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Coordinated and Force-Feedback Control of Hydraulic Excavators

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Abstract

The human interface of a Caterpillar 325FB feller-buncher was modified to allow the operator to use (i) a 5-DOF joystick, and (ii) a 6-DOF magnetically-levitated joystick with stiffness feedback. While the operator commanded the velocity of the endpoint, an onboard computer system managed total system power, solved the inverse kinematics, servoed the joint actuators, and controlled the magnetically-levitated joystick.

It was found that there were significant benefits to single joystick endpoint velocity control including smoothness of motion, less damage to product (trees), and ease of operation. Controlling joystick stiffness as a function of endpoint force, was found to be both a stable and effective form of feedback for a system where joystick position maps to endpoint velocity.

Two different hydraulic systems were implemented and evaluated. The first used valve control, as in a standard excavator. The second used hydrostatic control, by variable displacement pumps, and was found to lead to lower power consumption and higher operating speeds.

1. Introduction

The human interface for controlling hydraulic excavators has not changed significantly over many years. Traditionally, two spring-centered joysticks, each with two degrees of freedom (see Figure 1), have been used by operators to control the joint rates of a 4-DOF excavator arm in a joint velocity control scheme. Machine operators have to implicitly learn the inverse Jacobian of machines with different kinematic parameters - making use of vision to estimate the elements of the Jacobian at each moment. Since no single joystick mapping standard has emerged in the industry, operators may have to adapt to different mappings between joystick axes and arm joint axes when they change machines. In addition, the standard joysticks do not provide any force or tactile feedback from the environment.

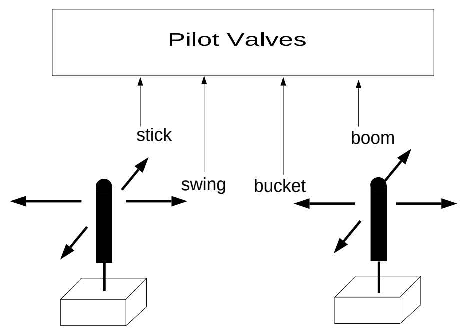

Figure 1. Standard Hand Controls

Although the difficulty of machine operation is most evident in new operators, some well-trained operators are much better than others in their ability to carry out workspace tasks using jointspace controls. A number of tasks such as digging deep trenches or leveling require the operator to work blindly or rely on secondary information such as engine noise or cab level to control bucket forces. These difficulties are even more pronounced when remote operation of machines is required, such as in the handling and removal of hazardous waste.

Our previous work and the work reported here was motivated by a possible reduction in learning time, reduction in adaptation time to different machines, reduction in fatigue, enhancement of safety through

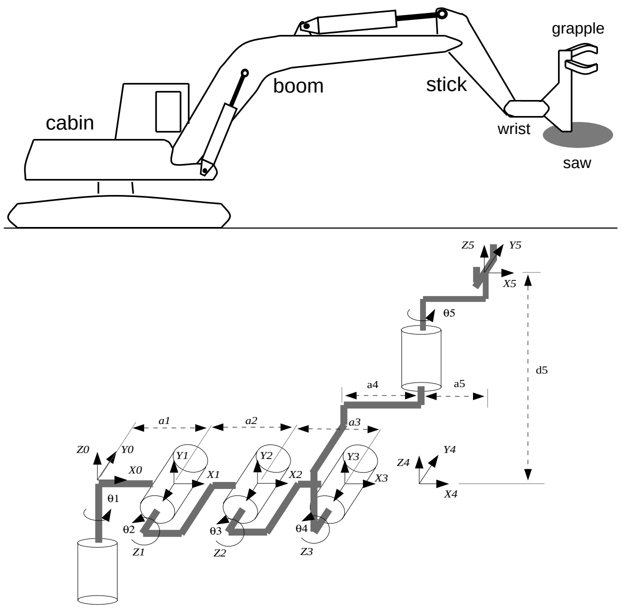

Figure 2. Feller-Buncher Schematic and Kinematic Configuration

remote operation, and improvement in productivity and uniformity of production between operators with different motor coordination skills.

Specifically, the objective of the project has been to study the benefits of endpoint velocity control (EVC) with and without force feedback (FFB) to the operator.

