Operator Efficiency Improvements from Novel Human-Machine Interfaces

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State of the art human-machine interfaces for multi-DOF mobile hydraulic machines are non-intuitive and require long periods of training and experience for operators to perfect control of the machine. This paper explores using a novel human-machine interface to control a simulated 5-ton mini-excavator. After a brief discussion of the simulation and the tests performed, it reports on improvements in operator productivity and efficiency of the novel interface over the standard interface. A new measure of fuel efficiency in terms of fuel per task is explained, and the test results show that a more intuitive input device increases fuel efficiency.

Keywords: Excavator, Human-Machine Interface, Simulator, Fuel Efficiency

Introduction

Operators of mobile, multi-degree of freedom, hydraulic equipment commonly used in construction, forestry, agriculture, and mining must have hours of training and experience to truly become expert operators. Such multi-degree of freedom equipment has non-intuitive kinematics and dynamics. Industry studies show that even when an operator is truly experienced, he/she continually makes small errors because of the large cognitive demand during operation **Stephenson, D.** (2009). By using a more intuitive human machine interface (HMI) that does not require the operator to do the inverse kinematics, the number of operator errors can be reduced and operator effectiveness increased. A more intuitive HMI allows the operator to complete the same task in less time resulting in greater productivity and fuel efficiency. For example, coordinated control and other methods have already been applied to multi-DOF systems, fluid-powered and otherwise, and have been shown to increase operator control and efficiency **Johnson, D. W.; Lovell, G. H.; Murray, J.J.** (1997).

In order to truly test the efficiency of HMIs, the standard and new interfaces must be tested against one another on machines doing the same task in the same environment. Changing the controls on a real machine is time consuming and can be expensive. In order to bypass these difficulties, a simulator was constructed where the different HMIs could easily be switched in and out for testing purposes. Simulation also allows the environment to be standardized for all tests. The excavator simulator discussed in this paper is a pump controlled Bobcat mini-excavator constructed at Purdue. **Williamson, C.; Zimmerman, J.; Ivantysynova, M.** (2008).

To test the operator effectiveness and fuel efficiency of the two different HMIs, 25 subjects performed a trenching task with the simulated mini-excavator using each of the two input devices.

excavator simulator

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In order to standardize the testing procedure and allow for quick modifications to the machine, environment, and control algorithms, an excavator simulator was constructed. The machine of interest is a modified Bobcat 435 mini-excavator, a five ton machine that has been modified to be pump-controlled rather than the standard, valve-controlled. It is one of the integrated test beds of the Center for Compact and Efficient Fluid Power (CCEFP).

Fig. 1: The pump-controlled Bobcat 435 excavator modelled in simulation

Simulation Software

A full dynamic model of the excavator's hydraulic and mechanical systems was constructed in Simulink and runs in real time at 1 kHz on an xPC target. A new soil interaction model was developed that calculated the soil-bucket interaction forces for any trajectory through the soil. A full description of the dynamic model and soil interaction model can be found in **Elton, M.** (2009). The xPC target was networked to another computer that displayed the simulated arm to the operator. The graphics program displays a 1080x1920 image that refreshes at 60 Hz. The program also plays continuous engine noise that varies in volume proportional to the power demand of the pumps.

Fig. 2: Screenshot from excavator simulator

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. Two speakers mounted behind the seat play the engine noise.

The original excavator was equipped with hydraulic joysticks. These were removed and electronic joysticks (Sauer-Danfoss model JS6000) were mounted on improvised supports near the location of the hydraulic joysticks. The electronic joysticks provided the first way to control the simulated excavator.

Fig. 3: Phantom and right hand joystick mounted and in use in the operator workstation

A Phantom Premium 1.0 (or simply, Phantom) was the second device used to control the simulated excavator. The Phantom model used here is a commercially available 6-DOF device with three degrees of force feedback. The Phantom linkage and excavator linkage are similar, except where the excavator has only one degree of freedom at its wrist (the bucket curl) the Phantom has three. Two of these three degrees of freedom were not used to control the simulator. As the Phantom moves about in space, commands are given to the excavator pumps so that the excavator wrist tracks the position commanded by the position of the Phantom wrist using a PID loop. The curl of the bucket is controlled by rotating the handle connected to the Phantom's wrist.

