MATCHING FEEDBACK WITH OPERATOR INTENT FOR EFFECTIVE HUMAN-MACHINE INTERFACES

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MATCHING FEEDBACK WITH OPERATOR INTENT FOR

EFFECTIVE HUMAN-MACHINE INTERFACES

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To all those who have helped me see this through

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SUMMARY

Various roles for operators in human-machine systems have been proposed. This thesis shows that all of these views have in common the fact that operators perform best when given feedback that matches their intent. Past studies have shown that position control is superior to rate control except when operating large-workspace and/or dynamically slow manipulators and for exact tracking tasks. Operators of large-workspace and/or dynamically slow manipulators do not receive immediate position feedback. To remedy this lack of position feedback, a ghost arm overlay was displayed to operators of a dynamically slow manipulator, giving feedback that matches their intent. Operators performed several simple one- and two-dimensional tasks (point-to-point motion, tracking, path following) with three different controllers (position control with and without a ghost, rate control) to indicate how task conditions influence operator intent. Giving the operator position feedback via the ghost significantly increased performance with the position controller and made it comparable to performance with the rate control. These results were further validated by testing coordinated position control with and without a ghost arm and coordinated rate control on an excavator simulator. The results show that position control with the ghost arm is comparable, but not superior to rate control for the dynamics of our excavator example. Unlike previous work, this research compared the fuel efficiencies of different HMIs, as well as the time efficiencies. This work not only provides the design law of matching the feedback to the operator intent, but also gives a guideline for when to choose position or rate control based on the speed of the system.

CHAPTER 1

INTRODUCTION

Operator performance depends heavily on feedback from the system being controlled. Many types of human-machine interfaces (HMIs) have been invented to provide operators with feedback to better their performance along some metric. This thesis shows that effective HMIs must give the operators feedback that matches their intent. Intent in this work will be defined as what the operator intends to have happen as a result of his/her input. Notably, operator intent is different from the operator's goal and from the operator's input.

Birmingham proposed that people perform best when their transfer function is as simple as possible. He viewed the goal of HMIs to be the simplification of the operator's transfer function to a simple amplifier [Birmingham]. This simplification requires a direct comparison between the input and output, or, in other words, feedback that matches the operator's input. As automation technology improved, Fitts proposed list of what men and machines do best [Fitts, Wickens, Corliss]. Sheridan suggested using Fitts' list to assign the task a level of control from both the operator and the machine [Sheridan (1989)]. Contrary to Birmingham's hypothesis that a human "is best when doing least," Sheridan outlines the operator's role as being much more complex than a simple amplifier in a supervisory control system; the operator is a planner, monitor, and teacher [Sheridan (2000), Jordan, Birmingham]. He called these combined roles supervisory control, and it requires feedback that matches the operator's goal [Sheridan (1978)].

This thesis proposes a theory that underlies both views: Effective HMIs must give the operator feedback of the same type as the operator's intent. Both Birmingham's and Sheridan's feedback nearly matched operator intent. In Birmingham's case, the operators controlled either the position or velocity of a single degree-of-freedom. The operator's intent likely was the resulting position or velocity of the slave device. Assuming this was the operator's intent in Birmingham's studies, operator intent and input were very similar. In Sheridan's case, the operator input was a "goal state," which could be something much more complex than a 1-DOF position or velocity [Sheridan (1992)]. The goal state could be accomplishing a task, e.g., picking up an object. The assumption was that the operator's goal was the goal state, and so feedback was provided to tell the operator if the goal state had been reached. In this case, the operator intent was likely an overall motion towards the goal state, making the operator's goal and intent very similar. The difference between input, intent, and goal is sometimes unclear, and not just for the researchers mentioned above. The following example will help to explain the difference:

Imagine that both Birmingham and Sheridan want to download a file from the internet. They both have the same goal: download the file to their computers. Birmingham works on a computer where he controls the download speed with the location of the mouse. The mouse location is his input. Sheridan works on a computer that allows him to select download (his input), and then the computer automatically sets the download speed based other demands for the computer's resources. Birmingham would select the download speed to be the feedback so that he could compare the current speed to his desired speed. Being able to directly compare the feedback to the command would allow him to appropriately adjust his input, but gives him no information about how close he is to reaching the goal unless he is mentally integrating the speed. Sheridan's feedback would be an icon showing if the file has downloaded completely or not, which gives no information about how the system is moving toward the goal. When selecting to download the file, both operators intend that the computer will begin doing so. This is different from how fast it does so (Birmingham's input) and actually downloading the entire file (Sheridan's goal state). Feedback that shows the motion towards the goal, i.e., how much of the file has downloaded and how fast it is downloading, is commonly visualized on the screen as a bar that is being filled from left to right.

The focus of this thesis is to demonstrate how matching feedback with the operator's intent affects performance, not for computer applications, but for large-workspace, dynamically slow manipulators. Most HMI research has focused on human-scale or smaller manipulators with human-scale or faster dynamics, e.g. [Mora, Jenkins]. For these systems, position control has been shown to outperform rate control [Kim, Zhai (1993)]. These studies have led to position control being accepted as generally superior to rate control and fostered the idea that position control is more intuitive [Sheridan (1978)]. However, for large-workspace and/or dynamically slow manipulators, rate control performance exceeds position control performance [Kim, Zhai (1997)]. Because of the large workspace and dynamically slow response, operators of these manipulators do not receive the immediate visual position feedback that operators of smaller and faster manipulators do. However, they do receive immediate visual rate feedback.

A new HMI displays a *ghost*, a graphical overlay of the input position, to the operator, matching position feedback with position control for large-workspace, dynamically slow manipulators. The ghost improves performance with position control for these manipulators and explains the previously found better performance with rate control. Operator fuel and time efficiency were increased by over 20% by the new HMI. The types of mistakes operators make with different HMIs were quantified and new control algorithms were implemented on the HMI.

This work also investigates if certain task conditions influence the operator's intent. For example, despite the previously agreed upon advantage of position control, Zhai et al. showed that rate control outperforms position control for tracking tasks for the system they used, which had fast dynamics [Zhai (1993), Zhai (1997)]. In this work, a series of human factors tests with different tasks (e.g., tracking, point-to-point motion) were performed with both position and rate control to determine if the task conditions affect the operator's intent. A second series of tests compared operator performance between rate and acceleration control for a system where velocity is the output. This test demonstrated that matching operator intent with the system feedback, regardless of the order of the output of the system, increases operator performance. Finally, tests were performed on an excavator simulator to verify the results on a real-world application.

CHAPTER 2

BACKGROUND

Operator's Role in Human-Machine Systems

As early as the 1940s, attempts were made to determine the human transfer function [James, Tustin]. They found that there is not a single human transfer function, but many, and that humans adapt their transfer function to maximize performance. Birmingham theorized that humans are better at simple transfer functions, so control engineers should design in a way to minimize the complexity of the operator's transfer function [Birmingham]. He viewed the best case scenario to be when the operator's transfer function is only a simple amplifier. He proposed two methods to reduce the operator's transfer function to a simple amplifier, quickening and aiding, and showed that they improved operator performance (see page 9 for descriptions of quickening and aiding). He was interested in controlling systems that had a single position or velocity output.

As the fields of human factors engineering and engineering psychology emerged, the scope of what the "system" was in a human-machine system widened [Chapanis]. It moved from single degree-of-freedom systems like Birmingham studied, to complex computer and mechanical systems, such as nuclear reactors and airplane cockpits. Instead of studying operators that had a given position or rate as a goal, the field focused on operators with more complex goals composed of many tasks, such as safely producing electricity with a nuclear reactor or landing a plane. The output of the system was no longer directly dependent on the human's input because some processes were partially or fully automated.

Fitts proposed a list of what men and machines do best (Table 1). Control was given to either the operator or the machine. The operator's role was either completely eliminated (the process was entirely automated), or the operator controlled the job completely. Better automation became the solution to better performance, again keeping the operator's role at a minimum.

Table 1. Fitts' List

Men Are Better At	Machines Are Better At
• Detecting small amounts of visual, auditory, or chemical energy • Perceiving patterns of light or sound • Improvising and using flexible procedures • Storing information for long periods of time, and recalling appropriate parts • Reasoning inductively • Exercising judgment	• Responding quickly to control signals • Applying great force smoothly and precisely • Storing information briefly and erasing it completely • Reasoning deductively

Sheridan and Verplank proposed levels of automation based on the ratio of human control to computer control [Sheridan (1978)]. They called the idea of having these levels of control supervisory control and proposed ten levels. The underlying idea was not to minimize the operator's role, but to maximize performance by using the strengths of both operator and machine simultaneously. More recent research has extended this idea from assigning static levels to the control ratio to changing the control ratio based on the situation [Parasuraman]. Much research has gone into the types of controls, displays, and environment to best help the operator [Wickens, Sanders]. How to integrate the automatic and human-controlled processes continues to be an active area of research [Bunte, Lin].

Telemanipulator Position, Rate, and Acceleration Control

Despite the long trend towards supervisory control and automation, most industrial manipulators in unstructured environments are driven at a low-level by human operators, either directly or tele-operated. For example, the manipulators used at the Fukushima disaster, military drones, and ROVs used at the Deepwater Horizon oil well are controlled at a low-level by human operators that give position or velocity inputs [Murphy], [Ohno], [Dusseault], [Oceaneering]. The first telemanipulator was controlled by being mechanically coupled to the master controller [Goertz (1952)]. Mechanical connections were soon replaced by electrical connections [Goertz (1954)]. Switching to an electrical connection allowed the system designer to decide which order derivative the input would be, i.e., zeroth order (position control), first order (rate control), etc. Although the system may respond equally well to any derivative order of input, it was quickly realized that human operators performed differently with each type of control. For example, operators perform better with rate control than acceleration control for positioning tasks [Massimino].

Early studies include Mullen's work with an E-2 manipulator that found that using a replica master (position control) was about 4 times faster than resolved rate motion control, or what would now be called coordinated rate control [Mullen]. Wilt et al. made the same comparison as Mullen, but with a large-workspace manipulator [Wilt]. He found that using a replica master was only 1.6 times faster than coordinated rate control in this case. NASA performed tests to determine if rate or position control would be better for space telemanipulation. They recommend using position control in situations where the work space is small (human-scale) or the dynamics are fast (the natural frequency of the system is >1Hz) [Kim]. Rightfully dubious of NASA's experimental method (they only had two subjects), Zhai performed human factors tests with greater experimental validity. His system had a human-scale workspace and fast dynamics. He found that with training the advantage of position control disappeared and rate control performance was comparable to position control performance for a 6-DOF docking task [Zhai (1993)], [Zhai (1997)].

In more recent studies using a dynamically fast, human-scale robot, Mora et al. found that position control is generally preferred, except when exact tracking is needed, and then rate control is slightly better [Mora]. Farkhatdinov et al. compared position and rate control for a small mobile robot and concluded that, for small motions, position control is much better, but rate control is preferred for larger motions, reiterating again the finding that position control is generally better, but not for large workspaces [Farkhatdinov].

Other research has focused on ways to improve the system by better matching the operator's intent. Birmingham proposed both aiding and quickening to simplify the operator's transfer function [Birmingham]. Quickening is used for systems with very slow dynamics, where the operator's command effects the acceleration or jerk of the machine, but he/she is interested in position. For example, submarines have used quickening displays because of the slow response of the position of the submarine to the angle of the depth-controlling mechanism [Johnsen, Corliss]. A quickened system shows the future state of the machine based on the current input. It provides anticipatory visual feedback based on the derivatives of the states. In many ways, quickening is similar to PID control, but it is applied to the feedback rather than the system input (Fig. 1). Birmingham's solution works because operator intent was of the same derivative order as the output, not the same derivative order as the input. Despite the fact that he shows a direct comparison between the input and the quickened output, the comparison is actually between the intent and the output.

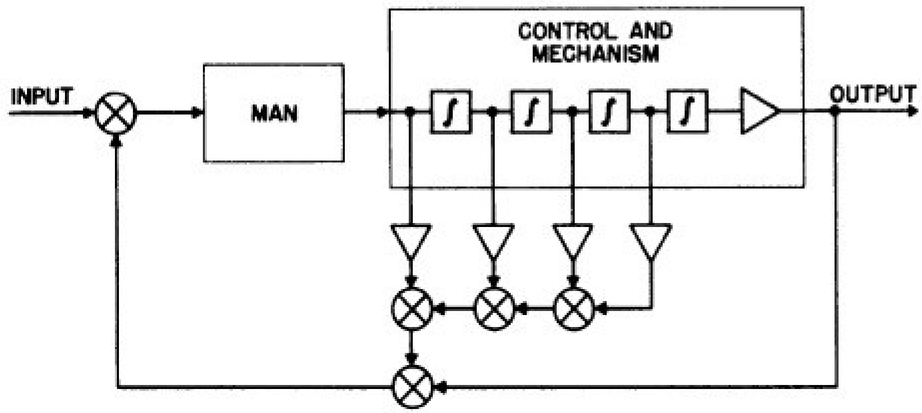

Fig. 1. Quickening display from [Birmingham]

An aiding control block is the inverse of the dynamics of the input device. This block is inserted directly after the input device to negate the filtering of the operator's command by the input device (Fig. 2). Then the system feedback better matches the operator's intent because the operator's intent is not clouded by the input device's dynamics.

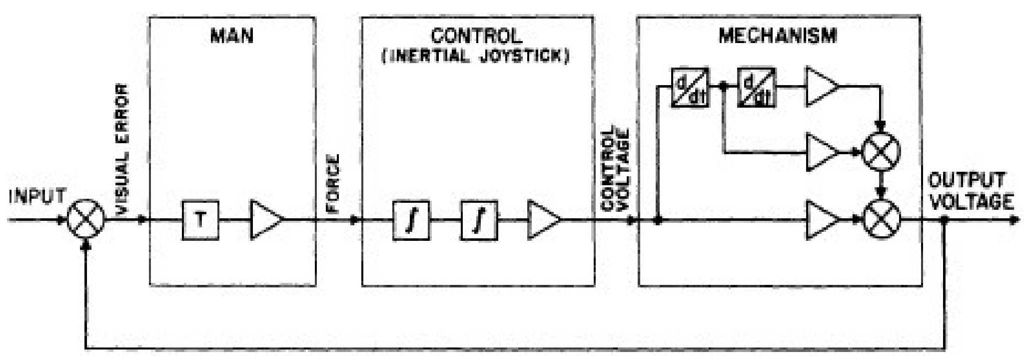

Fig. 2. Aiding from [Birmingham]. The aiding is the "mechanism" block

Coordinated control better matches the operator's mental model of the task to be done [Wickens]. In other words, the operator controls the end effector's position or velocity in a way that matches the way he/she views the position or velocity as occurring, i.e. in terms of left-right or up-down positions/velocities instead of a sets of joint positions/velocities. The visual feedback already matches the operator's intent. Coordinated control then matches the input with the operator's intent. Coordinated rate control has been shown to enable novice operators to more readily control hydraulic equipment [Lawrence, N. Parker, Wallersteiner].

Coordinated position control has been shown to be more effective than coordinated rate control in most circumstances, especially for novices [Kim, Zhai (1997)]. [Kontz] implemented coordinated position control on a backhoe, but found that the magnitude of the cab vibrations was great enough to lead to instability due to the biodynamic feedthrough. NASA also suggests rate control in the presence of vibrations for the same reason [J. Parker].

Even in the absence of vibrations, coordinated rate control has been shown to outperform coordinated position control for large-workspace and/or dynamically slow manipulators [Zhai (1997)]. When using position control for manipulators with slower dynamics, there is not a clear indication to the operator where the position he/she is commanding is located because the manipulator takes too long to arrive at the input position. This causes a "move and wait" tactic [Sheridan (1989)]. Operator complaints about being uncertain of the commanded position when using coordinated position control were also registered by [Osafo-Yeboah], [Winck], and [Elton (2011a)].

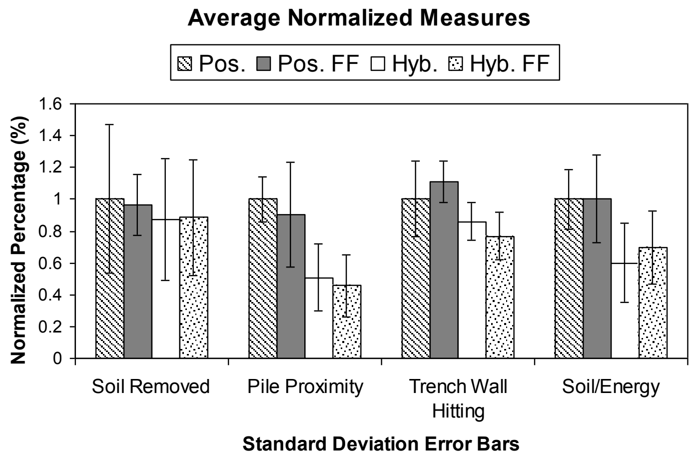

Fig. 3. A comparison of efficiency for four types of coordinated controllers

A previous study done on the excavator simulator discussed later compared the two types of coordinated control, each with and without force feedback [Elton (2009)]. The results of this study showed that position control for all joints was better than position control for the arm and rate control for the swing (see Fig. 3 and compare coordinated position control {Pos.} with hybrid position and rate control {Hyb.}. Higher is better for all measures). This result encouraged the use of position control later in the thesis.

Ghosting

Predictive Displays

Predictive displays show the operator the predicted state of the machine given the current input and computer-estimated future inputs. A simple example of a predictive display would be one that assumes the operator's rate command will remain constant and displays the manipulator's position at some time interval in advance. Predictive displays are used in very fast systems (e.g., jet planes) to extend the operators' knowledge of how their command will affect motion in the near future [Johnsen, Kelley]. In this case, the predictive display shows the operator’s future path because the operator must make input adjustments now because he/she will be unable to correct fast enough in real-time in the future (e.g., he/she must command the jet to gain altitude before approaching the mountain, not because the jet cannot perform appropriately, but because the operator react and correct quickly enough).

Predictive displays have also been shown to be effective in communication time delay situations [Sheridan (1992)]. The operators are shown what the effects of their input are from a faster-than-real-time model. He/She no longer has to wait to see how the machine responds, if the model is accurate. Predictive displays effectively remove the time delay from the feedback to the operator. Other HMIs have been proposed for teleoperation with time delay, most of which attempt to accomplish greater usability and/or productivity by removing the time delay from the system feedback [Niemeyer]. Providing non-delayed feedback better matches the operator’s intent because he/she views the states of the machine in real-time.

Ghost Arm Compensation for Communication Time Delay

To overcome the effects of time delay, [Noyes] built a two dimensional wire frame “ghost arm” overlay of the robot arm being controlled and superimposed it on the delayed video feed of the robot arm. The wireframe overlay showed the telemanipulator’s model-based predicted location at the current time. This allows the operator to control the wireframe arm without any communication delay. As noted by Noyes, this interface is only as good as the model, and it is difficult to model environmental interactions. Noyes used an Argonne E-2 manipulator that has fast dynamics, so the position of the overlaid ghost arm on the screen was basically the same as the operator’s position command.

[Conway] furthered this interface by constructing a teleoperation system with a ghost arm that had a time and position clutch. The time clutch allowed the operator to quickly move the ghost arm to define the path that the manipulator end effector should follow, without being constrained by the dynamics of the telemanipulator. Disengaging the position clutch disconnected the controller from the input stream. With the position clutch disengaged, the operator could move the ghost arm freely about, taking time to position it for the beginning of a complicated maneuver. Once the operator has the ghost arm in the correct location, he/she re-engages the position clutch, and that position is entered into the input stream. The goal was to save time with the time clutch on fast, easy maneuvers and then to use the saved time on positioning for complex maneuvers, all while mitigating the effects of time delay in the same fashion as Noyes. Both Noyes and Conway showed improvements in task completion times with their HMIs.

Human-Machine Interfaces for Hydraulic Manipulators

Evolution of Human-Machine Interfaces for Hydraulic Manipulators

Human-machine interfaces for heavy hydraulic manipulators continue to evolve. These manipulators were first controlled directly by levers or pedals that directly moved the valves controlling the manipulator. Then, pilot-operated valves were implemented that allowed the operator to control a smaller valve requiring less force to move that would in turn move the valves controlling the manipulator. Pilot-operated valves have been replaced in part by electro-hydraulic systems. In these systems, the operator controls the valves by moving electronic joysticks or other input devices that send a current to a solenoid that moves the valve spool. Because the operator’s controller and the manipulator are only electronically connected, new possibilities emerge such as teleoperation [Andreychek], coordinated control [Wallersteiner], and artificial force feedback (as opposed to the forces fed back from the mechanical or hydraulic coupling) [N. Parker, Kontz, Zhu].

Significant other work has removed the operator from the loop and focused on automating excavation [Dunbabin, Marshall, Bradley, Lever, Stentz]. The volume of work suggests the difficulty of the problem. While full automation of excavators will likely not be soon in coming, some excavators sold today come equipped with auto-dump and auto-return capabilities.

Why Move Towards Teleoperation?

There are several benefits to removing the operator from the machine, including safety. Worksites for hydraulic machinery are often hazardous. Specially designed excavators are used for the handling of nuclear waste and are teleoperated to protect the operator from radiation exposure [Andreychek]. The construction of ports requires expert divers to drive specialized excavators underwater [Hirabayashi]. When forest harvesting, trees can, and occasionally do, fall on machine operators – these trees are known in the business as widowmakers. Underground mines have the potential to collapse, such as the Upper Big Branch Mine collapse in West Virginia (5 Apr 2010, 29 dead), the Copiapó collapse in Chile (5 Aug 2010, 33 miners trapped for 69 days), and the Pike River collapse in New Zealand (19 Nov 2010, 29 dead). Even at everyday construction sites, accidents happen regularly. Removing the operator from the machine would increase operator safety.

There are other benefits to removing the operator from the machine. The operator could move to a different location to better view the end effector during precision tasks.

Vibratory feedthrough would be eliminated if the operator no longer sat on the machine. Teleoperation would also allow the operator to work remotely, which would allow the operator to switch between worksites quickly rather than physically commuting between them. Time that previously would have been spent sitting idle at a job site waiting until other tasks were completed could instead be used doing work at another site. Operators would no longer have to live at remote locations, such as the Challenger mine in the Australian Outback that operates on a fly-in fly-out roster.

Placing the operator at a remote location would remove all of the feedback to the operator. It would need to be replaced by sensors and an HMI. Teleoperation increases the freedom in designing HMIs. While sensors and interface devices could be costly, the cost would be offset because machines would no longer need a cab to house the operator, which often includes climate control, plush seats, and other expenses in addition to the cost of the materials and manufacturing the of the cab's metal, glass, etc. [Herrin].

Definition of Dynamically Slow and Large Workspace Manipulators

The underlying idea that defines a system as being dynamically fast or slow is a comparison between how long the machine takes to get from one position to another and the time it takes the operator to move from commanding the first position to the second using position control. *Dynamically slow* and *large workspace* both describe this same idea and are not independent of one another. For a dynamically slow manipulator the end effector speed of response may be slower than human motions resulting in longer machine response times compared to that human command times. With a large workspace manipulator the end effector may move rapidly compared to a human, but if the workspace is large then the resulting time to traverse from one point to another is longer than the time it takes the operator to command the new position (e.g. tower cranes). This is a function of the scaling of the slave workspace to the master workspace. Exactly how *dynamically slow* has been defined depends on the researcher. Kim et al. defined it in terms of the systems natural frequency [Kim]. They defined a dynamically slow system as having a natural frequency less than 1Hz. This works well for systems that are second order, but does not apply to systems such as the hydraulic cylinder modeled in this thesis, which is basically a first order system with a rate limit because the dynamics of the higher orders (e.g. the fluid dynamics) have a much higher time constant. The often and quickly reached rate limit adds in a nonlinearity that makes the idea of a system natural frequency difficult to apply. Other researchers have only heuristically suggested what defines fast and slow, e.g. [Wen-Hong]. While this approach may work well when examining only one system with fixed dynamics, this section gives a definition that can be used for any system. It takes into account both the overall speed of the machine (dynamically slow or fast) and the scaling between the input and the output (large or small workspace).

This thesis uses *dynamically slow* to denote the combination of the effects that others have labeled as *dynamically slow* or *large workspace*. The definition for dynamically slow in this thesis is:

Dynamic Speed Ratio (DSR) = To/Ts

where

To =Time for an operator to command a typical position step in a controlled fashion
Ts =Time it takes the system to move to the commanded position given the operator's input

DSR ranges between 0 and 1. Higher values of DSR correspond to dynamically faster systems. This definition was chosen specifically to bring out the underlying idea mentioned at the beginning of the chapter: the ratio of the time it takes to command the motion to the time the machine takes to execute this motion is the indicator of dynamic speed. The results of Chapter 5 investigating a possible crossover point indicate that the DSR of the system should be dependent on the task because the crossover point appears to vary with the task. This task dependency is incorporated into the definition of dynamic speed by making it dependent on a typical step command for the system. Therefore, the DSR of the same system may vary depending on whether fine positioning or gross movement tasks are being performed. The system used for finding the crossover point has a DSR of 0.2. The kinematic and dynamic systems described in Chapter 3 have DSR values of 1 and 0.05, respectively. The excavator simulator has a DSR of 0.25.

Excavator Simulator Testbed

New human-machine interfaces must be mounted on the actual machine being controlled to test their true effectiveness. Changing the controls of a machine is time consuming and can be expensive. To quickly interchange and test new HMIs, an excavator simulator was constructed that simulates the dynamics of the actual machine and its environment. The simulator was used to ascertain the effectiveness and efficiency improvements of the new HMI without the difficulties associated with implementing the new HMI on the actual machine. The system modeled for the excavator simulator is a Bobcat 435 mini-excavator. A comprehensive discussion of the simulator is covered here, and the full details can be found in [Elton (2009)].

About the Bobcat 435 Excavator

The Bobcat 435 excavator is a five-ton machine powered by a 48.8 hp diesel engine (Fig. 4) [Bobcat Company]. It has five joints: the cab (or swing), an offset joint that adjust the angle of the arm relative to the cab, and the three joints of the arm itself: the boom, stick (also called the arm, but it is referred to as the stick in this work to differentiate it from all three links together being called the arm), and bucket (Fig. 5).

Fig. 4. Bobcat 435 mini-excavator in a normal dig cycle

It also is equipped with two tracks that can be operated independently to position the excavator and a blade that can be raised or lowered to increase machine stability or backfill trenches.

During a standard dig cycle, only four of the joints are used: the swing, boom, stick, and bucket. The offset joint is generally adjusted prior to excavation and, except in tight spaces, is set so that the arm faces directly ahead from the point of view of the operator. The tracks and swing are driven by hydraulic motors, and all other links are actuated by hydraulic cylinders.

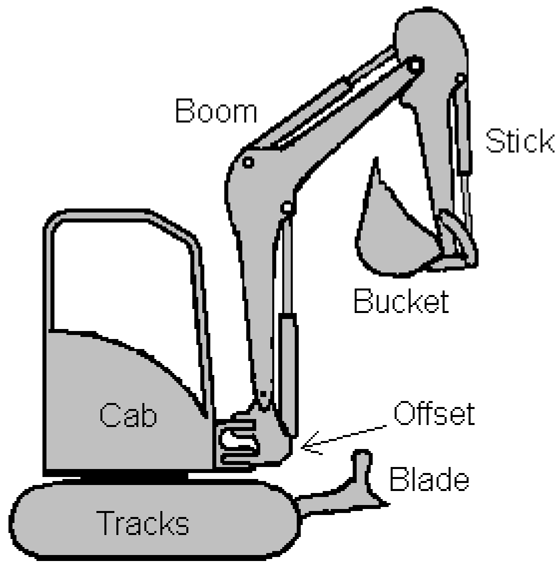

Fig. 5. Links of the bobcat mini-excavator

The Center for Compact and Efficient Fluid Power (CCEFP), which sponsored this research, also sponsored a related project at Purdue University to study the efficiency difference between pump controlled and valve controlled machines. A standard valve controlled 435 machine was tested for efficiency and then the valves and fixed displacement pump were replaced by four variable displacement pumps. Each pump controlled one of the four main functions (swing, boom, stick, and bucket) and also drove one of the four lesser used functions (offset, blade, and left and right tracks) [Zimmerman]. The variable displacement pump controlled excavator is modeled in this work, not the standard valve controlled excavator. The four minor functions are assumed not to be in use in the model, which is reasonable for normal dig cycles.

Operator Workstation

A special operator workstation was constructed to give the operator a realistic feel of operating an excavator. The operator sits in the cab of a Bobcat 435 mini-excavator and views the simulation on a 52-inch television screen mounted onto the front windshield of the excavator (Fig. 6).

Fig. 6. The operator workstation in use

The graphics program that displays the simulated excavator arm was written in C++ using the OpenGL library. The Bobcat Company provided the CAD files of the arm which results in a realistic image on the screen (Fig. 7). The trench the operator should dig is delineated in a flat green in contrast to the grass texture covering the rest of the soil. Trees and a shadow were added to the visualization to help with depth perspective. To make the visualization more realistic, soil was displayed in the bucket when taking a scoop, falling to the ground when emptying the bucket, and in piles upon hitting the ground. To further immerse the operator into the simulator, engine noise is played in the cab by two speakers. The volume of the noise was programmed to vary with the engine load.

Fig. 7. Excavator simulator screen shot

Input Devices

The original excavator was equipped with hydraulic joysticks that were removed, and electronic joysticks were mounted on supports near the location of the hydraulic joysticks (Fig. 8). The electronic joysticks provided the first way to control the simulated excavator. A Phantom Premium 1.0 (or simply, Phantom), a commercially available haptic device (see Fig. 8 and Fig. 23), was the second device used to control the simulated excavator. The Phantom is mounted on the right side of the cab on a tray that is welded to the wall of the cab, and is used for coordinated control. The coordinated controllers implemented with the Phantom are discussed in Chapter 3.

Fig. 8. Phantom and right hand joystick in the operator workstation

<u>Physical Cab Rotation</u>

To enable the cab to swing, an external pump was attached to the cab's swing motor. A 19 L/min Moog valve was used to regulate the flow through the motor. The rotation of the cab was measured by an encoder that was linked by a cable to the underside of the cab. The control diagram is shown in Fig. 9. The control gain, *k*, was adjusted based on the speed of the simulator. For most operating speeds, the gain was constant, but for low speeds, it exponentially decayed to zero. This adjustment caused more realistic, smoother accelerations, and a more consistent velocity at slower velocities. This adjustment was needed because the Moog valve is much more responsive than the spool valves used in excavators, resulting in much faster accelerations. The controller was designed to create responses that felt like actual machines. A deadband was also added to create a sensation of a hard stop of the excavator cab because the gain adjustment had made the stops feel softer. A first order hold was used to estimate the cab's position because the encoder only sent information at each tick. The simulator runs at 1kHz, and so it was common to have multiple time steps without receiving new encoder information. The first order hold extrapolated the position from the last two encoder ticks to give an estimated cab position (see Fig. 9). If more than 0.2 seconds passed without new information from the encoder, the first order hold was changed to a zero order hold, and the encoder position was used instead of the extrapolated estimate of the cab position (see far right of Fig. 11).