Early equipment for telerobotics used spatially-corresponding master/slave manipulators to achieve endpoint position control for "hot-cell" manipulation [1]. Bilateral force-feedback was either mechanically or electrically incorporated in these systems. With the availability of high-speed computation, non-spatially-corresponding masters were later used with bilateral force-feedback to control manipulators [2].

As the ratio of the length of the slave arm to the length of the master arm increases, it becomes difficult to accurately control the slave using endpoint position control. An alternative is to use endpoint velocity control for which the joint rates can be found using the manipulator inverse Jacobian [3]. Small hand controls for this purpose that are similar in size to the joint velocity hand controls shown in Figure 1 have been proposed for space manipulator control [4].

A project was initiated at the University of British Columbia (UBC) in 1985 to examine new control interfaces for hydraulic machines used in forest harvesting. For ease in communicating the concept, endpoint ve-

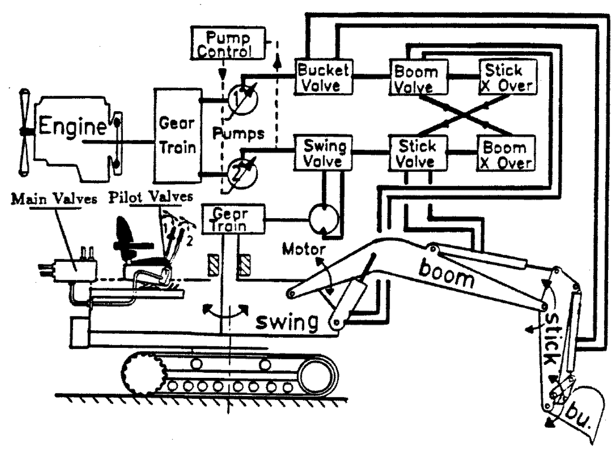

Figure 3. Excavator Hydraulics Circuit

locity control in an excavator-based forestry machine was termed "coordinated motion control". The results of early experiments were reported by Wallersteiner *et al.* for excavator-based machines [5] in which the operator rotates with the machine. A Swedish project studied truck-based log-loaders in which the operator works in a fixed world reference frame [6]. Also at about the same time, there was a proposal for telerobotic excavation [7].

The UBC project has addressed issues of:
(i) implementation of coordinated control on large hydraulic machines, including the design of joysticks, machine instrumentation and hydraulic system modifications,
(ii) evaluation of various coordinated motion schemes and joysticks from a human factors point of view, and
(iii) implementation of force-feedback to the operator by using an active 6-DOF joystick.

A number of machine simulators were developed ranging in complexity from simple kinematic models to full dynamic models [8] including the machine hydraulic system and actuators. The graphics interface to the simulators was implemented on workstations displaying the operator's view from the cab. Force feedback computed for simple dynamic interaction such as contact with the environment or payload inertial force was presented to the operator using an active 6-DOF joystick [9].

Extensive experiments were carried out with a CAT215B machine configured as an excavator, as a log-loader, and with a CAT325FB feller-buncher. This led to a month-long field demonstration of endpoint velocity control in tree harvesting and to the control of a machine using a single 6-DOF force-feedback joystick to control end-effector linear motion, angular motion, forces and torques.

This paper concentrates on the experiments carried out on the Caterpillar 325FB feller-buncher and includes 1) a comparison of the two hydraulic systems experimented with, the first one employing electrohydraulic pilot valves which push the spools of the main hydraulic valves, the second using variable displacement pumps instead of main valves for each actuating cylinder, (ii) a discussion of bilateral (force-feedback) control modalities and their effect on stability and performance.

2. Machine and Control System

An excavator has four major degrees of freedom - a cab rotation with respect to the base, a boom rotation (proximal arm segment), a stick rotation (distal arm segment), and a bucket curl (i.e. pitch). Different implements (end-effectors) can replace the bucket and these implements can have several degrees of freedom such as a grapple which can rotate (yaw direction), and open/close; or a feller-buncher head. A feller-buncher head, used for felling and accumulating trees, can pitch, roll, grasp (with two pairs of arms called "accumulator arms" and "grab arms"), and cut using an approximately 1m diameter circular saw (see Figure 2).
The Caterpillar 325 excavator used in these studies was modified by Balderson Inc. and Finning Inc. into a feller-buncher designated as a CAT325FB. The joints of a basic excavator are controlled by a set of main hydraulic valves which divert the hydraulic oil flow from the pumps into each of the single-ended cylinders that move the joints. The hydraulic system is shown in Figure 3. The simplest conversion to computer control of each joint is to replace the manually-operated pilot valves shown in Figure 3 with electrohydraulically-operated pilot valves, and add joint angle sensors to each joint of the machine.
A VME-Bus based machine computer system was assembled and consists of a UNIX^{TM} host, a VxWorks^{TM} host and active joystick controller, a Transputer-based board controlling the machine in resolved-rate mode and various input/output boards. Major variables such as joint angles, system pressures, and valve control signals were monitored in real-time using Stethescope^{TM}. Feasible desired endpoint velocities are computed based on machine hydraulic constraints. A PD controller then uses a form of compensation for load described in [10].