The Phantom is mounted on the right side of the cab on a tray that is welded to the wall of the cab. Although the Phantom configuration resembles an excavator, the Phantom is mounted facing towards the operator so that it does not interfere with the operators arm. Despite the kinematic similarities, the excavator mimics the motions of the operator's arm and not the Phantom's arm. Hence, as the operator moves his hand away from himself, the excavator arm extends. If he brings his hand in, the excavator arm comes in, if he moves his hand left, the excavator moves left, etc. Also, as he curls his wrist (which rotates the handle) the bucket curls, and as he uncurls his wrists, the bucket does the same.

Test Subjects and Procedure

A 25 subject test was conducted to compare the two interfaces. After filling out a brief survey to gather demographic information, the subjects began the test. They were told that their main objective was to remove as much soil as possible from the trench during each two-minute run. They were also instructed that they had the secondary goals of (1) dumping each pile of soil as closely together as possible and (2) entering the trench as cleanly as possible without clipping the sides of the trench. Each subject was given five minutes to warm up with the first interface (the order the subjects used each interface was reversed for each subject). Then they excavated as much soil as possible during 5 two-minute runs. The process was then repeated using the second interface. After they completed excavation, the subjects filled out a survey on how they perceived each controller. The average age for subjects was 25 and ranged from 21 to 33. There were 18 males and 7 females. One operator had 10 years of experience and the rest were novices. Twenty-four of the 25 subjects were right-handed.

Results

There is no standard or single way to measure operator effectiveness. Several measures were taken that have bearing on how well the operator was able to perform the assigned tasks. Depending on the task, certain measures may be more relevant than others.

Achieving Stated Goals

Some of the more obvious ways to evaluate performance are to measure how well operators reached their goals. The main objective was to remove as much soil as possible from the trench. All of the subjects, including the expert operator (subject 12), were able remove more soil with the Phantom than with the joysticks. The average for all subjects for the Phantom was 1.57 cubic yards, or about 10.2 full buckets. The average for the joysticks was 0.867 cubic yards, or about 5.62 full buckets. A small trenching bucket was used and the simulation limited the maximum amount of soil in the bucket to 0.154 cubic yards.

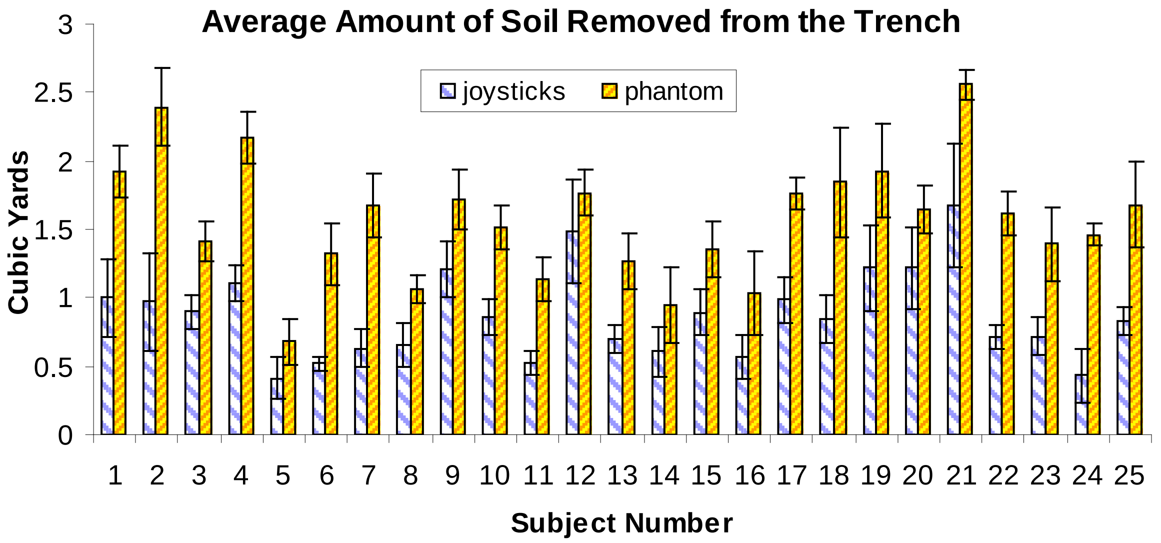

Fig. 4: Average amount of soil removed by each subject using the joystick and Phantom interfaces