While the cab did not track the simulator perfectly (there was a time lag of around 0.1 s, see Fig. 10), it resulted in performance that felt realistic for the operator. None of the subjects noted any error between the position of the simulator and the cab.

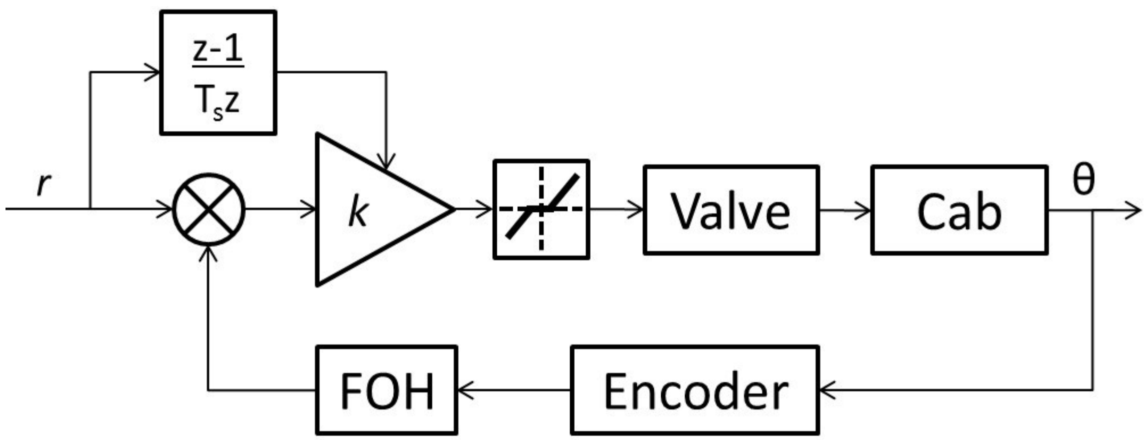

Fig. 9. Control diagram for the cab swing: r is the simulated cab position, and θ is the physical cab's position.

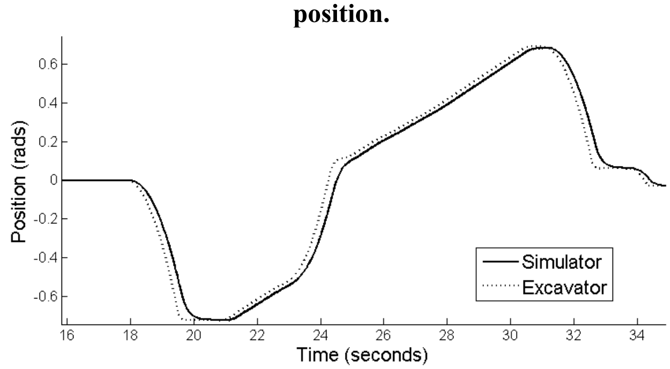

Fig. 10. Simulator and excavator cab positions

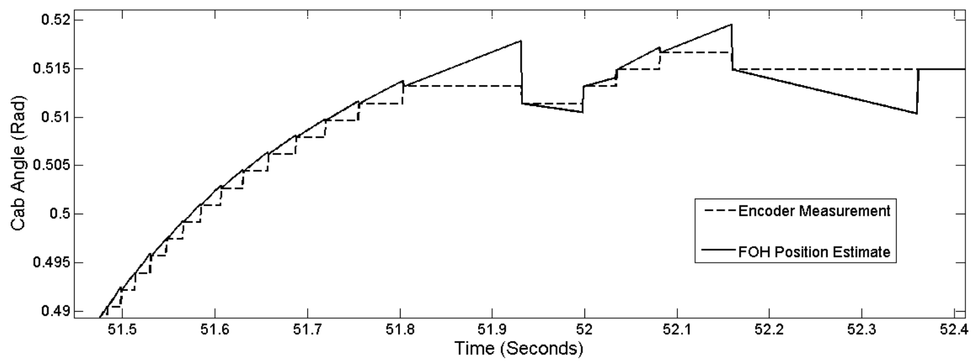

Fig. 11. Encoder position and FOH estimator used. Note that the estimated position is quite smooth even with slow velocities, but as the excavator comes to a stop, the estimation accuracy decreases.

Excavator Dynamics

The simulator mimics the dynamics of the excavator's hydraulic and mechanical systems and the interaction with the environment. The systems were modeled in Simulink and run on an XPC target real-time machine at 1kHz. The mechanical dynamics are calculated using the Newton-Euler formulation and are based on previous work [Fu, Koivo]. The literature does not have an accurate model of the 435 excavator, so with the assistance of the manufacturer and researchers at Purdue University, the necessary parameters for this simulation were measured so that the model would reflect the motion of the actual machine [Williamson, Zimmerman, Schuh].

Hydraulic System Dynamics

The hydraulic system consists of four identical circuits shown in Fig. 12. Each circuit has its own pump and all four pumps are powered by the same diesel motor. The swing motor circuit has a hydraulic motor instead of a cylinder as pictured in Fig. 12.

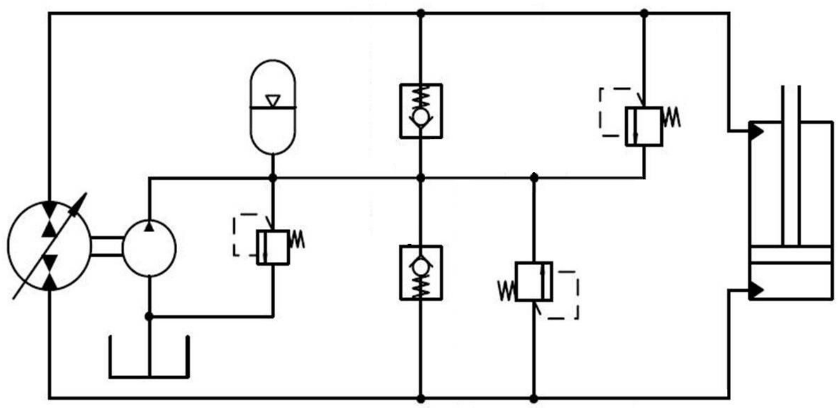

Fig. 12. Hydraulic circuit for each of the four variable displacement pumps

Dynamic models of the hydraulic pumps, cylinders, and motor were made in Simulink.

Soil Model

Soil is difficult to model since its parameters vary greatly from type to type and within a single type from day to day (e.g. water content changes). In the simulator, the soil is modeled as a homogeneous substance with all necessary parameters known. The soil model is based upon previous work [Reece], [Malaguti (1994)], [Malaguit (1999)], [Tan] and mainly on the work done by [DiMaio (1998)], [DiMaio (2001)]. These models all only examine trajectories where the bucket is coming towards the operator. The model developed for this work covers all possible scenarios. Also all previous soil simulations have only examined trajectories and soils where the soil can only exert a force on the bucket less than the force exerted on the soil by the bucket. The developed soil model allows the force applied by the soil to exceed the applied bucket force, which is necessary to create a realistic simulation of digging. The new model also includes a section on wrist-soil interaction forces, an interaction not previously included in any model in the literature. The soil outside the trench area can be penetrated by the bucket; however it cannot be picked up by the bucket, so the soil level is always the same. In the trench, the soil level changes as the bucket teeth pass through it.

The excavator simulator was used to test for improvements in operator efficiency. To get results that more clearly show the effects of the ghost interface on excavator simulator, seven dynamically simpler tasks were designed. A description of the coordinated controllers used on the excavator simulator and the controllers used in seven simpler 1- and 2D planar test are found in the next chapter.

CHAPTER 3

GHOST INTERFACES AND SYSTEM DESIGN

To investigate the effects of matching feedback with operator intent, three different systems were tested with and without a ghost interface. The two systems used in the planar tests had either one or two degrees of freedom and could therefore be clearly displayed on a computer monitor. The third system was the excavator simulator. This chapter covers the design of the controllers used in each one of these systems. Importantly, it also shows how the controller gains were matched so that optimal human performance with the position controller and the rate controller are nearly identical. This is done so that differences in operator performance are not caused by differences in controller capability.

Planar Systems and Controllers

Four different controllers were created:

- Position control of a dynamic system (PD control)
- Position control for a kinematic system (PK control)
- Rate control for a dynamic system (RD control)
- Rate control for a kinematic system (RK control)

The position and rate controllers for the dynamic system were designed to perform equally well for an optimal user, as were the position and rate controllers for the kinematic system. How “equal performance” was defined and measured is discussed after descriptions of the controllers are given.

The dynamic systems are generic force-acting-on-a-mass systems. Although the system modeled here can easily be applied to many physical systems, it was chosen to mimic a hydraulic cylinder. The acceleration limit is high, and the velocity limit is low, like hydraulic cylinders found on many off-highway machines. The kinematic system, by the fact that it does not have dynamics, does not model a physical system. This system represents a best case scenario of a fast acting system that tracks a human input: the dynamics are so much faster than the human's dynamics that there is no delay in the tracking. An example of such as system is a lightweight robotic arm driven by electric motors.

Position Controller for the Dynamic System (PD)

A full state feedback position controller applied a force, *u*, to the mass, *m*, to drive its position, x_1, to the desired location, *r*.

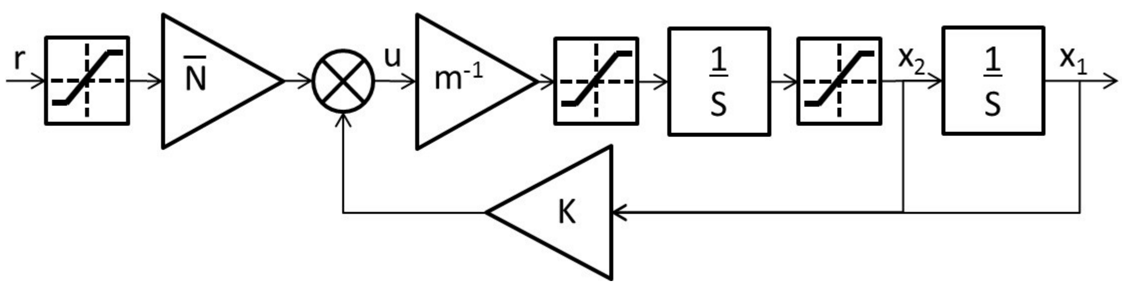

Fig. 13. Position controller of the dynamic system

The desired position was proportional to the displacement of the joystick. The system is in the form of

$$\dot{x} = Ax + Bu \quad (1)$$

$$y = Cx + Du \quad (2)$$

The state vector, *x*, includes the mass's position, x_1, and velocity, x_2.

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \quad (3)$$

The derivatives of the states are

$$\dot{x}_1 = x_2 \quad (4)$$

$$\dot{x}_2 = \frac{u}{m} \quad (5)$$

The matrices *A*, *B*, *C*, and *D* are

$$A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \quad (6)$$

$$B = \begin{bmatrix} 0 \\ m^{-1} \end{bmatrix} \quad (7)$$

$$C = \begin{bmatrix} 1 & 0 \end{bmatrix} \quad (8)$$

$$D = [0] \quad (9)$$

The reference input, *u*, can be found by the following [Kuo]:

$$Z = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \quad (10)$$

$$N = Z^{-1} \begin{bmatrix} 0 \\ 0 \\ \hline 1 \end{bmatrix} = \begin{bmatrix} N_x \\ \hline N_u \end{bmatrix} \quad (11)$$

$$\bar{N} = N_u + KN_x \quad (12)$$

$$u = \bar{N}r - Kx \quad (13)$$

K was selected to minimize the difference between the performance of the position controller and the rate controller.

$$K = [10006 \quad 304] \quad (14)$$

There were constraints on the system's acceleration, a_{limit}, and on the system's velocity, v_{limit}.

$$-a_{limit} \leq \dot{x}_2 \leq a_{limit} \quad (15)$$

$$-v_{limit} \leq x_2 \leq v_{limit} \tag{16}$$

The reference was also limited by the mechanical stops of the joystick.

$$r_{min} \leq r \leq r_{max} \tag{17}$$

The input range of the joystick was adjusted by a separate gain so that r_{min} was equal to the left-hand boundary of the task's space (marked by the outline of a white square in Fig. 33) and that r_{max} was equal to the right-hand boundary. A small saturation region was added to the extreme positions of the joystick so that the operator could easily command the maximum and minimum positions (see Fig. 14). The joystick without spring centering was used with this controller so that there would be no force on the operator's hand when giving a constant position command.

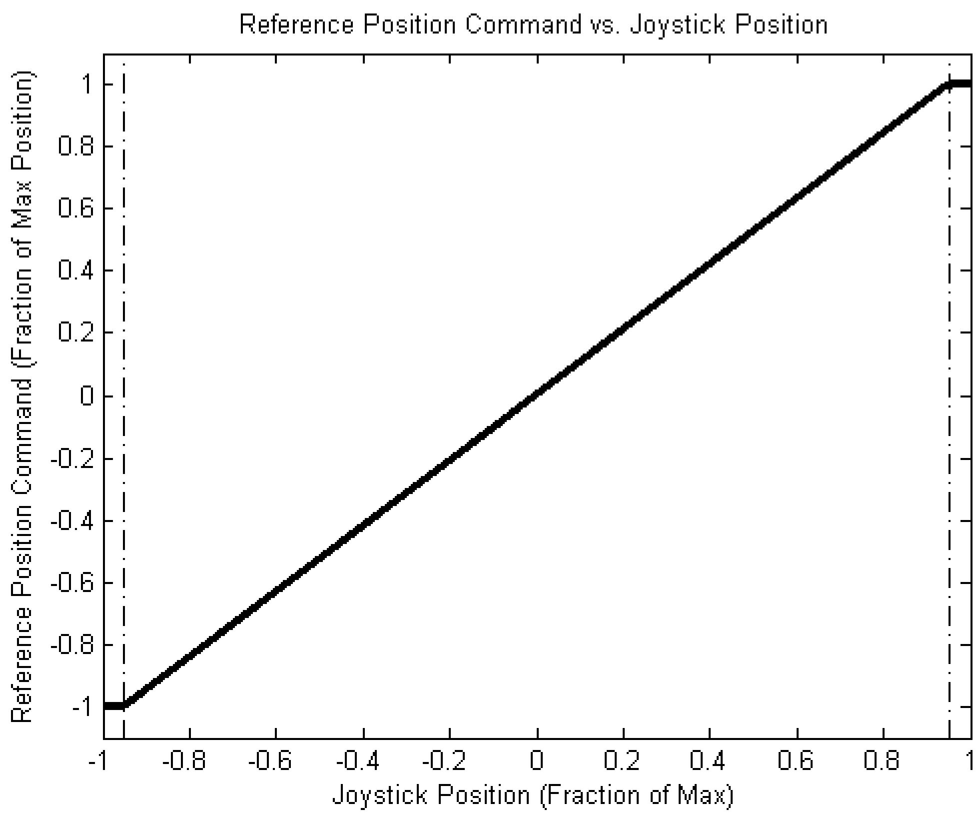

Fig. 14. Command curve for the position controllers

Rate Controller for the Dynamic System (RD)

Using a full state feedback controller, the velocity of a mass, *v*, was controlled. The system applied a force, *u*, to the mass, *m*, to drive it to the desired velocity, *r*.

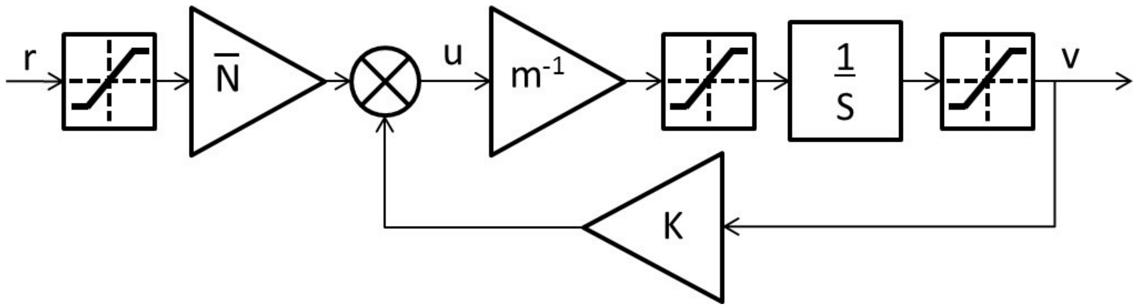

Fig. 15. Rate controller of the dynamic system

The system is in the form of

$$\dot{x} = Fx + Gu \quad (18)$$

$$y = Hx + Ju \quad (19)$$

The state vector, *x*, is only the mass' velocity, *v*.

$$x = [v] \quad (20)$$

The derivatives of the states are

$$\dot{v} = \frac{u}{m} \quad (21)$$

The matrices *F*, *G*, *H*, and *J* are

$$F = [0] \quad (22)$$

$$G = [m^{-1}] \quad (23)$$

$$H = [1] \quad (24)$$

$$J = [0] \quad (25)$$

The reference input, *u*, can be found by the following:

$$Z = \begin{bmatrix} F & G \\ H & J \end{bmatrix} \quad (26)$$

$$N = Z^{-1}\begin{bmatrix}0\\ \hline 1\end{bmatrix} = \begin{bmatrix}N_x\\ \hline N_u\end{bmatrix} \tag{27}$$

$$\bar{N} = N_u + KN_x \tag{28}$$

$$u = \bar{N}r - Kx \tag{29}$$

$$K = [300] \tag{30}$$

K was chosen to give a good response. There was no need to optimize K because the goal was to have rate and position controllers that performed equally well, not optimally. The same constraints on the system's acceleration, a_{limit}, and on the system's velocity, v_{limit}, were used for the rate controller as the position controller for the dynamic system. The input was also limited by the mechanical stops of the joystick, like the position controller.

The commanded velocity was proportional to the square of the position of the joystick (outside the saturation and deadband regions, see Fig. 16). Joystick position to actuator velocity correlations of hydraulic equipment are generally proprietary, so in this work a squared relationship between input and command will be used, as in [Williamson]. A deadband was added to the joystick to make it easy for the operator to command zero velocity. A saturation region was added to ensure that the operator could give the maximum and minimum commands. A joystick with spring centering was used for both rate controllers. The spring centering made it so there would be no force on the operator's hand only when the operator was commanding a constant position, exactly like the position controllers.

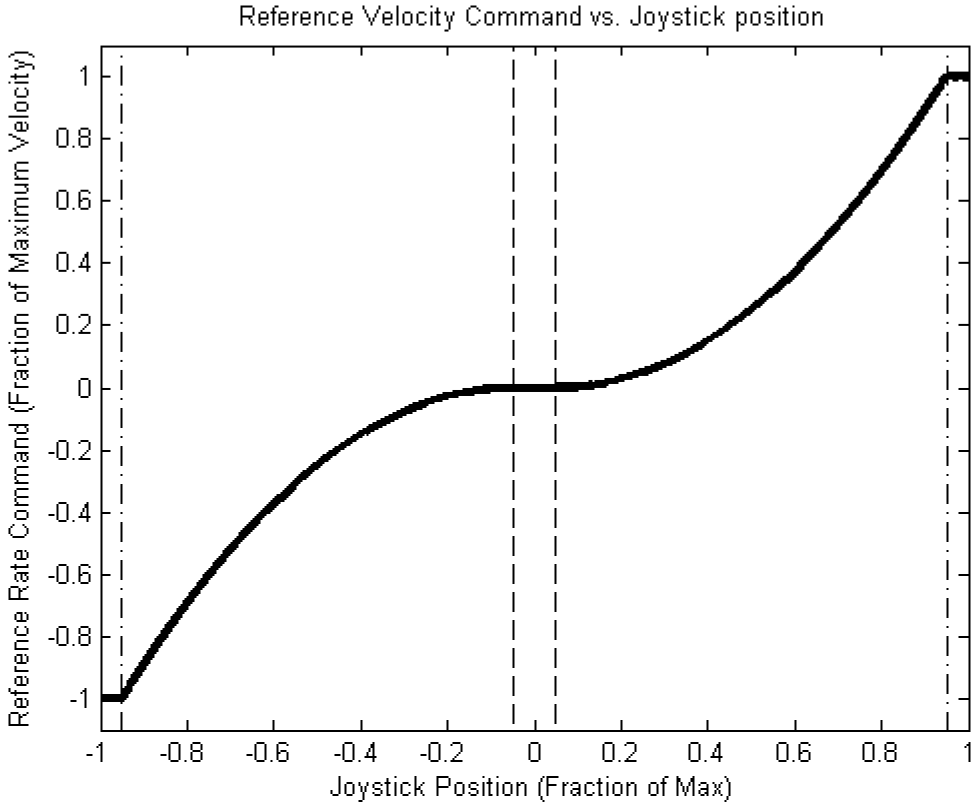

Fig. 16. Command curve for rate controllers

Position Controller for the Kinematic System (PK)

This controller removed the dynamics from the mass and made the position of the mass, x_1, equal to the desired position, r. In other words, the system had infinite power available to drive the mass to the desired position in zero time. The desired position was proportional to the displacement of the joystick (as in Fig. 14). This system is of the form

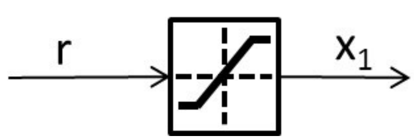

Fig. 17. Position control of the kinematic system

The input range of the joystick was limited in the same manner as the position controller for the dynamic system and had the saturation regions.

Rate Controller for the Kinematic System (RK)

This controller removed the dynamics from the mass and made the velocity of the mass, *v*, equal to the desired velocity, *r*. The command curve was the same as for the rate controller for the dynamic system (see Fig. 16), but the maximum speed, v_{limit}, was three times as great. The joystick with spring centering was used with both rate controllers.

The system is in the form of

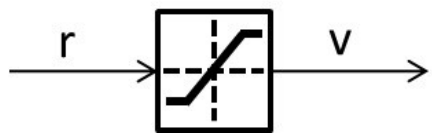

Fig. 18. Rate controller of the kinematic system

The maximum speed (gain) for the joystick was selected to make the rate and position controllers for the kinematic system perform equally well, but was later modified as discussed below.

Matching the Position and Rate Controllers for the Dynamic System

The gain, *K*, for the rate controller was chosen to give good performance. Then, the gains for the position controller were manipulated until both systems had similar performance for several tests:

- Large step (15 units of a 32 unit wide area)
- Small step (5 units of a 32 unit wide area)
- Sine tracking (.125Hz with an amplitude of 3 units)
- Sine tracking (.25Hz with an amplitude of 3 units)
- Sine tracking (.125Hz with an amplitude of 6 units)
- Sine tracking (.0625Hz with an amplitude of 6 units)

The step tests were used to compare the systems' responses to quick changes, and the sine tracking tests compared the systems' responses to slower but continuous changes. A control law was developed to act as the human operator for these tests to give a joystick position. For position control, the control law commanded the joystick position that would give the desired position as the reference, *r*. For rate control, the control law varied for the step and sine tracking tests. For the step tests, the control law was

$$r = K(x_d - x) + deadband \tag{31}$$

where x_d is the desired position, x is the current position, K= 3.3, and *deadband* adds an offset to counteract the deadband for nonzero commands. For the sine tracking tests, the derivative of the desired position was the reference velocity. The control law commanded the joystick position corresponding to the desired velocity. The deadband effects were removed as before.

Both position and rate control laws saturated at the limits of the joystick. Both control laws were rate limited in how fast the position of the joystick could change, to better mimic human performance. Three subjects were asked to move the joystick back and forth from one extreme to the other. The time that it took them to move the full joystick throw was recorded and averaged. The rate limit of the joystick was the full throw divided by the average time it took to move the joystick (i.e. 200%/ 115ms).

Both controllers performed similarly, as desired so that differences in the operators' performances will not be because of the unequal capabilities of the controllers. The step tests had slightly better performance with position control. This is because the joystick has to move farther for rate control to command the maximum speed, and so it takes longer to reach maximum velocity. The difference in position is very small for both steps – .0465 units, corresponding to 0.14% of the task area, or just under 1 pixel. The sine tracking tests were designed to keep the maximum desired velocity below the system's velocity limit. Both controllers performed similarly, with a maximum difference of 0.1128 units (or 0.35% of the task area, approximately 2.25 pixels). For both the step and sine tracking tests, the differences in the controllers were much less than operator induced error during the tests themselves.

Table 2. Difference in position and rate controllers for the dynamic system

Test	Maximum Percentage Difference
Large step (15 units of a 32 unit wide area)	0.31
Small step (5 units of a 32 unit wide area)	0.94
Sine tracking (.125Hz with an amplitude of 3)	1.91
Sine tracking (.25Hz with an amplitude of 3)	3.76
Sine tracking (.125Hz with an amplitude of 6)	1.88
Sine tracking (.0625Hz with an amplitude of 6)	0.95

See Appendix A for plots of the responses to these six test functions.

Matching these controllers assures the matching of the controllers used in the rate vs. acceleration rotational tests (see the Rate vs. Acceleration Planar Tasks section in Chapter 4) because it is the same controller, but the derivative order of the inputs, outputs, and states is simply increased by one (e.g., position becomes velocity, velocity becomes acceleration). Hence, the experiments described in Chapter 4 and analyzed in Chapter 5 should demonstrate the differences in performance due to the controller type and not the design parameters.

Matching the Position and Rate Controllers for the Kinematic System

The gain for the joystick was originally selected so that the time the system took to move from one side of the task area to the other side would be the same with both the position and the rate controller. The resulting gain for the rate controller was very high and made fine control very difficult. The gain was reduced to be easier to use, resulting in significant differences in the step responses, but the sine tracking results were still similar. See Appendix A for plots of the responses to these six test functions.

Table 3. Difference between the position and rate controllers for the kinematic system

Test	Maximum Percentage Difference
Large step (15 units of a 32 unit wide area)	93.14
Small step (5 units of a 32 unit wide area)	96.34
Sine tracking (.125Hz with an amplitude of 3)	1.03
Sine tracking (.25Hz with an amplitude of 3)	1.48
Sine tracking (.125Hz with an amplitude of 6)	0.51
Sine tracking (.0625Hz with an amplitude of 6)	0.74

Rotational Task Controllers

The rotational tasks that took a velocity or an acceleration input were basically the same as the position and rate controllers discussed earlier in this chapter. The differences came from the derivative order of the inputs and states, and switching the mass, *m*, for a moment of inertia, *I*, and the force, *u*, for a torque. Also, the linear states (*x*, *v*, *a*) are changed to rotational states (θ, ω, α). For example, the position control in Fig. 13 becomes the controller in Fig. 19.

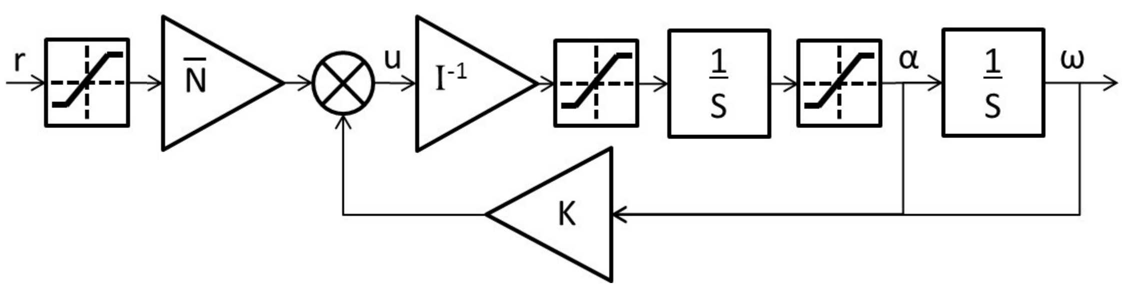

Fig. 19. Rate control of the dynamic rotational system

This controller is renamed the ωD controller. When a ghost is added, it becomes the ωG controller. The rate controller (RD) becomes the αD controller. The rate controller in Fig. 18 (RK) becomes the acceleration controller (αK) in Fig. 20.

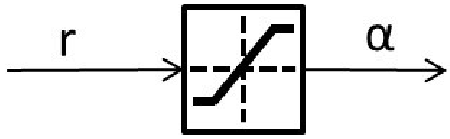

Fig. 20. Acceleration controller for the kinematic rotational system

Correspondingly, the PK controller becomes the ωK controller.

Ghost Feedback

For the position vs. rate planar tests, the ghost was added to the position controller of the dynamic system by showing in cyan the corners of a frame that fit around the excavator game piece. The corners were 1/8th the thickness of the game piece (Fig. 21 shows the ghost for two of the planar tasks). The same position controller (PD) was used whether the ghost was presented to the operator or not. To differentiate, position control without the ghost will be abbreviated PD, and position control with the ghost will be abbreviated PG.

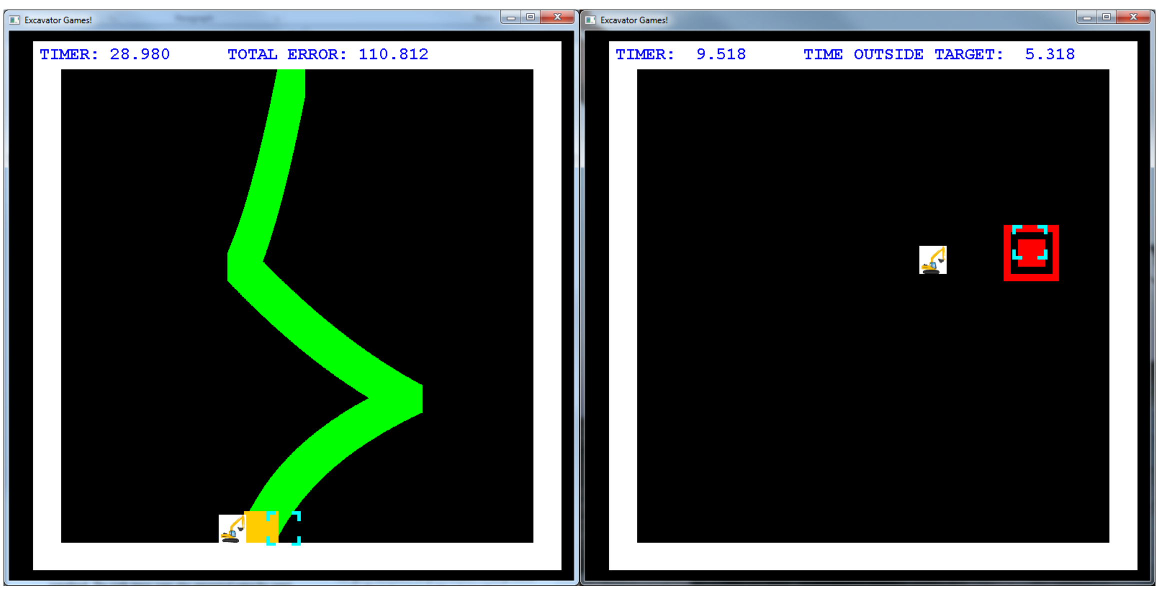

Fig. 21. Ghost for the (a) 1D tracking and (b) 2D point-to-point tasks

For the velocity controller of the dynamic system in the rotational tasks, the ghost was the outline of a cross of the same thickness as the ghost in the translation tasks (Fig. 22).