Figure 4. Feller-Buncher Hand Controller

3. Coordinated Motion Control

A 5-DOF hand controller (see Figure 4) for endpoint velocity control was designed that provided preferential motion (using slides) in the direction of cutting the tree (i.e. in the forward direction as the saw in the head cuts through the tree).

Two different hydraulic systems were investigated. The first, called "Valve Control", utilized electrohydraulic pilot valves which applied pressures to each end of the main valve spools. A description of this system and its performance is given in [10].
The second system called "Pump Control" was designed to replaced the original hydraulic system with a set of 8 variable displacement pumps in a hydrostatic drive configuration. In this arrangement, each main hydraulic actuator (tracks, cab rotation, boom, stick, feller-buncher head pitch and saw motor) is driven by a single variable displacement pump. The swash-plate angle on the pump is electrohydraulically controlled to vary the flow to the actuator. Each side of the actuator is connected to the corresponding side of the pump. A "hot-oil valve" and charge system are used to compensate for flows resulting from the difference in piston areas [11].
The less demanding functions (accumulator arms, grab-arms, and head roll) were valve-controlled. Figure 5 shows the outside cluster of 4 pumps symmetrically located on the face of the engine transmission. Beneath this layer is another layer of 4 pumps driven in tandem by the transmission.
The potential benefits of using pump control are that (i) there are no main valves to generate heat, and (ii) at each moment in time, excess energy from one function can be absorbed by another function. As an example, the potential energy released from a tree falling in the "pitch" direction while in the feller-buncher

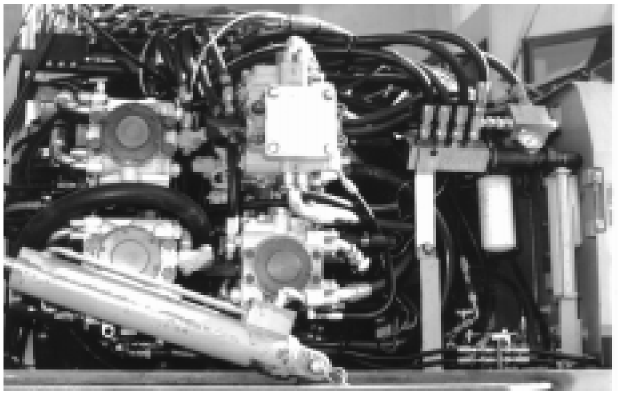

Figure 5. Hydrostatic Drive System

head's grasp, would be recovered by the saw pump through the transmission. A similar case can be made for combined boom and stick motions.

4. Rate Control with Stiffness Feedback

The benefits of force-feedback in telemanipulation are well known. In addition to faster completion time of assembly tasks [12], force feedback can also reduce stresses in the manipulator and the materials being handled (this is particularly important if the machine does not have six degrees of freedom). Additional information such as power consumption or hazardous operation can also be presented in an intuitive way as force-feedback information.

The use of force-feedback in the teleoperated control of excavators was considered before in [13], where a kinematically equivalent master controlling the excavator position and providing joint-level force feedback was proposed. The approach presented here addresses the problem of providing force-feedback in rate mode and used a 6-DOF magnetically levitated (maglev) hand controller designed and built at UBC [14] (motion range ±5 mm, ±6°, maximum continuous force 20 N).

When force-feedback is used in rate mode, it can be shown that if the end-point force is scaled and returned to the operator directly, the teleoperator cannot be transparent. A mass load would be felt as a viscous force, a damper as a spring, etc.. Although perfect transparency is still achievable when force-feedback is used in rate mode, it requires integration of hand forces and differentiation of environment forces, and has quite limited stability robustness [15, 9, 16].

