Operator Interface Design Principles for Hydraulics
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Abstract

The goal of this research is to make human operated hydraulic equipment safer, more efficient, and easier to use. This is achieved by optimizing the communication channels between operator and machine. The focus of this research is aimed at delivering a superior operator interface for hydraulic excavators, but the lessons learned will hopefully apply the wider range of hydraulic machinery currently in operation. Numerous tests have been performed on an excavator simulator in attempt to quantify the affects that user interface and control schema have on operator performance. New control configurations have shown substantial improvements in both soil excavated per unit time (85.6% improvement) and in soil excavated per unit fuel (18.6% improvement). A current focus of further research is on investigating and identifying the primary causes and modes for these improvements.

Introduction

High power hydraulic equipment is used for many tasks in construction, forestry, agriculture and other industries. Machine efficiency and effectiveness is dictated by operator skill level, with experienced operators significantly outperforming novices. To reach an expert skill level with the existing traditional user interface, operators have to overcome a slow learning curve and log many hours on a particular machine. There is a possibility that a better user interface exists, one that will reduce the learning curve associated with hydraulic equipment and ultimately make excavators and similar machines safer, easier to use, and more efficient. This research attempts to find such an interface, and uncover any underlying principles that can be used to design better interfaces in the future.

There have been previous efforts directed towards optimizing the interface between operator and machine. Kotz, Frankel, Enes, Elton & Winck explored coordinated control, a strategy that modifies the communication channels between human and machine, allowing operators to disregard the constraints of a system while providing higher-level commands. In the case of a hydraulic excavator, coordinated control allows the operator to command the end effector with inputs such as up, down, left, and right rather than manipulate each mechanical joint individually (as is done traditionally). Elton addressed whether coordinated control of rate or position is better suited for excavator operation [1]. Elton implemented both a coordinated rate controller (CRC) and a coordinated position controller (CPC) using an Omni Phantom (six degree of freedom joystick), and tested each interface during a human subject experiment. The experiment concluded that CRC was better suited for the excavator due to the slow dynamics of the excavator system (compared to the relatively fast dynamics of the joystick system). Winck implemented and tested the CPC with a joystick that was kinematically similar to an excavator arm [2]. The joystick consisted of two links whose length ratio matched the arm:boom length ratio on Winck’s excavator. The joystick was mounted in the excavator cab with identical orientation as the excavator arm. The joystick controlled the arm and boom in a master / slave configuration. Winck’s interface outperformed traditional control but suffered from fatigue.
issues. Winck tried to alleviate the fatigue concerns by rotating the kinematically similar joystick on its side. This rotated joystick allowed the operator to use the armrest to support the human arm weight. Over the course of longer runs, it did not display the same decrease in performance that the non-rotated version did.

**Theory**

Previous work has shown that coordinated control of an excavator is potentially an easier to use and more efficient alternative to traditional excavator control. However, the controllers and user interfaces tested required specialized hardware. This new hardware, in addition to being unnecessarily fatiguing to operators, presents a major roadblock to system adoption as current excavator manufactures are worried about alienating their existing customers and operators. If CRC could be implemented with only minor adjustments to traditional hardware, it would be feasible for a system to allow the operator to toggle between traditional control and the CRC based on preference. Such a system would allow excavator manufactures to offer a better user interface without alienating people already familiar and comfortable with their systems. This is the inspiration behind the user interface that was most recently implemented and tested: CRC with traditional joysticks. CRC with traditional joysticks should theoretically match the performance benefits shown with previous coordinated controllers while maintaining most of the traditional control hardware.

**Methods**

A 50-person experiment was performed on the Georgia Tech Excavator Simulator to validate the performance of CRC with traditional joysticks. Experiment participants used both TC and CRC to perform a trenching task. Their performance was recorded and graded based on several metrics. The subject pool consisted of students with little or no previous excavator experience. These subjects, not familiar with either UI, offered no experience based bias.

Participants operated the excavator simulator for three 30 minute sessions over the course of three days. Each session consisted of four 5-minute trials. The first trial was a training session with the results discarded. The training trial was designed to familiarize participants with the simulator, and the experiment overseer was present to answer any questions from participants. Each trial was followed by a 1-minute break during which the operators had time to relax while the excavator returned to its starting position and the soil model reset. Participants completed an introductory survey before their first session and subsequent surveys after each session.

For each session, participants were instructed to remove soil from a trench and dump it into one of two bins. Participants were told to remove as much soil as possible in the allotted time while maintaining control of the excavator and not driving recklessly. Participants were scored based on how much soil they were able to successfully dump into both bins, and how much fuel they consumed while doing so.

Subjects were randomly placed into two user interface groups. One group used the joystick CRC UI during the first two sessions before switching to the traditional UI. The other group used the traditional UI during the first two sessions before switching to the joystick CRC UI.
Results and Discussion

The exit survey for the experiment asked subjects, “How confident are you of your ability to operate this excavator simulator?” for each user interface. Twenty-six subjects (57%) said they had higher confidence operating the simulator with the joystick CRC UI, fourteen subjects (30%) rated each UI equally, and six subjects (13%) said they had higher confidence operating the simulator with the TC UI. While participants were more confident in their ability to operate the excavator with the joystick CRC UI, this did not translate to any measurable performance indicator.

When looking at a time efficiency comparison between control styles across the entire experiment (below), we can see that the average values (on the left) for soil removed per unit time are statistically equivalent.

![Time Efficiency UI Comparison](image)

This graph indicates several other interesting phenomena. The learning curve displayed by operators over the course of the experiment is steady. As for the effect of switching controllers on operators, the plot shows that it is less harmful to time efficiency when switching from the TC UI to the joystick CRC UI than vice versa. Note that the decrease in performance between trials 6 and 7 results from this interface switch.

Conclusion

The experiment comparing the joystick CRC UI to the traditional UI proved that coordinated control is not the only determining factor in interface performance. Other factors drive the performance increase seen in Elton and Winck’s work. Future research will be aimed at determining these factors and isolating why CPC of the excavator with the kinematically similar joystick and the Omni Phantom outperformed traditional control by such a wide margin.
This experiment also revealed a potential shortcoming in the metrics used to capture operator performance. There was no explanation for the disproportionate amount of people who favored the joystick CRC UI. Perhaps the reason so many people preferred the joystick CRC UI but did not perform better with it was because the traditional UI was easier to control quickly. Perhaps the traditional UI caused operators to perform more recklessly, and while they might dislike the feeling, they did not perform any worse. If this were the case, tracking the contact and collisions between excavator and environment and penalizing operators for any excessively quick or jerky maneuvers would be a realistic way to normalize for this effect.

At the end of the experiment, participants had driven the excavator for one hour. Expert excavator operators will log many more hours on a live machine. The chart(s) shown here illustrates only the beginning of the interface learning curve. Understanding the beginning of the learning curve is valuable and applicable to situations where the operator is not an expert, such as the rental equipment market. The beginning of curve can also be used to weakly extrapolate what the end of the curve looks like. However, to understand the effects that the user interface has on long-term operators, an experiment will need to be performed chronicling a much longer test period.

References