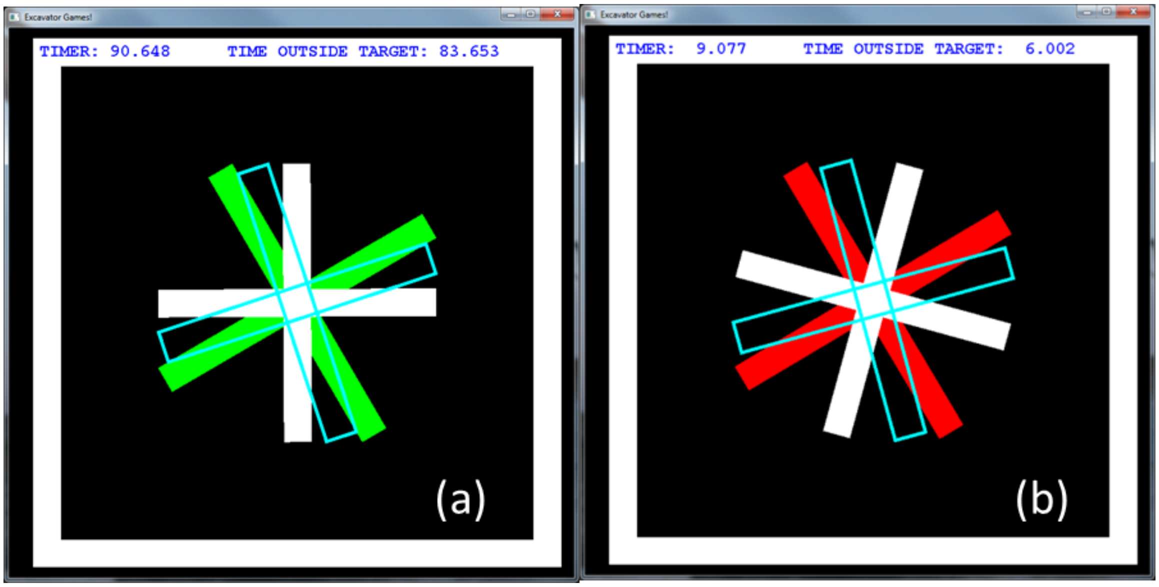

Fig. 22. Ghost for (a) the velocity matching (b) and velocity tracking tasks

Excavator Simulator System and Controllers

The position and rate controllers for the excavator simulator were designed to perform equally well for an optimal user. Both position and rate control were implemented in a coordinated manner with a Sensable Phantom.

About the Phantom

Phantom devices are commercially available 3- to 6-DOF joysticks with force feedback capability manufactured by Sensable Technologies [Sensable]. For this work, a Phantom Premium 1.0A is used (Fig. 23). The Phantom Premium 1.0A (or for simplicity in this work, Phantom) is constructed of three actuated links connected serially by revolute joints. A force of up to 8.5N can be displayed at the end of the third link. For coordinated excavator control, four degrees of freedom are necessary, and so Sensable's encoder stylus gimbal is attached at the end of the third link, which becomes the wrist of a 6-DOF joystick. The gimbal has three additional rotational degrees of freedom, but no additional force feedback mechanisms. Because the operator only controls four functions in the simulation, only one of the additional gimbal degrees of freedom is used. The other two degrees of freedom of the gimbal can be moved, but their information is discarded and not used. However, one of the additional degrees of freedom allows the Phantom handle to easily rotate between left and right handed positions.

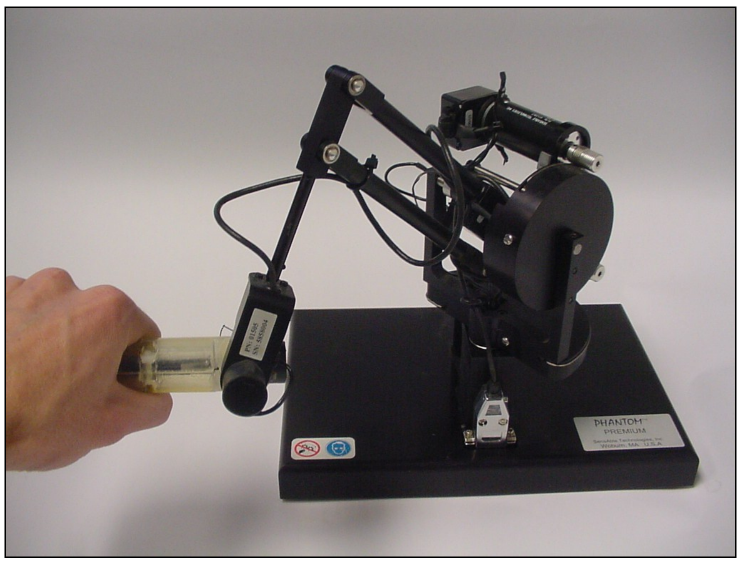

Fig. 23. Phantom Premium 1.0A

Coordinated Position Control of the Excavator Simulator

For position control, the wrist position of the Phantom is used to command the wrist position of the excavator (the end of the stick), and the curl of the handle controls the curl of the bucket. The result is that the excavator arm mimics the position of the operator's arm. As the operator moves left/right/up/down/in/out, the excavator correspondingly moves left/right/up/down/in/out. The position of the rotating handle corresponds to rotation of the bucket. As the operator curls/uncurls his/her wrist, the bucket curls/uncurls.

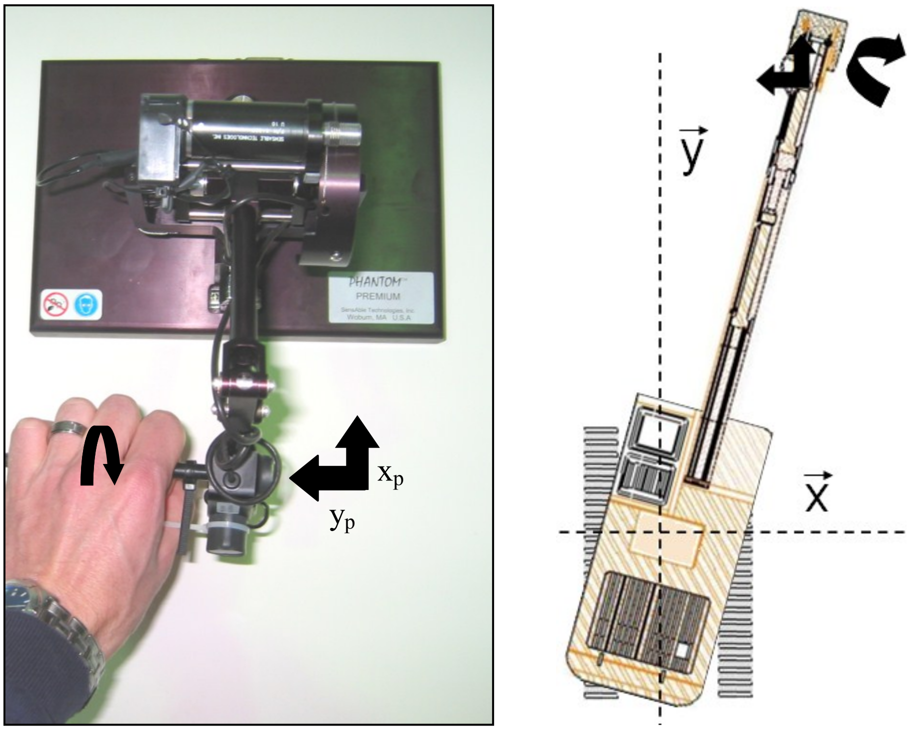

Fig. 24. Coordinated position control of the excavator

Coordinated Position Controller

The coordinated position controller converted the coordinated input into a position for each of the actuators. A separate PD controller drove each actuator to the commanded position (see Fig. 25)

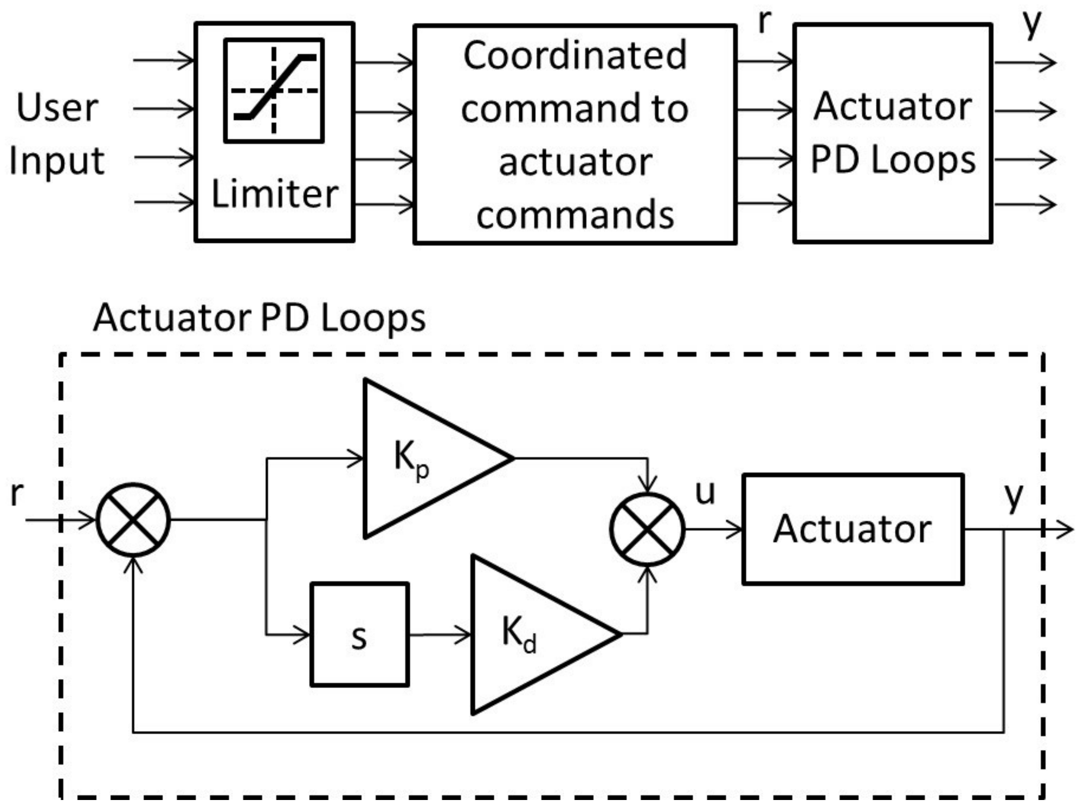

Fig. 25. Coordinated position control block diagram for the excavator

Limiting Input

The Phantom device workspace is very small compared to the excavator workspace. The workspace of the Phantom is scaled so that it covers the entire front half of the workspace of the excavator (Fig. 26). This scaling allows the operator to command positions outside the workspace, which must be converted to positions inside the workspace so that the transformation algorithms produce real and meaningful values and so that the machine works appropriately. The key parts of the input limiting algorithm are (1) to produce a smooth trajectory as constantly out-of-workspace commands are given and not to jump from one boundary point to another and (2) to create smooth transitions as a commanded trajectory passes from an in-workspace command to an out-of-workspace command and vice versa.

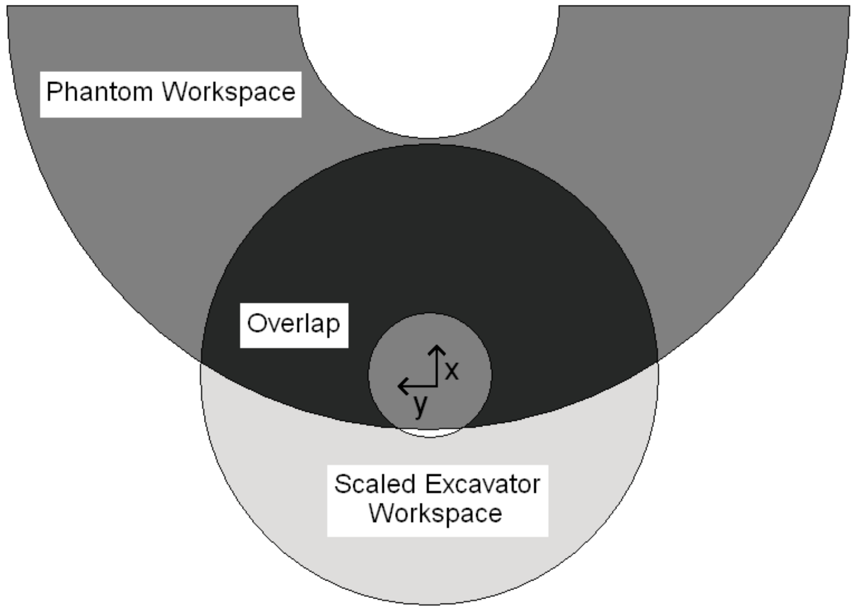

Fig. 26. Overlapping workspaces for the position controller. The figure shows a horizontal cross-section of the Phantom workspace and the scaled excavator workspace. Inner and outer diameters of both workspaces vary with height. The coordinate system shown is for the Phantom and the excavator with the z-axis coming out of the page.

The Bobcat 435 cab can rotate a full 360°. To decrease the scaling factor, the swing of the simulated excavator is limited to ±70° because the space behind the excavator is not of interest during HMI testing.

In the vertical plane, the commanded height is not limited unless it is higher than the highest reachable spot (area 1 on Fig. 27) or lower than the lowest reachable spot (area 2 on Fig. 27). If the commanded position falls in area 1, then the limiting algorithm commands the highest point possible. If the commanded position falls in area 2, then the limiting algorithm commands the lowest point possible.

If the commanded position (commands are in sets of $\{x_d, y_d, z_d, \theta_d\}$ that specify the position of the wrist and the orientation of the bucket) falls in either area 3 or 4, z_d is kept and the x_d:y_d ratio is maintained. The resulting commanded position is the closest point on the boundary of the workspace at the same commanded height.

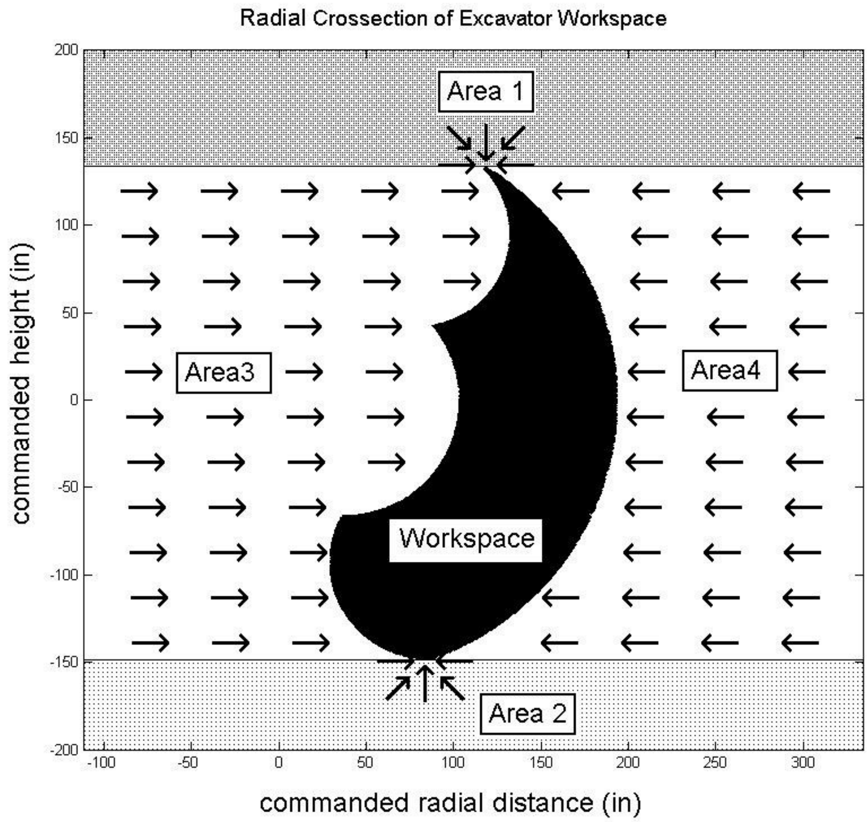

Fig. 27. Radial cross-section of the excavator workspace

Coordinated Rate Control of the Excavator Simulator

For coordinated rate control, the wrist position of the Phantom commands the wrist velocity of the excavator (the end of the stick). Unlike with coordinated position control, the reference frame rotates with operator, resulting in a cylindrical coordinate frame rather than a Cartesian frame used for coordinated position control. Left/right motion of the phantom commands a rotational velocity. In/out motion of the joystick commands the arm to extend/retract in whichever direction the excavator is currently facing. The up/down motion of the joystick causes the arm to raise/lower in the same direction as it did with coordinated position control. The bucket was not rate controlled, but position controlled in the exact same manner as with coordinated position control. A deadband was put in place in each direction, and the input saturated in each direction. The Phantom presented a spring force with a small initial wall force that pushed the operator back towards the deadband so that the operator could easily command zero velocity. The maximum velocity command in each direction was limited. After reaching the velocity command limit, the spring force was constant (Fig. 28).

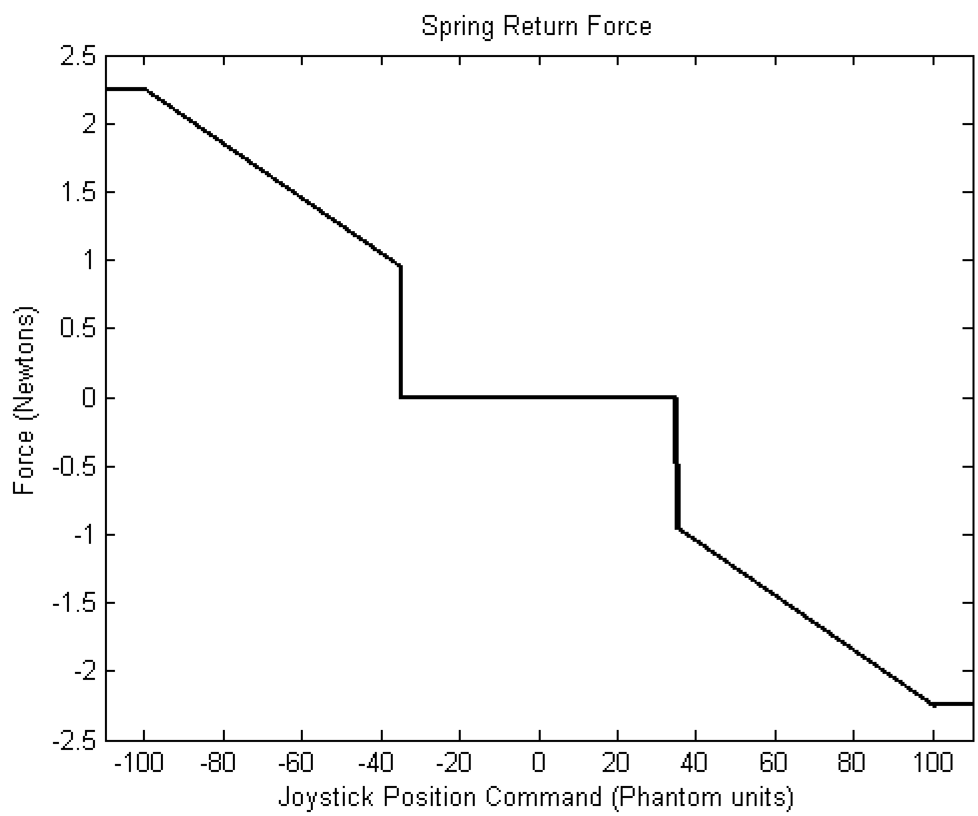

Fig. 28. Centering spring force used in each direction on the Phantom

<u>Discrete Haptic Jump Algorithm</u>

One of the contributions of this thesis is an algorithm that eliminates haptic chattering for discrete jumps in the force being fed back to the user. For the coordinated rate controller for the excavator simulator, the initial wall force creates a discrete jump in the haptic force so that it is clear to the user that he/she has moved outside the deadband.

This discrete jump creates the classic rigid wall problem: chattering. The algorithm developed here modifies the force as the operator moves in and out of the deadband. The force displayed to the user is a rigid wall as he/she moves out of the deadband. However, as he/she moves into the deadband, the force is reduced and then decays off to zero (Fig. 29). This reduction of the force makes the discrete jump small enough that chattering is not present, and the force decays quickly enough that the operator does not notice the decaying force while in the deadband, as it is below the just noticeable difference threshold [Dosher]. The force was filtered by a fourth order Butterworth filter with a passband of 64Hz to remove any high frequency buzzing. This algorithm works for applications where the input cannot be held precisely at the discrete jump, e.g., when a human is holding it and has some tremor and the discrete jump is relatively small (in this case it was 0.95 N).

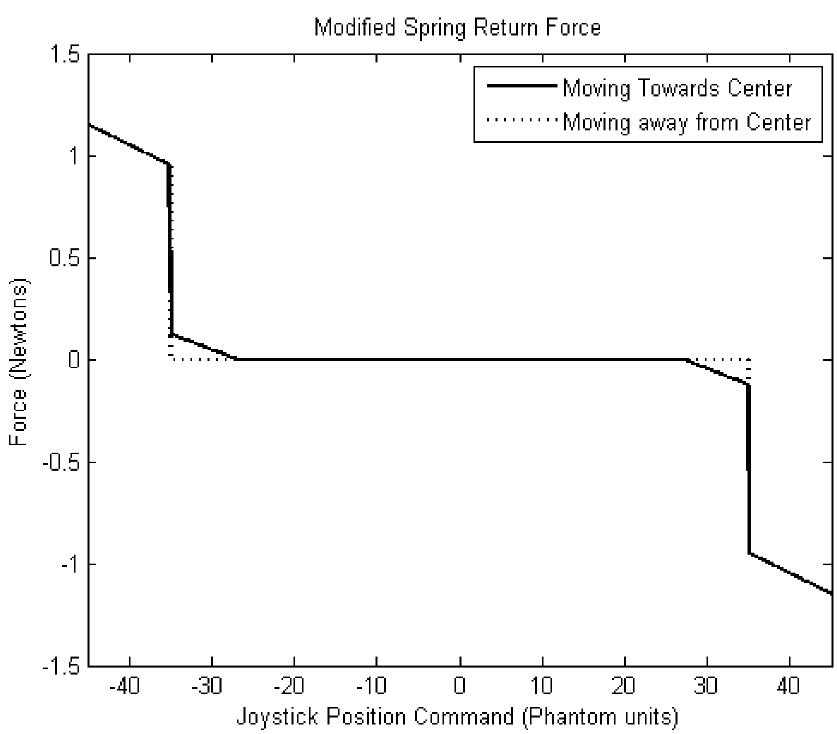

Fig. 29. Forces output by the discrete haptic jump algorithm depend on direction

Rate Controller

The rate controller converted the coordinated command into a command for each actuator, using a simplified dynamic model of the excavator's actuators, which also did not include any environmental interaction. The simplified inverted dynamics saved on computational cost. The result was fed into a proportional controller to drive each actuator to the desired velocity (Fig. 30).

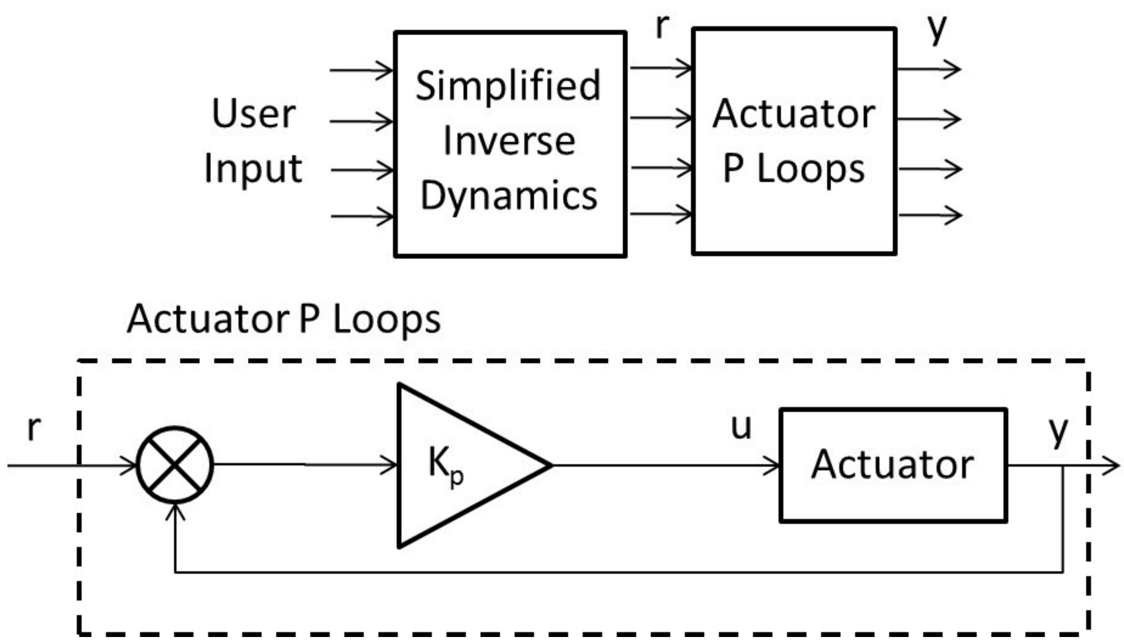

Fig. 30. Coordinated rate controller for the excavator simulator

Comparison of Coordinated Position and Coordinated Rate Control

The coordinated position and rate controllers were designed to be as nearly identical as possible. Because the controllers calculate the coordinated motion in different ways, the gains were tuned to produce results that showed a similar amount of error for both a step response and sine wave tracking, instead of following the exact same path. Each of these tasks was done in the plane for ease of plotting the response but involved the coordinated motion of the excavator swing, boom, and stick.

The step response moved 50 inches towards the operator and 100 inches to the left. This step was selected because it is of the same size as step the operator would have to make to move from the trench to the spoil pile to empty the bucket or vice versa. The path followed for the sine tracking response was composed of two sine inputs in the in-out direction (20 inch amplitude at .1Hz) and the left-right direction (40 inch amplitude at 0.071 Hz). The sine tracking test circled the bucket in a large pattern that does not reflect a real excavation task, but clearly shows the phase lag associated with each controller.

Like the planar tests, a control law was developed to act as the human operator for these tests to give an input. For position control, the control law commanded the phantom position that would give the desired position as the reference, *r*. For rate control, the control law was

$$r = K(x_d - x) + deadband \qquad (32)$$

where x_d is the desired position, x is the current position, and *deadband* adds an offset to counteract the deadband for nonzero commands.

Both position and rate control laws saturated at the limits of the joystick. Both control laws were rate limited in how fast the position of the joystick could change to better mimic human performance. See Appendix A for plots of the system response with each controller.

Ghost Feedback

For the excavator simulator tests, the ghost arm was displayed as a transparent yellow arm (see Fig. 31). Unlike [Noyes], the ghost arm used here had depth information included so that it appeared to be part of the scene rather than just an overlay. This was included to counteract the depth perception problem mentioned by Noyes.

Fig. 31. Ghost arm on the excavator simulator

This chapter has discussed the design of position and rate controllers for a dynamic system, a kinematic system, and the excavator simulator. The controllers were matched so that operator performance with the position or rate controller would not be affected by the ability of the controllers. How ghost feedback was provided for the position controller of each system was covered. The next chapter discusses the planar tasks that the controllers and the ghosts were applied to.

CHAPTER 4

DESCRIPTIONS OF THE PLANAR TASKS

Five planar translational tasks and two planar rotational tasks were designed to test operator performance with the controllers covered in Chapter 3. The translational tasks were designed to compare operator performance between position and rate control, and the rotational tasks were made designed to compare operator performance between rate and acceleration control. This chapter describes all seven tasks, why they were selected, and the experimental method used to test operator performance.

Position vs. Rate Planar Tasks

Five one- or two-dimensional planar tasks were coded to test the effects of matching feedback with operator intent. The visualizations have simple dynamics (i.e. no friction, compressibility, etc.) and are easily controlled using a joystick. These simpler planar tasks eliminate many of the variables in the excavator simulator, so that the results comparing performance and control effort of the HMIs are cleaner. In each task, the subject manipulated a square white excavator game piece (see Fig. 33) with a 2-DOF computer gaming joystick. The controllers for the planar systems described in the previous chapter were applied to the tasks discussed in depth in this chapter.

One- and two-dimensional point-to-point motion were selected as two of the tasks because they represent the “swing and dump” and “return to trench” part of an excavator dig cycle, where the operator has the excavator in one position and wants to move to another position as fast as possible. One- and two-dimensional tracking were selected as two of the tasks because they are similar to the digging part of the dig cycle where the operator follows a path through the soil to fill a bucket. The final task, the maze, is a combination of point-to-point motion and tracking, in that the operator wants to go from one point to another as fast as possible and has to follow a path, but without any time constraint. This task is similar to precision tasks performed with excavators, such as leveling or placing large rocks.

The tasks were given to the subjects in the following order:

- 1D point-to-point motion
- 2D point-to-point motion
- 1D tracking
- 2D tracking
- Maze

Each subject used only one of the following controllers to manipulate the excavator game piece to eliminate transfer effects [Poulton].

- Position controller
- Position controller with a ghost arm
- Rate controller

The subjects had 30 seconds of rest between each task. They played all tasks once during each session. There were a total of 6 sessions, none of which were on the same day. Most subjects averaged just below one session per workday (no sessions were held on Saturday or Sunday). The longest length between sessions was one week, due to a contracted illness. The subjects were asked to fill out a pre-test questionnaire to gather their demographic information. The results can be found in Appendix B.

Two Thrustmaster™ T16000 USB joysticks were used, one for position control and one for rate control. The joysticks have incremental Hall Effect sensors with 15-bit precision on each axis. The joysticks came with a helical spring to center them, but the spring was removed from one of them. The joystick used for rate control had spring centering, and the joystick without spring centering was used for position control.

Fig. 32. Thrustmaster™ T16000. The hand rest is interchangeable

1D Point-to-Point Motion

This task required the subject to move the "excavator square," the square white game piece with the profile of an excavator on it, to a target location in only the left or right direction. The target was twice the width of the excavator, and the entire excavator square had to be within the target area to count as being on target. The target was a red square within a red box (see Fig. 33a), both of which turned green whenever the excavator was on-target (Fig. 33b). A chimes sound was played whenever the excavator moved from being off-target to on-target. After remaining in an on-target position for a randomly generated time between 1 and 3 seconds, a new target location would appear in yellow (Fig. 33c). After another second passed, the current target would disappear and the yellow target would turn red (Fig. 33d). When operating hydraulic machinery, operators know the next target location. To mimic the real scenario, the next target position was shown to the operators before they were to move to it. Showing the next target beforehand also eliminated range effects [Poulton]. The target positions and the required on-target time were the same for all subjects in all trials. At the top of the task window, the remaining time and the time off target were displayed for the user.