An alternative approach has been presented in [15, 17], will be referred to as "stiffness feedback", and is shown schematically in Figure 6. In Figure 6 the master and operator hand impedances are incorporated in Z_m,

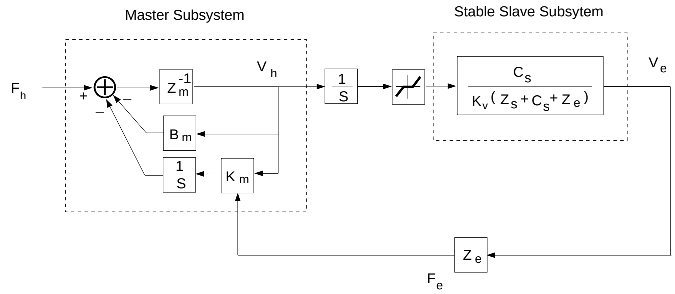

Figure 6. Schematic Diagram of Rate Control with Stiffness Feedback

and the slave, having impedance Z_s, is assumed to be controlled in a stable manner by a compensator C_s against an environment impedance Z_e. Instead of direct force feedback, the stiffness K_m of the master is modulated by the sensed environment force according to the rule,

$$K_m = \text{sat}[K_{nom} + f_e K_r \text{sgn}(x_h)] \qquad (1)$$

which is illustrated in Figure 7. The saturation function in (1) limits the joystick stiffness to $K_m \in [K_{min}, K_{max}]$ ($K_m > 0$), while the the sign function is needed to avoid having the slave "stuck" in a stiff environment because the master is centered by a high stiffness value.

Within the linear area of the stiffness adjustment rule, the operator experiences an environment-dependent force equal to $K_r|x_h|f_e$, which is essentially direct force feedback modulated by the joystick displacement. This suggests that the "transparency" of stiffness control should be good, at least locally. Stability proofs for stiffness control have been obtained so far only under very limiting assumptions on the operator impedance and either slow-varying assumptions on f_e, or large joystick damping B_m (see Figure 6) [9]. However, simulations and experimental results have been very good [15, 9].

5. End-Point Force Estimation

The accurate measurement and/or estimation of end-point forces for excavator-type machines is a difficult problem. The machine arms cannot be easily modified to accept multi-degree-of-freedom force-torque sensors mounted at the end-effectors, and, even if they did, large shock loading would make this option of dubious reliability [15]. Instead, it is better to measure cylinder forces via load-cells or differential pressure sensors. The cylinder pressures were measured by transducers mounted close to the hydraulic pumps. The vector of joint torques τ of the machine arm is computed from

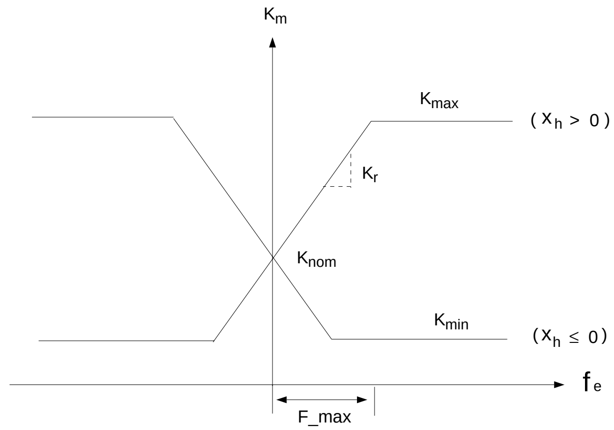

Figure 7. Stiffness Adjustment Rule

the cylinder forces by solving simple two-bar and four-bar linkage problems [15, 9]. The end-point wrench vector f_e can be computed from the arm dynamic equations and a Jacobian transformation as follows:

$$\begin{aligned} J^T(q)f_e &= \tau - D(q)\ddot{q} - C(q,\dot{q})\dot{q} - g(q) \quad (2) \\ &= \tau - D(q)\ddot{q} - C(q,\dot{q})\dot{q} - Y_g(q)p_g \end{aligned}$$

where q, J, D, C and g are the joint variables, arm Jacobian, mass matrix, centrifugal and Coriolis terms and the gravity force, respectively, and the gravitational terms have been re-written in a "linear-in-parameters" form [18]. Since neither the excavator nor the feller-buncher have six degrees of freedom, the Jacobian in (2) is not invertible. Either a pseudo-inverse (smallest norm satisfying (2) or setting components of f_e to zero can be used to solve this equation.

