TOUCHSCREEN INTERFACES FOR MACHINE CONTROL AND EDUCATION

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TOUCHSCREEN INTERFACES FOR MACHINE CONTROL AND EDUCATION

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SUMMARY

The touchscreen user interface is an inherently dynamic device that is becoming ubiquitous. The touchscreen's ability to adapt to the user's needs makes it superior to more traditional haptic devices in many ways. Most touchscreen devices come with a very large array of sensors already included in the package. This gives engineers the means to develop human-machine interfaces that are very intuitive to use. This thesis presents research that was done to develop a best touchscreen interface for driving an industrial crane for novice users. To generalize the research, testing also determined how touchscreen interfaces compare to the traditional joystick in highly dynamic tracking situations using a manual tracking experiment.

Three separate operator studies were conducted to investigate touchscreen control of cranes. The data indicates that the touchscreen interfaces are superior to the traditional push-button control pendent and that the layout and function of the graphical user interface on the touchscreen plays a roll in the performance of the human operators.

The touchscreen interface also adds great promise for allowing users to navigate through interactive textbooks. Therefore, this thesis also presents developments directed at creating the next generation of engineering textbooks. Nine widgets were developed for an interactive mechanical design textbook that is meant to be delivered via tablet computers. Those widgets help students improve their technical writing abilities, introduce them to tools they can use in product development, as well as give them knowledge in how some dynamical systems behave. In addition two touchscreen applications were developed to aid the judging of a mechanical design competition.

Chapter I

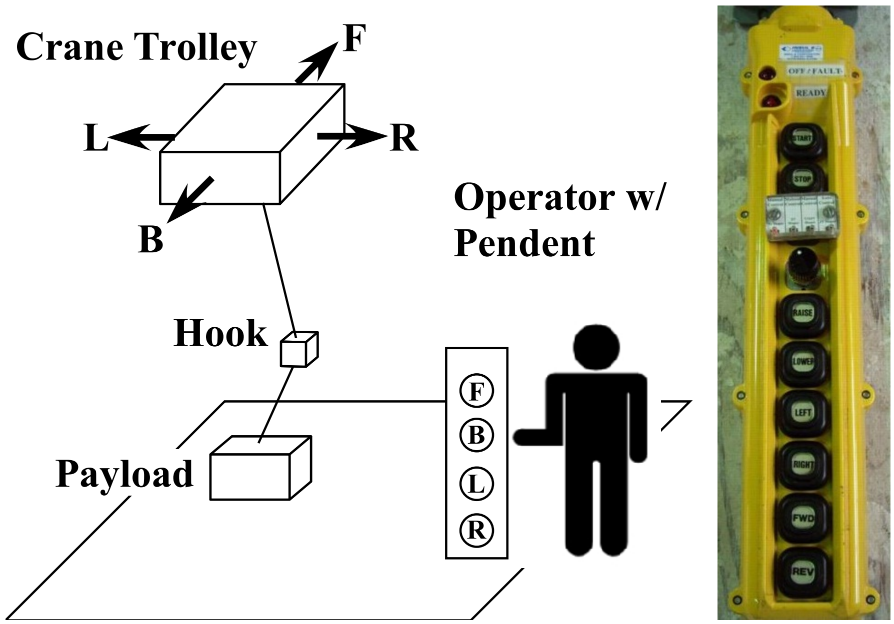
INTRODUCTION

After the introduction of the iPhone in 2007, followed by the iPad in 2010, small touchscreen devices became ubiquitous. Those devices were very capable for their size and packed a large array of sensors in a small package. People have begun to use those devices in many areas but not much work has been done so far to bring these devices to industry and to education. Two very important uses of controllers in those fields are crane control and textbooks. Manual tracking helps to determine how well the touchscreen controllers can be used in general dynamic situations.

1.1 Crane Control

Cranes perform vital roles in shipyards, warehouses, construction sites, material-handling facilities, and manufacturing plants. The effectiveness of the human crane operator has a large impact on the safety of the workplace and productivity of the company. One of the main characteristics that makes cranes hard to control is that their payloads tend to oscillate like a pendulum [1,7,19,33], a double pendulum [43,47] or even to display bouncing dynamics [56].

In addition to the complicated dynamics of the crane, operators must master the control interface. Figure 1 illustrates pendent control of a typical overhead crane. The payload is attached to the hook by rigging cables, forming a double-pendulum system. The operator must convert the desired payload path into a sequence of button presses that produce satisfactory crane movements. For example, if the operator wants to drive the crane through a cluttered workspace, then the desired path must be mapped into a sequence of events where the “Forward (F)”, “Backward (B)”, “Left (L)”, and



(a) Schematic

(b) Push-Button Pendent

Fig 1: Crane Control Using a Push-Button Pendent

“Right (R)” buttons are pushed at the correct times. In addition, the operators may move through the workspace to monitor the payload, which often causes the operators to change the direction they are facing. These rotations cause the “Forward" button on the control pendent to move the crane in a direction that is not in the operator’s forward direction. It has been proven that requiring such analytic problem solving during machine operation results in more errors [4, 38]. In a study described in [40], it was determined that the location and layout of controls is extremely important for successful operation of an overhead crane in a heavy engineering factory. The actual types and grouping of the controls had an important role in making the operator’s job simpler and also in making operation safer.

The basic requirements for a crane controller are shown in Figure 2. The controller must have a user interface through with the operator gives input. The interface can also include feedback. In this thesis the goal is not to try to emulate all of the features

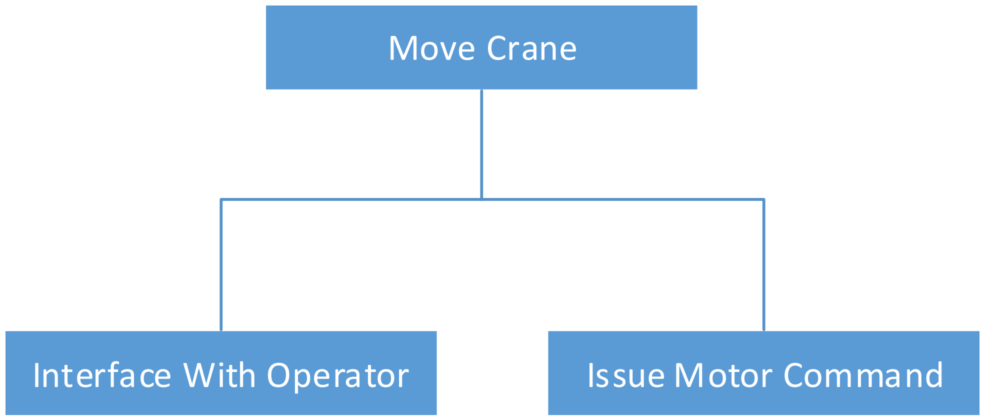


Fig 2: Function tree for a crane controller

found in traditional crane controllers, such as tactile feedback. The goal is to determine which interfaces on the touchscreen devices work best for crane operators and how they compare to the industry standards. The other important function of a crane controller is the ability to translate user commands to electrical signals that drive the crane's motors. The motor commands typically go through a Programmable logic controller (PLC). This thesis focuses on researching what interfaces are intuitive for novice users of cranes rather than for already experienced operators; that is because it is desired in the industry to greatly reduce the amount of time that it takes to train new operators. Chapters 2-4 of this thesis show that touchscreen controllers can be an effective the solution to the difficult aspects of crane control for novice users.

1.2 Manual Tracking

Crane control is a subset of the application area known as manual tracking. There are many situations where a human operator attempts to make the output of a system follow a desired state. Figure 3 shows a general block diagram where the human is represented with a transfer function $\mathbb{G}_h$ and the dynamics of the system by $\mathbb{G}_p$. The desired state is the reference signal *r(t)*, the output of the system is *y(t)*, the difference between the desired state and the actual state is *e(t)*, and the command that the human is giving to the system is *u(t)*. Additional examples of this kind of manual tracking task include aiming a tank turret [46], driving an automobile [16, 25] and piloting an aircraft [24].

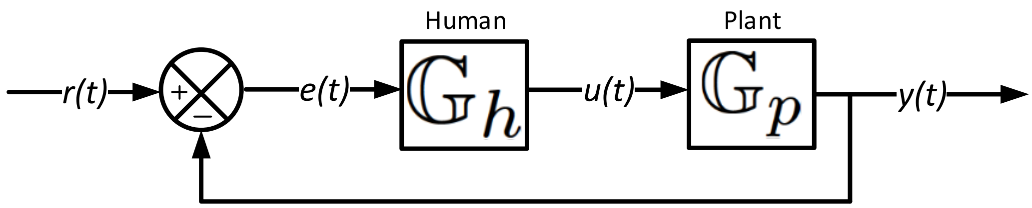


Fig 3: Block diagram of a human tracking task

These studies have mainly used steering wheels, joysticks and other mechanical input devices. Because mobile touchscreen interfaces have only recently become viable as input devices, no data exists about their capabilities in manual control. However, this data is needed because touchscreen devices are being used in more and more situations. In Chapter 5, this thesis will show how humans change their responses to tracking error when using different interfaces.

1.3 Previous Work

1.3.1 Human-machine Interfaces for Crane Control

1.3.1.1 Human-Crane Interfaces

There has been significant effort in the development of control systems to reduce the oscillatory response of crane payloads. However, there is insufficient data indicating optimal designs for the operator interface [45]. It has been proven that interfaces that are tailored to the cognitive processes associated with specific control systems have beneficial effects [8, 15, 17]. The advent of touchscreen smartphones ushered in a new area of human-machine interfaces. As of 2013, over a billion people worldwide were using touchscreen devices [37]. Obviously many people have become accustomed to using a portable touchscreen. One study showed that the age of a user can determine whether they prefer the touchscreen or not [39]. Some examples of their use other than personal computing are use in cars [36] and data entry [31]. In a related study it was determined that touchscreen and touchpad controllers offer benefits over typical rotary knob controllers to change some settings in cars [6]. Another potential advantage to the touchscreen interfaces could be faster adoption for novice operators [22]. There is very little data published on what kind of interface works best to control cranes.

1.3.1.2 Buttons on Touchscreens

The size of the button is one of the main difficulties when designing an interface on a touchscreen device. There is data published that suggests that the width of a button on a generic touchscreen needs to be at least 22 mm to be easy to press by most people [12, 21]. Although a lot of interface building guideline literature supports that size, it is not feasible to implement on small touchscreen devices that are on the market today. Results from a study by Perhi et al. claim that for the one handed thumb usage the optimum button size should be between 9.2 and 9.6 mm [30]. This result has been confirmed in [21,32], where it was found that buttons with a size of less than 10 mm showed greatly reduced performance. It has also been found that target areas in the center of the touchscreen are easier to press [32, 55]. In [54] Wroblewski shows how easy it is to touch areas on a small touchscreen device. These areas can be seen in Figure 4 where two iPhones (one with a 3.5" screen and the other with a 4" screen) are shown. It can be seen that the easiest regions for a person to touch are in the center to lower-left side of the screen while most of the right side is fair to touch. The upper left and top areas of the screen should not have controls which are to be used often.

Fig 4: Thumb Reach With Right-Handed Use [18]

1.3.1.3 Difficulties Finding the Correct Direction

Worringham et al. claim that some ergonomics problems persist either because knowledge is lacking altogether or because it is incorrectly assumed that the issues have been adequately dealt with by earlier research [51]. This is very true in crane control ergonomics, where there have been few advancements over the last decades. The cause of this may be that the technology has not been at an implementable level yet; however with the massive increase in small electronics devices this is definitely not the case anymore.

Fitts and Seegar were the first use to the term stimulus response compatibility, which means essentially that some tasks are simpler to do than others because of the particular sets of stimuli and responses that are used or because of the way the individual stimuli and responses are paired with each other [11]. In their experiment it was proven that subjects preferred display and controller combinations that follow the normal motion stereotypes. It was also determined that it was hard for the subjects to relearn their mappings for situations where the information they were receiving was different than what had learned in their past experiences. It has also been demonstrated by Fitts et al. that reaction times to stimuli are shorter when the stimuli are mapped onto the responses of the person in a spatially 'compatible' way [10, 11]. An example of spatially compatible mapping would be when pressing "left" makes the object go "left" instead of right.

Worringham claims that spatial relationships rest on a deep foundation, where directional movements follow clear principles [51]. An example of this is when we move our hand to the right, we do not see it go to the left. When, however we use teleoperated devices, like cranes, the mappings between the "right" of the operator and "right" of the controlled object are not always well connected. Michotte referred to control when the user is not directly controlling the object as a break in the perceived chain, and stated that for the chain to be restored requires mental computation more than mere perception [26].

One way to solve the problem of compatibility between stimulus-reaction is the principle of 'visual field'.*"Put simply, the direction of motion of a control, as defined by its movement when viewing the control, should correspond with the movement of the controlled object in the operator's visual field, while viewing the object"* [51].

In [52] Worringham defined three types of directional compatibility in a display-control situation: i) visual-motor - movement in a given direction in the subject's visual field is produced by a control movement in the same direction in the subject's 'visual' field (i.e cursor movement in the visual field should correspond to the motion of the user's limb when viewed); ii) control-display - control movements results in parallel movements of the cursor on the display; and iii) visual-trunk - control movement is in the same direction relative to the operator's trunk. Worringham compared the performance of those types of directional compatibility. Compatibility refers to the degree to which relationships are consistent with human expectations. It was found that performance was superior in those tests that used the visual motor form of compatibility. The evaluation was between reaction and movement times, and initial direction errors. The latter decreased by as much as ten-fold with the visual-motor compatibility [52, 53]. The actual direction of the motion that the test subjects performed had no consistent effect on performance [53]. In simpler terms this means that, for example, if the operator is viewing the object directly and gives the control input "forward", the object should move forward with respect to the operator.

The operator predicts the function of the system by developing explanations, beliefs, and theories about the system. Taken together, those can be considered the mental model of the system [13]. Mental models are derived from the user's background, experience, manipulating similar systems, and the structure of the human information processing system. Mental models are constrained by factors such as the user's technical background and previous experiences based on using other systems, but also the interface may cause the person to choose a certain mental model [28]. In an experiment by Ben-Porat et al. the data clearly indicates that removing the reversed visual motor mapping during endoscopic surgery increases performance [2]. It is also possible to manipulate users into using certain mental models; that may be accomplished by either by training the users or by designing visible features of the system to give desired impressions [50]. If all of the machines in the world that do the same tasks had the same interfaces, then there probably would be fewer problems for operators; however this is nearly impossible to achieve in real life. In [5] the Worrington visual field principle was confirmed by tests using mining machinery.

Even though it has been shown that stimuli-reaction tasks improve with practise and can be described by the law of practice [27], the effects of compatibility between stimulus and reaction do not generally disappear [9, 14]. So, if an operator gets used to a really nonintuitive interface problems may still arise later.

1.4 Concepts

1.4.1 Classification of interfaces

In this thesis graphical user interfaces for crane control are divided into 4 subcategories: 1) Discrete control - the user gives the maximum magnitude commands in one of the pre-determined directions; 2) Continuous control - the user has control over the magnitude of the command, but can only move in pre-determined directions; 3) Free control - the user has continuous control over both the direction and magnitude of the command; 4) Other - the designs in this category rely on non-touch inputs to determine the command.