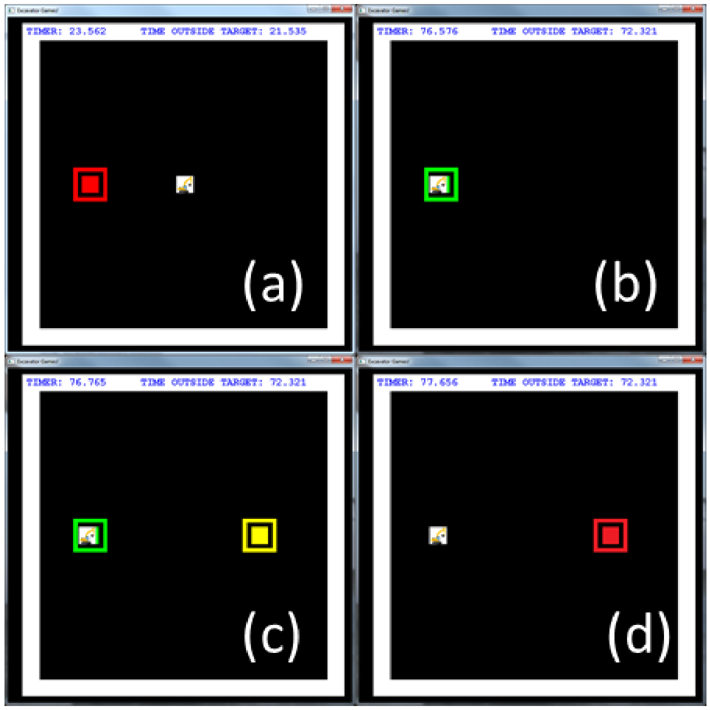

Fig. 33. Driving the game piece to a target in the 1D point-to-point motion task. Moving towards the first target (a). Arriving at the first target (b). Second target appears (c). First target disappears (d).

<u>How the target locations were determined</u>

The targets were chosen to give an equal distribution of step sizes across a large range (steps of 2, 5, 8, 11, 15, 20, 26), where the step size is the distance between consecutive target positions. There was one step of each magnitude in both the left and right directions. The target positions were never on the wall so that there would not be an artificial limit to the excavator's motion (i.e. overshoot was still possible). The excavator began centered on a target in the center of the screen. See Table 23 for target locations, where zero is the center of the screen.

How the required on-target time was determined

Upon reaching a target, each subject had to hold the excavator on-target for a certain time. By requiring the subject to hold the excavator on the target, any overshoot or other shakiness was recorded. The required on-target times were randomly generated numbers between 2 and 4 seconds. The on-target times were only generated once, and were the same for all runs for all subjects. The 2-4 second time range was selected to be long enough that the operators had to be truly on-target and not just passing through the box, and long enough to still have some variation so that operators wouldn't try to anticipate when to leave the box. The excavator began on target and had to remain there for 2 seconds. This 2 second requirement was not randomly generated. It was selected to give the subjects a brief period to immerse themselves in the task once it began without any penalty. See Table 23 for required on-target times.

2D Point-to-Point Motion

This task was setup the same as the 1D version, except that motion was now in both the left-right direction and the up-down direction (see Fig. 34 for a screen shot).

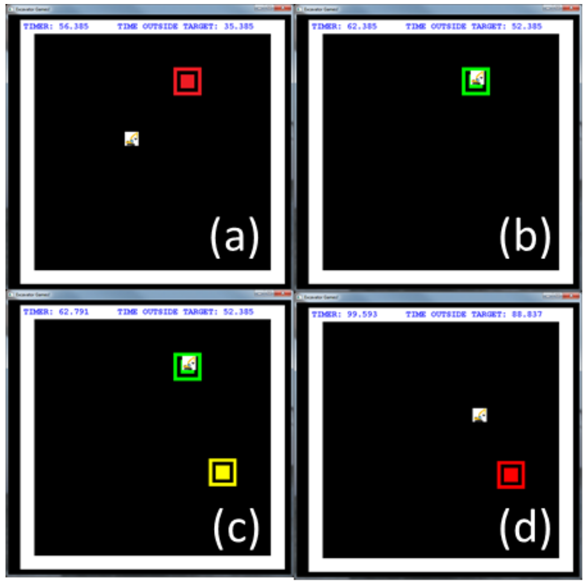

Fig. 34. Driving the game piece to a target for the 2D point-to-point motion task. Moving towards the first target (a). Arriving at the first target (b). Second target appears (c). First target disappears (d).

<u>How target locations were determined</u>

As in the 1D version, the targets were chosen to give an equal distribution of step sizes and directions. There were only three step sizes for this test: 4, 9, and 16. Three different directions were selected with horizontal:vertical ratios of 3, 1, and 1/3. There was one step size of each direction and magnitude taken towards each quadrant, for a total of 36 steps (see Table 24). Again, the positions were chosen not to be on the wall so that there would not be an artificial limit to the excavator's motion.

<u>How the required on-target time was determined</u>

This was determined in the same manner as for the 1D point-to-point task.

1D Tracking

The subjects were asked to follow a yellow square that took a predefined green path. The square was 1.25 times the width of the excavator square. The goal was to keep the excavator on the square. The path descended on the excavator at a fixed rate. The subjects had a 10 second preview of the path as it moved down the screen. The subjects were given a preview because, when operating hydraulic machinery, operators generally know the path they want to take at least a couple seconds into the future. The error and the time remaining were displayed at the top of the window. The path took 62.84 seconds to complete.

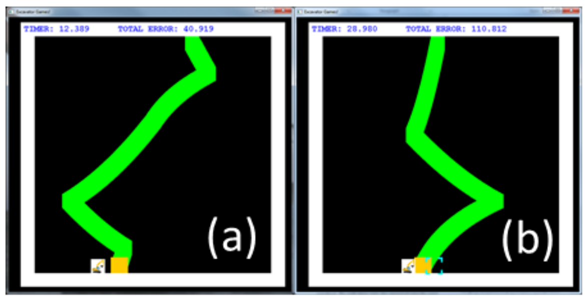

Fig. 35. 1D tracking with (a) and without (b) the ghost

<u>How the path was determined</u>

The path was made of segments connected in series. Each segment had a time, distance, and shape. The time was how long it took each segment to pass by the bottom of the screen. The distance was the difference between the left-right positions of the start and the end of the segment. Three mathematical functions were selected as path shapes: a line, a parabola, or a natural logarithm. A line was the natural choice for a path shape, being the shortest distance between two points, and would be the most logical choice for an operator in a field free of obstacles. However, obstacles are present in real-world operation, and so the other two path shapes were selected, one with positive and one with negative curvature, to represent paths that curve around objects.

The program begin with a 3 second vertical path that gave the subjects a moment to ready themselves for the task and judge how fast the path was moving without being penalized. The path segments had three distances: 4, 8, and 12. There was one segment of each distance in each direction with each path shape for a total of 18 path segments. The path times were randomly generated numbers between 2 and 5 seconds. This led to some paths that could not be followed due to the system's velocity limit. If the path could not be completed within the randomly generated time, the time was extended so that the maximum velocity of the path was the velocity limit.

2D Tracking

The 2D tracking task was similar to the 1D version; however, the motion was now in both the left-right direction and the up-down directions. Five seconds of the path in front of the current position was shown by a trail that faded from blue (5 seconds ahead) to green at the current location (see Fig. 36). The color changed so that when the path folded back on itself, the path was still clear. At the end of the path there was a yellow box, identical to the one in the 1D tracking task. The goal was to track the yellow box. This task lasted for 130.868 seconds.

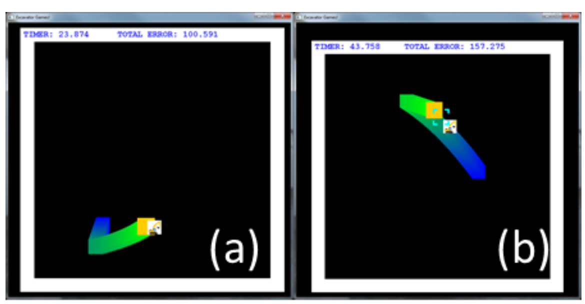

Fig. 36. 2D tracking with (a) and without (b) the ghost

<u>How the path was determined</u>

The path was broken into 36 segments. The target locations used in the 2D point-to-point motion task were the beginning and ending points of each segment. A path shape was added to each start and end point combination to define the path. As in the 1D tracking task, there were three path shapes: a line, a parabola, and a natural logarithm.

Each of these path shapes was given to a segment with each magnitude (the distance between the start and endpoints) in each direction (i.e. horizontal:vertical ratios of 3, 1, and 1/3), for a total of 9 segments of each shape. The 9 remaining segments were assigned a path shape so that there were an equal number of path shapes of each magnitude (see Table 26). Similar to the 1D tracking task, the program begin with a 3 second stationary target that gave the subjects a moment to ready themselves for the task and judge how fast the path was moving without being penalized. The path times were also generated using the same method as in the 1D tracking task.

Maze

The maze task required the subjects to drive the excavator through a course to a target at the end of the course. The target was the same size and shape as the target in the point-to-point motion tasks. The subjects were told to travel through the maze as fast as possible without hitting the walls. If the white game piece was in contact with the wall, a penalty of 100 times the amount of time it was in contact with the wall was added to the time. This large penalty was to deter subjects from hitting the walls at all costs, just as an excavator operator would avoid obstacles (e.g., buried pipes) at all costs. A timer was displayed at the top of the screen showing the elapsed time with the time penalty. The walls were fully penetrable by the excavator to mimic obstacles that are easily moved or crumpled by the excavator arm. The walls turned from a brown soil color to red whenever the excavator was in contact with the wall.

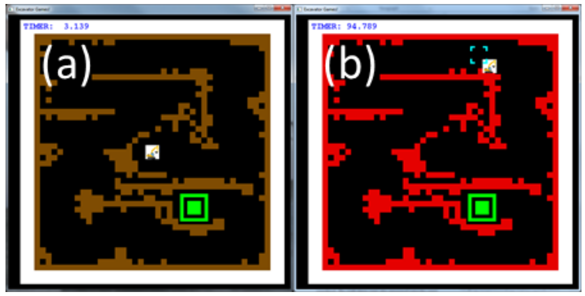

Fig. 37. Maze without the ghost (a) and with the ghost and in contact with the wall (b)

Rate vs. Acceleration Planar Tasks

Two rotational tasks were designed to see if the principle of matching feedback with operator intent applies to systems other than those with a position output. The tasks consisted of manipulating a spinning cross to match the rotational velocity of a spinning target cross behind it. The dynamics were the same as for the 1D point-to-point motion task and the 1D tracking task (see sections 1D Point-to-Point Motion and 1D Tracking in this chapter).

During each session the subjects played the velocity matching task first and then the velocity tracking task. The subjects had 30 seconds of rest between each task. There were a total of 6 sessions, none of which were on the same day. Most subjects averaged just below one session per workday. Each subject used only one of the following controllers to manipulate the excavator game piece to eliminate transfer effects [Poulton].

- Rate controller without a ghost
- Rate controller with a ghost
- Acceleration controller

The same joystick was used for these tasks as the previously mentioned planar tasks (see Fig. 32). However, for these tests, the rate controller joystick had no spring return and the acceleration controller joystick had a spring return. The results of the questionnaires can be found in Appendix B.

Velocity Matching

This task is the velocity equivalent to the 1D point-to-point motion task. Instead of matching target positions, the subject had to match target velocities. Two crosses were shown on the screen: a target cross and a white cross that the subject controlled (Fig. 38). The target cross was slightly longer than the white cross so that it could not be completely occluded. The goal was to match the controlled cross's rotational speed to the speed of the target cross, not the position of one cross to the other. The target cross turned from red to green and a chimes sound was played whenever the subject-controlled cross was on-target (Fig. 38a). The subject-controlled cross had to be within 20^{o}/s of the target cross to be considered on-target. After remaining at an on-target velocity for a randomly generated time between 2 and 4 seconds, a new target cross with a different velocity would appear. The target velocities and the required on-target time were the same for all subjects in all trials. At the top of the task window, the time and the time off target were displayed for the user.

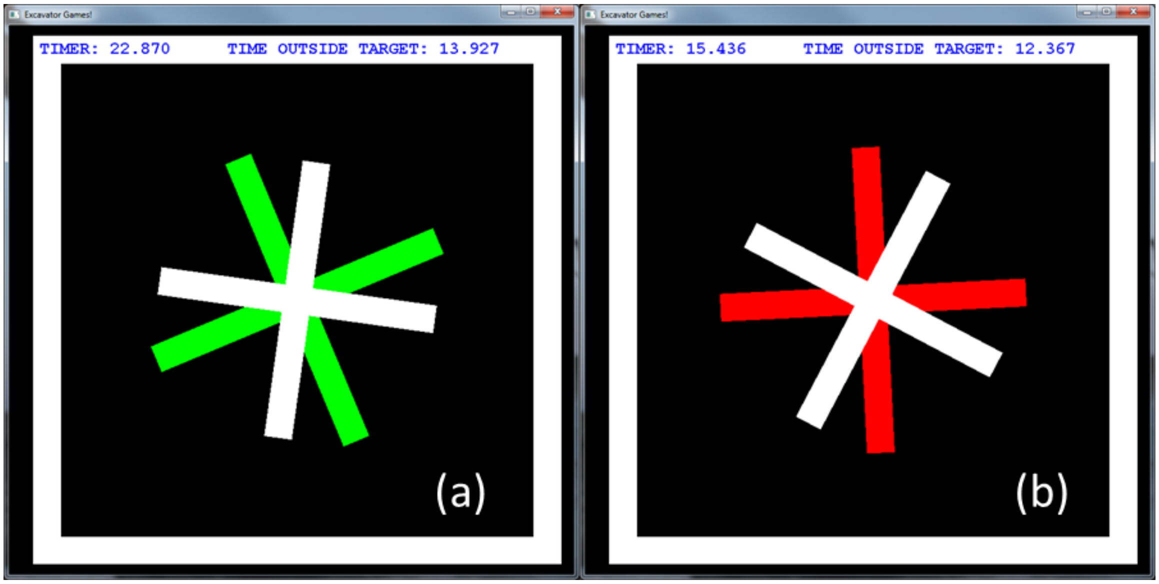

Fig. 38. The velocity matching task is the rotational equivalent of the 1D point-to-point motion task. When the operator commands a velocity that matches the target velocity the cross turns from red (b) to green (a).

How the target velocities were determined

The target velocity step sizes were the same as the position step sizes for the 1D point-to-point task (steps of 2, 5, 8, 11, 15, 20, 26. See Table 23) scaled by a factor of 8.57 so that the maximum speed was 120°/s, where the step size is the difference in velocity between consecutive target velocities. There was one step of each magnitude in both the clockwise and counter-clockwise direction. Both crosses began aligned with zero velocity.

How the required on-target time was determined

The required on-target time was the same as for the 1D point-to-point motion task (see Table 23).

Velocity Tracking

This task was the velocity equivalent of the 1D tracking task. Instead of tracking a position, the subject had to track a velocity. The same visualization was used as in the velocity matching task with two crosses. As before, the goal was to match the controlled cross' rotational speed to the speed of the target cross. The target cross' velocity was constantly changing. Unlike the velocity matching task, the target cross was always green.

How the target velocities were determined

The velocity path was the same as the position path used for the 1D tracking task, including the path shapes (see Table 25). The position path was scaled by a factor of 8.57 so that the maximum speed was 120^{o}/s. Both crosses began aligned with zero velocity.

Having described the controllers for the planar tasks in Chapter 3 and having described the tasks themselves in this chapter, we are prepared to discuss and analyze the results of the planar tasks in the next chapter. The controllers have been shown to have equal capabilities and the implementation of the ghost interface for the position controllers has been described.

CHAPTER 5

PLANAR TASKS RESULTS AND ANALYSIS

The planar tasks described in Chapter 4 were each completed by thirty subjects, the results of which are covered in this chapter. The operator intent for these tasks was assumed to be optimal motion towards the target, as far as was humanly possible. An analysis of the results of the position vs. rate control tasks was performed to see if matching the system feedback with operator intent by providing a ghost results in better performance with a position controller. The rate vs. acceleration tasks were undertaken to examine if the results from the position vs. rate control tasks can be extended to systems with inputs and outputs of higher derivative orders. The types of errors committed with each type of controller are compared, and a statistical comparison between how operators viewed their goal and how they performed is reported, suggesting that intent is not based on how the operators view the goal. The results from these tests led to another test to determine a crossover point where performance with either a rate or a position controller is not statistically different. This crossover point will assist in selecting what type of controller to use based up the system velocity limit.

The results of the tests are broken into two main sections: the results and analysis of the position vs. rate tasks and the results and analysis of the rate vs. acceleration task. These sections are followed by an analysis of operator intent and a section detailing the test to find the crossover point. This chapter closes with a conclusions section that summarizes the findings.

Methodology Used for Analyzing Results

Each subject performed each task six times, and the top three scores from each subject were used in the analyses in this chapter. The results from each planar task were analyzed for learning trends. There was an overall slight learning trend when an exponential curve was fit to the data. The learning trend was presumed to be slight because the tasks were fairly simple so little learning was required and the required learning took place quickly. For several subjects, the best fit curve had a positive (i.e. negative learning) slope. This negative learning trend perhaps came from the subjects changing techniques to improve their performance and failing to do so. Assuming that the subjects quickly approached the optimal and wanting to eliminate higher scores from the first trials while they were learning and from the later trials when they tried unsuccessfully to improve their performance, the average of the three best scores for each subject were used to compare the different controllers.

The plots in this chapter all show 95% confidence interval error bars that were found by doing a multiple comparison between all of the different controllers using the Tukey Honest Significant Difference. "Statistical significance" or just "significance" means that there is no overlap of these error bars. The abbreviations for each of the controllers first mentioned in Chapter 3 are used in this chapter as well:

- PD – position control of the dynamic system without the ghost
- PG – position control of the dynamic system with the ghost
- RD – rate control of the dynamic system
- PK – position control of the kinematic system
- RK – rate control of the kinematic system

- αD – acceleration control of the dynamic rotational system
- ωD – rate control of the dynamic rotational system without the ghost
- ωG – rate control of the dynamic rotational system with the ghost
- αK – acceleration control of the kinematic rotational system
- ωK – rate control of the kinematic rotational system

Position vs. Rate Planar Tasks Results

Overall, the results generally show the following:

- Performance with the kinematic system was better than with the dynamic system. This is not surprising because the kinematic systems were much faster.
- For the kinematic system, performance with position control was better than with rate control. This verifies previous work by [Zhai (1993)], [Zhai (1997)], and [Kim].
- For the dynamic system, performance with position control without the ghost was worse than with rate control. The improvement in operator performance with position control due to the ghost HMI is a major contribution of this thesis. The ghost HMI improves performance for the planar tasks test and the excavator simulator test.
- The ghost increased the performance of the position controller to be comparable to the rate controller for the dynamic system. Again, the improvement in performance is a major contribution of this thesis.
- The dynamic system had lower control effort costs than the kinematic system because of the limit on possible accelerations. The control effort

was defined as summation at each time step of the absolute value of the force or torque applied to the game piece. The control effort is u in Fig. 13, Fig. 15, and Fig. 19.

1D Point-to-Point Motion

The score for this test was the time spent outside the target, so lower scores are better. The scores were adjusted by removing the time that the subjects were outside the target in anticipation error, which was defined as any time that the subject left the current target when the location of the next target had appeared but before the current target disappeared. The anticipation error time was not included because it was assumed that with training this impulse would be stifled. By removing the anticipation error times, the results are expected to be closer to those of would-be trained operators. The operators' reaction times were also removed from the score, so that the score was a measure of the travel time between targets. The cost of the errors is also reported in seconds, as it refers to the additional time cost added to the operator's travel time, or score, because of the committed error. An optimum score was calculated for each subject and had the following constraints:

- The joystick input was rate limited. The limit was empirically found by finding the maximum rate that any subject moved the joystick. This limit prevents the optimum from being able to change the control input infinitely fast, and instead gives it a human-like ability to change the control input.
- The optimum path was at the same location and velocity as the subject when each target disappeared and the next target appeared. This requires

the optimum to move exactly as far as and not farther than the human to reach the next target.

- When a new target appears, the optimum does not move until the subject moves the joystick. This adds in a human-like response time to the optimum.

These constraints created an optimum that depended on the subject and, therefore, had some variability.

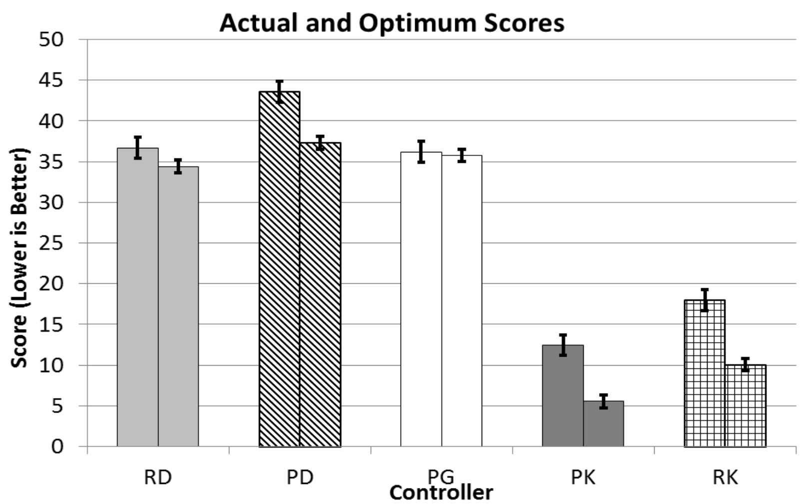

Fig. 39. Actual (left) and optimal (right) scores for the 1D point-to-point motion task

<u>Overall Results</u>

The PG controller performed at the level of the RD controller and 17% better than the PD controller, showing that matching the ghost feedback with the operator intent does indeed improve performance. The PG controller is also statiscally closer to the optimum than any of the other controllers. As with most of the tests, the kinematic subjects performed better than the ones with dynamics. For the kinematic system, performance with position control was surperior to performance with rate control, which is agreement with previous work [Zhai (1993), Zhai (1997), Kim]. The better PK score is from operators commanding lower speeds with the RK controller than the PK controller.

Error Types and Costs

Four types of errors were identified:

- Overshoot: Exiting the target from the opposite side that it was entered.
- Undershoot: Exiting the target from the same side that it was entered.
- Pause: Coming to a stop or moving away from the target before it was reached initially.
- Non-Minimum Phase Behavior (NMP): An initial small motion when the current target disappears in the opposite direction of the next target. Initially identified as pauses, the motions are small in magnitude, but with displacements large enough to be purposeful actions.

The PD controller had large pause, overshoot, and undershoot errors. The pause errors were easily the most common, but the costs of all three were comparable. The pauses are indicative of the move-and-wait strategy observed by [Sheridan (1992)], and is clearly observable in Fig. 41. Without knowing the commanded position, the operators of dynamic systems commit far more errors, as is clearly evident when comparing the number of errors between the PD and PG controllers (Fig. 40). The most common type and the most costly error for the PK and RK controllers was overshoot, which was consistent with the kinematic system's higher speed of response. Undershoot was much less common than overshoot. The RD controller had no undershoot or overshoot.

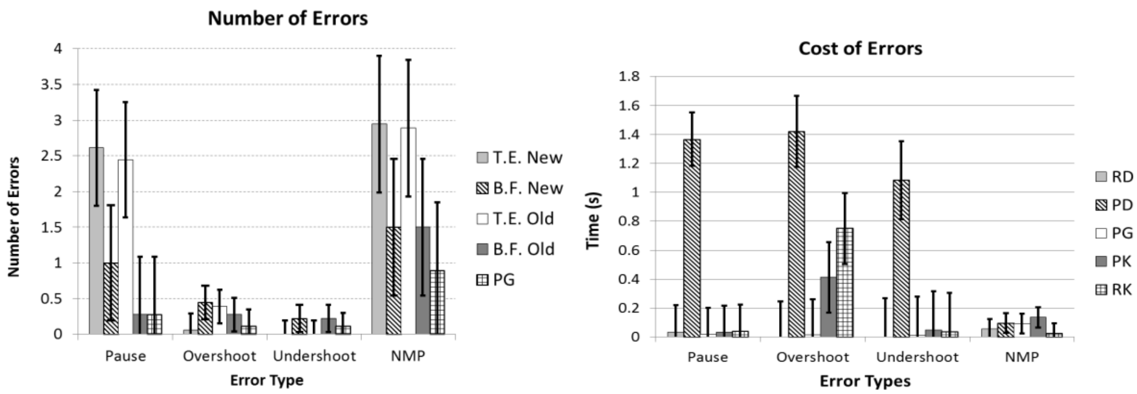

Fig. 40. Number and cost of errors of each type for the 1D point-to-point motion task

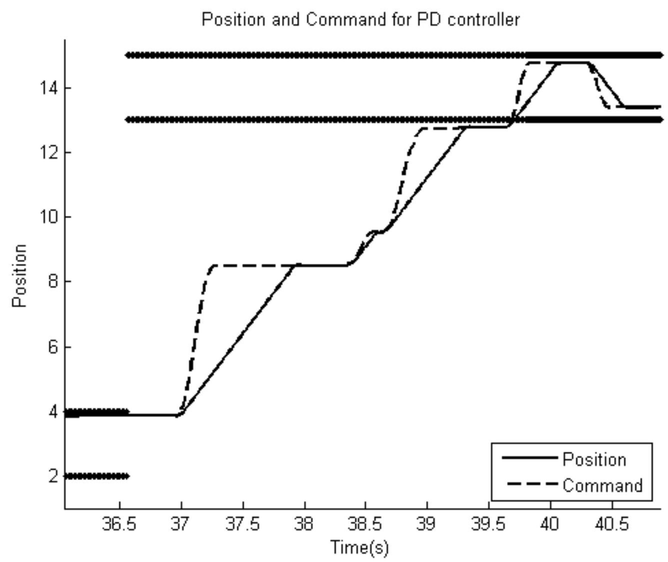

Fig. 41. Operator pauses with the PD controller. The target boundaries are marked by the heavy black line.

All four types of errors had a direct impact on the overall score, and all are from moving in an incorrect direction or pausing. The difference in the actual and optimum scores also reflects how close the subject's commands were to optimum input. This difference is the reason that the PG score is closer to the optimal although the RD controller had less errors accounted for in Fig. 40.

The control effort for the PD controller was significantly more than for the PG and RD controllers. Adding the ghost resulted in a 46% reduction in control effort for the position controller and is not statistically different from the control effort required by the RD controller. The difference in the PD and PG control efforts in Fig. 42 shows the control effort cost of the additional errors caused by a lack of system feedback that matches operator intent with the PD controller.

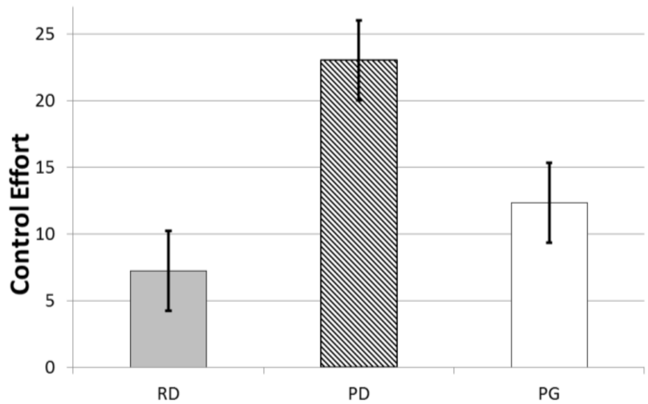

Fig. 42. Control effort for the 1D point-to-point motion task

2D Point-to-Point Motion

The score for this task is the total number of seconds spent outside the target, less the operators' reaction times and time from anticipation error, which was outlined in the previous section. The error cost is the additional time that any error caused the operator to be outside of the target. This task had the same trends in the results, which suggests that moving from the 1- and 2D planar tasks to the 3D excavator simulator will show similar results.

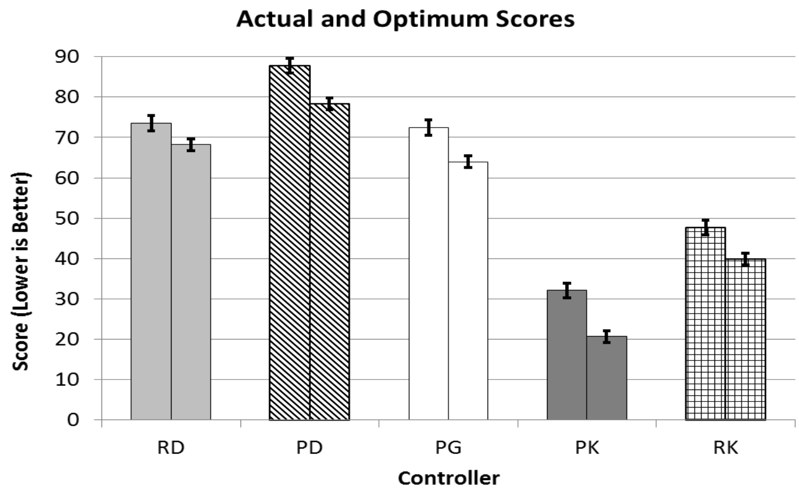

Fig. 43. Actual (left) and optimal (right) scores for the 2D point-to-point task

<u>Overall Results</u>

Again, the PG controller performed at the level of the RD controller and better than the PD controller (17% improvement), demonstrating how matching feedback with operator intent improves perfomance. As with most of the tests, the kinematic subjects performed better than the ones with dynamics. For the kinematic system, performance with the position controller was better than performance with the rate controller.

The scores for the RD, PD, and PG controllers for this task were all between 2.003 and 2.014 times greater than the scores for the 1D point-to-point motion task. The total absolute distance between points for the 2D point-to-point task was exactly twice that of the 1D version. The fact that these three values are so close to 2 indicates that the time moving between targets, i.e. the score, is dominated by the time it takes to travel between targets for the dynamic systems. So even though the operators have to mentally process more data (an extra dimension has been added) and physically respond in twice as many directions, the dynamics of the system still dominate the score. This domination of the score by the dynamics suggests that as the ghost feedback is extended from 2D in the planar tasks to 3D in the excavator simulator in Chapter 7, similar results may be expected.

Error Types and Costs

The types of errors identified for the 2-D point-to-point motion task are:

- Early Exit: Exiting the target in any direction after entering it. This error is the same as combining the overshoot and undershoot errors in the 1-D point-to-point motion task.
- Moving Away: Moving in a direction more than 90^o from the optimum. In other words, moving in a direction such that it is impossible to get closer to the target. This error is most comparable to the pauses in the 1-D point-to-point motion task.
- Deviate Right/Left: Moving outside, to the right or left, of a corridor with a width twice that of the target that is centered on the line connecting the game piece's position at the time that the previous target disappears and the center of the current target.

Without having feedback showing them the commanded position, operators using the PD controller committed far more early exit errors and move away errors than any of the other controllers (8300% more than the PG controller). The number of deviation errors for the PD controller was found to be much less than the early exit and move away errors. This finding is consistent with the operator knowing the direction in which to move the joystick but being unsure how far to move it, the exact problem that the ghost feedback is solving. The PG controller had significantly less deviation errors than the other controllers. This is probably because the operator knew where the commanded position was, and the motion of the excavator to get to the commanded position was fully automated. The errors for the PK and RK controllers were fairly evenly distributed.