Five minutes of practice clearly did not give operators enough time to master either input device. A best fit line was run through each subject’s data to give a feel for how much the operators were continuing to learn as the test progressed. For the joysticks, the average slope of the line was 0.403 cu. yds./trial, meaning that on average, the operators were removing 2.6 more full bucket loads of soil in the fifth run than in the first. The slope for each of the 25 subjects was positive, meaning that all of the subjects improved over time. For the Phantom, the average slope was 0.037 cu. yds/trial, so on average, the operators were removing 1.2 more full buckets of soil in the fifth run than the first. Also, only 15 subjects had positive slopes, meaning that 1/3 of the operators did not improve

with time. The order that the subjects used the Phantom and the joysticks was reversed for each subject. The odd numbered subjects (those that used the Phantom first) outperformed their even numbered counterparts by 8.0% with the joysticks and by 0.7% with the Phantom.
One of the secondary goals given to the operators was to dump all the soil removed from the trench in the same location. Eighteen of the subjects had a lower standard deviation of pile locations with the Phantom, including the expert operator (subject 12). Overall the average standard deviation of the piles for the Phantom was 10.1 inches and 13.0 inches for the joysticks.

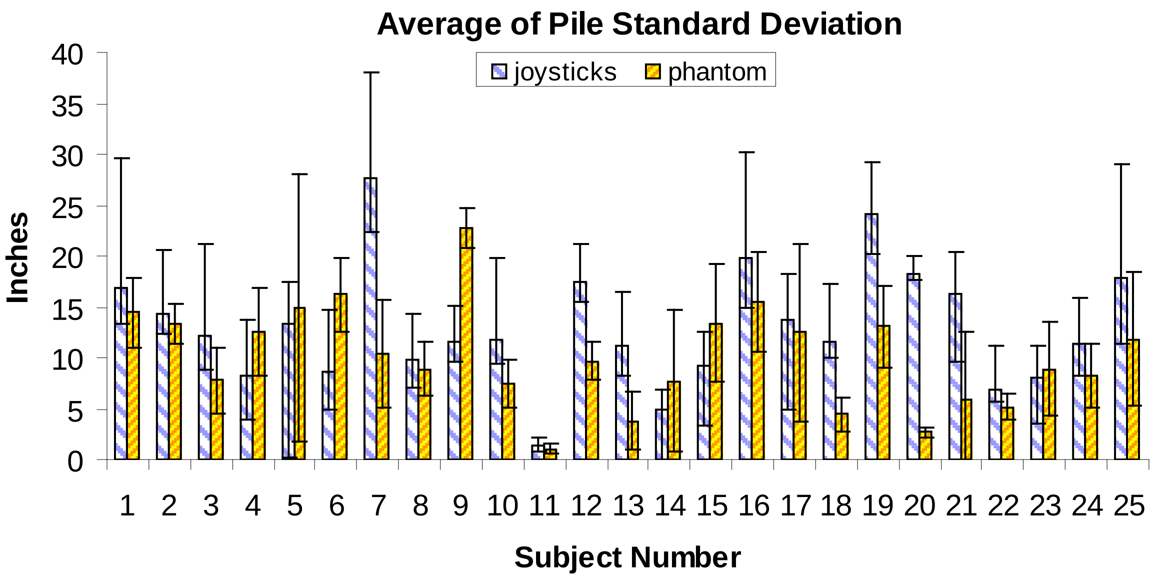

Fig. 5: Average standard deviation of the spoil piles for each subject using the joystick and Phantom interfaces