1.4.2 Input shaping

Cranes will always have an oscillatory payload response to a command. This unwanted dynamic effect makes it very hard for novice crane operators to control the crane, even if they have an excellent human-machine control interface. To reduce the effect of oscillations, a control technique called input shaping was used [3, 41, 42, 44]. Input shaping convolves the baseline input command with a series of impulses at specific time intervals. The result is a shaped command that is a little slower than the original command, but greatly reduces residual vibration. This process is illustrated in Figure 5.

In order to determine the impulse amplitudes and time locations of an input shaper, certain design constraints must be satisfied. The primary design constraint is a limit on the amplitude of vibration caused by the shaper. The normalized, percentage residual vibration (PRV) amplitude of an under-damped, second-order system from a sequence of n-impulses is given by [41]:

$$PRV = V(\omega,\zeta) = e^{-\zeta\omega t_n}\sqrt{[C(\omega,\zeta)]^2 + [S(\omega,\zeta)]^2} \tag{1}$$

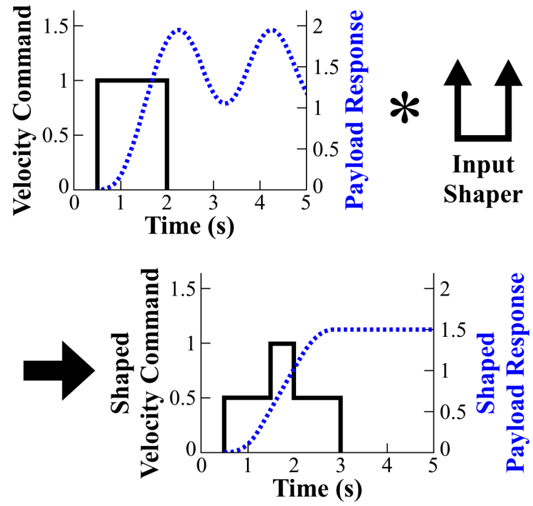


Fig 5: Input Shaping Process

where,

$$C(\omega,\zeta) = \sum_{i=1}^{n} A_i e^{\zeta\omega t_i}\cos(\omega t_i\sqrt{1-\zeta^2}) \quad (2)$$

$$S(\omega,\zeta) = \sum_{i=1}^{n} A_i e^{\zeta\omega t_i}\sin(\omega t_i\sqrt{1-\zeta^2}) \quad (3)$$

and ω is the natural frequency of the system, ζ is the damping ratio, and A_i and t_i are the i^{th}-impulse amplitude and time, respectively.

Equation (1) gives the ratio of vibration with input shaping to that without input shaping. A constraint on residual vibration amplitude can be formed by setting (1) less than or equal to a tolerable level of residual vibration at the estimated natural frequency and damping ratio. For the simplest Zero Vibration (ZV) shaper, the tolerable amount of vibration is set to zero. This results in a shaper of the form [41, 44]:

$$ZV = \begin{bmatrix} A_i \\ t_i \end{bmatrix} = \begin{bmatrix} \frac{1}{1+K} & \frac{K}{1+K} \\ 0 & \frac{\pi}{\omega\sqrt{1-\zeta^2}} \end{bmatrix}, \quad (4)$$

where,

$$K = e^{\frac{-\zeta\pi}{\sqrt{1-\zeta^2}}}. \quad (5)$$

For single-pendulum crane payloads, the natural frequency can be approximated as $\omega = \sqrt{g/L}$, where g is the gravitational acceleration and L is the cable length. The damping ratio of the payload swing can be found by experiment, although it is often near-zero for most cranes.

1.5 Thesis Road map

Chapters 2-4 of this thesis show that touchscreen controllers can be an effective the solution to the difficult aspects of crane control. In Chapter 5, the thesis will show how humans change their responses to tracking error when using different interfaces. In Appendix A, this thesis gives examples of what is possible using this new technology in educational settings.

Chapter II

TOUCHSCREEN CONTROLLERS FOR CRANE CONTROL

2.1 Introduction

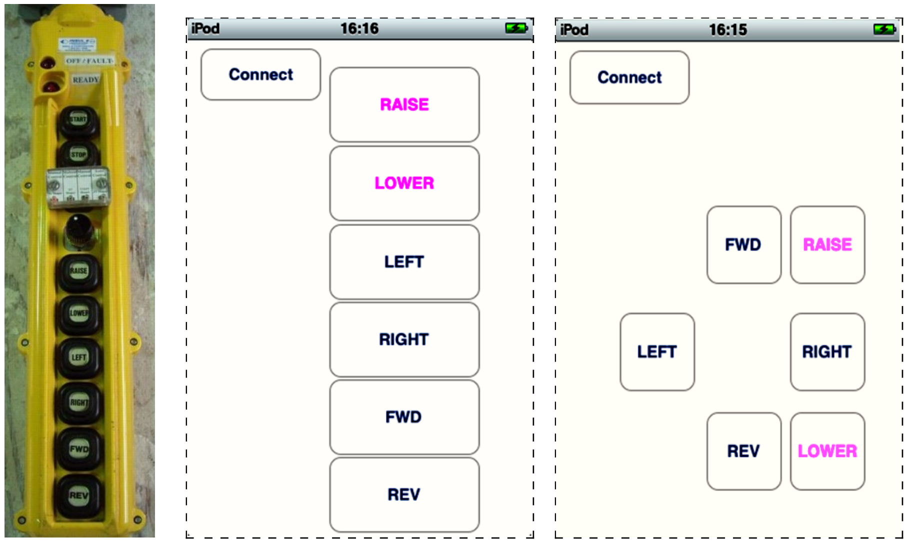
There is very little data published on what kind of interface works best to control cranes. Because the touchscreen interface can be easily modified, it could adapt to the operator's own preferences easily. A big benefit to using portable touchscreen devices is that they have a large number of sensors incorporated in a small package. Many modern smartphones have orientation sensors, light sensors, microphones, proximity sensors, and compasses. Most such small portable devices are programmable by third party software developers, making them ideal for next-generation crane controllers. An extra benefit to controlling cranes with devices that people are accustomed to is that the training time of the operators can be decreased drastically. This means that more people could drive a crane, thereby increasing the efficiency of the industry.

This chapter describes several touchscreen graphical user interfaces (GUIs) in Section 2.2. Operator testing of the interfaces is then presented and analyzed in Sections 2.3 and 2.4.

2.2 Interfaces

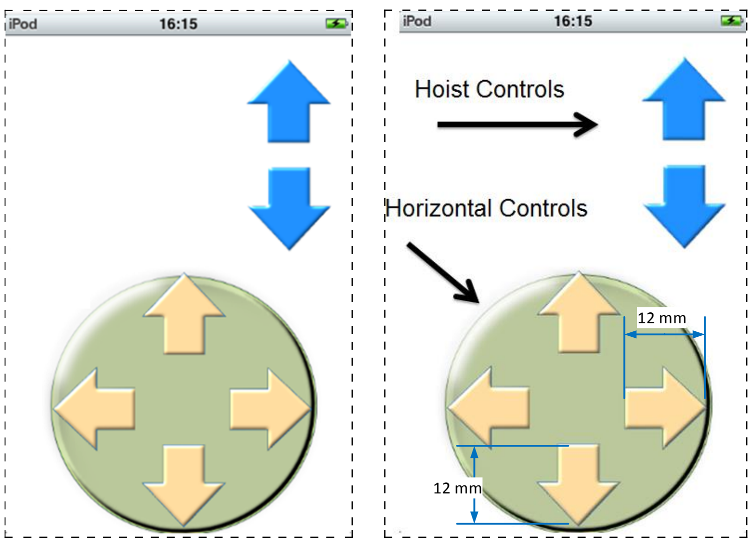
2.2.1 Interface Designs

The goal of this study was to generate a dataset that could drive the design of a new generation of crane control interfaces. To this end, the various interfaces were designed to be distinct from one another. One set of interfaces imitated the layout of a standard control pendent, as can be seen by comparing Figure 6(a) and Figure 6(b). The Pendent GUI is a button-for-button copy of the Push-Button Pendent, and the



(a) Push-Button Pendent (b) Pendent (c) Diamond-Pattern Pendent

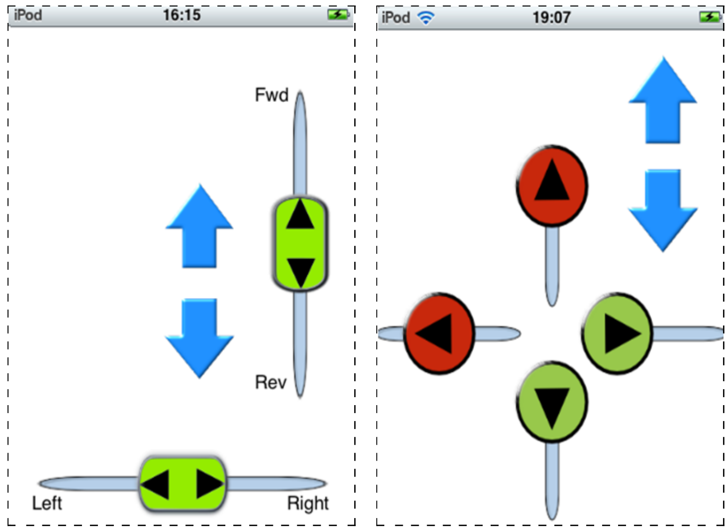
Fig 6: Pendent layouts



(a) Interface (b) Design

Fig 7: D-Pad

Diamond-Pattern Pendent in Figure 6(c) has buttons reorganized so that "Left" and "Right" are on opposite sides as well as "Forward" and "Reverse" in opposing locations. These interfaces fall into the discrete-control category where the user has only limited choices of direction and no control over the magnitude of the command. When a button is pushed, a full-velocity command is issued to the crane motors. Although



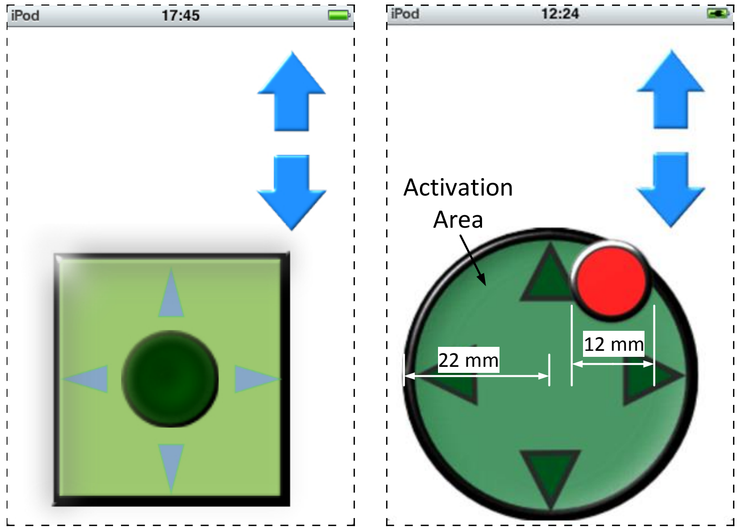
(a) RC Control (b) Sliders

Fig 8: RC Control and Sliders Interfaces

these interfaces do not offer the tactile feedback, or the option of issuing a half velocity, as does the physical Push-Button Pendent, these interfaces were still included in the study for comprehension. The designs of these interfaces are further discussed in Appendix B.

Figure 7(a) shows another interface in this category; it has arrow-shaped buttons so that the user can easily see what direction the buttons correspond to because humans often represent a direction with an arrow. The D-Pad (4-directional pad) and all of the other interfaces yet to be introduced have hoist controls clearly decoupled from the controls generating horizontal motion. For example, the hoist control is the pair of blue arrows in the upper right corner of the interface in Figure 7(a). The design of the D-Pad seen in Figure 7(b) follows the rules discussed in Section 1.3.1.2. The buttons change color to indicate a touch. The buttons are large enough to be touched with ease and are located in the area of the device where it is most reachable with one-thumbed operation.

Interfaces that belong to the continuous-control category can be seen in Figure 8.



(a) Interface (b) Design

Fig 9: Joystick GUI

The RC (radio control) Control GUI was inspired by the interfaces that control model airplanes. The Sliders GUI in Figure 8(b) is an extension of the D-Pad. The difference between the two interfaces is that with the RC Control the operator has control over an axis under one slider, for example the "Left-Right", while with the Sliders GUI the one slider only corresponds to one of the directions, for example "Left" or "Right". The drawing in Figure 8(a) shows the RC sliders in the "home" (zero command) positions. The drawing in Figure 8(b) shows the Forward and Left sliders moved away from their home locations. The design of these interfaces is further discussed in Appendix B.

The Joystick GUI shown in Figure 9(a) belongs to the free control category. The user has control of the magnitude and direction of the command under one finger, by sliding a button around the screen. The details of the design of the interface can be seen in Figure 9(b). The joystick in Figure 9(a) has the ability to send a maximum velocity command in both crane axis simultaneously while the joystick in Figure 9(b) has the magnitude of the command limited to the maximum velocity command of one crane axis. The reason for this will become evident in Section 2.2.2. The basic

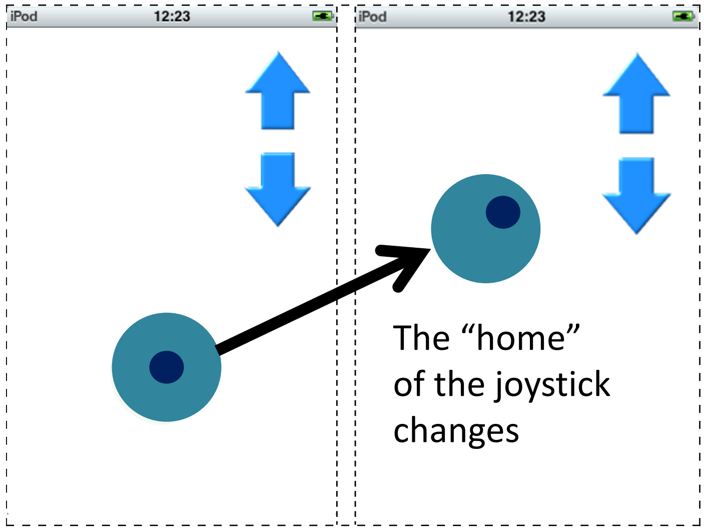
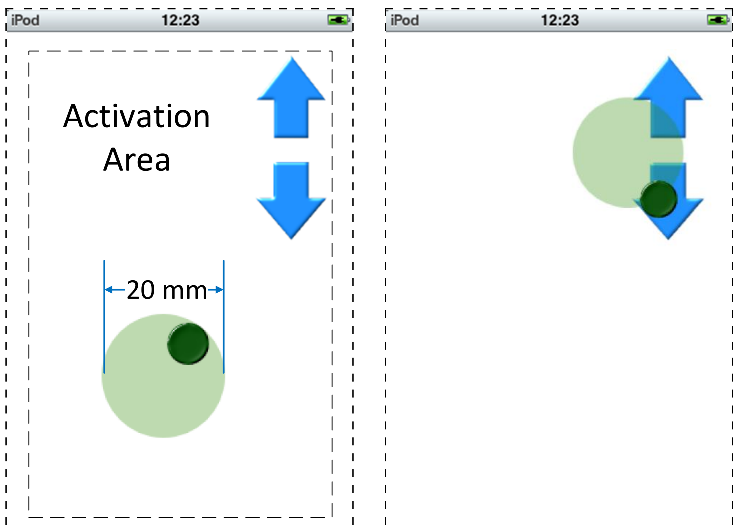