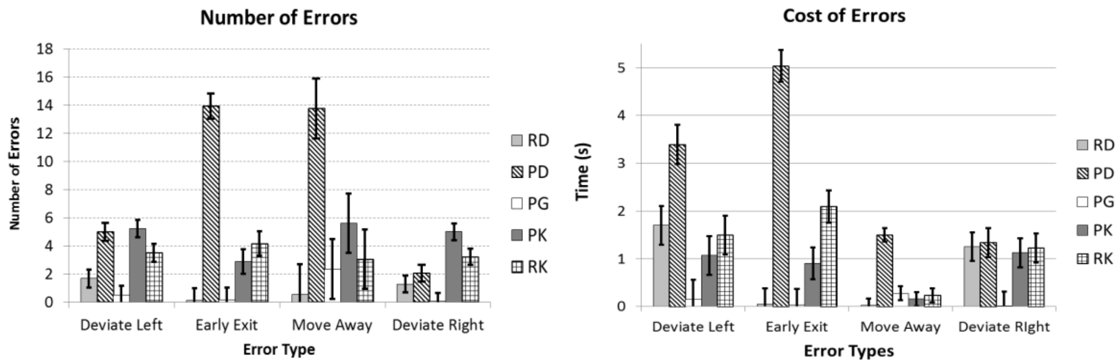

Fig. 44. Number and cost of errors for the 2D point-to-point motion task

The cost per error of the early exits for all controllers was low compared to the moving away cost. The cost per error for the kinematic systems was less than for the ones with dynamics, probably because the operator could correct faster. The control effort averages followed the same pattern as in the 1D point-to-point task, but without statistical significance between any of the measures.

1D Tracking

This task was scored by summing the products at each time step of the distance from the center of the excavator game piece (x_i) to the nearest edge of the path (p_i) and the time step (Ts_i). If 75% or more of the game piece's width was inside the yellow box, then the score for that time step was zero (i.e. $x_i - p_i = 0$ for the particular Ts_i).

$$score = \sum_{i=0}^{n} Ts_i \, |(x_i - p_i)| \qquad (33)$$

The error costs were the additional penalties added to the score for each error and have the same units as the score.

Overall Results

The variations in the scores were much higher for the tracking tasks than the point-to-point tasks, resulting in larger error bars in Fig. 45. The optimal score for the tracking tasks for all controllers was zero. As with the point-to-point tasks, performance with the PG controller is comparable to the RD controller, and the RD controller is significantly better than the PD controller. With the multiple comparions, the PG controller is not significantly different from the PD controller. However, if a t-test between the PD and PG controllers is performed, statistical significance arises. The PG controller performs 29% better than the PD controller, a major improvement in performance from matching the system feedback with the operator intent. As found in the previous two tasks as well as in the literature, the PK controller did significantly better than the RK controller. Surprisingly, the scores with the kinematic systems were not better than with the dynamic controllers, which suggests that the controller should be mapped to provide a limited input range for certain tasks. It also suggest that the natural frequency of the machine dynamics needed for superior performance with position control rather than rate control is task dependent. The velocity of the path to be tracked was rate limited so that the desired location never moved faster than the velocity limit of the dynamic system. The path rate limit perhaps worked to equalize operator performance of both the kinematic and the dynamic system because there was little advantage to moving being able to move faster.

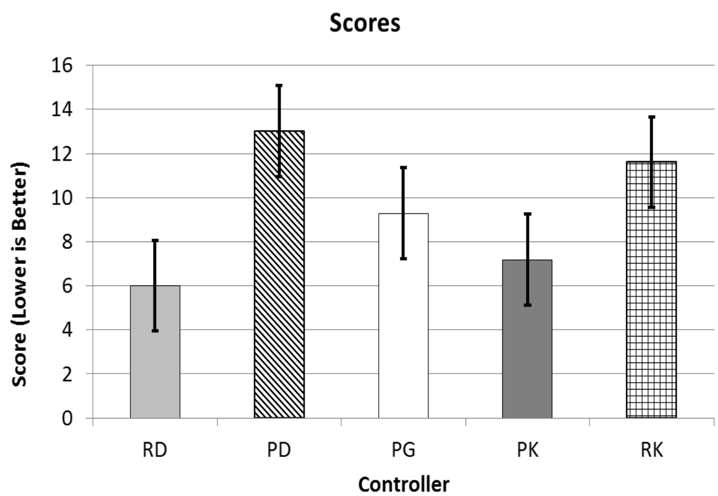

Fig. 45. Scores for the 1D tracking task. The optimal score for all controllers was zero

<u>Error Types and Costs</u>

The types of errors for this task were dependent on the game piece's and the path's motion.

- Ahead Pulling Away: The game piece is on the same side of the path as the path's velocity (e.g., it is to the right of the path and the path is moving to the right), and the gap between the game piece and the path is increasing.
- Ahead Closing the Gap: The same as Ahead Pulling Away, but the gap between the game piece and the path is decreasing.
- Behind Dropping Back: The game piece is on the opposite side of the path as the path's velocity (e.g., it is to the left of the path and the path is moving to the right), and the gap between the game piece and the path is increasing.
- Behind Closing the Gap: The same as Behind Dropping Back, but the gap between the game piece and the path is decreasing.

The RD controller had an even distribution of error while the PD and PG controllers spent significantly more time behind the target (Fig. 46). These distributions are also true in the cost of the errors. The similarities in these distributions means that the HMI can be selected based on if more or less lag is desirable. The lag of the PG controller is improved upon by the controllers described in Chapter 6.

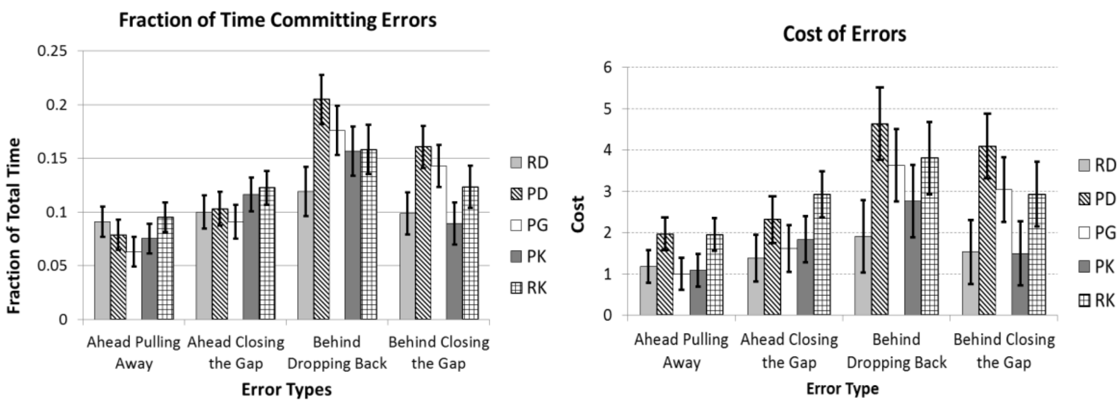

Fig. 46. Fraction of total time and cost of committing each type of error for the 1D tracking task

This task had three different types of path segments: logarithms, parabolas, and lines. The amount of time and total error for all segments of each path type were evaluated to see if the different path segment shapes had an effect on performance. As seen below in Fig. 47, there was statistical significance in the cost of the errors for different path types. Both rate controllers did significantly worse on the parabolic sections. The PD controller did significantly better on the logarithmic sections of the path. These results can be used for selecting an HMI if the path to be tracked is known.

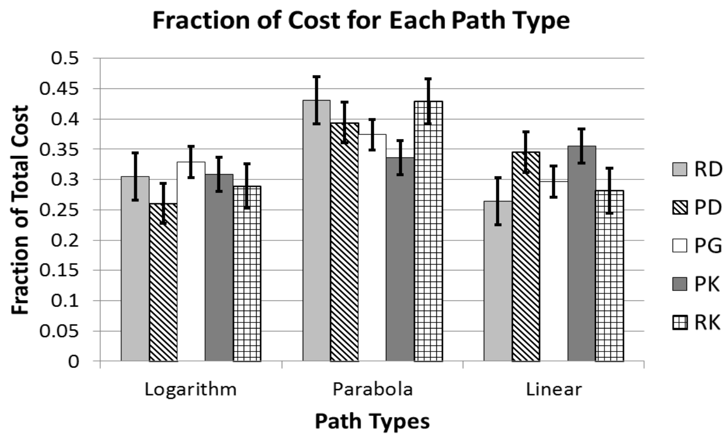

Fig. 47. Fraction of total error cost for each path type for the 1D tracking task

The RD controller was significantly more efficient than the PG and PD controllers. Unlike the point-to-point tasks, the PG controller used significantly more control effort than the PD controller and the RD controller. This result suggests that the task has a direct impact on the HMIs' efficiencies. Although not shown in Fig. 48, the controllers for the kinematic systems, as in the point-to-point tasks, used more control effort.

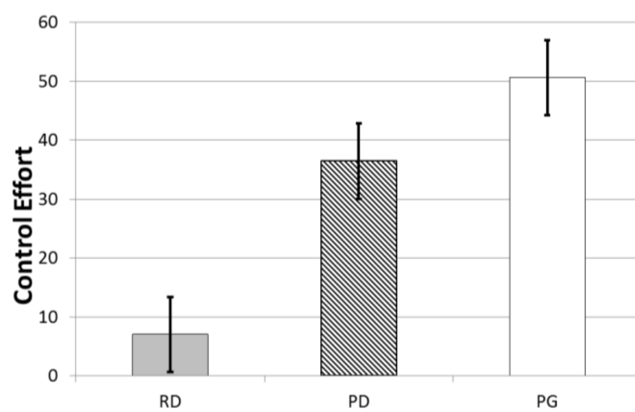

Fig. 48. Control effort for the 1D tracking task

2D Tracking

The 2D tracking task was scored in the same way as the 1D tracking task. It also had similar results, suggesting that the results could hold when implementing these controllers on the 3D excavator simulator.

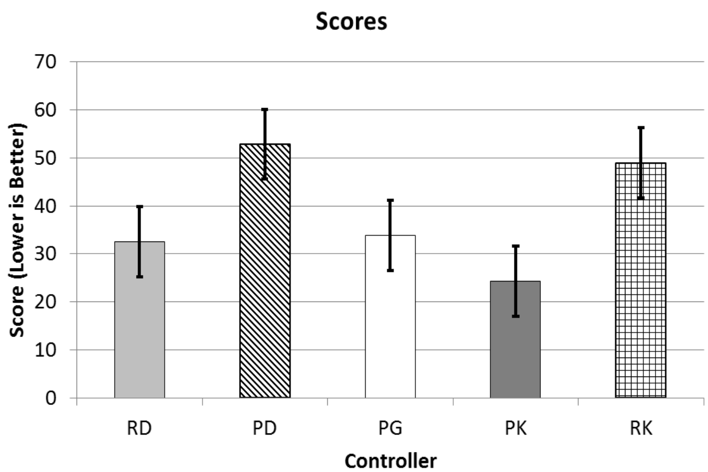

Fig. 49. Scores for the 2D tracking task. The optimal score for all controllers was zero

Overall Results

The overall scores reflect the general trend that the PG and RD controllers are comparable, and both are better than the PD controller. In this case, the average score with the PG controller is 36% less than the with the PD controller, demonstrating how the ghost feedback that matches the operator intent leads to better performance for dynamically slow systems. Subjects performed better with the PK controller than the RK controller, which is in agreement with previous work. However, performance with the kinematic system was not better than performance with the dynamic system. This suggests that scaling the input to fit the known maximum command necessary may assist the operator.

The 2D tracking task was 2.08 times longer than the 1D tracking task. Unlike the point-to-point tasks where the score was proportional to the distance traveled, the scores for the RD, PD, and PG controllers for the 2D tracking task were 5.4, 4.1, and 3.6 times greater than the scores for the 1D task. The variance in these values indicates that for tracking tasks, placing more demand on the operator's cognitive and physical abilities may play a significant role in performance as the amount of information given to the operator increases.

<u>Error Types and Costs</u>

The same errors were identified as in the 1D tracking task, and the time and cost of these errors followed the same patterns as in the 1D task but with generally higher values (Fig. 50).

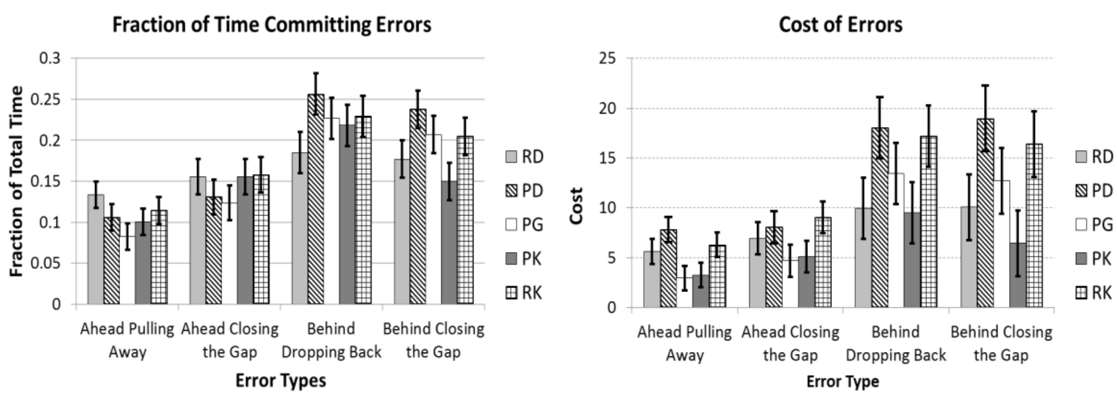

Fig. 50. Fraction of time and cost of committing each type of error for the 2D tracking task

The error time and cost is similar for both the 1D and 2D tracking tasks. This means that if lead or lag is important to system performance, then an appropriate type of controller can be selected. For example, if it is desirable to have the operator never be ahead of the target, than PG would be a better choice. The RD controller would be a better choice if a more even distribution of error was desired. Fig. 50 also suggests if one wanted to improve performance, he/she should design a controller to reduce lag, which is what is done by the controllers discussed in Chapter 6.

Unlike the 1D tracking task, subjects performed better on the logarithmic sections of the path, except with the PK controller, and there was no statistical difference between the linear and parabolic segments. This discrepancy with the 1D tracking results suggests that the findings from position vs. rate tasks are not generally applicable to systems of higher derivative orders.

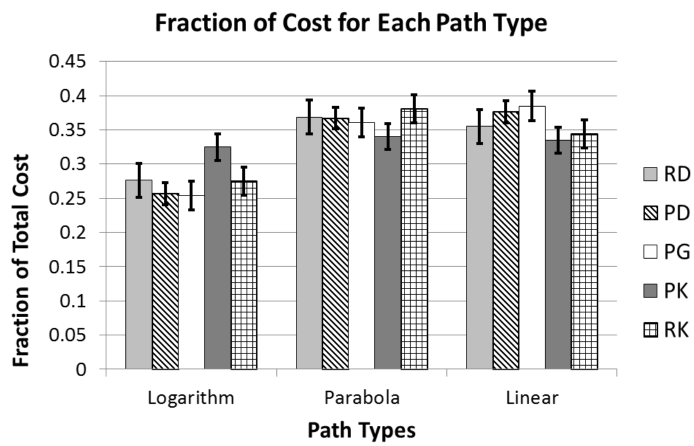

Fig. 51. The fraction of the error cost for each path type for the 2D tracking task

The control effort for this task follows the exact trends as for the 1D tracking task (Fig. 48). The PG controller required a comparable amount of control effort to the RD controller for the point-to-point task, but required more control effort for the tracking and maze tasks.

Maze

The maze was meant to be a task with a path to be followed at a rate that was comfortable to the subject so that they would not hit the walls, which carried a heavy penalty. From the test giver's observations, it often turned into a game where the goal was to recklessly go as fast as possible to win bragging rights at the cost of hitting the walls more often. The score was the total time it took to complete the maze: the summation of the time it took to traverse the maze plus any additional penalty from hitting the wall.

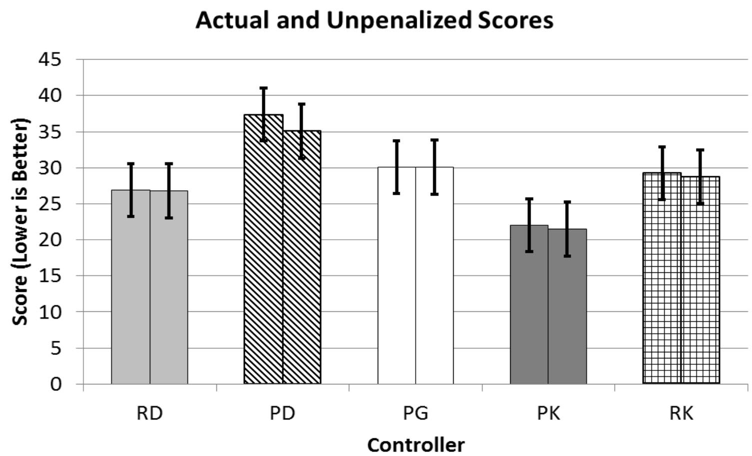

Fig. 52. Penalized (left) and unpenalized (right) scores for the maze task

<u>Overall Results</u>

Like all of the other position vs. rate task, the PG and RD controllers are comparable, and the RD and PG controllers were significantly better than the PD controller (28% and 19% improvement, respectively). Again, an improvement in perfomance is found with the addition of the ghost. Subjects performed significantly better with the PK controller than the RK controller, as they did for all five tasks.

<u>Error types and costs</u>

The cost of wall contact was measured for each controller, but there was no statistical significance between controllers, except that the PD controller was penalized significantly more than any of the other controllers. Therefore, ghost feedback significantly reduces the number and cost of errors for operators using position control to control the dynamic system. In this case, it reduced the average number of errors from

2.26 to zero. Despite the wide variability, the RD controller used significantly less control effort than either the PG or PD controllers (Fig. 53).

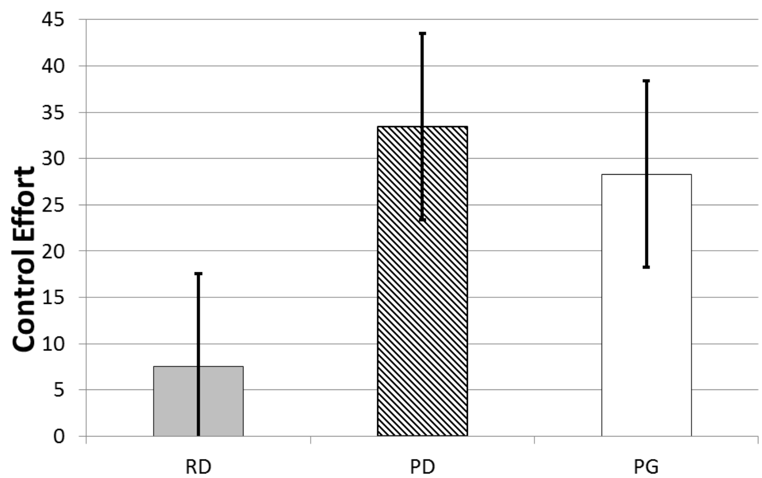

Fig. 53. Control effort for the dynamic systems on the maze task

Rate vs. Acceleration Planar Task Results

Human factors testing with the rotational tasks were undertaken to see if the findings from the above tasks could be applied to systems with higher derivative order inputs and outputs. Subjects were told to match the rotational velocity of target, not the rotational position, as described in Chapter 4. A rotational system rather than a translational system was selected so that accumulating differences in position would not require the resizing the field of view of the target and the controlled game piece. This is the first test of its type known to the author in the literature. That is, it is the first test comparing rate and acceleration control on a system with a rate output where the position of the system is wholly disregarded and unimportant. Because it is the first test of its type, all of the findings, including the comparisons to the results of the position vs. rate planar tasks, are contributions of this thesis.

Velocity Matching

The velocity matching task was analyzed in the same manner as the 1D point-to-point task. The results show that the same patterns hold as with the position and rate controller comparison in the five previous tasks:

- Performance with the kinematic systems was better than with the dynamic system. This is not surprising because the kinematic systems were much faster.
- For the dynamic system, performance with rate control without the ghost was worse than with acceleration control.
- The ghost increased the performance of the rate controller to be comparable to the acceleration controller for the dynamic system.
- For the kinematic system, performance with rate control was better than with acceleration control. This extends previous work by [Zhai (1993)], [Zhai (1997)], and [Kim], who compared performance for a system with a position output using rate or position control.
- The dynamic system had lower control effort costs than the kinematic system because of the limit on possible accelerations. The control effort was defined as summation at each time step of the absolute value of the force or torque applied to the game piece. The control effort is u in Fig. 13, Fig. 15, and Fig. 19.

The results in Fig. 54 look similar to plots in Fig. 39 and Fig. 43, which are the lower derivative order equivalent.

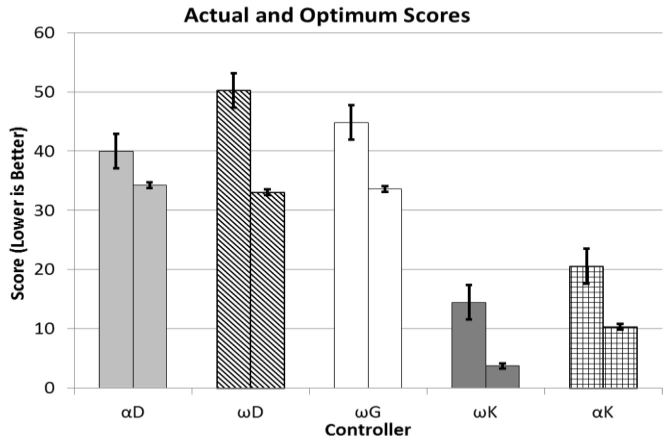

Fig. 54. Actual (left) and optimal (right) scores for the velocity matching task

The ωG controller improved performance by 11% compared to the ωD controller, which shows that adding in a ghost improves performance as it did with 1D point-to-point task. The number of errors was significantly reduced providing the operator with the ghost.

Velocity Tracking

In this task, like the 1D and 2D tracking task, the results were much more even than on the velocity matching task. The purpose of the velocity tracking task was to investigate if matching operator intent would apply to comparisons other than between position and rate control for tracking tasks. For the dynamic system, it did not. Interestingly, operators with the αD controller did 30% worse than with the ωD controller. Adding in the ghost (ωG) results in similar performance to the ωD controller but does not improve it.

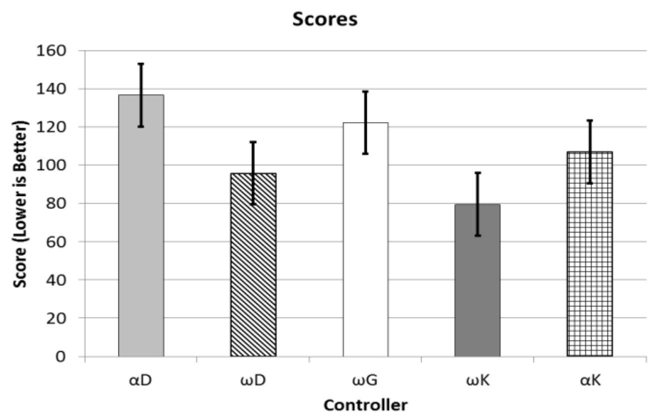

Fig. 55. Scores for the rotational velocity tracking task. The optimum score was zero for all controllers

Although there was good alignment in the results of the velocity matching tasks with the 1D point-to-point motion task, the results from this task show that the results cannot necessarily be extended to systems with different derivative orders of input and output. This is a new result because such a comparison (rate or acceleration control of a rate output) has not been made to the author's knowledge in the research literature. Others have compared rate or acceleration for controlling a position, but not a rate [Massimino].

Analysis of Operator Intent

Each subject was asked in an exit survey whether he/she viewed his/her goal as a position, velocity, or acceleration. A t-test was performed for each controller comparing the participants who saw their goal as position with those that saw their goal as rate for the position vs. velocity tasks, and between those who saw their goal as rate with those that saw their goal as acceleration for the rotational tasks.

For the most part, there was no statistical significance between performance with the controller and how the operator viewed their goal. There were the following exceptions: With the RK controller for the 2D tracking task, those who viewed the goal as a position outperformed those who viewed the goal as a rate ($p = 0.016$). For the velocity matching task with the αD and αN controllers, those that viewed the goal as an acceleration did better than those who viewed it as a rate ($p = 0.016$, $p = 0.006$). That there were very few exceptions and that one of the exceptions favored viewing the goal as a position while using rate control means that how the operator views the task has little bearing on their performance, even when considering the controller. The point is that in these tests matching the input and how the operator viewed the goal had no bearing on performance. This point is underscored by the fact that in the first exception listed above, the operators who viewed their goal as position did better with the rate controller than those who viewed their goal as a rate. On the other hand, the results from the testing have shown matching the feedback to the operator's intent improves performance.

Estimating the Crossover Velocity Limit

With the kinematic system, which did not have a velocity limit, performance with the position controller exceeded performance with the rate controller. However, with the dynamic system, which had a low velocity limit, performance with the rate controller exceeded that with the position controller without the ghost. It therefore seems plausible that at some velocity limit between v_{limit} and ∞, the performance would be about equal with both controllers. Knowing this crossover point could give insight into selecting a controller based on the velocity limit of the system.

The velocity limit for the dynamic system (v_{limit} in Eq. 16) was set at 5 graphical units/second, or about 15% of the task area per second, which, on the 14" laptop screen used for these tests, corresponds to about 1 inch/second. It was noticed by the test giver that the subjects using the RK controller rarely commanded the maximum speed. To make an estimate of where the crossover point is, the velocity commands for each subject were plotted. By examining the velocity commands with the RK controller for the maze task, it was noted that the subjects rarely commanded speeds in excess of 20 graphical units/second (Fig. 56 shows the velocity commands for all six runs of the maze task for Subject 11 plotted on top of one another. Note that he is rarely above 20 or below -20 graphical units/second).

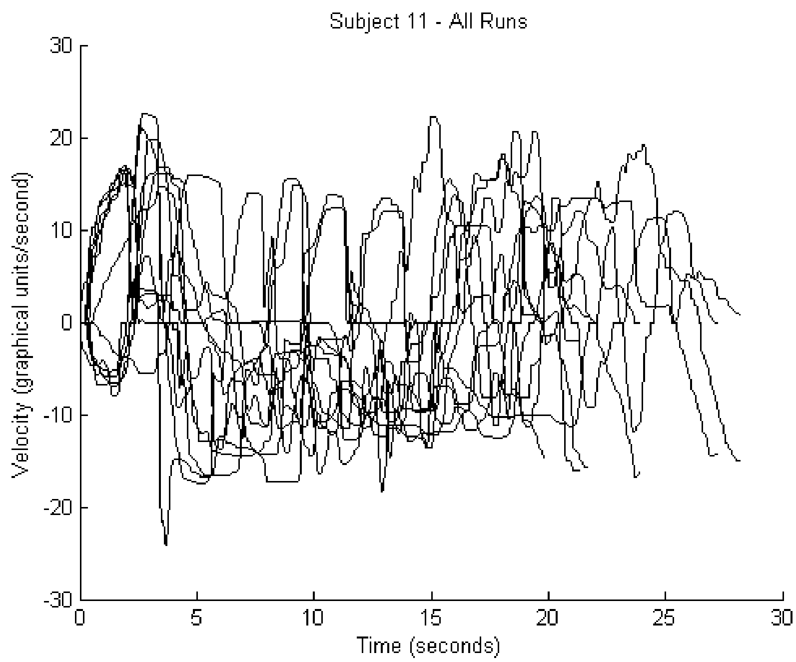

Fig. 56. Velocity commands or all runs with one subject using the RK controller

It was assumed that the operators didn't use the full capabilities of the controller (30 graphical units/second) because they couldn't do so in a controlled manner. In other words, the velocities were constrained by the ability of the operator, not the controller. Failure to use the full capabilities of the controller leads to suboptimal performance. On the other hand, as noted previously in this chapter, performance with the PD controller suffered from slow position feedback from the system. It was estimated that the crossover point would be near the point where the operators using a rate controller used the full capabilities of the controller and where the position feedback from the system was fast enough that the operators using a position controller would receive timely feedback, or, in other words, where the rate controller would be limited by the human as much as the position controller (or at least the position feedback) would limit the human. Hence, the estimated crossover point was selected to be 20 graphical units/second.

The controllers designed for the dynamic systems (see Fig. 13 and Fig. 15) were changed so that performance with both controllers would be similar to each other for the test functions, as in Table 2. The gains for the rate controller were kept constant, and the position controller gains were modified to *K= [4806 504]* and $N_{bar} = 4806$. A smaller test with only three (rather than six) subjects in each group, compared performance with the modified position and rate controllers. The testing protocol was the same as with the planar tasks described previously in this chapter. The results strongly indicate that there is a crossover point, and that it varies with the task.

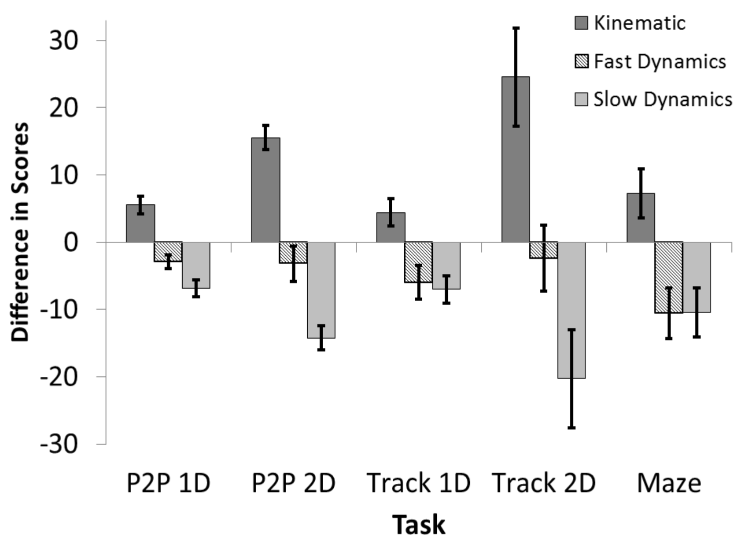

Fig. 57. Difference in scores for systems with varying speeds of response

In Fig. 57, positive results mean that performance with the position controller was better than performance with the rate controller. The kinematic system results are the difference in scores between the RK and the PK controllers reported previously in this chapter. The slow dynamics results are the difference in scores between the RD and PD controllers, also covered previously. The fast dynamics results are the difference between the modified RD and PD controllers that had a higher maximum velocity limit than the unmodified RD and PD controllers. The advantage of position control clearly decreases as the velocity limit drops, except for the maze task, where rate control has nearly the same advantage for both of the dynamic systems. This general trend suggests that there is a crossover point. The amount that performance drops by varies by task, indicating that the crossover point, like the other results discussed in this chapter, is somewhat dependent on the task. The estimated crossover point only hit the mark for the 2D tracking task (the error bars cross the horizontal axis, the point of zero difference).

Summary of Planar Tasks Results

Adding a ghost to match the feedback with the operator intent notably improved operator performance with the position controller for the dynamic system, showing that matching feedback with operator intent results in more efficient performance. No statistically significant performance benefit was found between the rate controller and the position controller with the ghost for the dynamic system. Adding the ghost also significantly decreased the number and costs of some errors, in particular pauses. The control effort decreased drastically when the ghost was introduced to the position controller of the dynamic system for the point-to-point tasks, but increased for the other three translational tasks. These benefits of the ghost HMI are the core contributions of this thesis.

