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Haptic Feedback for a Teleoperated Felling Machine

Summary

Scion and the University of Canterbury Mechatronics Programme have collaborated to develop a prototype teleoperated felling machine for steep terrain. This work, which began in 2010, is funded through the Primary Growth Partnership. Early work has investigated the human factors of teleoperation in harvesting, reviewed the state of the art in teleoperated equipment, and designed and built a development platform for a teleoperation system. This report investigates haptic, or touch force, feedback for use in a teleoperated control system for an excavator felling machine. With teleoperation, the operator is located well away from the machine and has no tactile cues to help in the control of the machine. Haptic feedback is desirable because it provides the operator with a "feel" of the machine, which should improve operator performance. Some of the most important human factors issues to be addressed in developing the hand controller system for forest machine teleoperation are outlined.

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Introduction

As part of the Primary Growth Partnership Harvesting research programme, Future Forests Research engaged the University of Canterbury Mechatronics Programme and Scion to develop a teleoperated felling machine for steep terrain harvesting.

Work in this project to date has:

- investigated the human factors of teleoperation in harvesting (Parker and Milliken, 2011);
- reviewed the state of the art in teleoperation for steep country harvesting (Milne *et al*., 2012); and
- designed and built a laboratory-based development platform for teleoperation (Milliken, 2012).

In very steep terrain forest environments, it is desirable to have the felling machine operator situated in a safe location away from the machine and falling trees, and to reduce the physical and mental workload on the operator. This requires a teleoperation system for the operator of the machine using video and audio feedback to the remote location to enable better vision of the terrain and the task. Other sensory feedback such as haptic (or touch force) feedback provides a realistic operating environment for the operator (Parker and Milliken, 2011).

Haptic feedback has not been used in forestry harvesting, but a review of the literature has demonstrated that the development of a steep slope teleoperated harvester with haptic feedback is technically feasible. In a New Zealand forestry context, conventional excavator joystick controls with modified functions have been combined with custom built devices to provide haptic feedback (Milne *et al*., 2012).

It is proposed to develop wireless communications and a user interface using video and audio feedback, and possibly haptic feedback, prior to integration on a full scale harvesting machine.

The objective of this part of the project is to design a haptic feedback interface that can be integrated with the remote controlled hydraulic ram. Force feedback will be a function of the output of a signal from a transducer, and will probably be implemented with a servo motor. This report outlines human factors issues surrounding haptic feedback in the control of mobile machines. This will assist in making the eventual decision of whether haptic feedback is required and what type of system will be used.

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Haptic Technology

Haptic technology is a tactile feedback technology which takes advantage of the sense of touch by applying forces, vibrations, or motions to the user to provide supplementary information about the state of the machine and its ability to respond to operator commands.

This mechanical stimulation can be used to assist in the creation of virtual objects in a computer simulation, to control such virtual objects, and to enhance the remote control of machines and devices. Haptic devices may incorporate tactile sensors that measure forces exerted by the user on the interface.

Haptic feedback prevents the operator putting the saw or grippers in a physically impossible place such as inside a tree or underground. Haptic feedback allows the operator to feel the tree or the ground and perhaps feel the saw cutting the tree, so know when the tree is severed from the stump.

Other advantages of haptic technology (Hayn & Schwarzmann, 2010) include:

- Warning the operator of damaging obstacles.
- Feedback on digging or gripping forces.
- Enabling the operator to sense the inertia of the machine's manipulator.
- Limiting the machine's workspace.
- Guiding the tip of the boom on a specific trajectory.