Due to the significant noise component in the velocity and acceleration signals $\dot{q}$ and $\ddot{q}$, and due to the uncertainty in the link inertial parameters, only the gravitational terms of the arm rigid body dynamics were used in the above computation. It is essential that the gravity terms be computed because, without gravity compensation, machine operation with an active joystick would be both tiring and hazardous. The parameter vector p_g was identified from $\tau - Y_g(q)p_g = 0$ ($Y_g(q) \in I\!R^{5\times 7}$) by driving the free CAT325FB arm very slowly to random locations and collecting the cylinder forces and joint variables, then using a recursive least-squares algorithm [15, 9]. With better joint-angle sensors, the complete forward dynamics could be used in the above equation. If the arm parameters are not known exactly, the identification procedure could be repeated, although there would be significantly more parameters to be identified.

6. Coodinated Control Experiments

The most objective comparison of coordinated control *vs* standard joint control would be to have two identical machines and have an operator use each machine on identical terrain and identical trees. This type of study had been previously carried out on a log loader (see [19]) but was not deemed to be feasible for a feller-buncher since the same trees cannot be cut twice. Instead, extended demonstrations were set up, to which machine operators and other representatives of forest companies, harvesting contractors, suppliers and machine manufaturers were invited to come and operate the feller-buncher.

For valve control, the machine was delivered to a forest harvesting site near Kelowna B.C. for a period of one week. For pump control, the feller-buncher was moved to a different forest harvesting test site near Kelowna B.C. It was also evaluated for one week at a second site near Quesnel B.C.

Operator Reaction

Each visitor to any of the sites observed a demonstration, operated the machine for a period of time and then responded to a questionnaire.
It was observed [20] that that novices could be reasonably comfortable in controlling the machine after several hours compared to much longer times of at least several days to a week for the standard machine controls. A major problem with long learning times is the potential damage to the machine during the learning period.
Experienced operators observed that the machine was smoother in operation and somewhat faster - especially for the pump-controlled version. This was hard to quantify since operators use different manufacturer's machines and there was no direct comparison between machines on the site.
Because of the large diameter of the saw and the necessity of perfectly coordinating the joints to produce a horizontal motion during cutting, it is not uncommon that the butt of the tree will be damaged (split) during felling using standard controls. It was observed that that the incidence of butt damage was much reduced with coordinated control.

Power and Speed Comparison

During the feller-buncher field trials, estimates of head speed and power consumed by boom, stick and head pitch were computed. The bottom trace in Figure 8 shows a typical recording of head speed during valve controlled operation. The top trace shows the power consumed by the three functions. Figure 9 shows the corresponding recordings during a typical pump con-