A smaller test indicated that there is a crossover point in the maximum system velocity where performance with the position controller without a ghost and performance with the rate controller have no statistical difference. Adding in the ghost shifted this crossover point to beyond the slower velocity limit of the dynamic system, which is another benefit of the ghost HMI and contribution of the thesis.

For the kinematic system, previous work was verified in that performance with the position controller was superior to performance with the rate controller. This held for all tasks, including the tracking task, where [Mora] had found that rate control was superior, and Zhai et al. had found that performance between the rate and position controllers was not statistically different [Zhai (1997)].

The dynamic rotational system task showed conflicting results. Although many of the results of the translational system were also results for this system, the conflicting results mean that the position vs. rate control results cannot unilaterally be applied to systems with higher derivative order inputs and outputs. For the velocity matching task, the ghost improved the performance to the equal that of rate control. However, for the velocity tracking task, the ghost degraded performance. In both cases, adding the ghost caused the performance with the position controller to move towards being comparable to performance with the rate controller. For the kinematic rotational system, performance with the position controller was better than that with the rate controller.

The results are summarized in Table 4. The relative rankings are indicated ('+' indicating better performance and '-' indicating poorer performance in terms of the score). As mentioned the, the RD and PG columns have similar performance, which is clearly seen by comparing the two columns.The relationships in the scores were similar for both the 1- and 2D versions of the point-to-point and tracking tasks, indicating that applying a ghost to the 3D excavator simulator may also show similar improvement with the PG controller over the PD controller. The cost of the errors for the point-to-point motion tasks was small for the RD and PG controllers. For the tracking tasks, the scores between these two controllers were comparable, but the error distribution was different. The RD controller has a much more even amount of error time and error cost ahead and behind the path, whereas the PG controller was found to have notably more error time and cost behind the path. This finding leads to the next chapter, which covers new controllers designed to eliminate the amount of lag in the system.

Table 4. Results for the planar task tests. '+' indicates good and '-' indicates poor performance

	RD	PD	PG	PK	RK
1D Point-to-Point	+	-	+	++	++
2D Point-to-Point	+	-	+	++	++
1D Tracking	+	-	+	+	-
2D Tracking	+	-	+	+	-
Maze	+	-	+	++	+
	αD	**ωG**	**ωG**	**ωK**	**αK**
Velocity Matching	+	-	+	++	++
Velocity Tracking	-	+	-	+	+

CHAPTER 6

CONTROL ALGORITHMS TO BETTER MATCH OPERATOR INTENT

The results of the analysis in Chapter 5 had no statistical difference in operator performance with the RD and PG controllers. Previous work states that position control is more intuitive than rate control [Sheridan (1978)], which leads to the belief that better performance should be achievable with the PG controller than the RD controller. In an effort to achieve better performance with the PG controller, new control algorithms were developed to improve performance with the PG controller. Information about the task and environment was assumed to be unknown, so that any resulting improvements could be applied to real-world tasks where this information is unknown by the control algorithm. This chapter describes the improved controllers and the offline test used to (a) determine what the improvement would be with the controller when applied to the position vs. rate planar task and (b) what the gains should be. It then reports on a human factors test that compared the improved controllers to the PG controller, showing significant improvements in the tracking and maze tasks, and performance with no statistical significant difference for the point-to-point motion tasks.

The control algorithms fell into two categories: error detection algorithms and input smoothing algorithms. The error detection algorithms attempted to determine when the operator was making a mistake. Three algorithms were applied to inputs recorded during the planar tasks test: heuristic comparison of states, neural networks, and FFT analysis. The heuristic comparison of states looked for system state comparisons that would appear to indicate an error. None were found that predicted when the subject was in error with a large degree of certainty. The same state comparisons were entered into neural networks in various combinations. The best of the neural networks detected 100% of the errors, but had many false positives, especially when the game piece started from rest, or came to rest. The FFT was applied to the joystick command to see if it was more erratic when the operator was in error. Differences in the magnitudes of the FFTs for when the operator was in error and when he/she was not in error were analyzed for patterns. No reliable patterns were detected.

Input Smoothing Algorithms

Three control algorithms that smoothed the command input were invented to improve performance. As noted earlier in Chapter 5, the largest errors were on the tracking tasks, especially for the PG controller, which had near optimal performance for the point-to-point motion tasks and no wall contacts for the maze task (see Fig. 52). Examining the input for the PG controller for the tracking tasks, it was noted that the command followed a stair step pattern (Fig. 58). These algorithms assume that the user means to command a smooth path and attempt to estimate the smooth path.

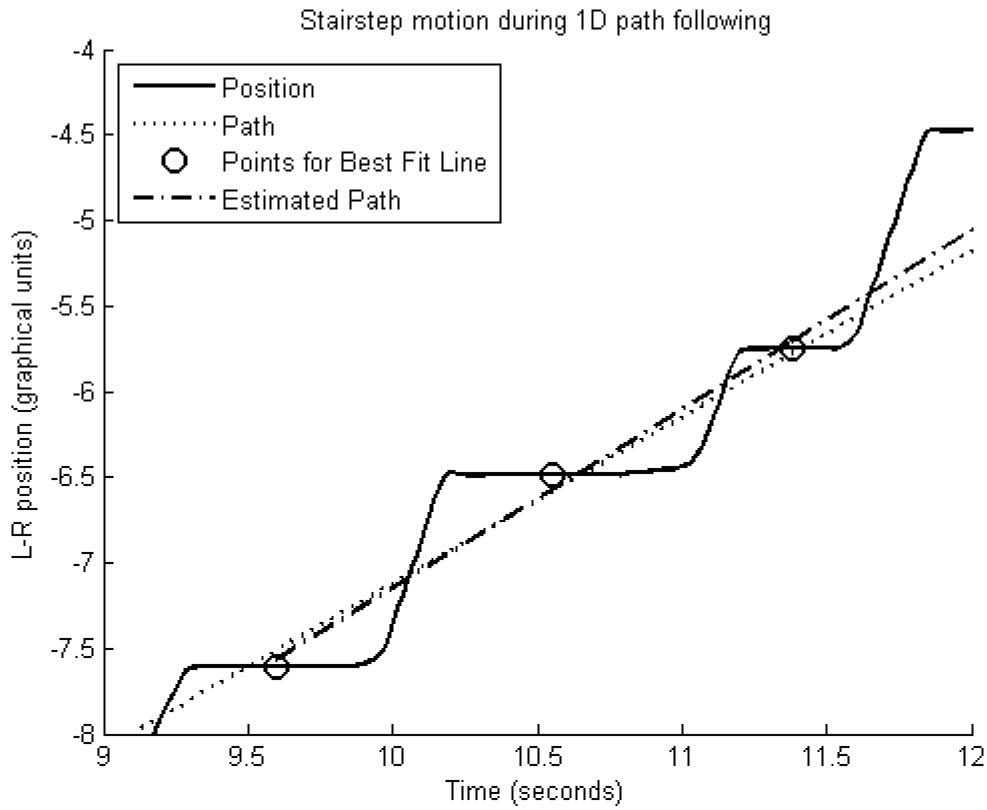

Fig. 58. How the best fit estimate is found

Best Fit Algorithm

This algorithm looks for pauses in the system's position when the operator's command stays within a small radius for a brief period of time (the pauses correspond to the horizontal portions of the stair steps in Fig. 58). The algorithm assumes local linearity and uses the least squares method to calculate a best fit line between the middle points of the vertical "stair step" and the current commanded position. The resulting new command is blended with the operator's command through the gain *k* (Fig. 59). *k* ranges from 0 to 1 and is the fraction of the estimated path position used in the resulting command input, *u*.

To select *k*, it was assumed that the operator's commands would remain the same with this new controller. This assumption allowed using the data taken during the testing in Chapter 5 to compare performance with different *k*-values. This assumption was not made with the maze tasks, and so the following analysis was only done on the point-to-point and tracking tasks. The commands from the planar tasks tests were used as the reference, *r*, and the resulting output, *x*, was scored in the same manner as it was in Chapter 5. *k* was varied in steps of 0.001 from 0 to 1, and the *k* with the best score was selected.

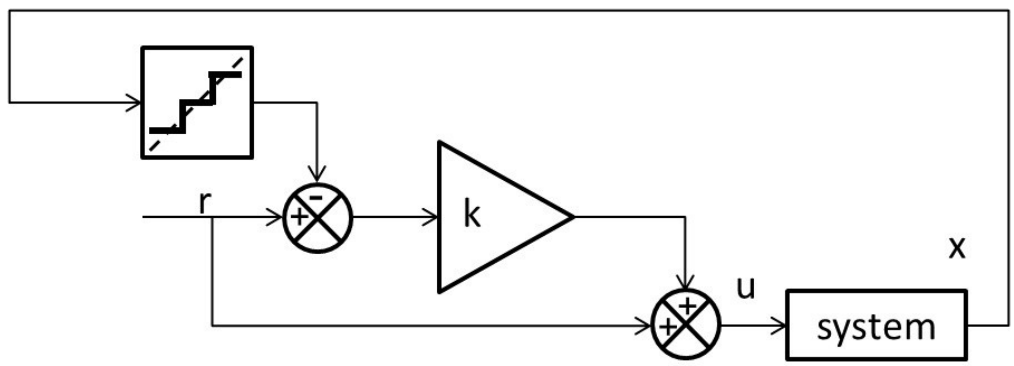

Fig. 59. Best fit algorithm block diagram

k was selected to be 0.78 for the 1D tests, which showed an improvement of 1.8% on the 1D tracking task, and neglible improvement in the 1D point-to-point task. *k* was selected to be 0.24 for the 2D test, which showed an improvement of 1.0% on the 2D tracking task and had neglible improvement on the 2D point-to-point task.

Time Elimination Algorithm

The same path estimation used in the best fit algorithm is used as an input into the time elimination block. This block uses the path estimation to calculate the closest point where the game piece and the path can intersect and the desired direction to travel at to get to the closest point. The desired direction is added to the commanded position through the gain *k* (Fig. 60).

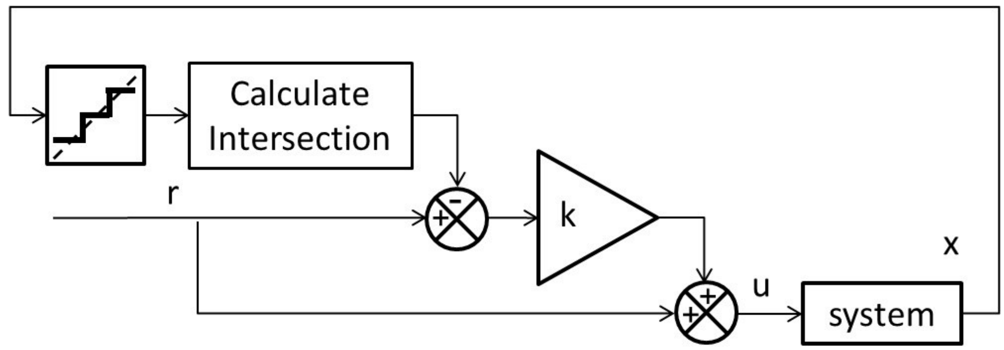

Fig. 60. Time elimination algorithm block diagram

The same method to find the optimal *k* was used as with the best fit algorithm. *k* was selected to be 0.024 for the 1D tests, which showed an improvement of 5.2% on the 1D tracking task, and 0.25% improvement in the 1D point-to-point task. *k* was selected to be 0.012 for the 2D test, which showed an improvement of 2.25% on the 2D tracking task and had neglible improvement on the 2D point-to-point task.

Testing the Improved Control Algorithms

The best fit (B.F) and time elimination (T.E.) algorithms were compared to the PG controller in the position vs. rate planar tasks test. Each of these improved controllers displayed either the old ghost (B.F. Old, T.E. Old) that displays the position command of the joystick (the same as was used in the position vs. rate planar tasks test for the PG controller which is kinematically connected to the reference, *r*), or the new ghost (B.F. New, T.E. New) that displays a ghost at the position input command of the system (*u* in Fig. 59 and Fig. 60). The testing of the improved control algorithms was done in the same manner as the planar tasks testing, outlined at the beginning of Chapter 4. The responses to the pre-test questionnaire are found in Appendix B. As in Chapter 5, the average of each subjects best three runs for each task were used for the analysis of operator performance.

Overall the performance with the best fit algorithm with either ghost was better than the PG controller, and the time elimination algorithm with either ghost was slightly worse. Notably, the control effort was much higher for the time elimination algorithm because of a high frequency oscillation that appeared when the operators command was nearly constant. The oscillation was barely visible, if at all, but used significantly more control effort. This shortcoming could be addressed in the future.

1D Point-to-Point Motion

The scores for the different controllers for this task were in line with what the offline test to find the optimal *k* predicted: there was no statistically significant difference in performance between any of the controllers (Fig. 90 in Appendix D). The PG controller was already within 2% of the optimal, so improvement would be difficult to find. But it is important that performance with the improved controllers was not any worse, as seen in Fig. 90. All of the controllers were within 1-2% of the optimal, and none were significantly closer (Fig. 91).

The same four types of errors were measured as before in the position vs. rate planar tasks testing. Just as the scores were similar to the PG controller, the number and cost of the errors were similar too (Fig. 92). The time elimination controller had significantly more pauses and non-minimum phase errors. The control effort for time elimination controller is much higher than for best fit or PG controllers (Fig. 93).

2D Point-to-Point Motion

Like the 1D point-to-point motion task, the scores for the smoothing controllers were not statistically different from the scores with the PG controller. This lack of statistical difference, like the 1D point-to-point motion results, is in line with the analysis to find the optimal *k*. However, unlike the 1D version, the improved controllers with the old ghost (T.E. Old and B.F. Old) were significantly further away from the optimum (Fig. 95).

The number of errors is much higher for the smoothing controllers because these controllers are constantly changing the input (Fig. 96). However, the cost of the errors is much more comparable to the PG controller because the errors are so small (Fig. 97). The time elimination algorithm had a greater tendency to move away from the target than the other controllers; however, the cost of the errors was about the same. The control cost was higher for the time elimination controller. This was due to the high speed oscillation when the operators command was nearly constant.

The results of the 2D point-to-point task being similar to the 1D point-to-point task, in that performance with all controllers was the same, would suggest similar performance would be seen in a point-to-point task with the 3D excavator simulator.

1D Tracking

The variations in the scores were much higher for the tracking tasks than the point-to-point tasks. The improved controllers were designed with the tracking tasks in mind, so greater improvement was expected here than in point-to-point tasks. Both best fit controllers did significantly better than the PG controller and the time elimination controllers. The average score with the B.F. New and B.F. Old controllers were 29% and 48% less than the average score with the PG controller (Fig. 61). This improvement is remarkably higher than the percentage improvement estimated in finding the optimal *k*-value.

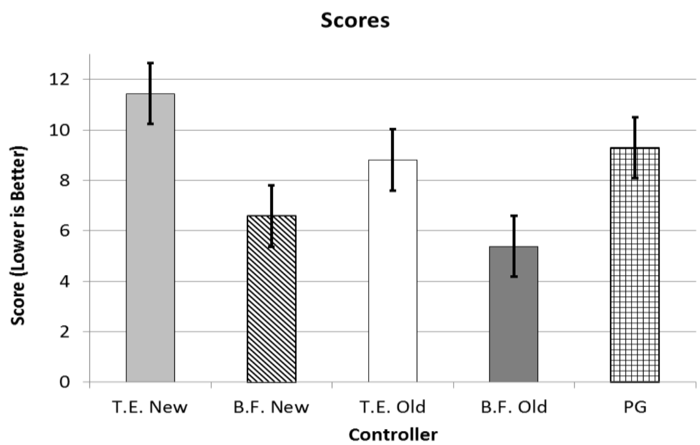

Fig. 61. Scores for the improved algorithms for the 1D tracking task

The types of errors for this task were the same as in the position vs. rate planar 1D tracking task (see Chapter 5). The smoothing controllers were designed to smooth the game piece's trajectory. The smoothing controllers accomplished this design objective because the time committing errors of each type and the cost of the errors of each type for all of the smoothing controllers, except T.E. New, had a more even distribution of error time and error cost ahead and behind the path than the PG controller (Fig. 62). The improvements of the B.F. Old and B.F. New controllers came almost entirely from eliminating the time and cost from being behind the path.

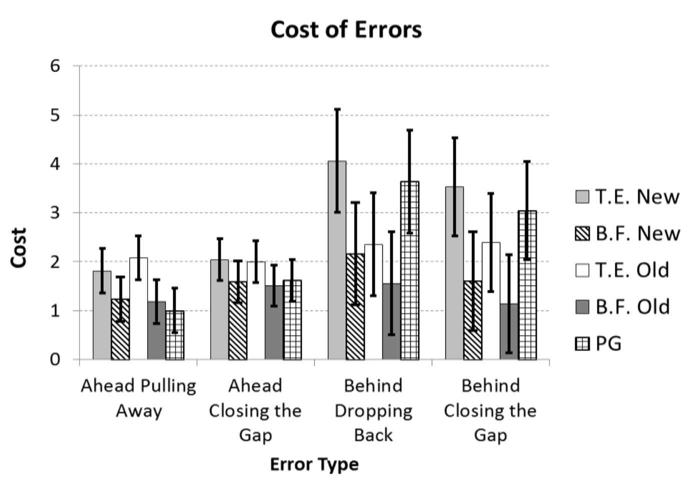

Fig. 62. Cost of the errors for the improved algorithms for the 1D tracking task

This task had three different types of path segments, logarithms, parabolas, and lines. The amount of time and total error for all segments of each path type were evaluated to see if the different path segment shapes had an effect on performance. No statistically significant measures were found. Control effort was evaluated and had significantly larger values for the time elimination controllers than for the other three controllers (Fig. 63).

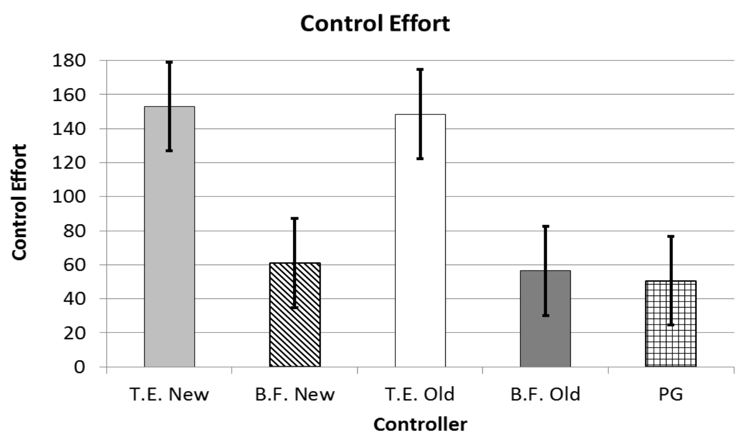

Fig. 63. Control effort for the improved algorithms for the 1D tracking task

The best fit controllers are the best choice for this task because they use a comparable amount of energy while boosting performance by 29% and 48%.

2D Tracking

The 2D tracking task was scored in the same way as the 1D tracking task. Performance with the B.F. Old controller was significantly better (27% improvement) than performance with the PG controller. Unlike with the 1D tracking task, there is not statistical significance between the PG and B.F. New controllers.

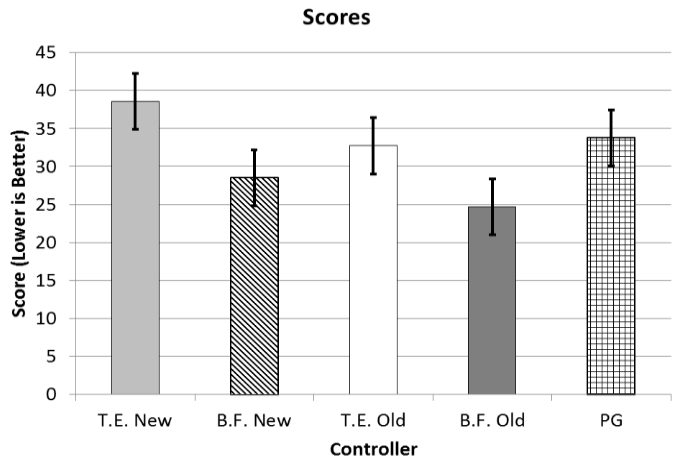

Fig. 64. Scores for the improved algorithms for the 2D tracking task

The same errors were identified as in the 1D tracking task, and the time and cost followed the same patterns as the 1D task, but with generally higher values.

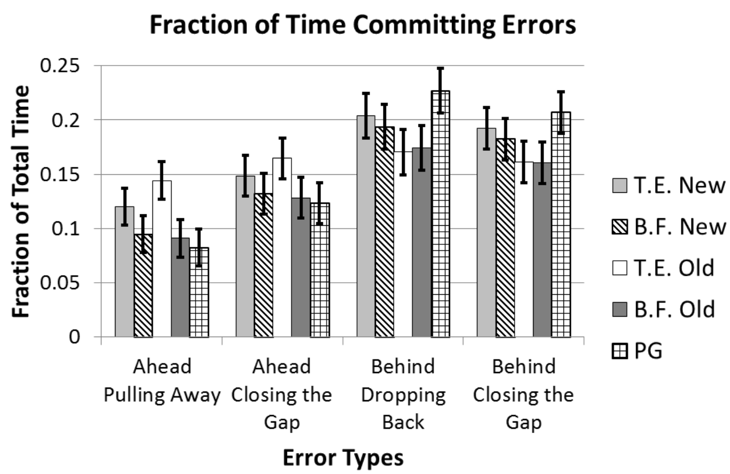

Fig. 65. Fraction of time committing errors for the smoothing algorithms for 2D tracking

The smoothing controllers again averaged out the amount of time ahead of and behind the path, which was what they were designed to do. Again, the control effort of the best fit controller was significantly better than with the time elimination controller and on par with the PG controller.

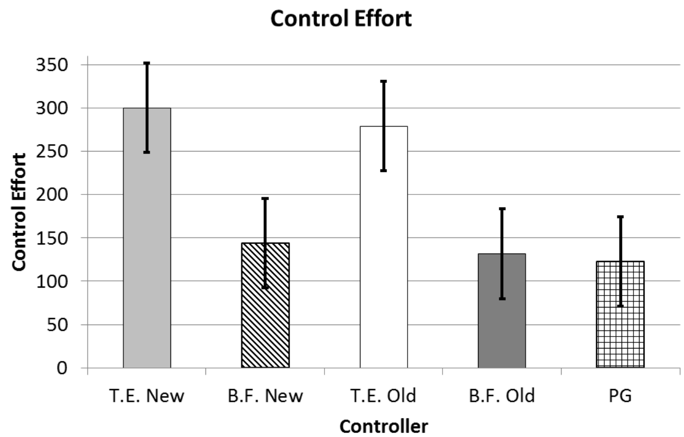

Fig. 66. Control effort for the improved algorithms for the 2D tracking task

The B.F. Old controller is the best choice for this task, as it improves performance by 27% while using a comparable amount of control effort.

Maze

This task most resembles excavation in that there is a path to follow with obstacles that must not be hit, but there is not a specific time to be at any given point along the path. So the results of this task are likely more indicative of performance with an excavator than the other tasks.

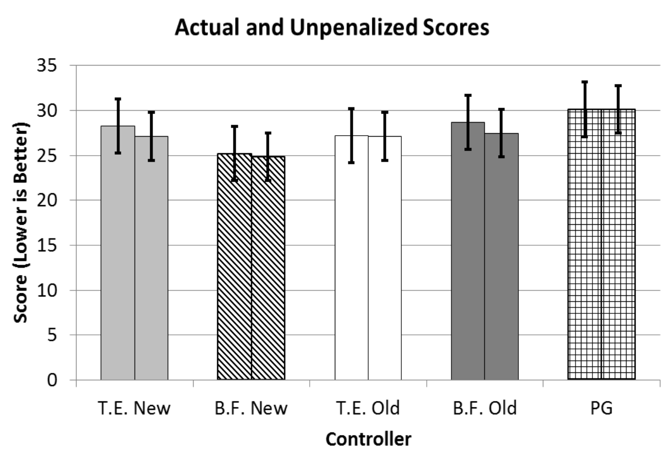

Fig. 67. Scores for the maze task with the improved control algorithms

The best performing controller, B.F. New, resulted in a 16% improvement in performance over the PG controller. When looked at as a group with a Tukey HSD (honestly significant difference), none of the scores are significantly different. However, a t-test between the PG controller and the B.F. New controller shows that the best fit algorithm's performance is statistically significant. The time and cost of wall contact was measured for each controller. There was not a statistically significance difference in either measure. There also was not a statistical difference between control efforts for the different controller (Fig. 99). Because the only statistical difference is in the score, the best controller for this task is the B.F. New controller.

Analysis of Operator Intent

Each subject was asked in an exit survey whether he/she viewed his/her goal as a position or a velocity. A t-test was performed for each controller comparing the participants who saw their goal as a position with those that saw it as a rate. There was no statistical significance difference between performance with the controllers and how the operator viewed their goal. This lack of difference confirms the findings in Chapter 5 that how the operator views the task has little bearing on their performance, even when considering the controller.

Summary of Smoothing Controller Results

The results from the smoothing controller test showed that the best fit algorithm is worth testing on more complicated systems, such as the excavator. There was no statistical difference between performance with the B.F. controllers and the PG controller for the point to point tasks, but at least one of the best fit algorithms did significantly better than the PG controller on the tracking and maze tasks. The control effort of the best fit controllers is comparable to the PG controller for all tasks. The improvement estimates made while selecting the control gain k (see Fig. 59 and Fig. 60), were close for the point-to-point motion tasks, but low for the tracking task. Although the results with the best fit controller are not statistically different from the rate controller, it is worthwhile to determine if, when applied to the excavator simulator, statistical significance will arise. A comparison of coordinated rate control and coordinated position control with the ghost (although without the best fit algorithm) on the excavator simulator is discussed in the next chapter, to determine the validity of the results from the planar task tests.

CHAPTER 7

EXCAVATOR SIMULATOR TESTING

The planar tasks were used to produce "cleaner" comparisons between systems that matched feedback to operator intent and systems that did not match feedback to operator intent. The planar tasks were not clouded by many degrees of freedom, system nonlinearities, and environmental interactions. The planar tasks test was a laboratory test to determine if the underlying hypothesis that matching system feedback with operator intent increases performance was valid or not. To measure how this new HMI affects performance when teleoperating a real-world system, testing was done on an excavator simulator, which is described in Chapter 2. The excavator simulator is a system with slow dynamics and a large workspace that is used to do a variety of tasks, and is, therefore, a good testbed for this research.

This chapter covers two tests that were performed on the excavator simulator. The first test compares coordinated position control to joint rate control of the excavator simulator. The operators from this test noted the need for feedback indicating the commanded position of the excavator arm. The second test gives the operator this feedback via a ghost arm and compares coordinated position control with and without the ghost to coordinated rate control.

Coordinated Position vs. Joint Rate Control

The first test benchmarked the efficacy of coordinated position control compared to conventional joint control. The Phantom (discussed in Chapter 3) was used for coordinated position control, and two 2-DOF joysticks were used for joint rate control, in the same manner as in a state-of-the-art excavator. The physical cab swing of the excavator workstation discussed in Chapter 2 was not implemented at the time when this test was performed.

Experimental Methodology

One expert and 24 novices operated the excavator simulator. The operators all came in for a single one hour session, at the beginning of which they were asked to fill out a demographic survey (see Appendix B for survey results). The subjects were then informed of the goals. The primary goal was to remove as much soil from the trench as possible. They were also given two secondary goals: to dump all of the soil as close together as possible (they could choose the location, unlike in the next test where they were asked to dump the soil in bins), and to enter and exit the trench as cleanly as possible. Subjects were then given five minutes to warm up with the first controller. Then the subject performed five two-minute runs with approximately 90 second pauses in between each run. The process was then repeated with the other controller. The order that the subjects used each controller was reversed from subject to subject. Each subject completed a survey about the ease of use of both interfaces after completing all test runs.

Coordinated Position vs. Joint Rate Control Results

The results show that the novices removed 86% more soil with coordinated position control and were 19% more fuel efficient (Fig. 68). The one expert performed similarly with both controllers. Pile placement, which was measured by the inverse of the standard deviation of the radial distance between pile locations and the average pile location, was better with the coordinated position control (higher is better for all measures in Fig. 68). Importantly, novices using coordinated rate control performed at the level of the expert using joint rate control. Further details of the testing methodology, operator opinions, and analysis of the results can be found in [Elton (2011b)]. Because performance with the coordinated position controller exceeded performance with the joint rate controller, coordinated control was used in the planar tasks described in Chapter 4 and the second test on the excavator simulator in this chapter.

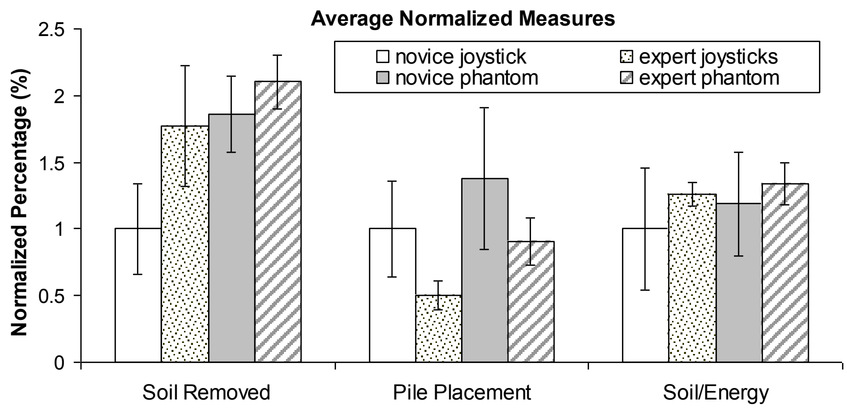

Fig. 68. Performance with the Phantom and joystick for novices and expert operator. The bars in the plot show the standard deviation rather than the confidence interval.

Later, the Phantom was used to drive the physical excavator at Purdue University that was modeled for the simulator (see Chapter 2). While no formal tests were performed, the feasibility of using a Phantom to control an excavator was demonstrated. If the operator controlled the excavator while sitting in the cab, significant biodynamic feedthrough was observed. Off of the excavator, biodynamic feedthrough was not a problem.

Coordinated Position vs. Coordinated Rate Control

The second test had eighteen subjects drive the excavator simulator for two roughly one hour sessions at least a day apart but no more than four days apart. The subjects were randomly assigned into three groups: coordinated position control without a ghost, coordinated position control with a ghost, and coordinated rate control. Because all of the controllers are coordinated, in the sections discussing this test "coordinated" is dropped from the controller descriptions, and they are referred to as position control without the ghost (Pos in the following figures), position control with the ghost (Ghost in the following figures), and rate control (Rate). Conventional control is the standard joint rate control with two 2-DOF joysticks used the previous test. The physical cab swing of the excavator workstation was in place for this test. The graphics program was slightly modified from the previous test to show two bins where the subjects were instructed to dump the soil.