Fig 10: Action of a Varying-Home Joystick



(a) Design (b) Example Situation

Fig 11: Varying Home Joystick

operating approaches of the interfaces are the same. The full velocity command in one axis direction is issued if the finger is moved at least 22 mm away from the center of the green area in the direction of the axis. The operator can begin issuing the command by placing a finger anywhere in the “Activation Area”. If the finger leaves the green area the maximum command is still issued at the direction that is determined by the line from the center of the green area to the location of the finger. The sliding button will not follow the finger outside the green area and will remain on the edge of the

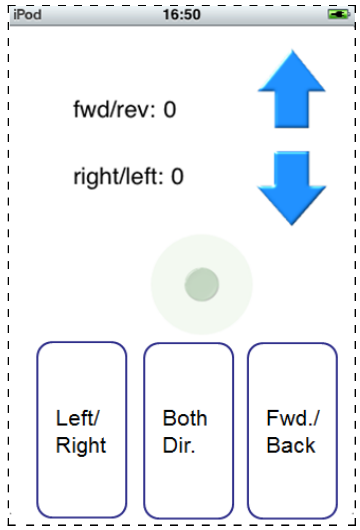
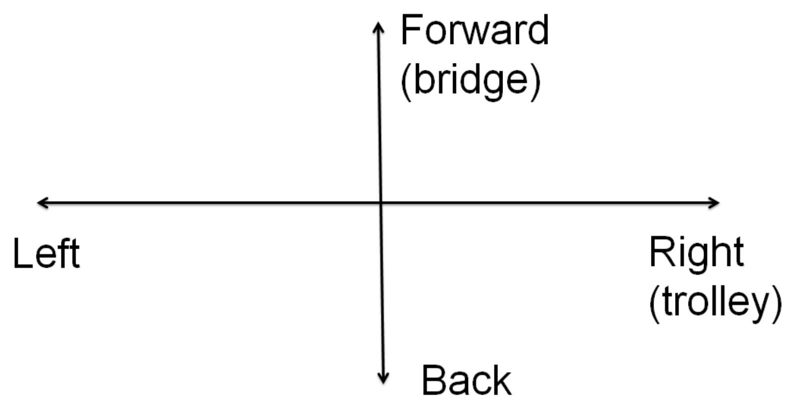


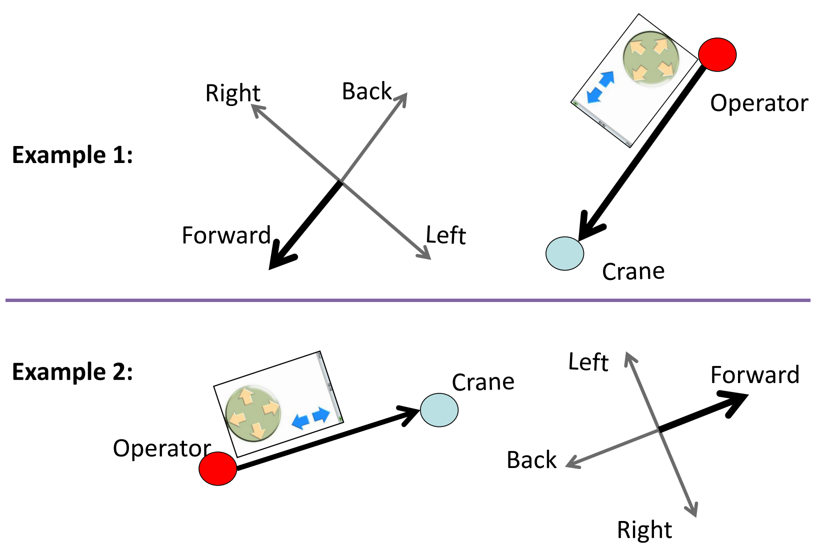
Fig 12: Tilt GUI

"joypad". The command is stopped once the touch has ended. The sliding button changes color from green to red when touched. The joystick is placed at the bottom of the screen because it is easy for the operator to reach with a thumb as discussed in Section 1.3.1.2.

Another version of the Joystick GUI is the Varying-Home Joystick shown in Figure 10. The place where the user initially touches the screen becomes the home location for the joystick. With this interface capability, there should be no reason for the operator to look down at the screen. The interface tries to eliminate the need for muscle memory when using the device with the hopes of facilitating faster adaptability. The design of the Varying Home Joystick can be seen in Figure 11(a). In this controller, the user can activate the joystick from most areas of the screen. The maximum command is issued when the touch location is moved 10 mm. The move distance is much smaller compared to the Joystick because the user can place the finger close to the edge of the screen. When the finger reaches an edge of the screen, the user should feel it with his/her finger. When the user presses the hoist buttons the joystick will not be activated. However, when the joystick is activated near the hoist buttons and the finger moves to the buttons, hoisting commands will not be issued, and the joystick



(a) Static driving axis



(b) Rotating driving axis based on location

Fig 13: Driving Axis

works as if the buttons were not there. This is illustrated in Figure 11(b).

The final GUI that will be discussed in this Chapter is the Tilt GUI, which can be seen in Figure 12. With this interface the user sends commands by twisting and tilting the device, utilizing its accelerometer. The operator can choose which axis to control by pressing on one of the buttons at the bottom of the screen. The design of this interface is further discussed in Appendix B.

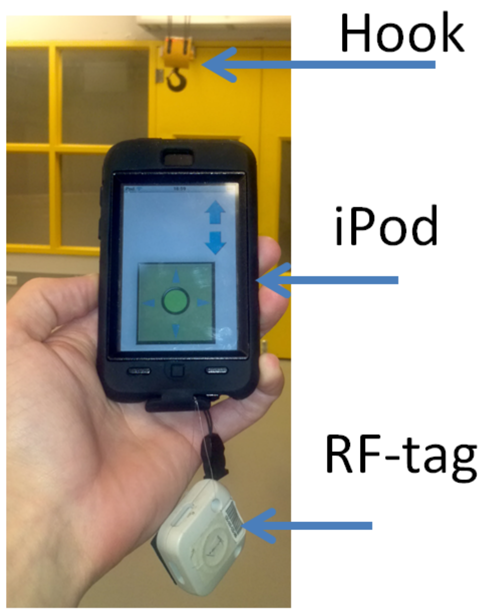
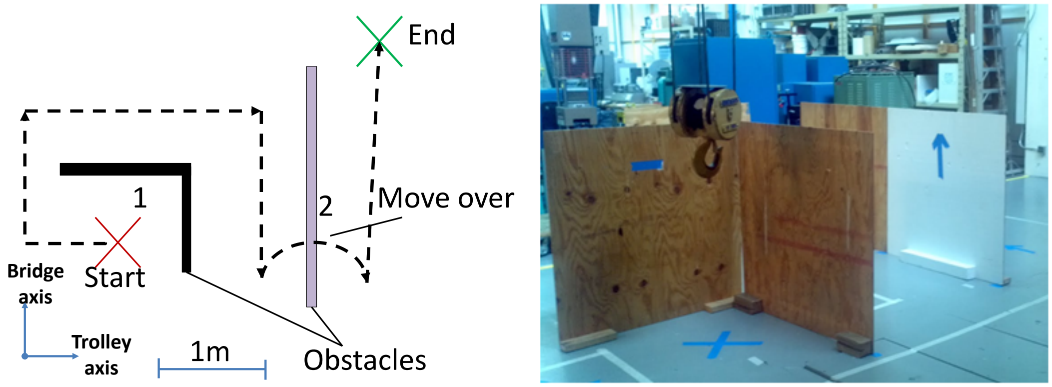


Fig 14: A Touchscreen Controller with an RF-tag

2.2.2 Rotating Driving Axes

Traditionally, the driving axes of a crane are independent of the operator's orientation. This is illustrated by the two examples in Figure 13(a), where the "Forward" direction is directed toward the top of the page and the operator orientation has no effect on this direction. This means that when the operator pushes the "Forward" button, the crane will move "Forward" in its own reference frame, which may be different than "Forward" relative to the operator. This creates an additional cognitive step where operators must account for their own orientation and location relative to the crane's driving axes. To eliminate this cognitive step, rotating-driving axes were developed. This concept is illustrated in Figure 13(b). When the user presses "Forward", the interface calculates the relative position between the crane and the operator and then sends commands to the crane such that the crane moves "Forward" relative to the user.



(a) Top View (b) Side View

Fig 15: Obstacle Course

2.3 Human Operator Testing

To obtain good results from an operator study, the auxiliary conditions should be as constant as possible. So input shaping, which was described in Section 1.4.2, was used for all of the interfaces, including the standard push-button pendent, so the human operators could focus on following the reference trajectory without worrying about the swing of the payload. This simplification of the task allows the data to better indicate differences between the interfaces, rather than the effectiveness of the operator's ability to suppress load swing.

All of the GUI designs were implemented on a 2^{nd} generation iPod Touch connected through Wi-Fi to a Siemens PLC, which controlled a 10-ton bridge crane. To measure the location of the operator, an RF tag was attached to the controller [34], as shown in Figure 14.

Every design described in Section 2.2 was tested twice - once with the rotating driving axes and once without. Ten volunteers, who had no crane operating experience prior to the tests, had to maneuver the crane hook through the obstacle course shown in Figure 15. They had to go around obstacle 1 and over obstacle 2 to reach the target. To test the intuitiveness of the interfaces, the operators were not instructed on how to use them.[1] Each operator used all of the interfaces, plus the standard push button pendent. Therefore, each operator performed 17 runs of the obstacle course. To minimize the learning effect, the tests were done in random order. At the end of each run the operators filled out a questionnaire that evaluated the performance of the interfaces.

2.4 Results

Figure 16 shows the average completion times for all of the interfaces. The users performed the best with the two joysticks and the D-Pad interfaces. Note that in almost all cases, rotating the driving axes made the performance worse. The large deviations shown by the error bars indicate that performance varied significantly from person to person.

When it came to finding the right button while operating the crane, the regular joystick scored the highest, as shown in Figure 17. Even though the operator does not have to look down at the interface when using the Varying-Home Joystick, many operators were not confident in doing that. There were large deviations in how intuitive the operators perceived the interfaces to be, as seen in Figure 18. This result probably occurred because the operators were not told how the interfaces would function. The Joystick, R/C Control and the D-Pad scored well, as the users apparently recognized them, while the Varying-Home Joystick GUI and the Tilt GUI were found to be confusing.

The operators felt that it was easiest to operate the crane with the Joystick and D-Pad, while the pendents scored the lowest, as shown in Figure 19. Figure 20 shows how safe the users felt controlling the crane. When comparing Figure 19 and Figure

[1]This concept was used because the goal of this research is to develop an extremely intuitive control interface. After the testing was completed and the data analyzed it became apparent that at least some small level of instructions should be given to the novice crane operators.

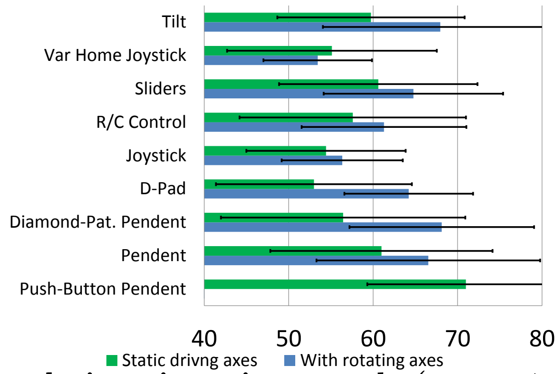


Fig 16: Average completion times in seconds (mean ± standard deviation in all figures)

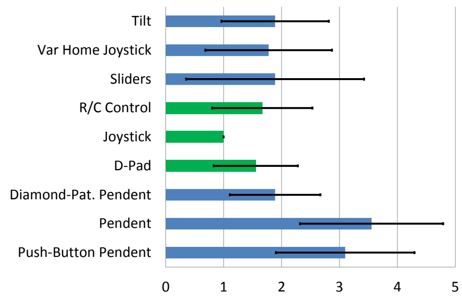


Fig 17: Ease of finding interface buttons (1=easiest, 5=hardest)

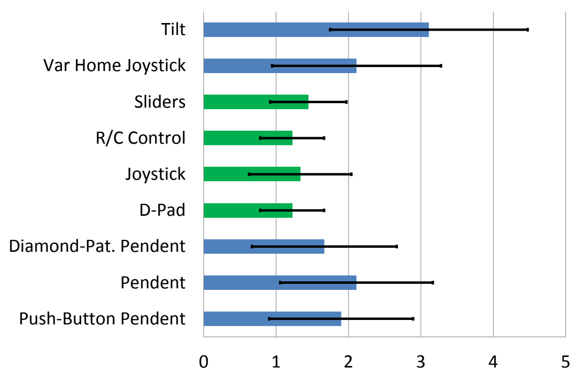


Fig 18: Understanding interfaces (1=easiest, 5=hardest)

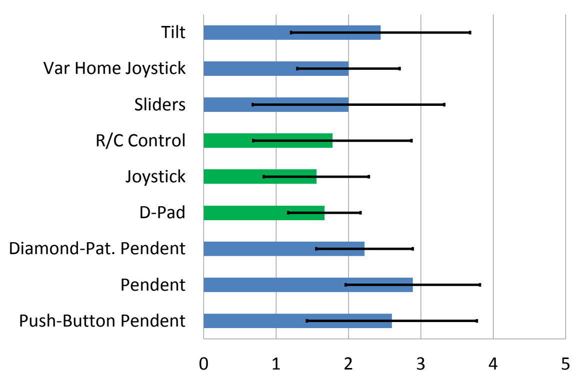


Fig 19: How hard was it to control the crane? (1=easiest, 5=hardest)

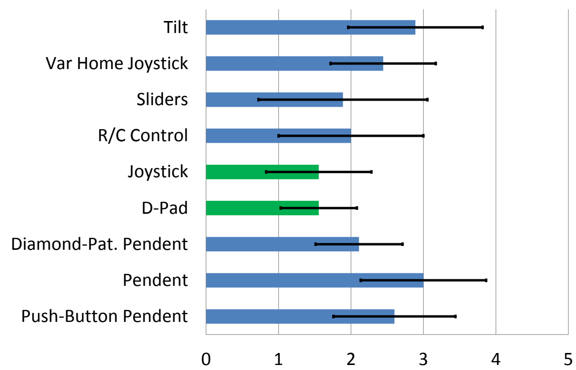


Fig 20: How safe did the interfaces feel? (1=very safe, 5=not safe at all)

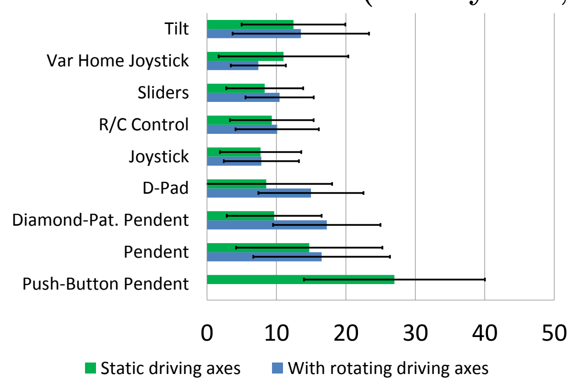


Fig 21: Time that no command was issued

20, it can be seen that the users felt safer controlling the crane with interfaces that made maneuvering easier.