Human Factors Considerations

There are some basic principles of control and display design that apply in any engineering design exercise (Bullinger *et al.,* 1997; Pheasant, 1987; Sanders & McCormick, 1993):

- *Intuition:* Type, design and layout of controls needs to correspond to the control task, taking into account human characteristics including innate and learned responses. These innate and learned responses clearly are not readily predictable, and will vary significantly between operators. An example is the movement stereotype differences between those countries where electrical switches flick up to go off, as opposed to down.
- *Travel and resistance:* Needs to be selected on the basis of the specific control task and of biomechanical and anthropometric data.
- *Demands:* The strength, attention and other demands of the control and display interaction must be sustainable for the operator for the designed period of operation.
- *Compatibility:* Control movement, equipment response, and display information need to be mutually compatible.
- *Coding:* Function of the controls must be easily identifiable. Coding is commonly achieved by one or a combination of: arrangement / placement, structure / material, colour / labelling.
- *Safety:* Critical controls need to be safeguarded against inadvertent operation.
- *Rate and direction of feedback* needs to be compatible with that of the rate and direction of change of the primary source of that information.
- *Prioritisation:* Where controls or displays are numerous, the arrangement should be set according to: importance, frequency of use, functionality [clustering], and common or critical sequences of use.

Input Device

There are numerous choices for the type of input device and type of control of that device. Useful details of many aspects of hand controller design and operation are in the doctoral thesis of Shumin Zhai (Zhai, 1995).

The most common input device for teleoperated systems mentioned in the literature is the hand controlled force feedback joystick. There are other devices which have a place in particular situations.

A commercially available haptic control system such as the Phantom OMNI device has been used to control a backhoe (Hayn and Schwarzmann, 2010) as shown in Figure 1.

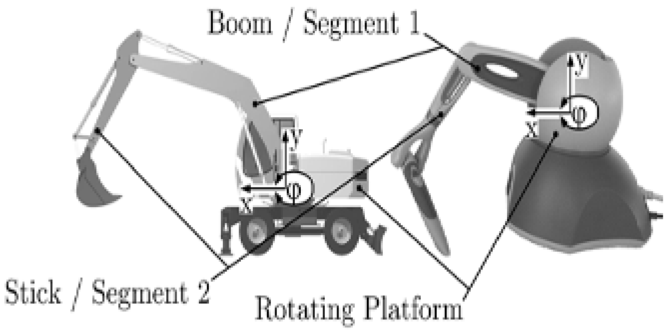

Figure 1: Example mapping of the positions of a Phantom OMNI haptic device to excavator backhoe boom motions (Hayn and Schwarzmann, 2010).

More recently the Phantom Omnihaptic hand controller developed by Sensable Technologies has become a standard tool for developing haptic feedback control systems (Figure 2).

Figure 2: Sensable Technologies 'Phantom Omni' controller which provides haptic feedback

The Phantom OMNI haptic device naturally lends itself to control of an excavator arm due to its similar mechanics (Milne *et al*., 2012).

Isometric vs. isotonic controllers and elastic controllers (Zhai, 2000) provide an interesting comparison of options for control.

Isotonic Device

An isotonic control device is freely moving. It can have zero resistance to movement such as an instrumented glove or a flying mouse. The movements of these devices are typically mapped to the slave displacement, so are called position control. Most are tracked by magnetic sensors.

Advantages:

- Easy to learn – natural direct mapping of controller to slave movement.
- Movements can be fast.

Disadvantages:

- Limited movement range – need a "clutch" to disengage controller and reposition (like lifting a mouse).
- Poor coordination because slave movement is directly related to controller movement (e.g. cannot rotate slave through 360° because the hand cannot rotate through 360°).
- Fatigue to the users arm because the controller must be suspended in the air.
- Poor acquisition because the controller will not stay where it is placed when released – no position persistence.

Isometric Device

An isometric device has infinite resistance, it does not move. Control is brought about by applying a force to the device. An example is the "Spaceball" by Spacetec IMC Corporation. When released, the slave returns to the null position although there is no actual movement of the controller.

Advantages:

- Arm or hand can be rested on a table, resulting in reduced fatigue and improving coordination.
- Acquisition good because the device will stay on the table.

Disadvantages:

- No force feedback or elastic "feel".

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- Usually in rate control (or velocity control) mode, which takes longer to learn than position mode.

Elastic Device

An elastic device has some resistance to movement and this resistance restores the device back to the null position – for example the six degrees-of-freedom (DOF) elastic rate control EGG (elastic general-purpose grip). The EGG is a control device suspended by elastic tethers in a cage. The user can feel the restoring force and displacement.