Experimental Methodology

Each group had six subjects so as to provide statistically significant results [Poulton]. The first session consisted of a filling out a consent form and a pre-test questionnaire (the results of the questionnaire are in Appendix B). The subjects were then informed on how to control the excavator simulator and that the goal was to remove as much soil from the trench as possible and dump it in the bins on either side of the trench. The subjects then had 5 minutes to warm-up with the excavator simulator. Only during this 5 minute period were the subjects watched by the test giver and coached on how to remove more soil. After this warm-up, five three-minute digging runs were performed. The subjects had a short 1-2 minute break between each run while the data were saved. The second one-hour session consisted of a five minute warm-up, five three-minute digging runs, followed by two five-minute digging runs. This testing arrangement is the same as the one in [Winck], and was used so that the results could be compared with the test done earlier by Winck.

Results

Overall the results show the same pattern as the planar tasks tests: The ghost improved the position controller to have performance that was not statistically different from the rate controller. The subjects removed an average of 23.5% more soil per unit time and 24.0% more soil per unit fuel with the ghost than without the ghost (Fig. 69 and Fig. 70). The data from all of the runs were used in the analysis, as in [Winck]. As with the planar tasks, the addition of the ghost to match the operators' intent results in better performance with the position controller that is not statistically different from performance with the rate controller.

Position control with a ghost removed more soil from the trench on average than rate control, although not with statistical significance. Rate control placed more soil in the bins, again not with statistical significance. Position control also took more scoops, but not significantly so (Fig. 71). It is possible that if the operators were better instructed and capable of removing full scoops from the trench, position control with a ghost would outperform rate control.

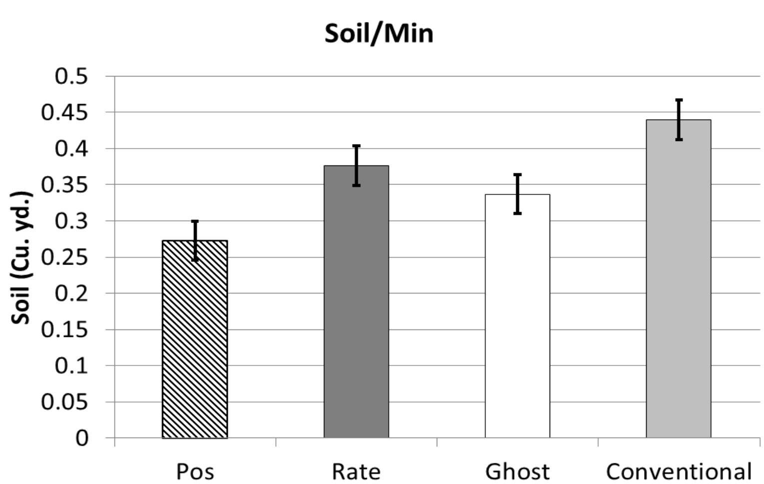

Fig. 69. Amount of soil place in the bin per minute in the excavator test

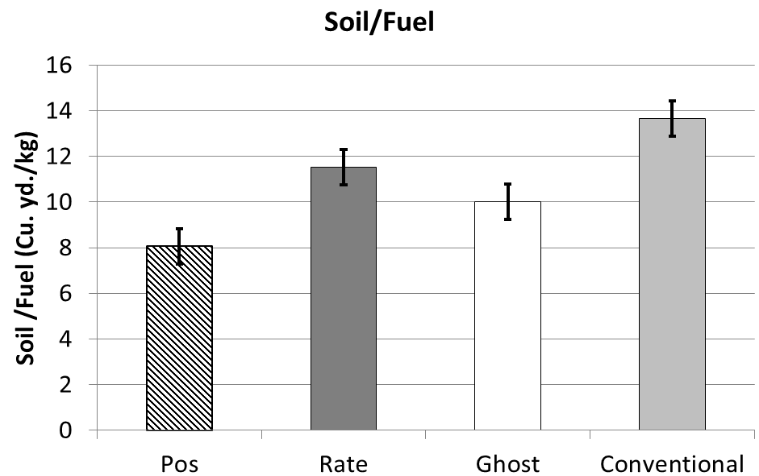

Fig. 70. Amount of soil placed in the bin per kilogram of diesel fuel

Compared to the [Winck] data, all of the coordinated controllers removed less soil per time and fuel than the conventional joysticks, which is the opposite of what was found in the previous test in this chapter comparing coordinated position control and conventional control. The difference in the two test results is possibly due to the fact that during the Winck testing, the operators were heavily coached throughout the testing process, which did not come to light until after the testing was performed. The number of scoops removed per minute by the conventional controller in the Winck study matched what was found in the previous test in this chapter (3.3 scoops/min). In this previous test, the operators removed 5.7 scoops/min with the coordinated controller. However, the operators did not have to dump the soil in a bin, which may be the reason that operators in the current test removed fewer scoops per minute (3.6 scoops/min) than in the previous test. Several of the subjects complained that it was difficult to gauge when the bucket was over the bin, even with the visual assistance of a shadow, so additional time was probably needed by the operators to dump the soil in the bin. To give better depth perspective, a 3DTV could be used for the visualization.

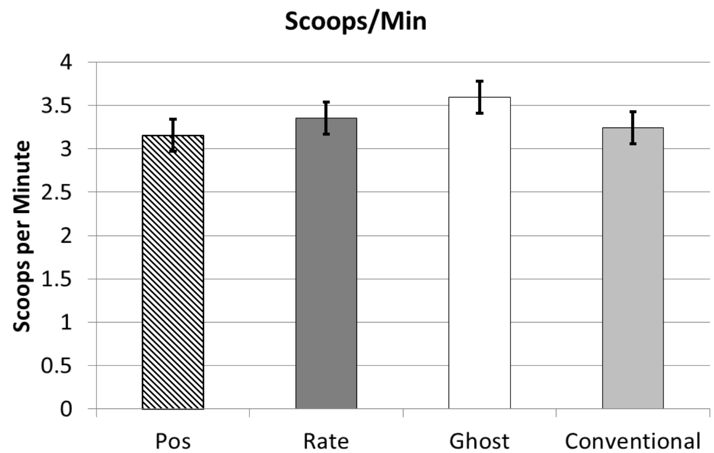

Fig. 71. Number of scoops removed from the trench per minute

If the number of scoops from this test is held constant (Fig. 71), but the average bucket load is set to equal to that of [Winck], then the amount of soil removed by the coordinated controllers increases more than threefold and dwarfs the amount removed with the conventional controller, as seen in Fig. 72. This estimate of what is possible with better trained operators who can remove full bucket loads may be a best case scenario, but even if the gain from coaching in reality is half of what is predicted here, the coordinated controllers would still easily outperform the conventional controller.

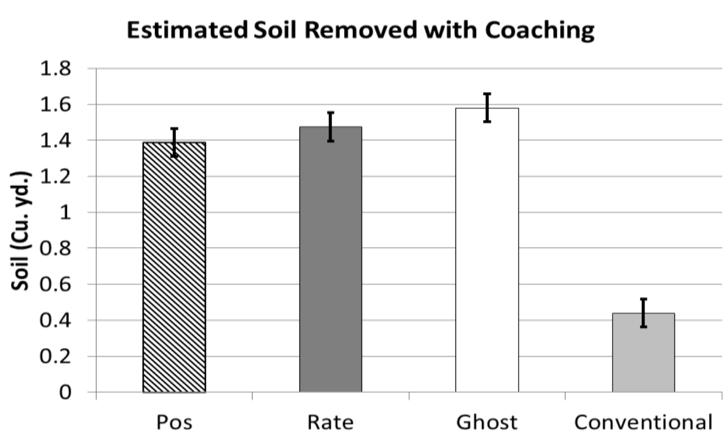

Fig. 72. Estimated amount of soil removed with more aggressive coaching

Another possibility is that the spring return of Phantom used with the coordinated rate controller allows the operator to do force control of the bucket. If the operator commands a slight downwards velocity while the bucket is in contact with the soil, the bucket will penetrate the soil only a couple inches before the cylinders stall. Then the operator only has to command the bucket to come towards him/her to scrape off the top layer of soil, which is how professional operators excavate. The addition of haptics to the coordinated position controller may lead to better performance.

Five of the six subjects that had the ghost interface stated that it was helpful. They said the following about the ghost, reflecting how the ghost feedback matches their own intent:

- "It was helpful to know what my movements were doing in comparison to the actual [excavator arm's] movements."
- "Without it, it would have been very hard to predict where the excavator would go next, especially in the trench."
- "The ghost was very helpful in differentiating my control input vs. actual machine capability and position."

For the subject that did not find the ghost interface helpful, it appears that the interface simply adds to the information clutter on the screen:

- "It wasn't helpful because I was not looking at it anyway."

One other subject noted a similar feeling, but only after becoming experienced with the excavator:

- "At first it was helpful to get a feel for the excavator arm movement, but as I became accustomed to the movement, I didn't really notice it."

One subject said that the ghost interface distracted too much from actual machine.

- "I didn't notice if the real bucket was stuck on something."

Analysis of Operator Intent

As with the planar tasks tests, each subject was asked in an exit survey whether he/she viewed his/her goal as a position or a velocity. A t-test was performed for each controller comparing the participants who saw their goal as a position with those that saw their goal as a rate. The subjects with the position controller with the ghost, did significantly better if they viewed their goal as a position ($p = 0.01$). There was no significance to the analysis of the other controllers.

Summary of Excavator Simulator Testing

This chapter has described the experimental methodology and results for two human factors tests performed on the excavator simulator (see Chapter 2 for a description of the simulator). The first test compared performance with coordinated position control to joint rate control. Coordinated control boosted novice performance 86% in terms of productivity and 19% in terms of fuel efficiency. The one expert operator also performed better with coordinated control. The novices with the coordinated control performed at the level of the expert with joint rate control. The second test compared performance with coordinated position control with and without the ghost to coordinated rate control. As was found in the planar tasks, adding the ghost increased performance with the position controller and made it comparable to performance with the rate controller. In this test, operators did 23.5% better in terms of productivity, and 24.0% better in terms of fuel efficiency.

CHAPTER 8

CONCLUSION

This thesis has investigated why past studies have shown that coordinated position control is superior to coordinated rate control except when operating large-workspace or dynamically slow manipulators. An experiment on an excavator simulator comparing operator performance with joint rate control to coordinated position control showed that novices perform better with coordinated position control and, from operator comments, suggested that providing feedback that showed the commanded position would be useful. The hypothesis that matching feedback with operator intent would result in an effective HMI was first tested using several planar tasks. The results were supportive of the hypothesis. A second planar task test was performed to see if the results would hold on a system with a velocity output and a velocity or acceleration input. The results of this test supported the hypothesis for the velocity matching task, but not for the velocity tracking task. A third test was performed to determine whether a crossover point existed where there would be no statistical difference between performance with a rate or a position controller. Additionally, two new controllers were designed based upon the enumeration of the errors with the position controller in the planar task tests and were tested using the same planar tasks. One of the controllers (the best fit controller) showed significant improvement in operator performance. A final human factors test compared performance with coordinated position control with and without a ghost arm and coordinated rate control on an excavator simulator. The contributions from all of the tests are enumerated below and are followed by a section of possible future directions for this research.

Contributions

- Showed that ghosting improves operator performance with position control for dynamically slow and large workspace manipulators. This was verified both on the excavator simulator (Chapter 7) and in planar task tests (Chapter 5). These results support the hypothesis that a performance gain comes from the ghost providing feedback that matches operator intent. From the operators' own views of the task, it was determined that the way that the operator views his/her goal, which is different from intent, does not influence performance, regardless of the controller used.
- Documented the "move and wait" strategy previously observed in communication time delay systems and showed that adding a ghost eliminates the need for this strategy (Chapter 5).
- Experimentally demonstrated that there is a crossover point in the system velocity limit where there is no statistical difference between operator performance with either controller. This crossover point appears to be dependent on the task (Chapter 5).
- Showed that for a dynamically slow system with a velocity output, rate control is better than acceleration control for a velocity tracking task; however, for a velocity matching task, acceleration control was better than rate control for the dynamically slow system. For a dynamically fast system, rate control had better performance for both tasks (Chapter 5).

This is, to the author's knowledge, the only human factors test in the literature where rate and acceleration control are used to control the velocity output for a system where the position is disregarded (i.e. others have used acceleration and rate control to control the velocity, but they were concerned with the system position as well as velocity).

- Demonstrated that the previously claimed intuitiveness of position control comes from the operators' failing to fully use the capabilities of the rate controller, i.e. the maximum speed. The results of the tracking task suggest that scaling the input velocity to fit the needed output range will improve performance.
- Designed a best fit controller that improved the performance with the position controller with the ghost for a dynamically slow system for the tracking and maze tasks, without degrading performance on the point-to-point tasks (Chapter 6).
- Enumerated the types of operator mistakes induced by position or rate control. The cost in terms of time and fuel of these mistakes was also recorded.
- Designed a practical implementation for a discrete haptic jump for low force haptic joysticks (Chapter 3). This method can be used for a wide variety of human-scale haptic interactions.
- Measured the fuel efficiency and time efficiency for the HMIs implemented on the excavator simulator. The ghost resulted in 23.5% more soil removed per unit time and 24.0% more soil removed per unit

fuel with the coordinated position controller. Demonstrated that coordinated position control results in novices increasing performance by 86% in terms of productivity and 19% in terms of fuel efficiency over joint rate control (Chapter 7). The novices with the coordinated position controller performed at the level of a single expert using joint rate control.

- Constructed an excavator simulator with dynamic models of the mechanical and hydraulic system and of the environmental interaction, including a rotating cab (Chapter 2).

Recommendations for Future Work

Immediate future work should include:

- Implementation of a 3D TV display on the excavator simulator to give better depth perception during teleoperation. The improvement of depth perception should help operators be able to more quickly dump the soil in the bins. Another test would allow for coaching more similar to the [Winck] study, which would allow for a better comparison between results with this study than was given in this document.
- Testing with the best fit controllers on the excavator simulator to find how well these controllers work on three dimensional machines rather than in planar tasks. Special notice should be given to the amount of control effort needed. Methods to remove high speed oscillations in the controller should be investigated to see if these oscillations can be eliminated and what the effect would be on control effort.

- Teleoperating a physical excavator, such as the excavator at Purdue that was modeled for this work, with the coordinated controllers tested on the excavator simulator. Tests could be done to verify the results from the simulator testing.
- Using the Phantom's force feedback capabilities to provide haptic feedback to the operator may increase productivity with the position controller. This hypothesis could be tested on the excavator simulator.
- Further testing could reduce the variance in the measurements. This would particularly useful for the test with large variances, such as the tracking task in Chapter 5 and the tests with the improved controllers in Chapter 6.

APPENDIX A

SYSTEM RESPONSES TO TEST FUNCTIONS

Responses of the Dynamic System

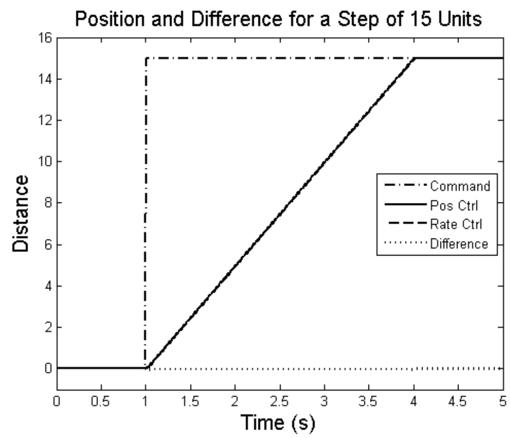

Fig. 73. Difference in dynamic position and rate controllers for a large step

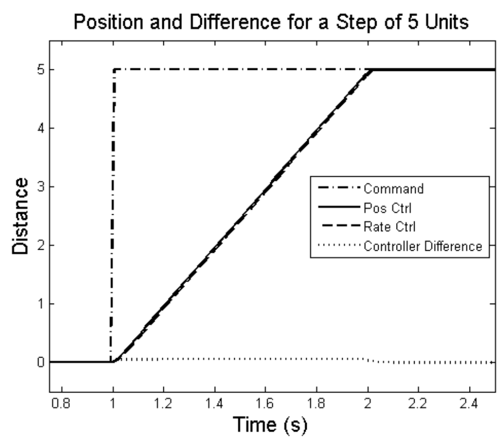

Fig. 74. Difference in dynamic position and rate controllers for a small step

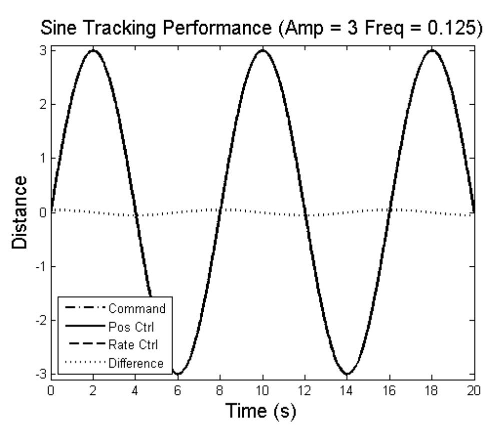

Fig. 75. Difference in dynamic position and rate controllers for a small amplitude low frequency sine

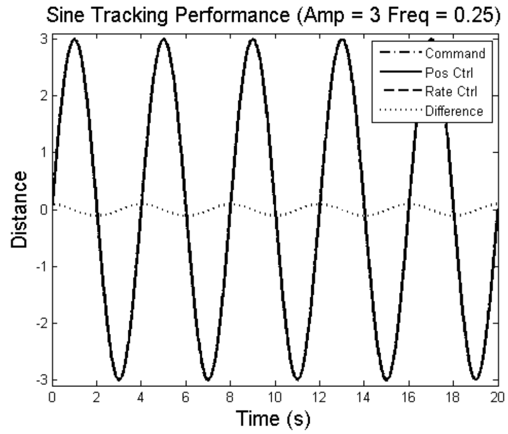

Fig. 76. Difference in dynamic position and rate controllers for a small amplitude high frequency sine

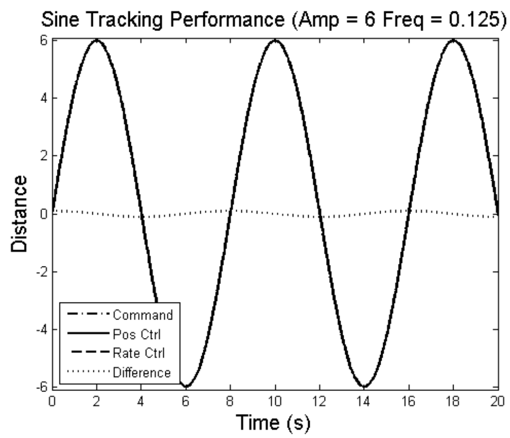

Fig. 77. Difference in dynamic position and rate controllers for a large amplitude high frequency sine

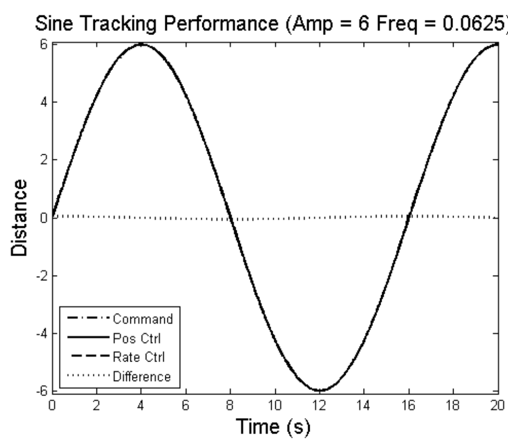

Fig. 78. Dynamic position and rate controllers response to a large amplitude low frequency sine

Responses of the Kinematic System

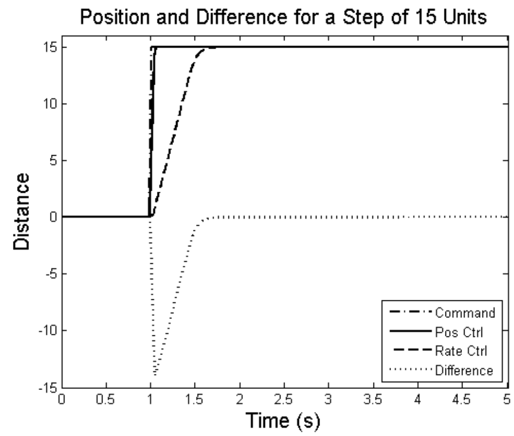

Fig. 79. Difference in kinematic position and rate controllers for a large step

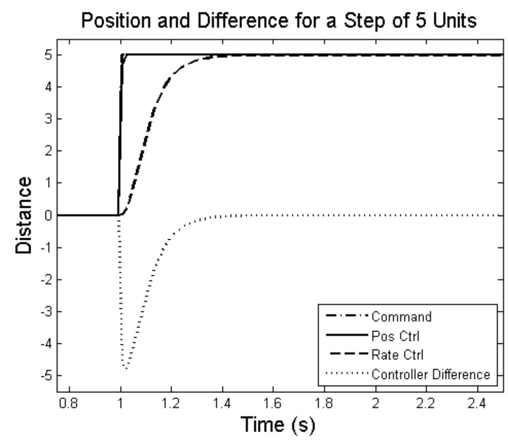

Fig. 80. Difference in kinematic position and rate controllers for a small step

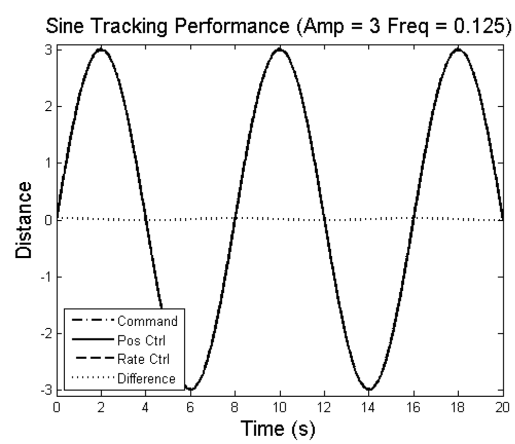

Fig. 81. Difference in kinematic position and rate controllers for a small amplitude low frequency sine

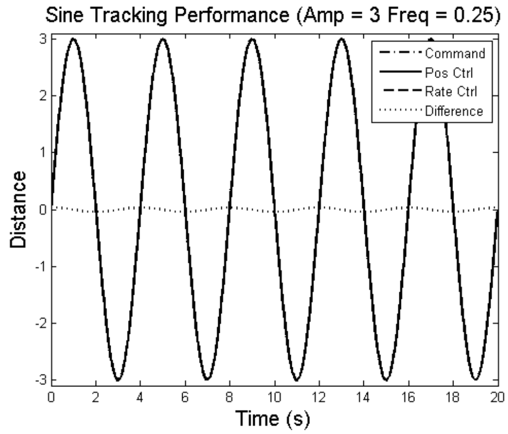

Fig. 82. Difference in kinematic position and rate controllers for a small amplitude high frequency sine

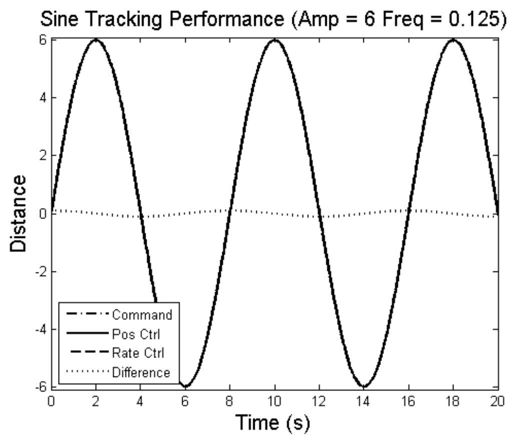

Fig. 83. Difference in kinematic position and rate controllers for a large amplitude high frequency sine

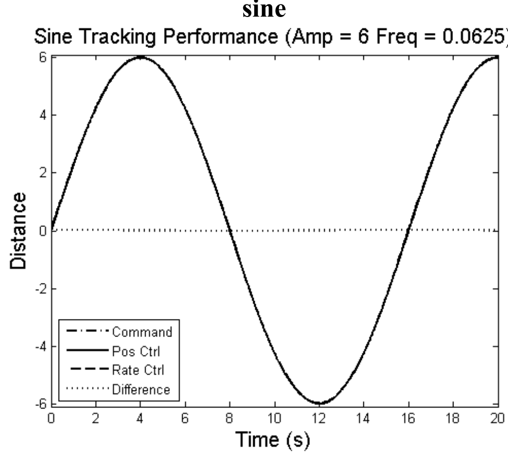

Fig. 84. Difference in dynamic position and rate controllers for a large amplitude low frequency sine

Excavator System Responses

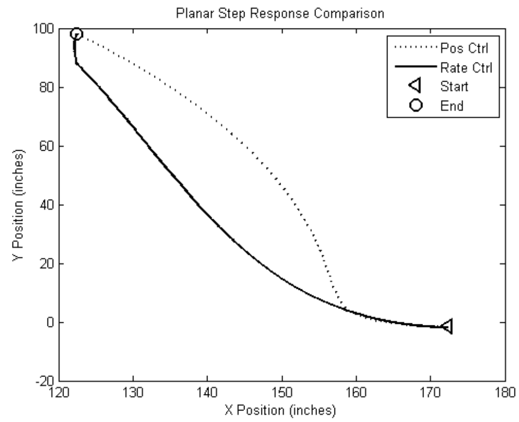

Fig. 85. Step response of the excavator with position and rate control. Note that the position and rate controllers take different paths.

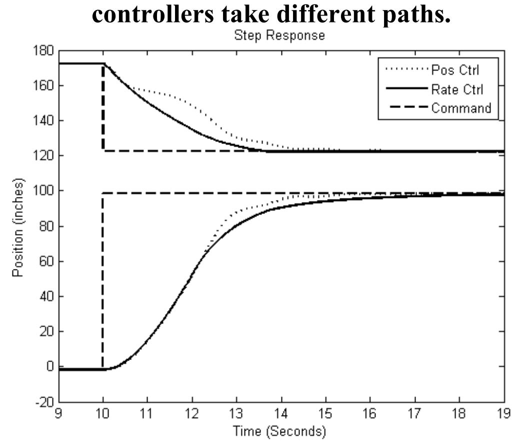

Fig. 86. Step response in Fig. 85 in x (top) and y (bottom) directions

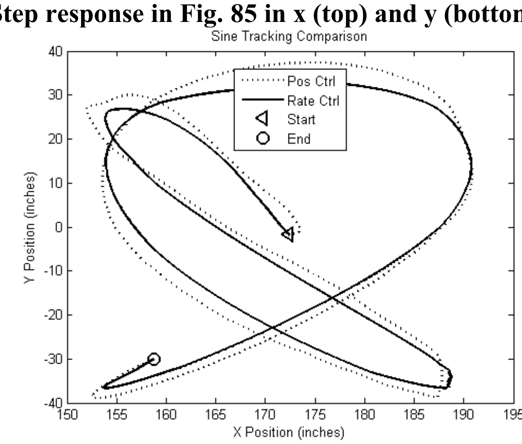

Fig. 87. Sine tracking response of the excavator with position and rate control

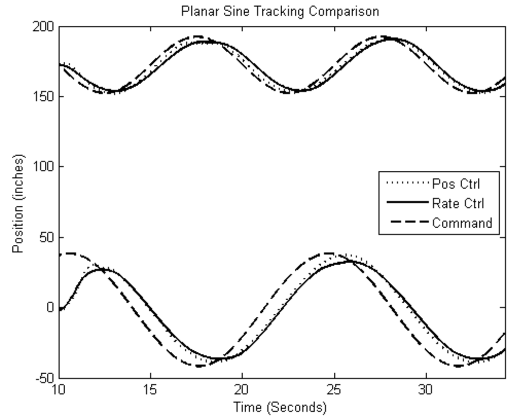

Fig. 88. Sine tracking response in Fig. 87 in the x (top) and y (bottom) directions

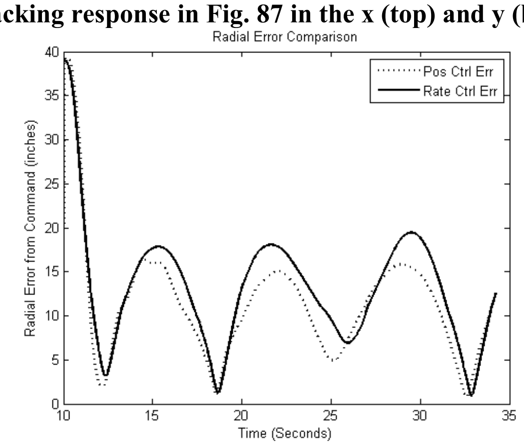

Fig. 89. Absolute sine tracking error for the position and rate controllers for the sine response in Fig. 87.

APPENDIX B

SUBJECT DEMOGRAPHIC INFORMATION

Subject Demographics for Position vs. Rate Planar Tasks

Thirty participants volunteered to do the planar tests for no compensation. The subjects were randomly assigned one of the five controllers so that there would be six subjects using each controller. The subjects filled out a questionnaire before the first session that asked them their age, gender, handedness, how often they used joysticks (with six options: daily, multiple times a week, weekly, monthly, less than monthly, and never), and how competent they felt they were at using joystick on a 5 point Likert scale. The subjects' affiliation with Georgia Institute of Technology was also noted. The subjects were predominately male, right-handed, college students with varying joystick usage and expertise (Table 5 - Table 8).

Table 5. Subjects' handedness and gender for position vs. rate tasks

Handedness	Number of Subjects
Right handed	27
Left handed	0
Ambidextrous	3

Gender	Number of Subjects
Male	20
Female	10

Table 6. Subjects frequency of joystick usage for position vs. rate tasks

Frequency of Joystick Usage	Number of Subjects
Daily	0
Multiple times a week	1
Weekly	4
Monthly	1
Less than monthly	11
Never	13

Table 7. Subjects' proficiency of joystick usage for position vs. rate tasks

Joystick Proficiency	Number of Subjects
1 (Least Proficient)	6
2	7
3	13
4	4
5 (Most proficient)	0

Table 8. Subjects' ages and affiliations with Georgia Tech for position vs. rate tasks

Age Bracket	# of Subjects
<20	1
21-25	9
26-30	15
31-35	2
51-55	1
56-60	2

Georgia Tech Affiliation	# of Subjects
Student	20
Staff	3
None	7

Subject Demographics for Rate vs. Acceleration Rotational Tasks

As with the position vs. rate planar tasks, thirty participants volunteered to complete the rate vs. acceleration rotational tasks for no compensation. None of the same subjects did both sets of tasks. The subjects were randomly assigned one of the five controllers so that there would be six subjects using each controller. As before with the position vs. rate planar tasks, the subjects were predominately male, right-handed, college students with varying joystick usage and expertise (Table 9 - Table 12).