In Figure 21 the amount of time during which the users did not send any command to the crane is shown. It can be seen that for most of the interfaces when the operators were using the touchscreen device they exhibited lower times of hesitation. On most interfaces the times did not increase with the addition of rotating axes.

The rotating driving axes made controlling the crane, despite its intentions, more strenuous, which is shown in Figure 22. The users found it very frustrating that when they were standing still, the crane changed its trajectory, even though the command they were issuing was the same. Figure 23 shows typical ways the operators controlled the crane with the rotating axes with the Joystick GUIs. The solid blue line in the figure shows the location of the operator. In Figure 23(a) the operator followed the

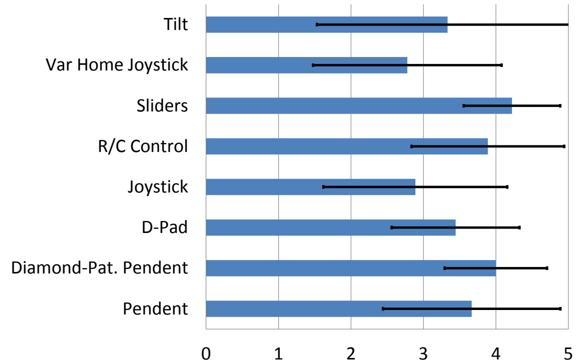


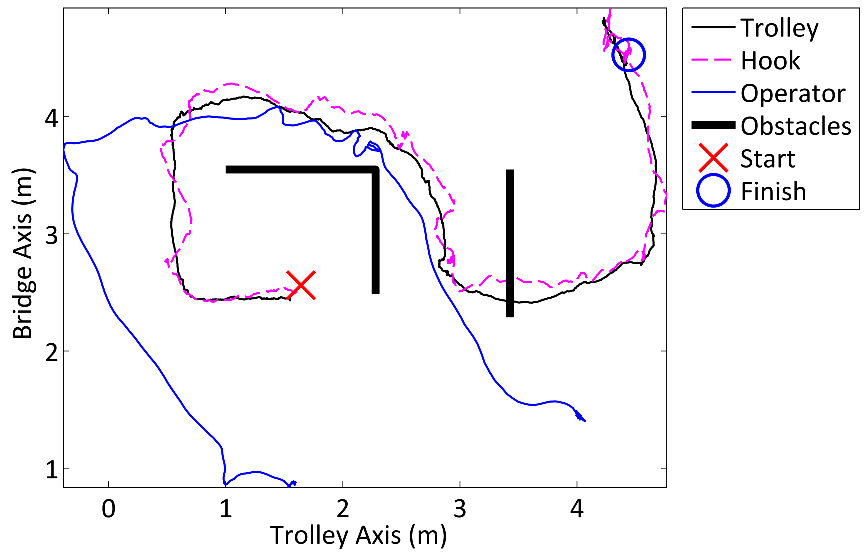
Fig 22: How the operators felt about the Rotating driving axes (1=it helped a lot; 5=it made controlling of the crane impossible)

payload through the obstacle course. However Figure 23(b) shows a typical case where the operators moved very little doing these tests; they found a suitable position and stood there throughout the tests. Therefore, the rotating axes would have no benefit for these stationary operators and would actually cause them to do more cognitive calculations, as the axes changed while they were still. Figure 24 shows the task was typically completed with the D-Pad in Figure 24(a) and the Sliders GUI in Figure 24(b). It is worth noting that all of the trajectories look very similar.

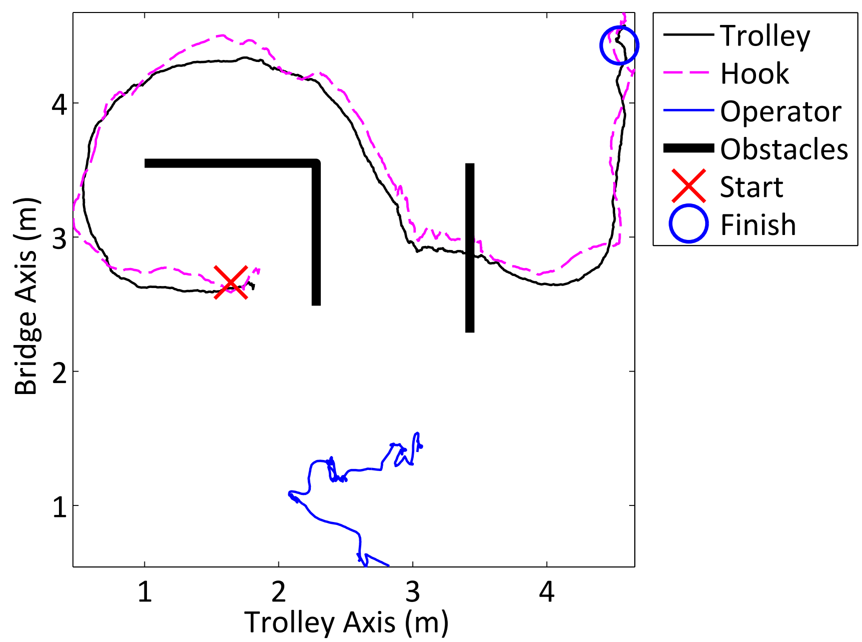
To summarize the results, the D-Pad and the regular Joystick performed well in all of the test conditions, while the classical pendent interfaces were among the worst performers. Even though the D-Pad has only four possible directions and in contrast to the Joystick, no way to vary the magnitude of the command, operators found it very useful. The common ground between those two designs is that the control area lies right under the place where the operators would naturally hold their thumbs while holding the touchscreen device. Furthermore, the appearance of those controllers resembles that of physical controllers that are widely used.

2.5 Discussion

The results show that some interfaces are preferred over others in almost every test condition. In addition to that, the touchscreen interfaces scored better than the



(a) Operator following the playload

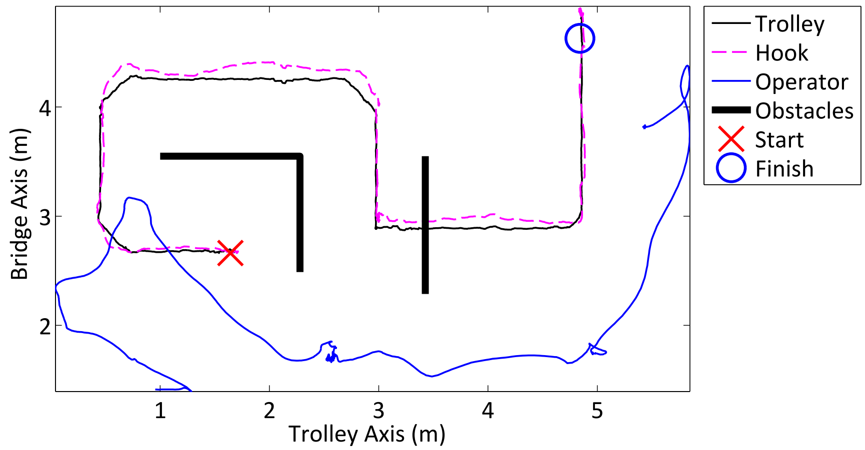


(b) Operator not following the playload

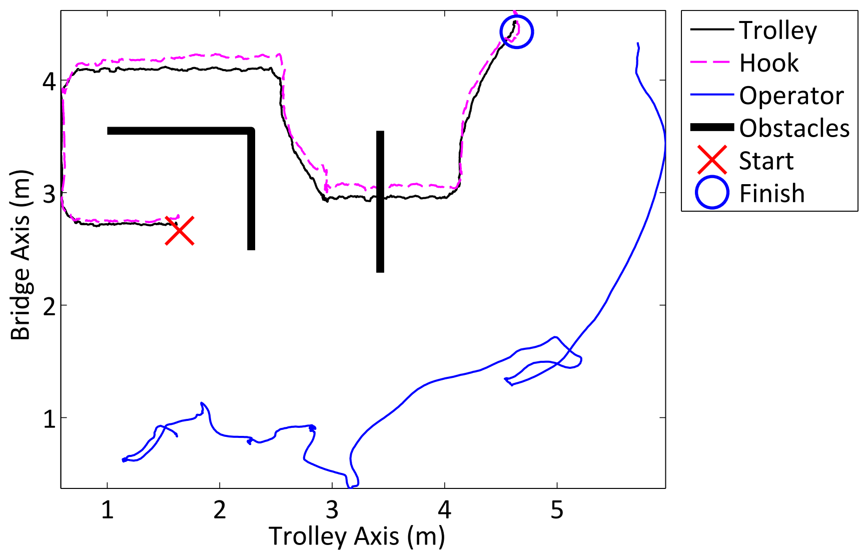
Fig 23: Examples of trajectories with Rotating axes

traditional push-button pendent controller, that is widely used in industry. Another great benefit of the touchscreen controllers is their cost compared to traditional controllers. Their low cost results from the number of devices amount being produced.

The obstacle course that the interfaces were tested on was on a very small scale



(a) D-Pad



(b) Sliders

Fig 24: Examples of trajectories

compared to real-life scenarios where cranes are used. This could lead to some discrepancies with the performance seen in industry. As can be seen in Figures 23 and 24 the trajectories for all of the interfaces did not vary a lot, and the operators had a lot of room to maneuver the crane in. Therefore even if they made any mistakes due to the interface not being intuitive, these would probably not show up in the results. Figure 22 indicates that the rotating driving axes did not help the operators, and at most times even inhibited their operation, as can be seen in Figure 23(b). However this result may be due to the small size of the testing area, where the operators did not have to move. This let them orient themselves relative to the crane fairly easily, and they did not need to move through the workspace. Figure 23(a) shows the way the rotating axes were supposed to be used. The operator followed the hook of the crane, and in that test situation the operators would need no prior knowledge of the cranes axes.

2.6 Conclusions

It was shown that a touchscreen controller can be used very effectively to control a crane when compared to a standard controller. An operator study showed that users performed better with user interfaces that are simple and easily understood. In general, all of the interfaces worked, and with a simple task like that used in this operator study, humans coped well with most of the interfaces that were on the touchscreen device. To better determine the best user interface designs for crane control, testing must be done with more challenging tasks. The rotating axes inhibited the intuitiveness of crane control; however, that may very well been due to the nature of the task the operators were given and to the fact that the operating principles of the interfaces were not explained.

Chapter III

DRIVING AXES OPERATOR STUDY

3.1 Introduction

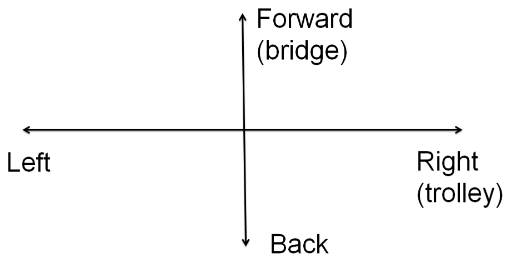
The operator study presented in the previous chapter did not use a task that was complex enough to require the operators to move their bodies significantly during the operation. Therefore, the potential advantages of rotating driving axes were not revealed, and an operator study with a more complex task was conducted.

Section 3.2 describes the ways to make crane control more intuitive. Section 3.3 describes the operator study which was done to investigate the matter and the results can be seen in Section 3.4.

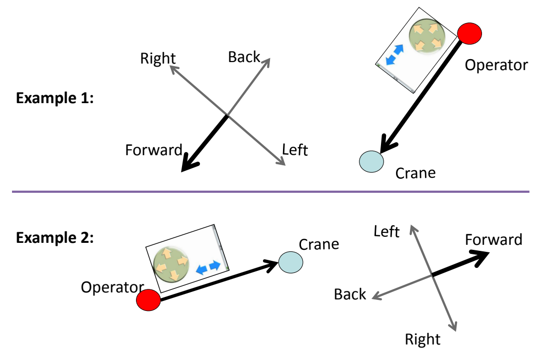
3.2 Rotating Axis

The different types of driving axis used in this operator study can be seen in Figure 25. Figure 25(a) shows the current industry standard where the axes are always fixed no matter what the operator does. Crane operators need to have *a-priori* knowledge of the axes' orientation in order to limit movement errors. The big benefit to this approach would be when the majority of the crane movements are along the Cartesian axes directions, so the operators do not have to worry about the crane traveling off course.

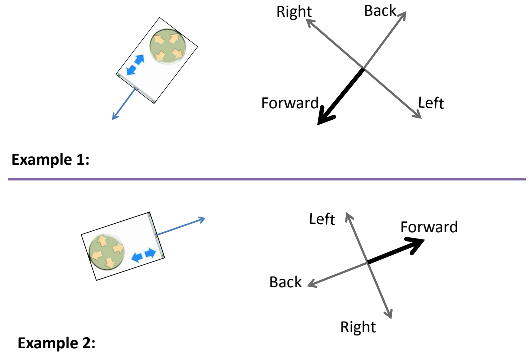
Figure 25(b) shows how the driving axes can rotate with the operator. The control system tracks the operator's position relative to the trolley of the crane and aligns the "Forward" direction to the line directed away from the operator to the crane. The main benefit to this approach is that it does not matter how the interface is being held and therefore does not limit the operator to hold the device in a certain way.



(a) Static driving axis



(b) Driving axis based on the location of the operator

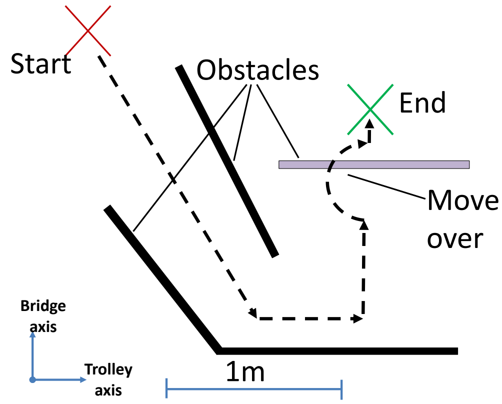


(c) Driving Axis based on device orientation

Fig 25: Driving Axis

The drawback to these kinds of axes is that, for example, if the operator is standing still and gives the crane a non-"Forward" or "Backward" command, then the axes will change, and this will be detrimental to the overall performance, as was in discussed in Section 2.4.

Figure 25(c) shows another version of the rotating axes that is dependent on the orientation of the device. "Forward" will always be in the direction that the interface is pointing. It does not matter where the person is in relation to the crane. This means that if the interface is held fixed then the axes will be stationary. The main drawback with this approach is that the interface orientation has to be maintained carefully during the entire duration of the crane's movement. This inhibits the operator from



(a) Top view

(b) Operator's view from Start

Fig 26: Obstacle course

lowering his/her hand arbitrarily.

The main benefit for both of the rotating axes cases is that no *a-priori* knowledge about the directions of the trolley and bridge axes is required.

3.3 Human Operator Study

3.3.1 Setup

The course that was used for the operator study can be seen in Figure 26. The operators had to start with a diagonal move, then translate along the trolley axes and finally move along the bridge axes towards the end point. The last step required hoisting the hook over a wall. From the operator study described in Chapter 2 it was found that if the task only required movements in the trolley and bridge directions, then there is little need for a rotating axes. This, however, is often not the case in the real world, where complex maneuvers have to be performed. As can be seen in Figure 26(b) the walls of the obstacles were made high so the operators could not remain fixed in one position, as they did in the operator study described in Chapter 2.

