visual information to synthesise virtual force fields for injecting cells under a microscope [27].

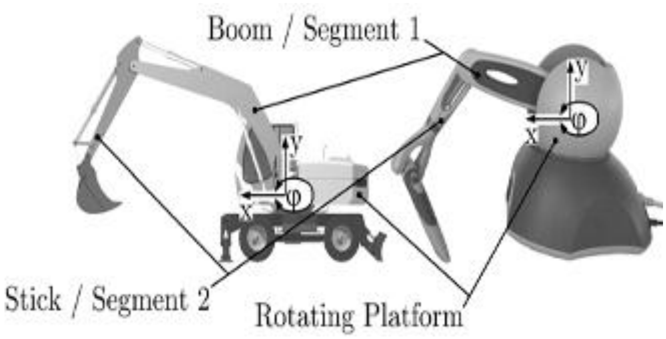

Figure 9: Example mapping of the positions of a Phantom OMNI haptic device to excavator boom motions [28].

There are commercially available haptic control systems such as the Phantom OMNI [28] as shown in Figure 9. The Phantom OMNI haptic device naturally lends itself to control of an excavator arm due to its similar mechanics Haptic control systems have been used in backhoes [21], and it is also possible to design and build custom haptic devices [22]. Figure 10 shows a Phantom OMNI haptic device being used to control a backhoe [28].

Figure 10: Phantom OMNI in use on excavator test interface [28].

Figure 11: Possible teleoperation architecture using haptic feedback direct to operator's arm [23].

Figure 11 shows a concept design for using the operator's arm to directly control a backhoe. Haptic feedback is applied directly to the operator's arm.

Software

Computer software is responsible for processing commands and data. For development, LabView or Matlab can be used to gather data and create models. Linux-like operating systems are attractive due to their flexibility and modularity. Figure 12 shows an example of top-level software architecture using a web browser as the top-level control interface.

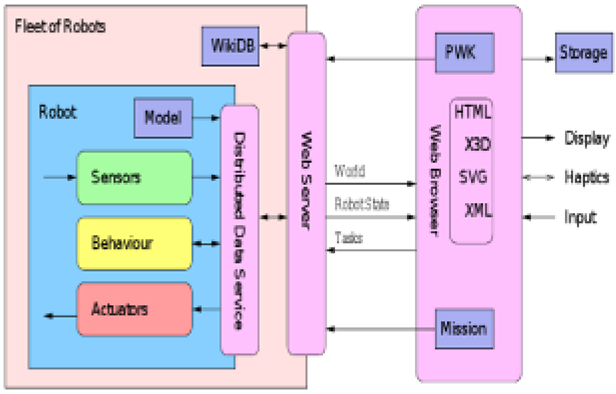

Figure 12: Teleoperation system using standard web browser and server [6].

A web browser interface has a huge advantage of not requiring specialised software on the operator's computer.

Conclusion

A review of the literature has demonstrated that the development of a steep slope teleoperated harvester with haptic feedback is technically feasible. Existing methods from the papers reviewed are summarised as follows:

- Excavators have been successfully retrofitted for teleoperation
- Teleoperation over the internet is in use in commercial environments

- 3D vision has been used with teleoperation
- Semi-autonomous control has been developed for forestry harvesting
- Haptic feedback has been used to control excavators
- Customised haptic devices can be developed if required

The main research issues are:

- Ensuring the stability of the harvester on steep slopes
- Operation of wireless internet hardware in a forest environment
- Ensuring the operator is aware of the surroundings and at all times has the best possible information to determine what actions are safe to perform
- Setup and usage of 3D vision systems
- Ensuring the stability of the control system in the presence of delays and data loss
- Interfacing the cutting head control with the harvester boom control
- Implementation of user interface software
- Signal processing and bandwidth requirements of semi-autonomous control and visual feedback
- Use of haptic feedback in forestry harvesting

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