Table 9. Subjects' handedness and gender for rate vs. acceleration tasks

Handedness	Number of Subjects
Right handed	28
Left handed	2
Ambidextrous	0

Gender	Number of Subjects
Male	24
Female	6

Table 10. Subjects frequency of joystick usage for rate vs. acceleration tasks

Frequency of Joystick Usage	Number of Subjects
Daily	0
Multiple times a week	3
Weekly	0
Monthly	7
Less than monthly	16
Never	4

Table 11. Subjects' proficiency of joystick usage for rate vs. acceleration tasks

Joystick Proficiency	Number of Subjects
1 (Least Proficient)	5
2	10
3	9
4	6
5 (Most proficient)	0

Table 12. Subjects' ages and Georgia Tech affiliations for rate vs. acceleration tasks

Age Bracket	# of Subjects
<20	0
21-25	15
26-30	11
31-35	2
36-40	2

Georgia Tech Affiliation	# of Subjects
Student	20
Staff	3
None	7

Subject Demographics for the Smoothing Controllers

Twenty-four participants volunteered to complete the rate vs. acceleration rotational tasks for no compensation. None of the same subjects participated in this test and the position vs. rate test. The subjects were randomly assigned one of the four smoothing controllers so that there would be six subjects using each controller.

Table 13. Subjects' handedness and gender for rate vs. acceleration tasks

Handedness	Number of Subjects
Right handed	23
Left handed	1
Ambidextrous	0

Gender	Number of Subjects
Male	22
Female	2

Table 14. Subjects frequency of joystick usage for rate vs. acceleration tasks

Frequency of Joystick Usage	Number of Subjects
Daily	4
Multiple times a week	2
Weekly	3
Monthly	1
Less than monthly	10
Never	4

Table 15. Subjects' proficiency of joystick usage for rate vs. acceleration tasks

Joystick Proficiency	Number of Subjects
1 (Least Proficient)	1
2	10
3	7
4	3
5 (Most proficient)	3

Table 16. Subjects' ages and Georgia Tech affiliations for rate vs. acceleration tasks

Age Bracket	# of Subjects
<20	1
21-25	7
26-30	12
31-35	2
36-40	1
56-60	1

Georgia Tech Affiliation	# of Subjects
Student	16
Staff	3
None	5

Demographics for the Coordinate Position vs. Joint Rate Control Test

Twenty-four novices and one expert volunteered to drive the excavator simulator with the Phantom and with the conventional joysticks. Each subject was compensated $20 for his/her one-hour participation. The expert was an ambidextrous, 33 year-old male who used joysticks less than monthly (he was no longer employed as an excavator operator). The demographics for the novices are tabulated below.

Table 17. Subjects' handedness and gender for excavator test

Handedness	Number of Subjects
Right handed	23
Left handed	1
Ambidextrous	0

Gender	Number of Subjects
Male	17
Female	7

Table 18. Subjects frequency of joystick usage for excavator test

Frequency of Joystick Usage	Number of Subjects
Daily	1
Multiple times a week	3
Weekly	0
Monthly	3
Less than monthly	10
Never	7

Table 19. Subjects' ages and affiliations with Georgia Tech for excavator test

Age Bracket	# of Subjects
21-25	14
26-30	10

Georgia Tech Affiliation	# of Subjects
Student	17
None	7

Demographics for the Coordinated Controller Test on the Excavator

Eighteen subjects agreed to drive the excavator simulator for two one hour sessions. The sessions were not held on the same day and no more than two workdays apart. Each subject was compensated $20 for his/her participation.

Table 20. Subjects' handedness and gender for excavator test

Handedness	Number of Subjects
Right handed	17
Left handed	1
Ambidextrous	0

Gender	Number of Subjects
Male	15
Female	3

Table 21. Subjects' frequency of joystick usage for excavator test

Frequency of Joystick Usage	Number of Subjects
Daily	2
Multiple times a week	1
Weekly	0
Monthly	2
Less than monthly	8
Never	5

Table 22. Subjects' ages and affiliations with Georgia Tech for excavator test

Age Bracket	# of Subjects
<20	1
21-25	11
26-30	4
31-35	1
55-60	1

Georgia Tech Affiliation	# of Subjects
Student	14
Staff	0
None	4

APPENDIX C

PLANAR TASK DEFINITIONS

Table 23. 1D point-to-point motion locations and on-target times

Location	Next step size	Required on-target time for current location
0	-11	2
-11	20	2.2211
9	5	3.3672
14	-26	3.5643
-12	15	2.5486
3	11	3.0977
14	-20	2.349
-6	-8	2.8964
-14	26	2.041
12	-15	3.7118
-3	2	2.747
-1	8	2.1377
7	-2	2.9377
5	-5	3.2738
0	--	3.0836

Table 24. 2D point-to-point motion step locations and on-target times

horizontal position	vertical position	step size	step ratio (horizontal: vertical)	step direction (towards which quadrant)	Required time on-target for current location
0	0	4	3	3	2
-3.79473	-1.26491	16	3	1	2.1472
11.3842	3.794733	9	1	2	2.1269
5.020239	10.15869	16	1/3	4	3.1537
10.07988	-5.02024	4	1/3	2	2.468
8.814972	-1.22551	9	1/3	2	2.9526
5.968922	7.312644	9	1/3	3	3.7632
3.122872	-1.22551	16	1	3	3.0186
-8.19084	-12.5392	4	1/3	1	3.8087
-6.92593	-8.74448	9	3	4	3.7183
1.612224	-11.5905	4	3	1	2.8597
5.406957	-10.3256	16	1/3	1	3.7776
10.4666	4.853313	16	3	2	2.8328
-4.71233	9.912958	16	1	4	3.9582
6.601377	-1.40075	9	1/3	1	3.5929
9.447427	7.137399	16	3	3	3.0758
-5.73151	2.077754	9	1	1	3.2413
0.632456	8.441715	9	1/3	4	2.3302
3.478505	-0.09643	4	3	2	2.5094
-0.31623	1.168477	4	1	2	3.9467
-3.14465	3.996904	16	1/3	3	2.0142
-8.2043	-11.182	9	3	1	3.9314
0.333851	-8.33598	4	1	1	2.6487
3.162278	-5.50755	9	3	3	3.7433
-5.37587	-8.3536	16	1	1	2.2579
5.937836	2.960107	9	3	2	3.3286
-2.60031	5.806157	16	3	4	2.4133
12.57862	0.746512	4	1/3	3	2.3219
11.31371	-3.04822	9	1	3	3.2217
4.949747	-9.41218	4	3	4	3.142
8.744481	-10.6771	16	1	2	3.6661
-2.56923	0.636616	4	1/3	4	2.4015
-1.30432	-3.15812	9	1	4	3.3745
5.059644	-9.52208	16	1/3	2	2.2953
0	5.656854	4	1	3	2.1225
-2.82843	2.828427	4	1	4	2.8476
0	0	--	--	--	3.5539

Table 25. Path segment descriptions for 1D tracking

Start position	Step size	Time	Path shape
0	0	3	line
0	-12	3.5925	line
-12	4	2.5136	log
-8	4	4.1181	line
-4	-8	2.0955	parabola
-12	12	2.8308	parabola
0	8	2.1385	log
8	-4	2.2914	line
4	-8	4.4704	log
-4	12	4.0845	log
8	-12	2.9513	parabola
-4	4	4.8507	parabola
0	-8	2.1033	line
-8	-4	3.3162	log
-12	8	3.1447	line
-4	12	4.2966	line
8	-4	2.7267	parabola
4	-12	4.7102	log
-8	8	2.6703	parabola
0	--	--	--

Table 26. Path segment descriptions for 2D tracking

horizontal position	vertical position	step size	step ratio (horizontal: vertical)	step direction (towards which quadrant)	path shape	time
0	0	0	0	--	line	2
0	0	4	3	3	log	4.6727
-3.79473	-1.26491	16	3	1	line	4.8779
11.3842	3.794733	9	1	2	line	3.6416
5.020239	10.15869	16	1/3	4	parabola	2.4159
10.07988	-5.02024	4	1/3	2	parabola	2.4479
8.814972	-1.22551	9	1/3	2	parabola	2.7725
5.968922	7.312644	9	1/3	3	line	4.5222
3.122872	-1.22551	16	1	3	log	2.7628
-8.19084	-12.5392	4	1/3	1	line	4.4429
-6.92593	-8.74448	9	3	4	log	2.7306
1.612224	-11.5905	4	3	1	log	4.7878
5.406957	-10.3256	16	1/3	1	log	3.05
10.4666	4.853313	16	3	2	line	2.5898
-4.71233	9.912958	16	1	4	parabola	2.7533
6.601377	-1.40075	9	1/3	1	parabola	3.8481
9.447427	7.137399	16	3	3	parabola	3.4199
-5.73151	2.077754	9	1	1	line	3.055
0.632456	8.441715	9	1/3	4	log	4.4925
3.478505	-0.09643	4	3	2	parabola	3.7558
-0.31623	1.168477	4	1	2	line	3.6492
-3.14465	3.996904	16	1/3	3	line	4.7516
-8.2043	-11.182	9	3	1	parabola	2.8575
0.333851	-8.33598	4	1	1	log	4.2716
3.162278	-5.50755	9	3	3	parabola	4.2612
-5.37587	-8.3536	16	1	1	log	3.1413
5.937836	2.960107	9	3	2	line	3.7035
-2.60031	5.806157	16	3	4	log	2.2276
12.57862	0.746512	4	1/3	3	parabola	2.1619
11.31371	-3.04822	9	1	3	log	3.5924
4.949747	-9.41218	4	3	4	line	4.3375
8.744481	-10.6771	16	1	2	line	4.802
-2.56923	0.636616	4	1/3	4	line	2.3897
-1.30432	-3.15812	9	1	4	log	3.7065
5.059644	-9.52208	16	1/3	2	parabola	3.4082
0	5.656854	4	1	3	log	2.0357
-2.82843	2.828427	4	1	4	parabola	3.0114
0	0	--	--	--	--	--

APPENDIX D

IMPROVED ALGORITHM TEST RESULTS

1D Point-to-Point Results

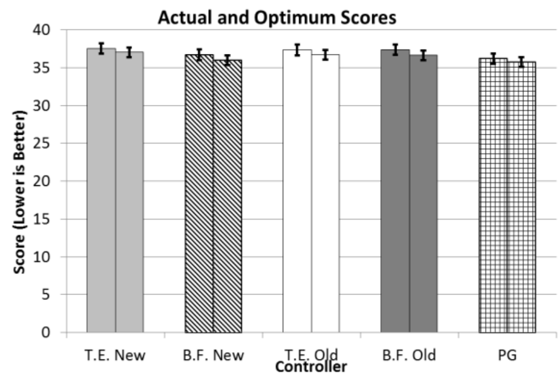

Fig. 90. Actual (left) and optimal (right) scores for the improved algorithms for the 1D point-to-point task

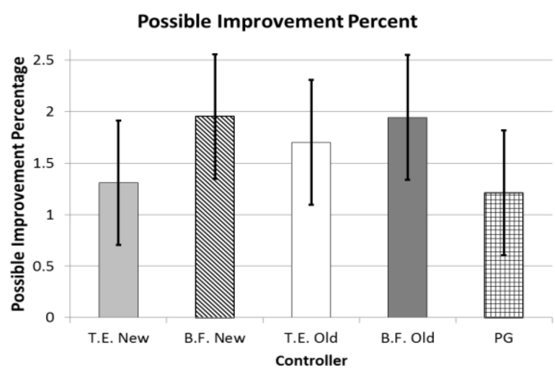

Fig. 91. Possible improvement for the smoothing controllers on the 1D point-to-point task

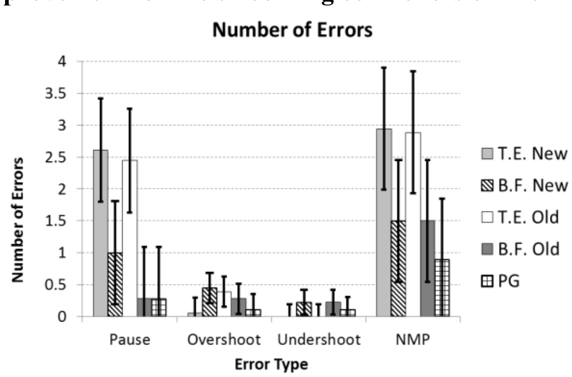

Fig. 92. Number of errors for the improved algorithms for the 1D point-to-point task

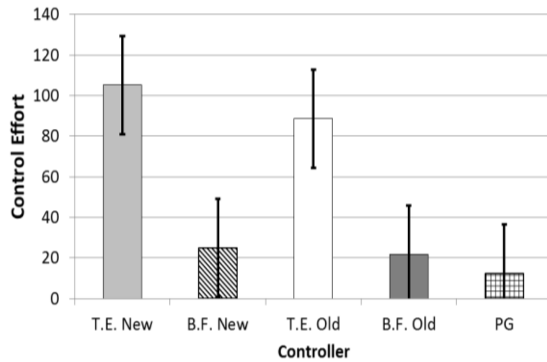

Fig. 93. Control effort for the improved algorithms for the 1D point-to-point task

2D Point-to-Point Results

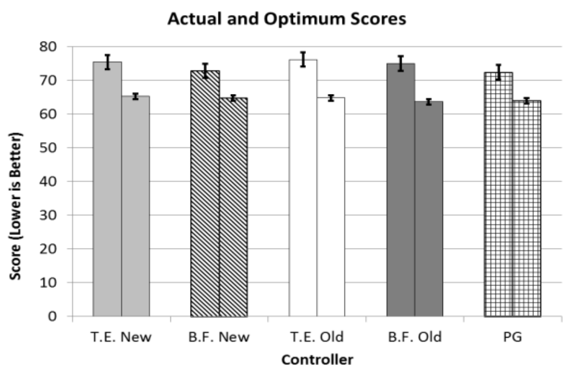

Fig. 94. Actual (left) and optimal (right) scores for the improved algorithms for the 2D point-to-point task

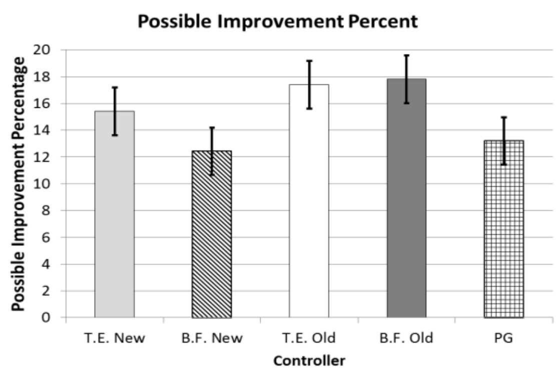

Fig. 95. Possible improvement for the smoothing controllers on the 2D point-to-point task

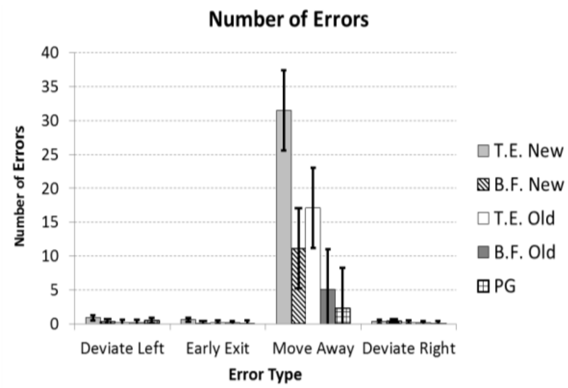

Fig. 96. Number of errors for the improved algorithms for the 2D point-to-point task

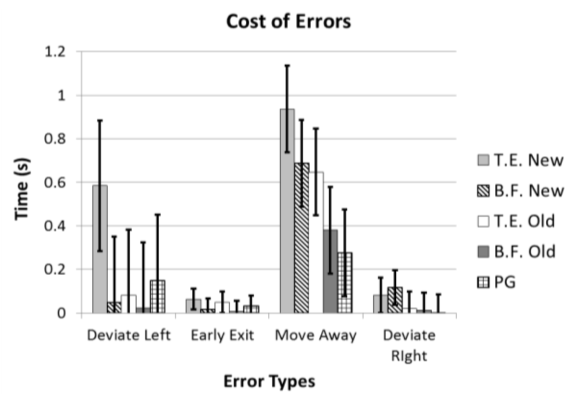

Fig. 97. Cost of the errors for the improved algorithms for the 2D point-to-point task

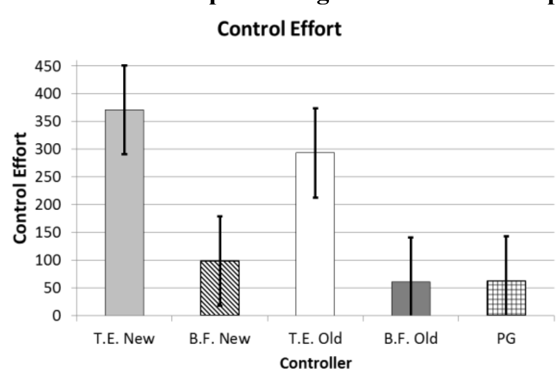

Fig. 98. Control effort for the improved algorithms for the 2D point-to-point task

Maze Task Results

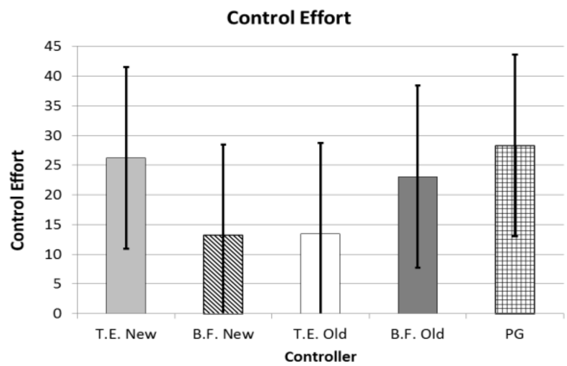

Fig. 99. Control effort for the improved controllers for the maze task

REFERENCES

Andreychek, T., “T-Rex – A Remotely Operated Excavator,” ANS Proc. of the Seventh Topical Meeting on Robotics and Remote Systems. Apr. 1997, pp. 201-208. Augusta, GA.

Birmingham, H.P., Taylor, F.V., "A Design Philosophy for Man-Machine Control Systems," Proceedings of the IRE, vol. 42, no.12, pp.1748-1758, Dec. 1954.

Bobcat Company, http://bobcat.com, January 22, 2009.

Bradley, D.A., Seward, D.W., "Developing real-time autonomous excavation-the LUCIE story," Proceedings of the 34th IEEE Conference on Decision and Control, vol.3, pp.3028-3033, 13-15 Dec 1995.

Bunte, T., Brembeck, J., Ho, L.M., "Human machine interface concept for interactive motion control of a highly maneuverable robotic vehicle," IEEE Intelligent Vehicles Symposium (IV), pp.1170-1175, 5-9 June 2011.

Chapanis, Alphonse. "The basics and the background." Consulting Engineer, vol. 32, no. 3, 1969, pp. 117-123.

Conway, L., Volz, R., Walker, M., "Tele-autonomous systems: Methods and architectures for intermingling autonomous and telerobotic technology," Proc. of 1987 IEEE International Conference on Robotics and Automation, vol.4, pp. 1121-1130, Mar 1987.

Corliss, W. R., Johnsen, E.G., *Teleoperator Controls: an AEC-NASA Technology Survey*, National Aeronautics and Space Administration, Washington D.C.,1968.

DiMaio (1998), S. P., Salcudean, S., Reboulet, C., Tafazoli, S., Hashtrudi-Zaad, K., “A virtual excavator for controller development and evaluation,” Proc. of the 1998 IEEE Intl. Conf. on Robotics and Automation, Leuven, Belgium, 1998, pp. 52–58.

DiMaio (2001), S. P., Salcudean, S., Reboulet, C., “A virtual environment for the simulation and programming of excavation trajectories.” Presence, vol. 10, no. 5, pp. 465-476. MIT Press, Cambridge, Massachusetts.

Dosher, J.A, Hannaford B., “Detection Thresholds for Small Haptic Effects.” SPIE Proceedings of Telemanipulator and Telepresence Technologies, vol. VIII, pg. 50, Feb. 7, 2002.

Dunbabin, M., Corke, P., “Autonomous excavation using a rope shovel,” Journal of Field Robotics, vol. 23, issue 6, Wiley & Sons, 2006.

Dusseault, C., “General Atomics aeronautical systems, Inc.: Remotely operated aircraft systems,” Proceedings of AUVSI's Unmanned Systems North America 2004, pp. 873-901

Elton (2009), M., “An Efficient Haptic Interface for a Variable Displacement Pump Controlled Excavator,” MS thesis, The Georgia Institute of Technology, G.W. Woodruff School of Mechanical Engineering, 2009.

Elton (2011a), M., Book, W., “An Excavator Simulator for Determining the Principles of Operator Efficiency for Hydraulic Multi-DOF Systems,” International Fluid Power Exposition. March 22-26, 2011, Las Vegas, NV.

Elton (2011b), M., W. Book, “Comparison of Human-Machine Interfaces Designed for Novices Teleoperating Multi-DOF Hydraulic Manipulators,” Proc. of IEEE RO-MAN. Aug. 1-3, 2011, Atlanta, GA.

Farkhatdinov, I., and Ryu., J., “Hybrid position-position and position-speed command strategy for the bilateral teleoperation of a mobile robot,” Intl. Conf. on Control, Automation and Systems, Oct 17-20 2007, Seoul, South Korea, pp. 2442-2447.
Fitts, P. M. “Human engineering for an effective air navigation and traffic control system.” Ohio State University Foundation Report, Columbus, OH, 1951.
Fu, K.S., Gonzalez, R.C., and Lee, C. S. G. “Robotics: Control, Sensing, Vision, and Intelligence.” McGraw-Hill, New York, New York, 1987.
Goertz (1952), R., “Fundamentals of General-Purpose Remote Manipulators,” Nucleonics, vol. 10, pp. 36-42, Nov. 1952.
Goertz (1954), R., Thompson, M., “Electronically Controlled Manipulator”, vol. 12, no. 11, Nov. 1954 pp. 46-47
Herrin, J., Sauer-Danfoss. Personal communication. March, 2011.
Hirabayashi, T., Akizono, J., Yamamoto, T., Sakai, H., Yano, H., “Teleoperation of construction machines with haptic information for underwater applications,” Automation in Construction, vol. 15, Issue 5, 21st International Symposium on Automation and Robotics in Construction, Sept. 2006, pp. 563-570.
James, H. M., Nichols, N. B., Phillips, R. S., "Theory of servo-mechanisms," Radiation Lab. Series No. 25, McGraw-Hill Book Co., Inc., New York, N. Y., pp. 360-368; 1947.
Jenkins, L., "Telerobotic work system-space robotics application," IEEE International Conference on Robotics and Automation, vol.3, pp. 804- 806, Apr 1986.
Johnsen, Edwin G, Corliss, William R., *Human Factors Applications In Teleoperator Design And Operation*. New York: Wiley-Interscience, 1971.
Jordan, N., “Allocation of functions between man and machines in automated systems,” Journal of Applied Psychology, 47, 161-165, 1963.
Kelley, Charles R., *Manual And Automatic Control: a Theory of Manual Control And Its Application to Manual And to Automatic Systems.* New York: Wiley, 1968.
Kim, W., Tendick, F., Ellis, S., Stark, L., “A Comparison of Position and Rate Control for Telemanipulations with Consideration of Manipulator System Dynamics,” IEEE Journal of Robotics and Automation, vol.3, no.5, pp. 426-436, Oct. 1987.
Koivo, A., “Fundamental for Control of Robotic Manipulators.” Wiley & Sons, New York, New York, 1989.
Kontz, M., “Haptic Control of Hydraulic Machinery Using Proportional Valves,” PhD thesis, The Georgia Institute of Technology, G.W. Woodruff School of Mechanical Engineering, 2007.
Kuo, B.C., Golnaraghi, F., ”Automatic Control Systems.” 2003, Wiley, Hoboken, NJ.
Lawrence P. D., Salcudean, S. E., Sepehri, N., Chan, D., Bachmann, S., Parker, N., Zhou, M., Frenette, R., “Coordinated and Force-Feedback Control of Hydraulic Excavators,” Proc. of the Intl. Symp. On Experimental Robotics IV, Stanford, CA, pp. 181–194, June 1995.
Lever, P.J.A., Wang, F., Chen D., "A fuzzy control system for an automated mining excavator," IEEE International Conference on Robotics and Automation, vol.4, pp.3284-3289, 8-13 May 1994.
Lin, Y., Zhang, W.J., "A function-behavior-state approach to designing human-machine interface for nuclear power plant operators," IEEE Transactions on Nuclear Science, vol.52, no.1, pp. 430- 439, Feb. 2005.

Malaguti (1994), F., "Soil machine interaction in digging and earthmoving automation," Intl. Symp. on Automation and Robotics in Construction, (Brighton, UK), pp. 187–191, May 1994.

Malaguti (1999), F., "Improved Model of soil for environment-robot excavator interaction". Proc. of the 16th IEEE Intl. Symp. on Automation and Robotics in Construction. Sept. 1999, Madrid, Spain. pp. 523-527.

Marshall, J.A., Murphy, P.F., Daneshmend, L.K., "Toward Autonomous Excavation of Fragmented Rock: Full-Scale Experiments," IEEE Transactions on Automation Science and Engineering, vol.5, no.3, pp.562-566, July 2008.

Massimino, M., Sheridan, T.B., Roseborough, J.B., "One handed tracking in six degrees of freedom," Proceedings of the IEEE Intl Conf. on Systems, Man and Cybernetics, pp. 498-503, vol.2, 14-17 Nov 1989.

Mora, A., Barrientos, A., "An experimental study about the effect of interactions among functional factors in performance of telemanipulation systems," Control Engineering Practice, vol. 15, Issue 1, January 2007, Pages 29-41.

Mullen, D., "An Evaluation of Resolved Motion Rate Control for Remote Manipulators." Charles Stark Draper Laboratory, 1973.

Murphy, R., "Human-robot interaction in the wild: Land, marine, and aerial robots at Fukushima and Sendai," plenary talk, IEEE RO-MAN, July 31-Aug. 3, 2011.

Niemeyer, G. and J. Slotine, "Stable Adaptive Teleoperation," American Control Conference, pp.1186-1191, 23-25 May 1990.

Noyes, M.V. "Superposition of Graphics on Low Bit Rate Video as an Aid in Teleoperation," M.I.T. Master's Thesis. 1982.

Oceaneering, http://www.oceaneering.com/rovs/rov-technologies/atlas-hybrid-manipulator/, May 15, 2012.

Ohno, K., Kawatsuma, S., Okada, T., Takeuchi, E., Higashi, K., Tadokoro, S., "Robotic control vehicle for measuring radiation in Fukushima Daiichi Nuclear Power Plant," IEEE Intl Symp on Safety, Security, and Rescue Robotics 2011, pp. 38-43, 1-5 Nov. 2011.

Osafo-Yeboah, B., Elton, M., Jiang, X., Book, W., Park, E., "Usability Evaluation of a Coordinated Excavator Controller with Haptic Feedback," 2010 Industrial Engineering Research Conference, Cancun, Mexico.

Parasuraman, R., Sheridan, T.B., Wickens, C.D., "A model for types and levels of human interaction with automation," IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans, vol.30, no.3, pp.286-297, May 2000.

Parker, J. F., West, V. R., eds. *Bioastronautics Data Book*, Second edition, NASA SP-3006, 1973.

Parker, N., Salcudean, S., Lawrence, P., "Application of Force Feedback to Heavy Duty Hydraulic Machines," Proc. of the Intl. Conf. on Robotics and Automation, Atlanta, GA, pp. 375–381, May 1993.

Poulton, E.C., Tracking Skill and Manual Control. New York Academic Press, 1974.

Reece, A., "Fundamental equation of earth-moving mechanics", Proc. of the Symp. on Earth-Moving Machinery, London, England, vol. 179, no. Part 3F, 1964, pp. 16-22

Sanders, M. S, McCormick, E. J., *Human Factors In Engineering And Design*. 7th ed. New York: McGraw-Hill, 1993.

Schuh, S., Personal communication, Bobcat Company, May 2009.

Sensable Technologies, http://sensable.com.
Sheridan (1978), T. B., Verplank, W. L., "Human and Computer Control of Undersea Teleoperators," Technical report for the Office of Naval Research, Work Unit Number NR196-152, 15 Mar 1977-14 Jun 1978.
Sheridan (1989), T.B., Telerobotics, Automatica, vol. 25, Issue 4, July 1989, Pages 487-507
Sheridan (1992), T. B.. Telerobotics, Automation and Human Supervisory Control. Cambridge, MA: MIT Press. 1992.
Sheridan (2000), T. B., "Function allocation: algorithm, alchemy or apostasy?", International Journal of Human-Computer Studies, vol. 52, Issue 2, February 2000, pp. 203-216.
Stentz, A., Bares, J., Singh, S., Rowe, P., "A Robotic Excavator for Autonomous Truck Loading," Proceedings of the 1998 IEEE Intl. Conference on Intelligent Robots and Systems Victoria, B.C., Canada, October 1998.
Tan, C., Zweiri, Y., Althoefer, K., Seneviratne, L.D., "Online soil parameter estimation for autonomous vehicles" Proc. of IEEE Intl. Conf. on Robotics and Automation, Sept. 2003, Taipei, Taiwan, pp. 121-126
Tustin, A., "The nature of the operator's response in manual control and its implications for controller design," Jour. IEE, vol. 94, pp. 190-202, 1947.
Wallersteiner, U., Lawrence, P., Saufer, B., "A Human Factors Evaluation of Two Different Machine Control Systems for Log Loaders," Ergonomics, Aug. 1993, pp. 927-934.
Wen-Hong, Z., Saculdean, S.E., & Zhu, M. (2004). Experiments with transparent teleoperation under position and rate control. *IEEE international conference on robotics & automation.* 1870–1875.
Wickens, C., *An Introduction to Human Factors Engineering*. Prentice Hall, Upper Saddle River, New Jersey, 1998.
Williamson, C., Power Management for Multi-Actuator Mobile Machines with Displacement Controlled Hydraulic Actuators, PhD thesis, Purdue University, 2010.
Wilt, D., Pieper, D., Frank, A., Glenn, G., "An Evaluation of Control Modes in High Gain Manipulator Systems," Mechanism and Machine Theory, vol. 12. pp. 373-386, 1977.
Winck, R., M. Elton, and W.J. Book, "Advanced hand controllers for hydraulic machines." Automation in Construction. (submitted).
Zhai (1993), S., Milgram, P., "Human Performance Evaluation of Manipulation Schemes in Virtual Environments," IEEE Virtual Reality Annual International Symp., pp.155-161, 18-22 Sept. 1993.
Zhai (1997), S., Senders, J., "Investigating Coordination in Multi-Degree of Freedom Control I: Time-On-Target Analysis of 6 DOF Tracking," Proc. of 41st Annual Meeting of the Human Factors and Ergonomics Society, Sept. 22-26, 1997, pp. 1249-1254.
Zhu, M., S. Salcudean, "Achieving Transparency for Teleoperator Systems under Position and Rate Control," Proc. of IEEE/RSJ International Conference on Intelligent Robots and Systems, vol.2, pp.7-12, Aug 1995.

Zimmerman, J., Williamson, C., Pelosi, M., Ivantysynova, M., “Energy consumption of an LS excavator hydraulic system,” Proc. of the ASME IMECE, v 4, pp. 117-126, Nov, 2008.