The Varying-Home Joystick interface seen in Figure 27 was used to test the effectiveness of the different driving axes. The interface emulates the physical joystick; however, the position where the user initially touches the screen becomes the home

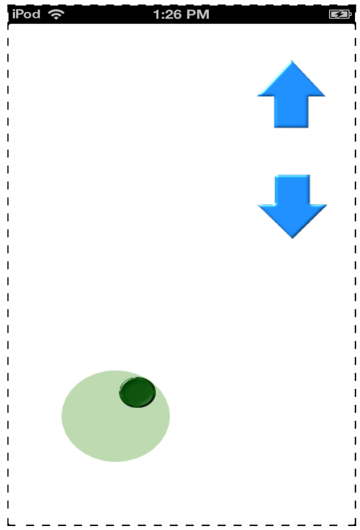


Fig 27: Varying-Home Joystick GUI

location for the joystick. Theoretically, there should be no reason to look down at the screen. To get the location of the person for the driving axes based on the location of the operator, an RF-Tag was attached to the controller [34]. For this operator study the controller was a 4^{th} generation iPod. An iPhone 3gs was used as the device to test the driving axes that were based on the device orientation. It was determined that there was not enough magnetic interference in the testing room to cause the compass to give false readings. Even if there are big sources of magnetic interference, the gyroscope, which is a part of most newer smartphones could help maintain the correct heading. Input shaping was used on all of the interfaces that were implemented on the touchscreen devices.

3.3.2 Participants

Eleven novice operators volunteered for this operator study. They were between the ages of 21-50 years. No compensation was given for them to participate in the trial.

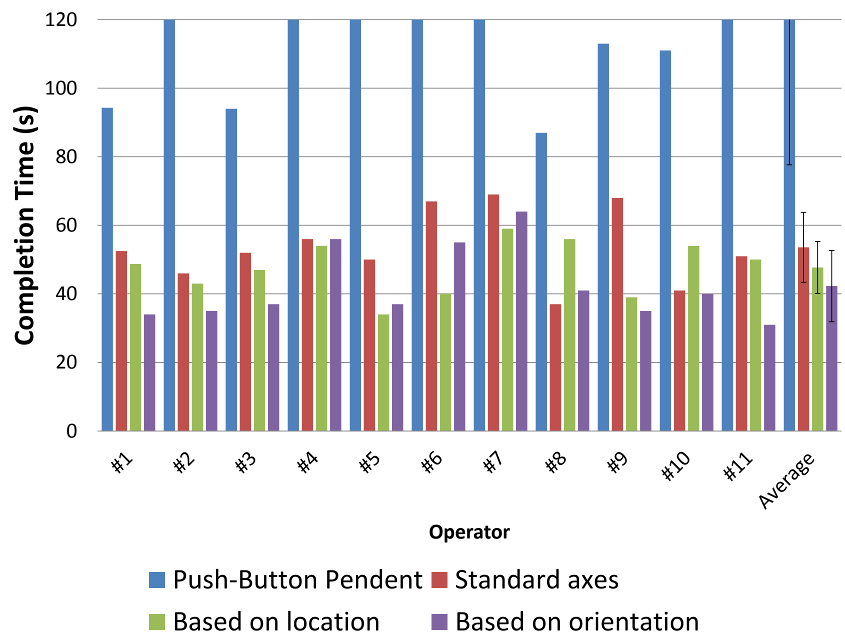


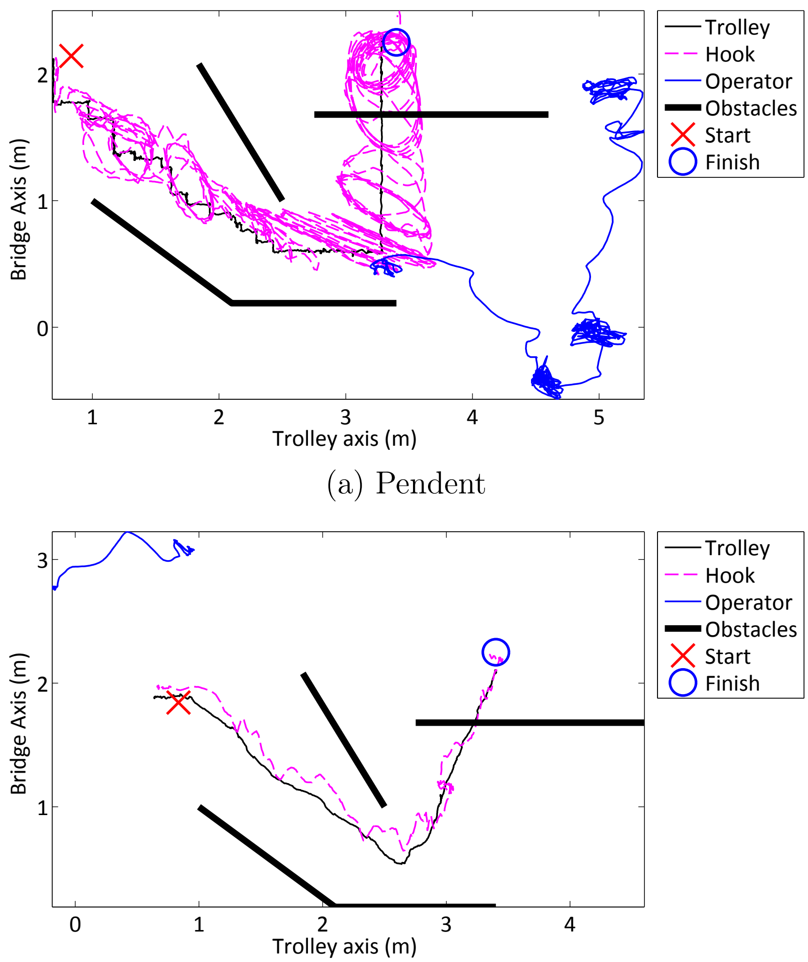
Fig 28: Completion times (maximum limited to 120 seconds)

3.3.3 Testing Procedure

Each participant did 4 trial runs: 3 types of axes implemented on an iOS device, plus one trial with the industry standard pendent with no input shaping. The participants completed a qualitative questionnaire after every run, plus a summarizing questionaire at the end of the trials. All of the trials were done in random order to minimize the learning effect of the crane's dynamics.

3.4 Results

Figure 28 shows the completion times of every operator in addition to the mean values. The vertical axis of the figure is limited to 120 s so that differences between the driving axes can be seen. The average completion time for the pendent was 172 seconds. In addition to every form of control performing better than the industry standard pendent, it can be seen that operators using both of the rotating axes' performed better than they did using the standard axes, although that is not true for every operator. Using an Analysis of Variance (ANOVA) test with Tukey's honest significance test (HSD) at 95% confidence level, it was determined that each of the axis types implemented on the touchscreen device yielded results that were significantly different from those obtained for the Pendent (p<0.0001 for all cases). In addition, the results for the standard axes were significantly different from those obtained for the axes based on orientation (p=0.0092). There was no statistical difference between the results obtained for the location-based axes compared to those obtained for the standard axes and the axes based on orientation (p=0.14 and p=0.15 respectively).



(a) Pendent

(b) Touchscreen Interface

Fig 29: Examples of typical trajectories without rotating axes

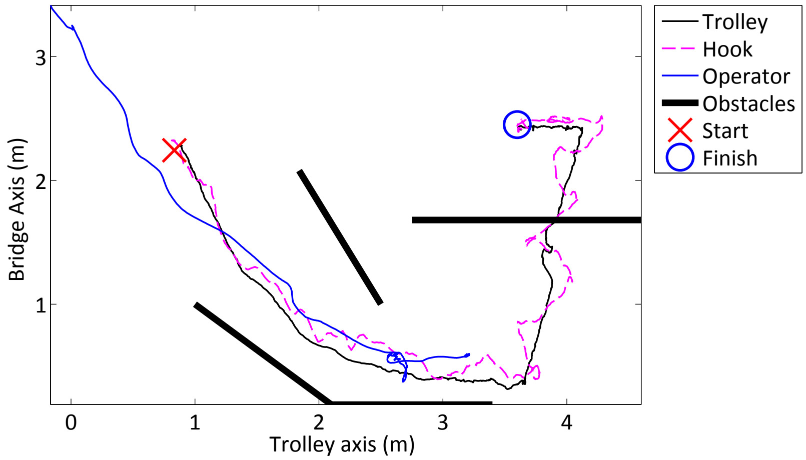


Fig 30: Typical Trajectory with rotating axes

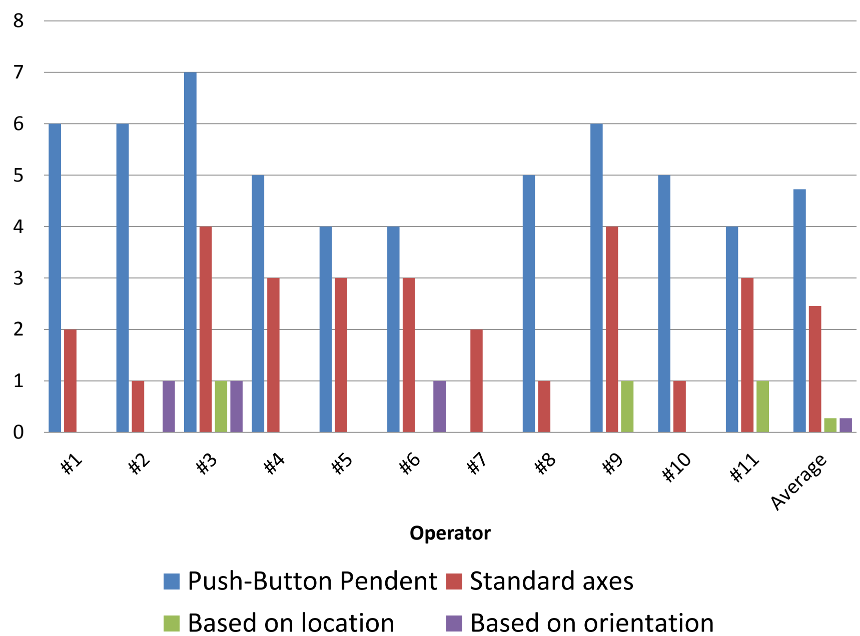


Fig 31: Number of collisions with obstacles

Figure 29 shows how the task was typically completed without the rotating driving axes. The Pendent made it cumbersome for operators to perform diagonal movements, and the lack of input shaping often caused the operators loose control. These effects are shown in Figure 29(a). The dashed purple line indicates significant payload swing.

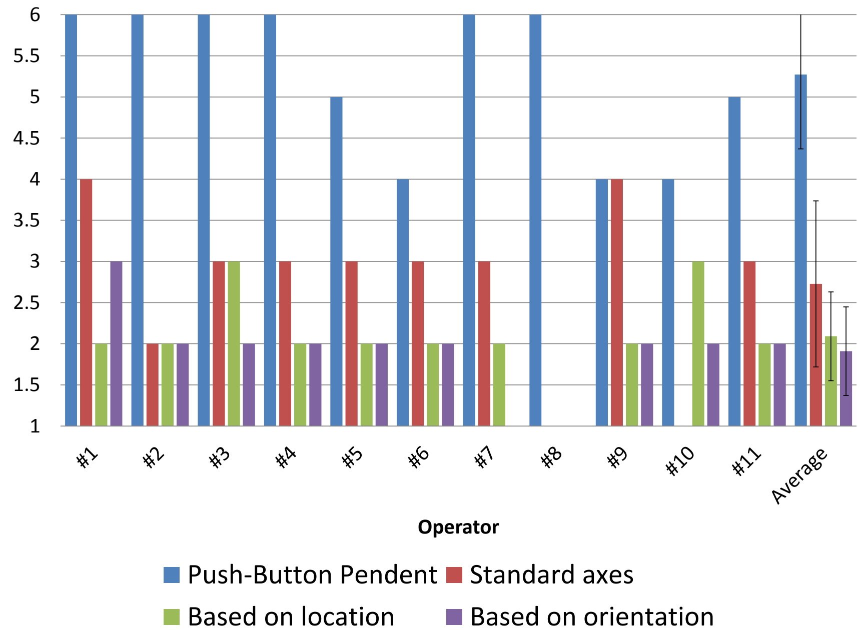


Fig 32: How safe did the different driving axis feel? (1=very safe 6=not safe at all)

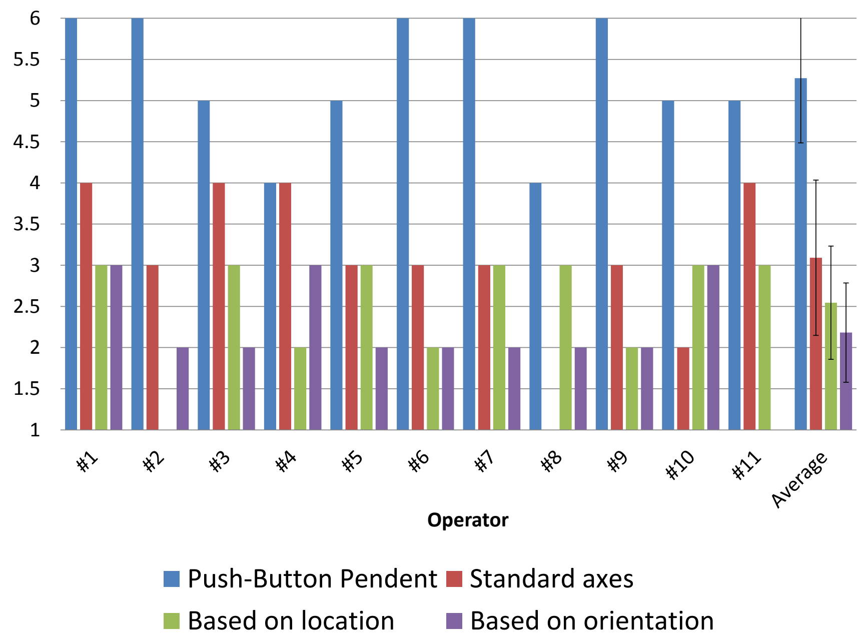


Fig 33: How much did you have to concentrate? (1=not at all 6=a lot)

The typical results with the axes based on device orientation shown in Figure 29(b) indicated a much better result. When the rotating axes were enabled the operators often decided to follow the hook, as can be seen in Figure 30. Other strategies that were documented in the operator study included holding the device pointed to the crane's "Forward" direction at all times with the standard axis while the operator moved about. Some operators moved very little and only issued the "Forward" command and turned the device accordingly when using the axes that were based on orientation. As with the operator study described in Section 2.4, some people tried to stand in one position for all of the trials.

Figure 31 shows that with the standard pendent there were a lot of obstacle collisions, as the operators could not control the swing of the payload with the nonintuitive interface. The number of collisions with the other interfaces was minimal. Figure 32 shows that the users did not feel safe with the industry standard pendent and were much more comfortable with the interfaces on touchscreen devices, as was the result in the operator study described in Chapter 2. It is noteworthy, however, that the majority of the users believed that the axes based on the orientation of the device made them feel safest.