Advantages:

- Some feedback from restoring force of suspension and the displacement of the device.
- Does not have to be held in mid air.
- Acquisition good.

Disadvantages:

- Rate control can be poorer because self-centring is weaker at greater displacement.

Kaber (1996) stated guidelines for controllers to be incorporated in a teleoperation system interface:

- A six-DOF force-stick, such as the SpaceBall is superior to using two three-DOF joysticks in six-DOF applications. Operation of two joysticks is less instinctive than using the SpaceBall and may also serve to confuse operators (Vertut & Coiffet, 1986).
- A six-DOF electro-magnetic sensor, such as the Polhemus, should be provided to avoid limiting operators to a small work envelope due to a fixed-base controller (e.g., joystick, SpaceBall, etc.).
- A teach pendant can be useful for programming etc., but should not be relied on to directly facilitate teleoperator movement, especially along several DOF simultaneously.
- If a multi-fingered end-effector is to be integrated with the teleoperator to achieve human-like handling capabilities, an anthropomorphic dextrous controller, such as the Exos DHM or the Dataglove, should be incorporated in the system interface.

Fingers vs. Hand Control

Performance advantages have been demonstrated with controllers where the fingers can be utilised in control (Zhai, 1995). Experiments have been conducted which indicate that the fingers have an information processing rate almost twice that of the wrist and four times that of the arm. The small muscle groups of the fingers and thumbs should perform control functions better than the larger muscle groups of the wrist or arm. However, Zhai (1995) states that for the design of a six-DOF control device, the whole arm from the shoulder to finger tips can be used to take advantage of the power of the upper arm, the range of movement of the shoulder, elbow and wrist and the dexterity of the fingers and thumb.

Hand Grips

Good hand grip configuration is essential for successful hand controller design (Jacobus *et al.,* 1992). In their summary of design requirements for a six-DOF robotic hand controller (for use in the space shuttle or space station) they emphasise the need for changeable hand grips to support use by 5th percentile female users through to 95th percentile male users.

Table 1 overleaf indicates that higher force levels can be controlled using a wrap-around or finger-heel grips than can be controlled using finger-tip-only grips such as those used to turn track balls (Jacobus *et al.,* 1992).

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Table 1: Variability parameters for the human hand (Jet Propulsion Laboratory).

	Between straight fingers and heel of hand	Fingers wrapped around object - joystick	Square object between fingers and thumb	Round object between thumb and forefinger	Flat object between thumb and forefinger	Index finger controlling trigger on joystick
5% female	24 kg	24 kg	3.4 kg	3.4 kg	4 kg	1 .8 kg
95% male	67 kg	67 kg	14 kg	14 kg	15 kg	6 kg
Torque capability	Excellent	Excellent	Good	Poor	Some	Excellent
Endurance	Good	Good	Poor	Fair	Fair	Good

Control Mode

Rate Control Mode

Rate Control Mode is where a change in the input variable (force or displacement) to the control device results in change in velocity of the "slave" (e.g. robot arm). This is also known as "first-order" control or velocity control, i.e. if you push the joystick harder the arm moves faster.

Position Control Mode

Position Control Mode is where a change in the input variable (displacement) to the control device results in a scaled movement of the slave. I is also known as "zero-order" control, i.e. if you push the joystick harder the arm doesn't go any faster.