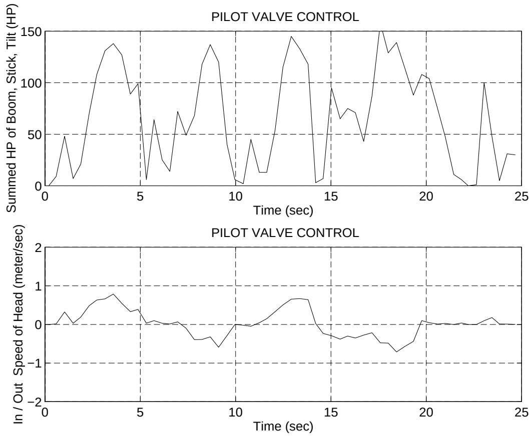

Figure 8. Machine Power and Head Speed with Valve Control

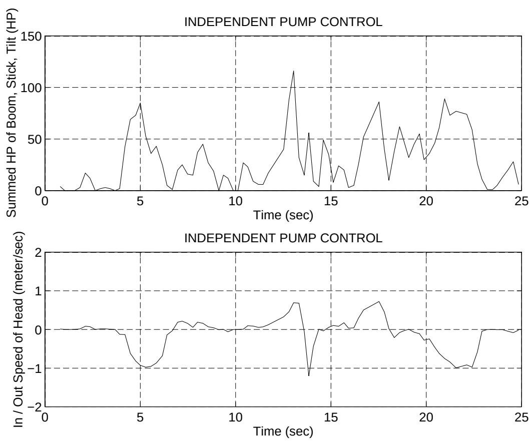

Figure 9. Machine Power and Head Speed with Pump Control

trolled motion. It can be seen from these curves that higher speeds (conservatively 10-15%) can be achieved at about 30% lower power. The net benefit would be that machines using pump control would require less cooling, would consume less fuel, and would have a longer working life. There were two disadvantages of pump control that were evident. The first is that the hydraulic system is more complex and consequently would cost more than a conventional system. This could be reduced somewhat by improved manifold design. The second is a small inherent drift in cylinder position that has to be actively controlled using the joint sensors (in valve control, centering the valve stops cylinder motion). This has safety implications and requires reliable joint or cylinder displacement sensors.

7. Stiffness Feedback Experiments

Force feedback control was also implemented. The UBC maglev hand-controller was mounted inside the machine cab. End-point forces were computed according to (2), in the cab-attached frame, assuming that the cab yaw torque component is negligible (this is equivalent to using a 5×5 Jacobian in (2)). Direct force feedback in rate mode was implemented and found to be unsatisfactory, since stability could only be maintained for very low force-scaling back to the master. The stiffness control scheme illustrated in Figure 6 was implemented along each axis of the hand-controller, except yaw, with the following parameters (see Figure 2):

Axis	K_{min}	K_{max}	B_m	Deadband
	N/mm	N/mm	N/mm/s	mm
X_0	3.00	8.00	0.06	1.5
Y_0	2.00	4.00	0.06	1.5
Z_0	3.00	9.00	0.06	1.5
	Nm/rad	Nm/rad	Nm/rad/s	mrad
X_0-rot.	0.30	0.80	0.04	35.0
Y_0-rot.	0.30	0.80	0.04	35.0

Thresholds for the computed machine forces were also implemented in order to avoid feeding back machine cylinder stiction forces, as well as pressure oscillations due to the pumps, hose elasticity, etc.. These thresholds were in the range of 6,000 N. End-effector forces as high of 55,000 N were encountered.

The overall haptic feedback provided by the above scheme was excellent. Although a thorough set of measurements could not be completed due to the difficulty of working with such a large machine, the ability to apply controlled forces was demonstrated. For example, Figure 10, displays the result of an experiment requiring the operator to apply an end-effector force against the ground as displayed on the screen of a laptop computer. By contrast, if no stiffness feedback is employed, the task becomes impossible to perform. Finally, Figure 12 shows the radial force encountered during tree-cutting.

These experiments have shown that stiffness feedback presents a viable way of controlling a large excavator-based machine in a stable fashion with sufficient haptic feedback to enable the application of controlled forces. Further work is necessary to improve the sensed cylinder forces, to quantify the degree of "transparency" provided by the stiffness feedback, and to demonstrate that real tasks can be completed faster when force information is displayed to the operator.