Figure 33 shows how much the operators thought they had to concentrate. The volunteers reported that with the rotating axes they did not have to concentrate as hard. The axes based on orientation were the most highly evaluated by the operators, while the nonintuitive standard pendent performed poorly, as expected. Analogous results were found when the operators evaluated the different interfaces based on how comfortable they thought it was to change direction. The interfaces ranked in the same order when the users reported the number of times the crane went in a direction they did not intend the crane to go, as can be seen in Figure 34. The result is not a surprise due to the layout of the task, where most of the operators reoriented themselves multiple times. Figure 35 shows how much the operators moved around while performing the task. It can be seen that averages differ greatly from person to person. The reason why the operators moved a lot with the Push-Button Pendent could be attributed to the fact that the tether connecting the pendent to the PLC was

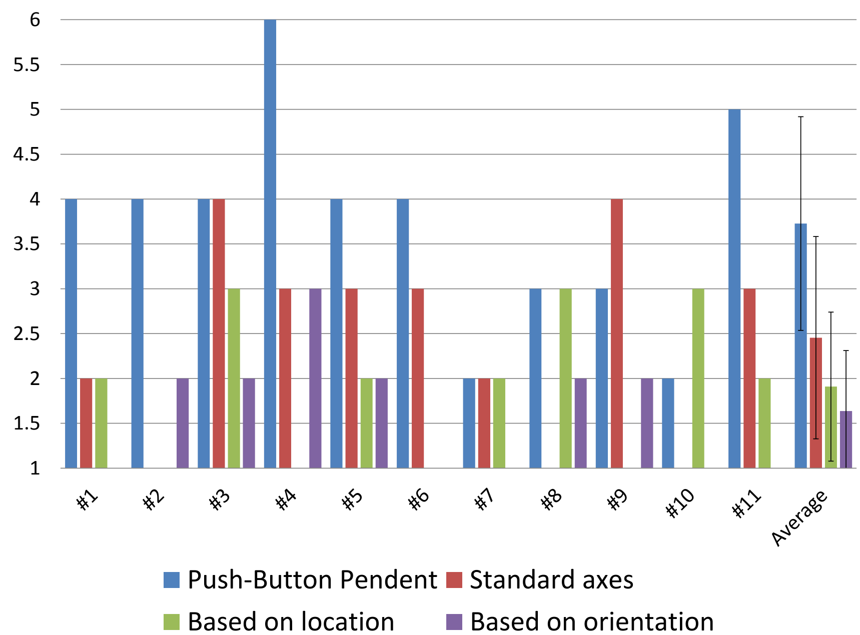


Fig 34: How many times did the crane go to an unexpected direction? (1=max once 6=very often)

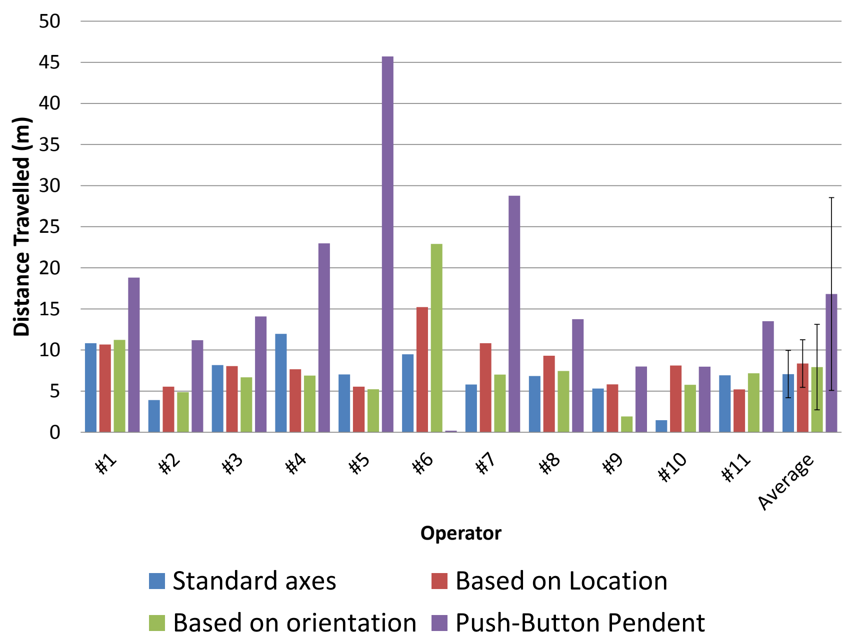


Fig 35: Average distance the operators traveled

often caught by the obstacle walls, and some of the operators did not want to move inside the obstacle course for that reason. Figure 36 shows how far the operators were from the payload on average throughout the test. It can be seen again that the results

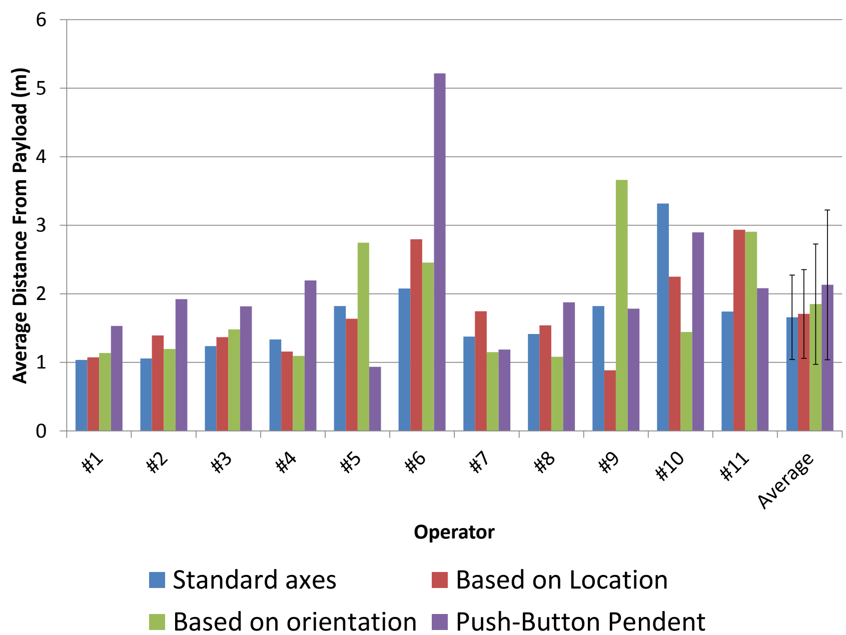


Fig 36: Average distance between the payload and the operator

differ greatly from person to person. It can be noted however that in general the rotating axes do not make the operators be closer, and therefore be in more danger of being injured, to the payload compared to the static axes.

The results of this operator study can be summarized with Figure 37 where the operators ranked the different driving axes against each other, with 1 as the best and 3 as least preferred. The operators as a group reported that they prefer the axes based on the device orientation the most, followed by the driving axes based on location the standard static axes was considered the worst out of the three.

3.5 Discussion and Conclusion

Although the operator testing indicates that the rotating axes are more intuitive, it is worth remembering that all of the operators were novices. If implemented in industry, then crane operators with experience might not adjust to these kinds of changes. In addition, the task the operators had to perform was probably harder than

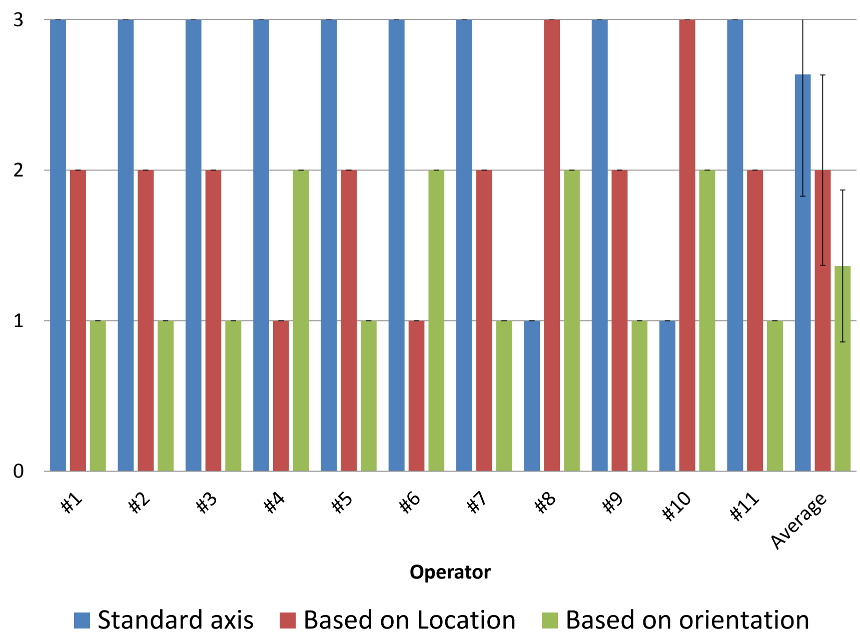


Fig 37: Ranking of the different driving axis

the average crane manipulation task. All of the results correspond with Worringham's past experiments [51–53]. It seems that based on the operator study presented in Chapeter 2 it can be said that for simple tasks, rotating driving axes are not needed, and the operators are able to cope with the standard fixed axes. However, when the task is more demanding, rotating axes, and especially axes based on the orientation of the device, appear to be superior compared to the fixed control axes.

Chapter IV

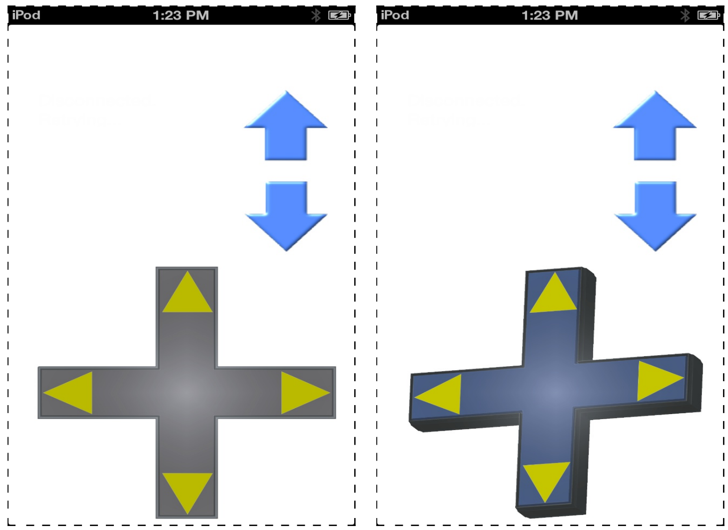
WELL-INFORMED OPERATOR STUDY

4.1 Introduction

The operator study discussed in Chapter 2 gave data on what kind of interfaces people like in general. However, the task they had to perform was a special case where movements only along the trolley and bridge axes were sufficient. In addition, the operators were not instructed how to use the interfaces, while this may give an idea how intuitive they are to use it, crane operators would normally get instructions on how to use the control interface. Also the standard pendent they were benchmarked against had input shaping to reduce the sway, which is not the current industry standard. The most promising interfaces used in the study in Chapter 2 were refined and used with an instructional session. Another inclusion in these refined interfaces is the addition of auditory feedback. Section 4.2 introduces the interfaces used in this well-informed operator study, Section 4.3 describes how the study was conducted, and Section 4.4 analyzes and presents the results.

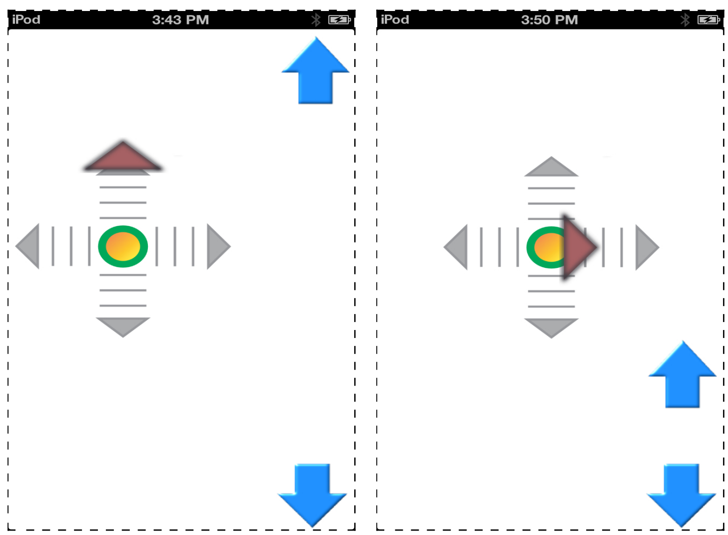
4.2 Interfaces

The D-Pad and Joystick interfaces were the preferred ones in most categories in the operator study discussed in Chapter 2. Refinements were done to make them even more user friendly. Figure 38 shows the action of the redesigned D-Pad, which has 3D effects incorporated in the design. The inspiration came from Apple's interfaces, where buttons are made to look as realistic as possible. In theory the users will have a more clear indication which command is being issued to the crane. In addition, the



(a) Not pressed (b) Forward-Left pressed

Fig 38: D-Pad

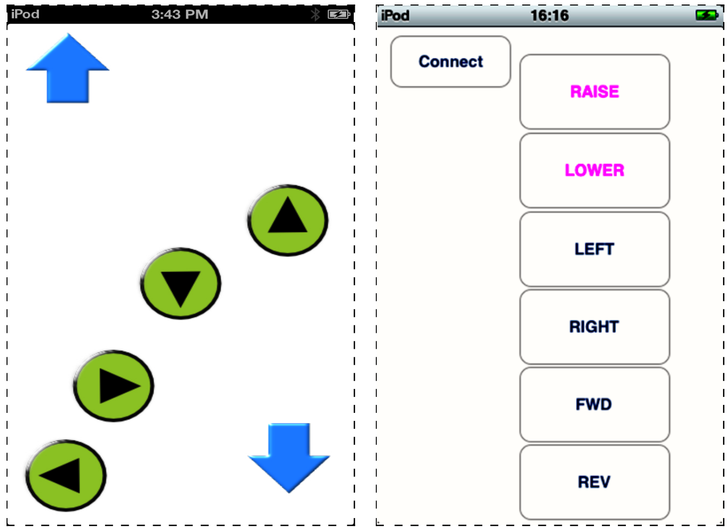


(a) Varying-Home Discrete D-Pad (b) Varying-Home Analog D-Pad

Fig 39: Varying-Home D-Pads

operator has the ability to perform diagonal movements by pressing the finger between the nominal directions, as can be seen in Figure 38(b). The Design is discussed further in Appendix B.

Another approach to the D-Pad was to give it the capabilities of the Varying-Home Joystick, which was introduced in Section 2.2. The idea is that the operator could

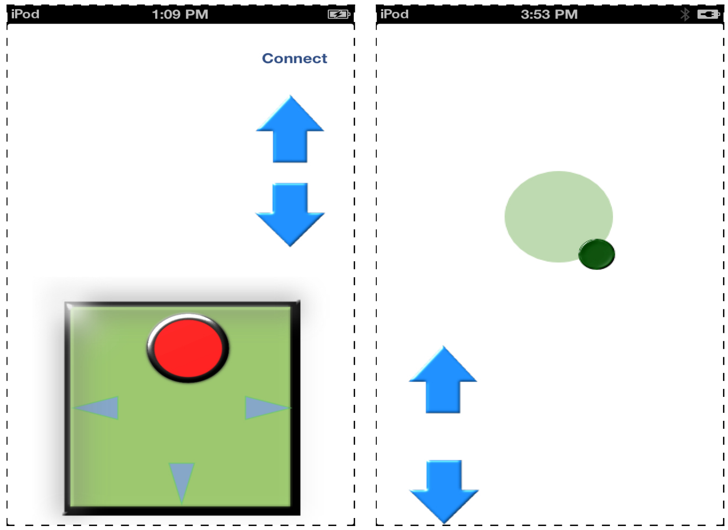


(a) Thumb Path GUI (b) Pendent GUI

Fig 40: Thumb Path and Pendent GUI

have the directional certainty of the D-Pad while not having to look down on the interface. When the operator places a finger on the touchscreen, that point is the new center for the D-Pad. When the user moves that finger past a certain threshold value in one of the Cartesian directions, a command in that direction will be issued to the crane. Everything will reset itself once the touch has ended. Figure 39 shows the two versions of the Varying-Home D-Pad. The interface depicted in Figure 39(a) has the ability to only give maximum velocity commands. In contrast, the interface in Figure 39(b), lets the users slide their fingers different amounts to determine the magnitude of the command. This puts the interface into the second interface category where the operator has the capability to change the magnitude of the command in pre-determined directions. The interface resembles the Sliders UI introduced in Section 2.2 which gave average performance in the operator study described in Chapter 2. However, the "varying home" capabilities should allow the operators not to have to worry so much about moving the correct slider and therefore to show better performance. The interfaced are discussed further in Appendix B.