Fuel Efficiency vs. Task Efficiency

When measuring fuel efficiency of a machine, the machine is run on a standardized cycle. For example, a car is driven through the standardized city and highway drive cycles to determine its fuel efficiency. Automobiles' primary task is to carry people from one point to another. To measure how well an automobile performs this task in terms of fuel consumption, a typical human input is given to the vehicle and the amount of fuel consumed is measured. Fuel efficiency therefore is a measure of how much fuel a vehicle uses to complete its task, or in other words, its task efficiency. In other contexts, the connection between fuel efficiency and task efficiency is not 1:1.
Mobile hydraulic equipment tasks vary greatly. As with automobiles, the actual efficiency is dependent on the operator. Just like automobiles, a valid way to determine the fuel efficiency of a piece of equipment is to give the machine a typical human input and measure how much fuel is consumed. For mobile hydraulic machinery, fuel efficiency is often presented to the consumer in terms of amount of fuel per time. This is valid if there is a strong correlation between time on each machine and amount of the task completed. This is generally true, in that despite the make of the machine, and operator completes the task in the same amount of time (i.e. it takes the same time to complete a benching task using a twenty-ton excavator from Manufacturer A as using a twenty-ton machine from Manufacturer B).
However, if task completion time varies widely from one machine to another, then this view of fuel efficiency is deceptive. If the operator interface allows the operator to complete the same job in less time but by burning more fuel per hour, then the amount of fuel per hour no longer reflects the critical measure of amount of fuel required per task. For example, if a new interface allows the operator to complete the same task in 25% of the time required using the standard interface, but also burns fuel twice as fast, then task efficiency has doubled even though fuel efficiency (in terms of

fuel per time) is halved. Task efficiency determines how much fuel is consumed on the job, not fuel efficiency.

With this view in mind, task efficiency measurements are more important than fuel efficiency measurements. Fuel efficiency was designed as a way to measure task efficiency – if you knew how long a task would take on the jobsite and knew the fuel efficiency of the machine being used, then you could calculate the task efficiency in terms of fuel used to complete the task. If the time to complete the task varied with machine, a true task efficiency calculation would need to be done. For the experiment discussed here, the task efficiency was measured in terms of soil removed per unit of energy. The amount of soil removed per unit fuel would be a better measure, but the excavator simulator does not currently have a model of the engine. Instead the power output of the pumps was recorded and used. Task efficiency information is also often given to consumers in terms of ton of soil per liter of fuel. There does not exist a standardized cycle for excavators, and so each manufacturer tends to give the best results of the best operators. There is no combined measure that combines task efficiency with task time, which would be a way to measure operator effectiveness.