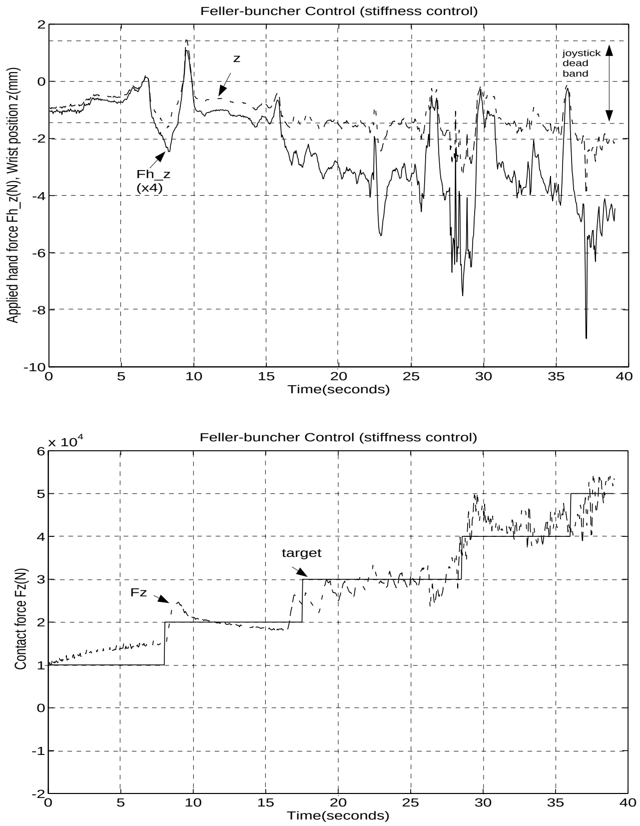

Figure 10. Controlled Force Application using Stiffness Feedback

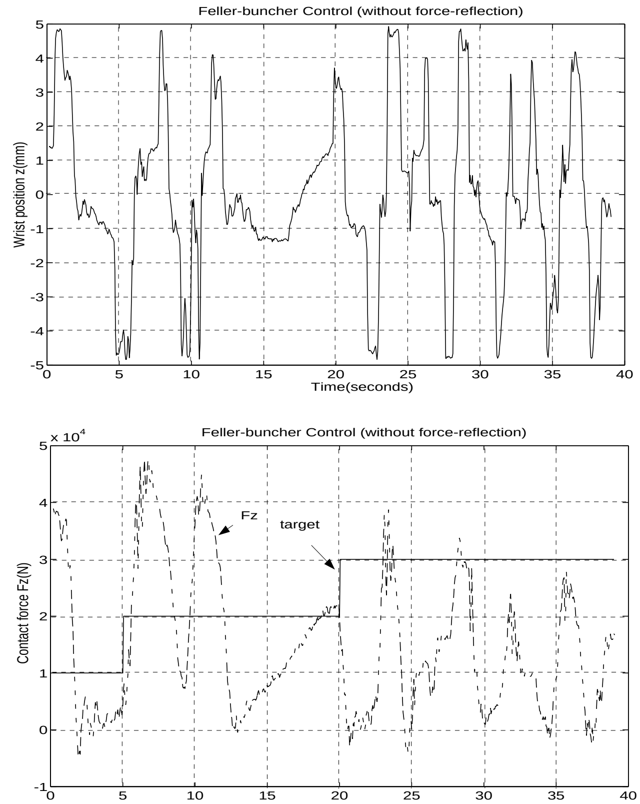

Figure 11. Attempts at Controlled Force Application without Force Feedback

8. Conclusions

Coordinated motion control in either pump or valve controlled systems was found by experienced operators to provide smoother machine motion and less damage to the tree stems during cutting. It was also found that novice operators were able to operate the machine more readily than with the standard controls.

It was found that, although somewhat more complex, a pump controlled machine is both faster and consumes lower power than a valve controlled machine.

Stiffness control was found to be a stable and effective method of controlling force application in endpoint velocity controlled systems.

As a result of these experiments, we feel that there is a considerable potential for improvement in the human interfaces in excavator type machines.

9. Acknowledgements

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References

[1] Edwin G. Johnsen and William R. Corliss. *Human Factors Applications in Teleoperator Design and Operation.* John Wiley and Sons, New York, New York, 1971.

[2] B.Hannaford, L.Wood, B.Guggisberg, D.McAffee, and H.Zak. Performance evaluation of a six-axis generalized force-reflecting teleoperator. Technical Report 89-18, California Institute of Technology-Pasadena, 1989, Pasadena, California, Jun. 1989.