The last new interface layout that is introduced in this operator study can be



(a) Joystick GUI (b) Varying-Home Joystick GUI

Fig 41: Joystick GUIs

seen in Figure 40(a). It is Called the Thumb Path GUI, and it belongs to the first interface category where the operators can only issue the preset magnitude in the predetermined directions. The buttons are laid such way that they lie on a trajectory that corresponds to the natural thumb movement of the operator's right hand. Figure 40(b) shows the Pendent GUI, Figure 41 shows the joystick layouts and Figure 42 shows the RC Control layouts that were introduced and discussed in Section 2.2. Note that the hoisting buttons are at different locations on all of the interfaces to evaluate whether the operators think there is a difference. The touchscreen device used in this operator study has a 4" screen rather than 3.5" that was used in the operator studies described in Chapter 2. All of the interfaces that are the same for both operator study have been modified to fit the bigger screen better, but the way they operate remained the same. The rotating axes that are based on orientation are applied to the D-pad and the Varying-Home Joystick as the two extremes to see how they compare to the rest of the interfaces. Furthermore, the resulting data can confirm or disprove that users prefer to have non-fixed driving axes. In this operator study two different types

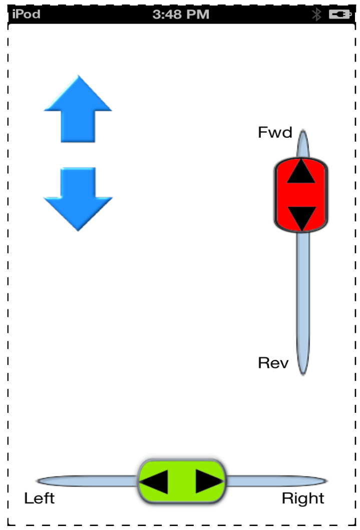
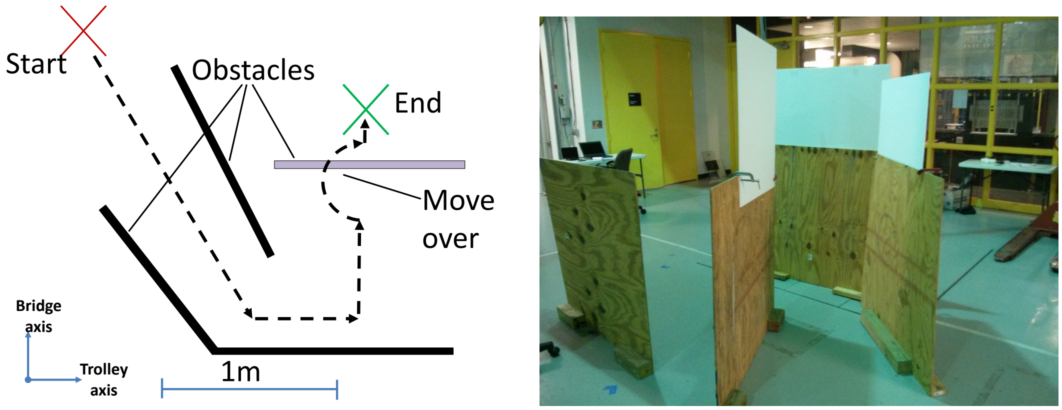


Fig 42: RC Control

of auditory feedback were provided on certain interfaces. The first type of feedback was a beeping sound that told the operator when they started and stopped issuing a command to the crane. The other feedback was a verbal notification, that told the operator which command was being issued ("Forward", "Reverse-Left" etc.) Table 1 shows which auditory feedback, if any was used with the interfaces.

Table 1: Auditory feedback on interfaces

Interface	Sound
Push-Button Pendent	-
D-Pad	verbal
Thumb Path	verbal
Var Home Joystick	-
Pendent	-
Joystick	nonverbal
Var Home Discrete D-pad	-
D-Pad w/ rot axis	-
Var Home Joystick w/ rot axis	nonverbal
RC Control	nonverbal
Var home Analog D-Pad	verbal



(a) top view (b) Operator's view from Start

Fig 43: Obstacle course

4.3 Human Operator Study

4.3.1 Setup

The course that was used for the operator study can be seen in Figure 43. The operators had to start with a diagonal move, then translate along the trolley axis and finally move along the bridge axis towards the end point. Near the end, they had to hoist the hook over a wall. From the operator study described in Chapter 2 it was found that if the task is easy, then there is really no need for rotating driving axes. This, however, is often not the case in the real world, where complex maneuvers have to be performed. It was also desired that the mapping from desired trajectory to input command be somewhat complex. This could be induced by requiring the operators to move about and change their heading. As can be seen in Figure 43(b) the walls of the obstacles were made high, so that the operators could not just stand in a single position, as they often did in the operator study described in Chapter 2. The obstacle course used in Chapter 3 when investigating which type of driving axes the operators preferred was used again for this test. Input shaping was added to all of the interfaces that were implemented on touchscreen devices. The Push-Button Pendent was used without input shaping to simulate the standard industrial setting. A 10-ton industrial crane at the Georgia Institute of Technology was used for the experiment.

4.3.2 Participants

Sixteen novice operators volunteered to complete this study. They were not compensated in any way.

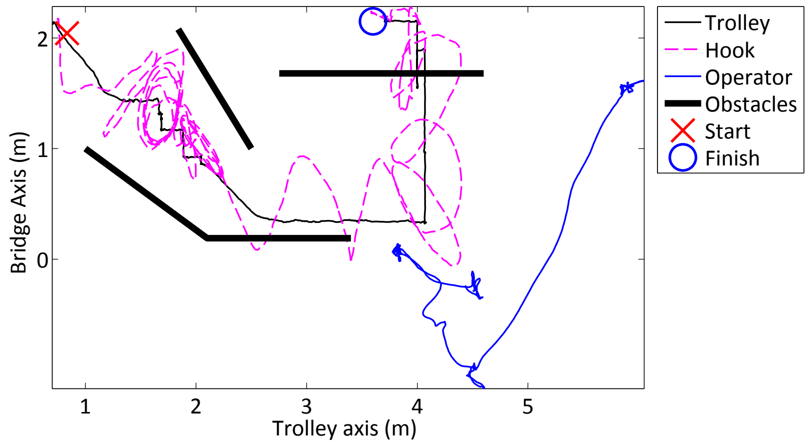
4.3.3 Testing protocol

All of the trials were done in random order to minimize the learning effects. After each trial the operators completed a qualitative questionnaire; a summary questionnaire was also completed after the end of the last trial. Each operator did a total of 11 trial runs (the Push-Button Pendent, 8 interfaces without rotating axes, and 2 interfaces with rotating axes). Prior to running the trials the operators received instructions on how to use each of the interfaces and were allowed as much practice time as they requested.

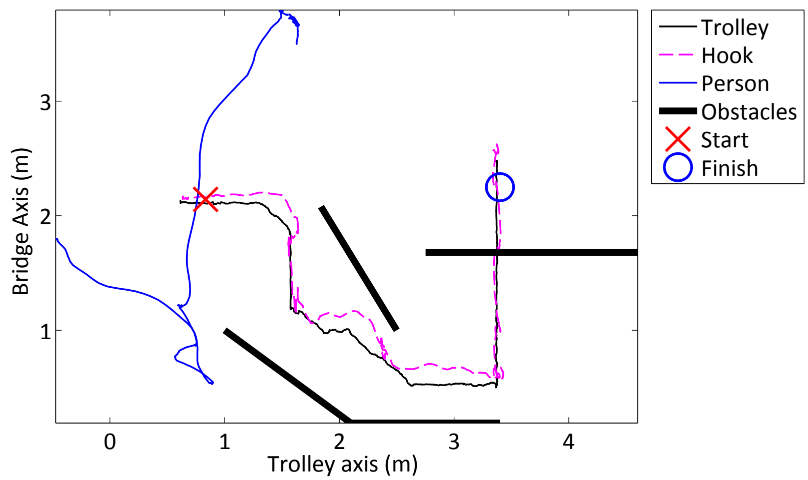
4.4 Results

Figure 44 shows two typical results. Figure 44(a) shows how hard the operators found the course with the standard Push-Button pendent. The payload often swung close to the walls and crashed into them. Figure 44(b) shows how the course was typically dealt with using the D-Pad. Even though the directions of the commands the operators could issue with the interface were limited, they turned out to be effective. The input shaping included with the touchscreen interfaces helped to reduce the hook's sway.

Figure 45 shows the mean completion times for each of the interfaces. The error bars indicate one standard deviation above and below the mean for every graph in this section. It is clear that the operators performed worst when using the Push-Button Pendent. The Analysis of Variance Test (ANOVA) indicated that there are significant differences in the data. Tukey's honestly significant difference test (HSD) showed



(a) Push-Button Pendent



(b) D-Pad

Fig 44: Examples of typical trajectories

that the Push-Button Pendent completion time was significantly different from all of the interfaces that were on the touchscreen devices with ($p < 0.0001$). Tukey's test also showed that the results with the RC Control interface, Varying Home Analog D-Pad UI, and the Pendent UI were significantly different from the interfaces with rotating axes ($p < 0.05$). None of the other completion times were proven to be significantly different from one-another at the 95% confidence level. The interfaces with the rotating axes had the best performance, followed by their static driving axes counterparts. The completion times for those interfaces did not significantly differ from one-another. Figure 46 shows that with the Push-Button Pendent, operators

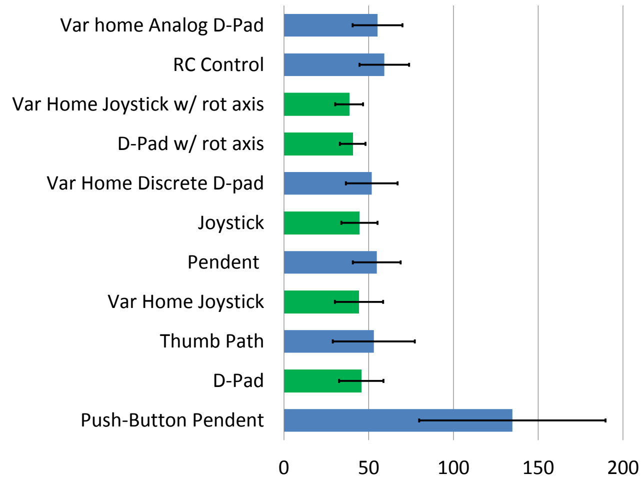


Fig 45: Average completion times in seconds (mean ± standard deviation in all figures)

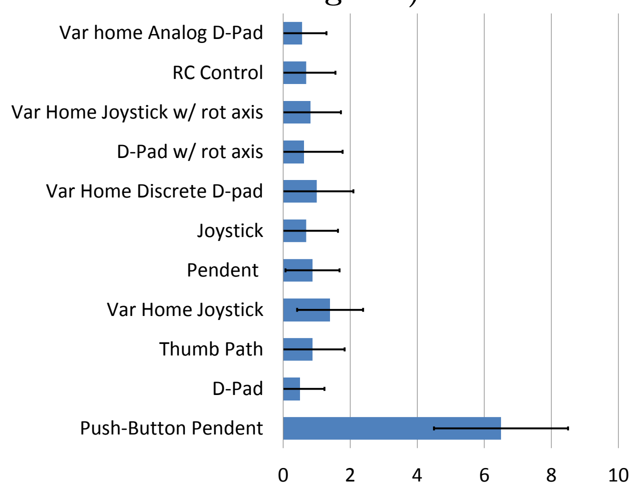


Fig 46: Number of collisions with obstacles

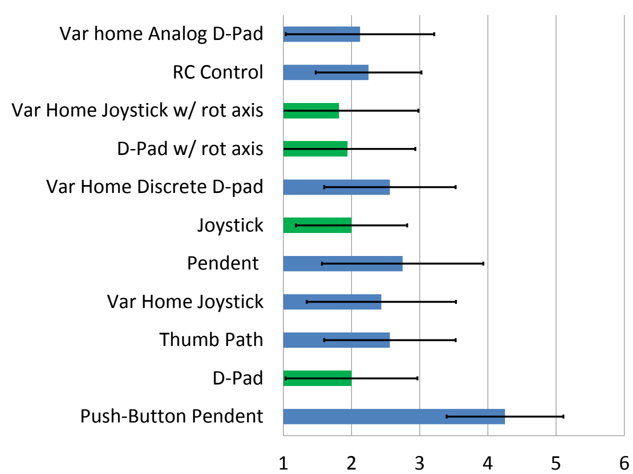


Fig 47: Ease of operation (1=very easy 6=very difficult)

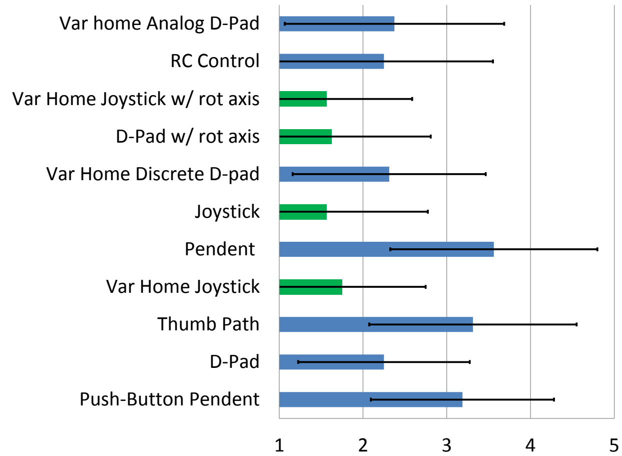


Fig 48: Finding Buttons (1=very easy, 6=very difficult)

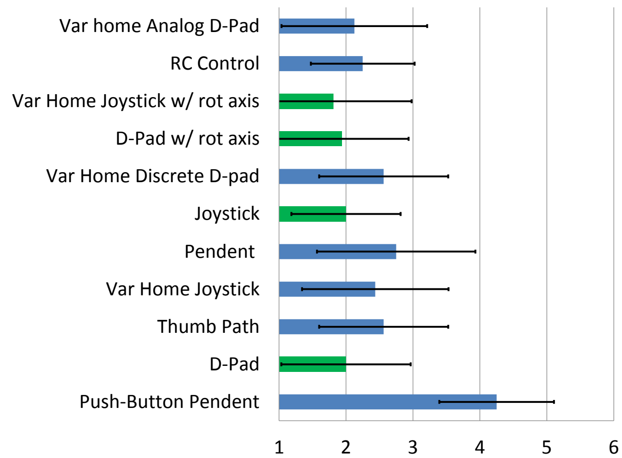


Fig 49: Confidence in pressing the correct button (1=very confident, 6=not confident at all)

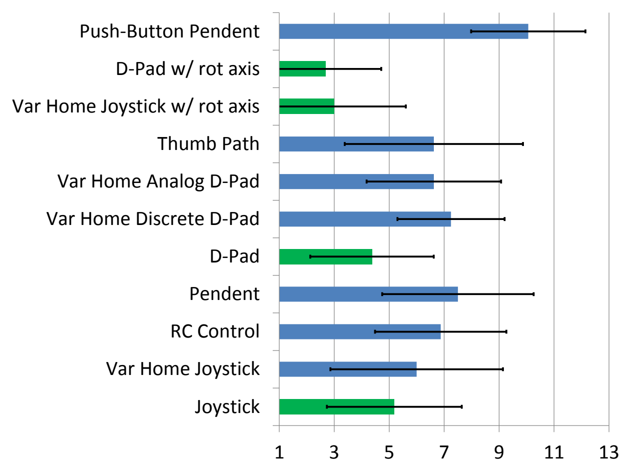


Fig 50: Ranking of the interfaces based on the operators from 1=the best to 11=the worst

experienced difficulty in keeping the hook from swinging against the walls; this was mostly due to the lack of input shaping. All of the other interfaces caused operators to have a minimal number of obstacle collisions.