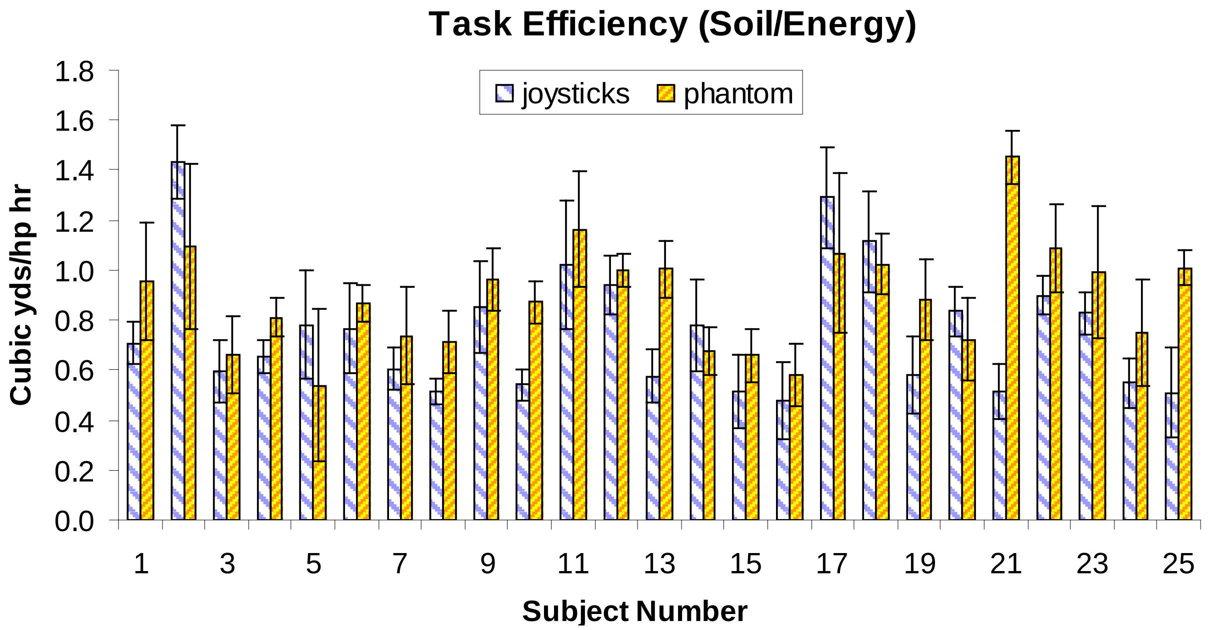

Fig. 6: Task efficiency for all 25 subjects using both the joystick and Phantom interfaces

Nineteen of the subjects, including the expert operator, were more task efficient with the Phantom. The average standard deviation for the joysticks was 0.161 cu. yds./hp hr while the standard deviation for the phantom was 0.135 cu. yds./hp hr, showing that operator performance was more consistent with the Phantom.

Overall Performance

To better examine improvements in operator effectiveness, several variables were recorded. Some of these variables are better high, some are better the lower they are, and some of them are important only when compared with others.

The number of piles dumped (the number of times the operator scooped soil into the bucket and then dumped it) was 69% greater with the Phantom. The load size, or the amount of soil loaded into the bucket on each cycle was 6% greater with the Phantom. The number of excavator functions (swing, boom, arm, bucket) being used at over 10% of the maximum, was 224% greater with the Phantom. The standard deviation in pile location was 23% less (better) with the Phantom. As mentioned, all the subjects removed more soil with the Phantom than with the joysticks – on average 81% more. And the operators removed 81% more soil using 42% more energy, resulting in an 18% increase in task efficiency. The number of piles accidentally dropped back into the trench varied widely, and 11% less were dropped when the joysticks were used.