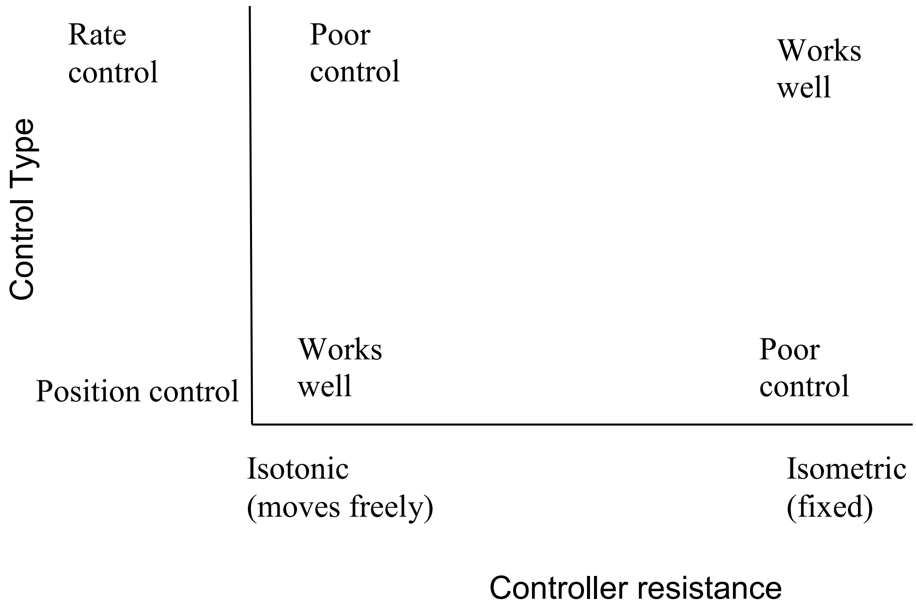

Figure 3: Relationship between control type and controller resistance (from Zhai, 2000)

In 1984, workers in the NASA Space Telerobotics Program evaluated alternative modes of control of a robot manipulator undertaking tasks similar to those done manually by astronauts (Das *et al.,* 1992). For example, in extravehicular activity to repair the Solar Max satellite, tasks included the removal and reinsertion of screws on an electrical panel. Data on forces, torques and times to complete tasks and positions of the robotic end effector were collected for different control modes. Position control modes yielded better performance and were preferred by operators over rate control modes for these tasks.

Mapping of Device to Robot Movements

Jacobus *et al.* (1992) discuss various types of hand controller or master controller and the mapping options with each. Their mapping recommendation for a six-DOF hand controller was for a "universal controller" which takes coordinate transforms for translation from the controller to the slave and from the slave to the controller. In this way the master and slave can be quite kinematically dissimilar. In other words motions of the controller are not reflected in identical motions of the slave, providing flexibility in design. Otherwise the controller would have to move identically to the arm being controlled.

Feedback to User

Most telerobotic systems use a force-reflecting hand controller of some kind. Johnsen & Corliss (1971) cited by Batsomboon *et al.* (1996) stated simply that "a joystick is often a better control device than other available options such as a mouse, switchbox, keyboard or touch-screen input because the operator identifies better with the task". With force reflection at the joystick, performance of the operator is greatly improved (Batsomboon *et al*., 1996).

In an ergonomic survey of expert remote manipulator operators in the nuclear industry, Sundstrom *et al.* (1995) found the operators wanted an efficient hand-control interface. Their ideal device would be light weight, mobile, force reflecting hand controller with adjustable force reflection. The force reflection is needed most when the operator does a new task, and less when the operator is experienced in that task.

Sundstrom *et al.* (1995) stated that high force-reflection ratios cause fatigue, and concluded that highly adjustable force reflection is well worth incorporating in control systems. A surprising finding, not found elsewhere in the literature, was that the expert operators preferred fewer functions on the hand controller itself, perhaps even having foot switches to control some functions.

Acquisition

Acquisition is how convenient the device is to use, and is an important human factors attribute of a controller device. For example a two-DOF mouse has a greater ease of acquisition than a computer stylus or pen. One reason a mouse has greater acquisition is its "location persistence". A computer mouse or a track ball has "location persistence" in that it does not move when it is released.

In contrast, a computer stylus or pen will not stay in the location it was released. Elastic joy sticks and other self-centring hand controls move once released if they are displaced from the null position. These devices do not have location persistence.

Conclusion

Haptic feedback is likely to be useful for a teleoperated felling machine such as an excavator. The main benefits of haptic feedback (as opposed to a no haptic feedback system) for a teleoperated excavator in a felling application include productivity improvements by allowing the operator to feel the force at the grapple and the saw and avoid obstacles. This should allow easier positioning of the grapple or saw head in

relation to the tree. It is most likely that the hand controller will be a joystick because operators are familiar with their function.

This work has outlined some of the most important human factors issues of which developers should be aware when selecting a hand controller for forest machine teleoperation.

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