[3] Daniel E. Whitney. Resolved motion rate control of

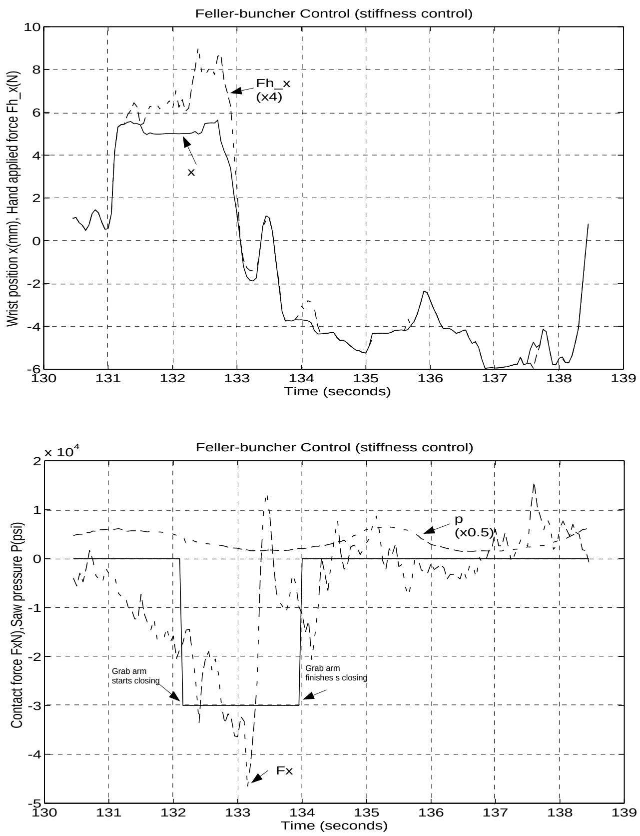

Figure 12. Hand-Controller and Feller-Buncher Radial Displacements and Forces During Tree-Cutting Process

manipulators and human prostheses. *IEEE Transactions on Man-Machine Systems*, MMS-10(2):47–53, Jun. 1969.

[4] John M. O'Hara. Telerobotic control of a dextrous manipulator using master and six-dof hand controllers for space assembly and servicing tasks. In *Proceedings of the Human Factors Society-31st Annual Meeting*, pages 791–795. Human Factors Society, 1987.

[5] U. Wallersteiner, P. Stager, and P.D. Lawrence. A human factors evaluation of teleoperator hand controls. In *International Symposium on Teleoperation and Control*, pages 291–296, Bristol, England, Jul. 1988.

[6] Bjorn Lofgren. Kranspetsstyrning. Technical Report Meddelande Nr 18, Skogsarbeten, Box 1184, 16422 Kista, Sweden, 1989.

[7] M. Ostoja-Starzewski and M. Skibniewski. A master-slave manipulator for excavation and construction tasks. *Robotics and Autonomous Systems*, 4:333–337, 1989.

[8] Darrell Wong, Peter D. Lawrence, and Ahmed Ibrahim. Efficient computation of the mass matrix for tree structured systems using orthogonal complements. In *Canadian Conference on Electrical and Computer Engineering*, pages 342–346, Montreal, Canada, Sep. 1989.

[9] M. Zhu. Master-slave force-reflecting resolved motion control of hydraulic mobile machines. Master's thesis, University of British Columbia, December 1994.

[10] N. Sepehri, P.D. Lawrence, F. Sassani, and R. Frenette. Resolved-mode teleoperated control of heavy-duty hydraulic machines. *ASME Journal of Dynamic Systems, Measurement and Control*, 116(2):232–240, Jun. 1994.

[11] Alan J. Hewitt. Hydraulic circuit flow control. U.S. Patent, allowed Jan 12, 1994, 1994. U.S. filing Jan 21, 1993.

[12] Dragan Stokic, Miomir Vukobratovic, and Dragan Hristic. Implementation of force feedback in manipulation robots. *International Journal of Robotics Research*, 5(1):66–76, Spring 1986.

[13] M. Ostoja-Starzewski and M. Skibniewski. A Master-Slave Manipulator for Excavation and Construction Tasks. *Robotics*, 4(4):333–337, 1989.

[14] S.E. Salcudean and N.M. Wong. Coarse-fine motion coordination and control of a teleoperation system with magnetically levitated master and wrist. In *Third International Symposium on Experimental Robotics*, Kyoto, Japan, Oct 28-30, 1993.

[15] N. Parker. Application of force feedback to heavy duty hydraulic machines. Master's thesis, University of British Columbia, October 1992.

[16] M. Zhu and S. Salcudean. Achieving transparency for teleoperator systems under position and rate control. In *Proceedings of the 1995 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'95)*, Pittsburgh, PA, August 5-9 1995.

[17] N.R. Parker, S.E. Salcudean, and P.D. Lawrence. Application of Force Feedback to Heavy Duty Hydraulic Machines. In *Proceedings of the IEEE International Conference on Robotics and Automation*, pages 375–381, Atlanta, USA, May 2-6, 1993.

[18] C.H. An, C.G. Atkeson, and J.M. Hollerbach. *Model-Based Control of a Robot Manipulator*. MIT Press, Cambridge, MA, 1988.

[19] U. Wallersteiner, P. Lawrence, and B. Sauder. A human factors evaluation of two different machine control systems for log loaders. *Ergonomics*, 36(8):927–934, Aug 1993.

[20] Marvin Clark. Coordinated motion of a feller-buncher. Technical Report TN-223, Forest Engineering Research Institute of Canada, Vancouver, B.C., Canada, 1994.