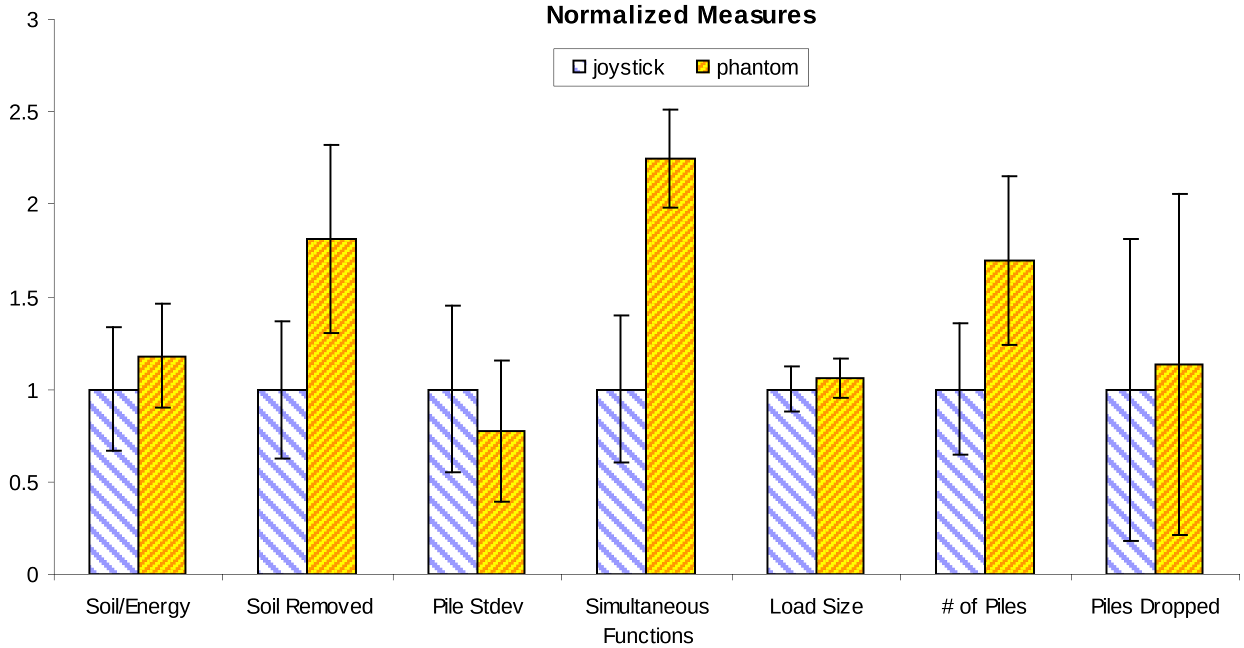

Fig. 7: Measurements comparing the standard joystick interface to the Phantom. All measurements have been normalized using the joystick performance.

Operator Survey

The survey given to the subjects afterwards asked the subjects to rate which of the controllers better aligned with each of the following statements: easier to learn, gave more accurate bucket control, faster to dig with, easier to use, more comfortable, and their personal preference.

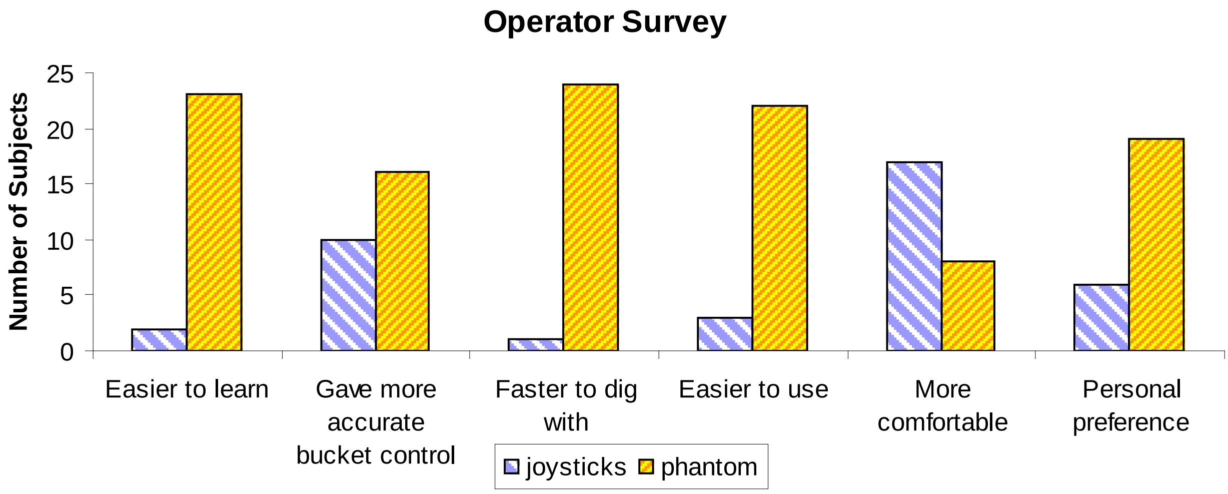

Fig. 8: Number of subjects that selected the interface that better agreed with the statement beneath

The operators were also asked to state why they selected each interface for their choices in the survey. They repeatedly noted that the Phantom interface was more intuitive and required less focus or thinking to operate. They also noted that they were never confused on which way to move the Phantom, whereas with the joysticks, many said that they often weren't sure which joystick or which direction on a specific joystick to move. Several noted that the Phantom was too sensitive to small motions and felt that the joysticks gave them better control. Almost all noted that the joysticks gave them the ability to hold the excavator arm still. Most found the joysticks more comfortable, although some preferred that they could operate the Phantom with one hand and that it wasn't as stiff as the joysticks.

Conclusion

More intuitive operator interfaces can improve the fuel efficiency, or better said, task efficiency, of mobile hydraulic equipment. In a 25-subject test using an excavator simulator, operators removed 81% more soil using 42% more energy. This results in an 18% increase in task efficiency using the exact same machine. This far exceeds current expectations of fuel efficiency increases by redesigning pumps, motors, or control systems to be more efficient. Future work should include determining what the underlying laws are for the design of human-machine interfaces. Further testing should be preformed, especially with experienced operators and on actual excavators. Before industrial implementation, costs should be evaluated and safety measures designed and implemented.

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