Figure 47 shows how easy the operators considered the operation of the crane with the different interfaces. The results are very similar to the operator study in Chapter 2, and none of the newer proposed interfaces managed to be among the top interfaces. As the completion times suggested, the interfaces that used the rotating axes proved to be the easiest for the operators to use. Figure 48 shows how difficult the operators thought finding the buttons was. Although the subjects understood the concept of the “varying home” interfaces, they still reported that sometimes the wrong command was given to the crane (not the case for the Varying Home Joystick UI). This might have been a result of the short training they received. The different Joystick interfaces proved to be best along with the D-Pad with the rotating axes, where users reported that they often used only one command throughout the trial. The operators typically issued the “Forward” command and rotated the touchscreen device as needed.

Figure 49 confirms that the operators were more confident in the command they were issuing when the interface was static on the screen. The D-Pad and the Joystick were among the better interfaces. The Varying Home Joystick with the rotating axes was among the best because the operators did not have to change the command they were issuing as many times. Figure 50 shows the overall ranking the operators gave to the interfaces. It is not a surprise to see that the interfaces that were the best among all of the qualitative criteria are the ones that the users prefer overall. The interfaces with the rotating axes were chosen as the most preferred, followed by the D-Pad and the Joystick. These interface layouts also performed best in the operator study described in Chapter 2.

Table 2 shows the summarized results from the questionnaire that the volunteers filled out after the last trial run. It can be seen that the operators found the rotating axes very helpful. The users had interfaces with either no sound, simple beeps, or verbal feedback when they pressed and released the buttons. The users claimed that the sound effects did help somewhat and that verbal feedback was better than beep feedback. The data also indicates that the 3D effects on the D-Pad helped users to determine what command was issued, and that the layout of the hoist buttons had a small effect on the performance. The comments from the users suggest that they wanted the buttons to be located close together but with a large enough gap that a finger could not accidentally press the wrong button.

Table 2: Summary of the final questionnaire

	Average	Standard Deviation
Did the rotating axis help?	4.94	1.18
Were the sound effects helping at all?	3.63	1.45
Did the positioning of the hoist buttons affect the control or finding buttons in any way?	3.25	1.44
Were the 3D animations in any way helpful?	3.25	1.53
Was the verbal feedback more helpful compared to just sounds?	3.88	2.06

(1=not at all 6=a lot)

4.5 Future work

Testing needs to be done on a larger scale to prove statistically that these results can be applied to the general population. In addition, no data was gathered on how experienced and highly skilled crane drivers would cope with these human-machine interfaces. Such data might be crucial before implementing this technology widely in industry.

4.6 Discussion and Conclusion

The operator study showed that the touchscreen interfaces seem to be superior to the standard Push-Button Pendent used commonly in industry. Data indicates that users feel safer, are more in control, and produce much faster completion times. Data shows that the results vary from person to person and that it is hard to draw concrete conclusions from one interface layout to the other. However, two interface layouts seem to be associated with better performance than the others, and they are the D-Pad and the Joystick. With the inclusion of the data gathered from the operator study described in Chapter 2, where the same interfaces prevailed and the task was much easier, it can be assumed that those interfaces work the best in most situations the crane operator might encounter. The rotating driving axes seem to make the interfaces even more intuitive regardless of the interface layout.

Chapter V

MANUAL TRACKING USING TOUCHSCRREN INTERFACES

5.1 Introduction

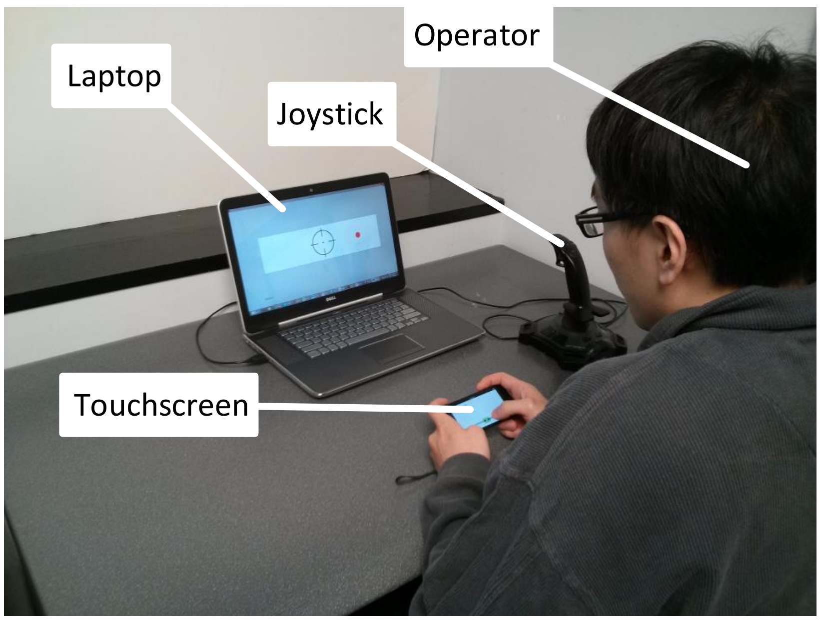


Fig 51: An operator performing the tracking task

A manual tracking task is a common way to investigate the transfer characteristics of a human operator. In manual tracking a moving target represents the reference input, and a cursor represents the controlled-element output that the human operator tries to keep as close as possible to the target. This chapter explores how interfaces implemented on a touchscreen device compare to the joystick, which is the most common type of interface used for manual tracking.

This study explores the relationships between interfaces, and human control behavior using data gathered from a human operator experiment. Section 5.2 describes the task, then Section 5.3 gives details about the operator experiment. Section 5.4 describes the Cross-over model used to describe the control behavior of the human and Section 5.5 analyzes the experimental results.

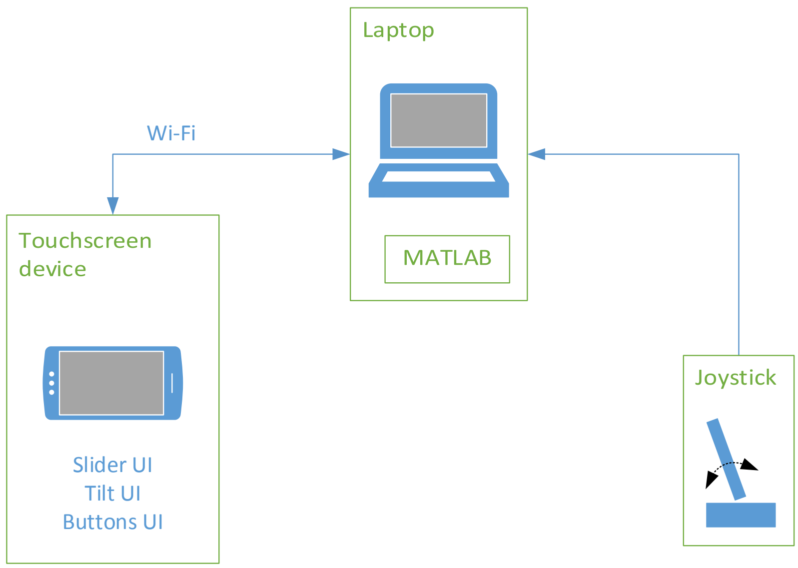


Fig 52: Testing Setup

5.2 Tracking Task

Previous studies have made extensive use of single-axis manual tracking tasks to investigate the control behavior of human-machine systems [24]. Figure 51 shows the basic setup. The human operator watches a display and attempts to track the moving target. There are two objects on the screen: one is a target that represents the reference input, and the other object is a cursor that represents the controlled-element output. The human can control the cursor with either an interface on a touchscreen device or with a joystick, as shown in Figure 52. The tracking program used here runs in MATLAB. The program ran at 30 frames per second, which is a standard video refresh rate where the human sees objects continuously moving. The control value from the joystick was obtained each frame. The round trip latency between the touchscreen device and the computer was measured to be less than the refresh rate of the screen. The program specifies which interface is active for each trial. Figure

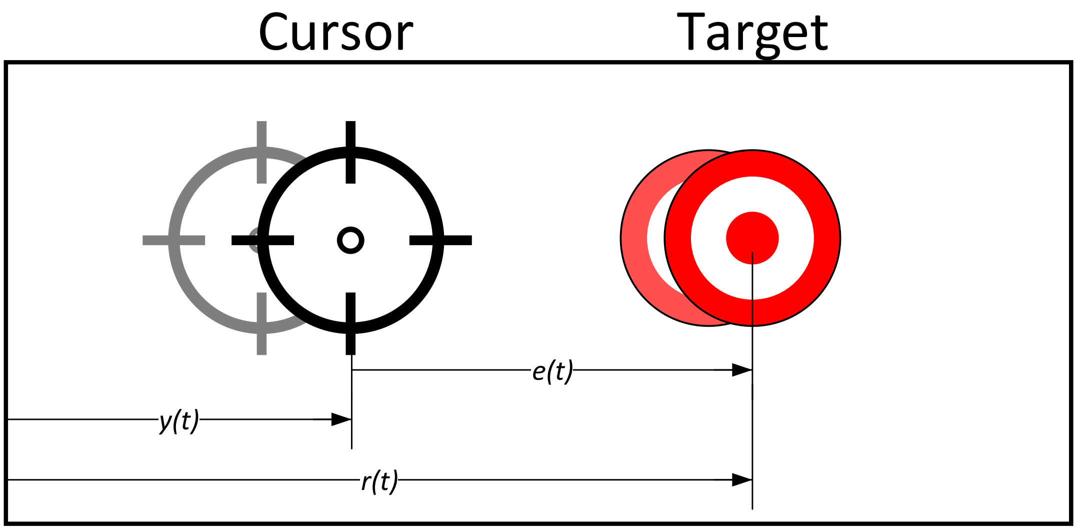


Fig 53: Pursuit Display

53 shows the pursuit display used in this study where both the target and cursor positions are independently displayed. $r(t)$ is the position of the target, $y(t)$ is the position of the cursor, and $e(t)$ is the distance from the cursor to the target. The goal for the operator is to keep the cursor as close as possible to the target.

The target motion must be complicated enough to appear random to the human operator, or else the operator can "cheat" by predicting the future behavior of the target. From past studies, it has been shown that the sum of 5 or more sine waves with arbitrary relative phase is unpredictable to human operators. While real-world tracking tasks rarely consist of summed sine waves, using them is a convenient way to generate an unpredictable signal that tests control behavior over a wide range of frequencies simultaneously.

A representation of the cursor dynamics can be seen in Figure 54, where m is the mass of the "cart", b is the damping constant, and $u(t)$ and $y(t)$ are the input to, and

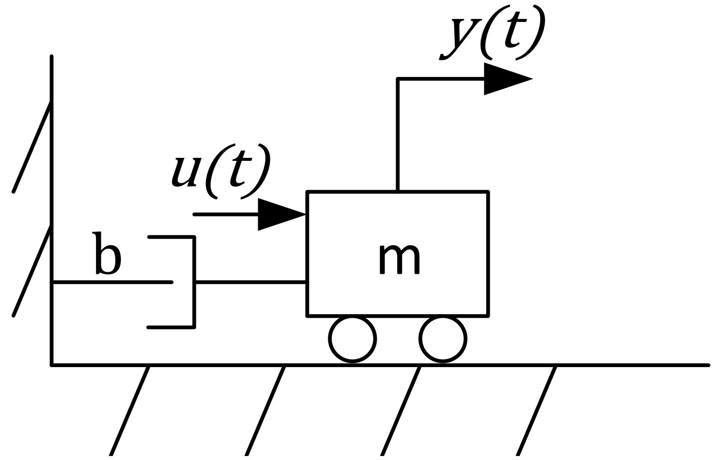


Fig 54: Model of the cursor dynamics

output of the system respectively. No flexible part was added to the cursor in this experiment so the system responds like a first-order lag.

5.3 Operator Experiment

5.3.1 Testing Procedure

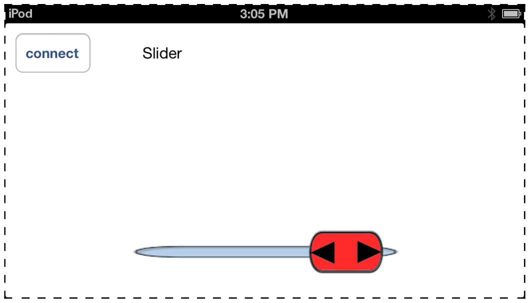
Fourteen volunteer human operators (4 female and 10 male) took part in the experiment. All of the participants were between the ages of 21 to 29 years. Although three operators said that they had used joysticks for some tasks in the past, they did not consider themselves experts. The others claimed they had no real experience with these kinds of interfaces. Subjects performed a series of tracking trials, each lasting 115 seconds. The first 15-second period allowed the operator to become familiar with the cursor dynamics. Only measurements from the final 100 seconds of the trial were analyzed. Before every test the display showed the name of the interface that would be used next. Each operator did one practice trial with each interface, then two measured tests with every interface in random order. After the manual-tracking tests, the subjects answered a series of qualitative questions.

5.3.2 Interfaces

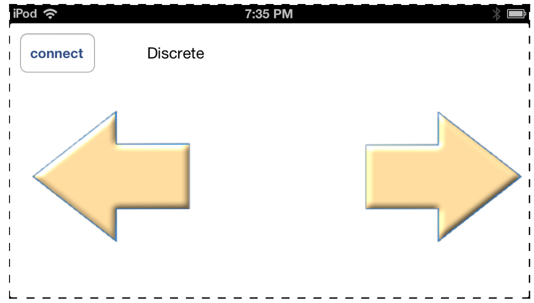
The MATLAB program chose automatically where to read data from. If a randomly selected interface was on the touchscreen device, then the program automatically sent an instruction packet to the device to choose the correct interface. The interfaces can be seen in figure 55. The physical joystick was a Logitech "Attack 3". The slider interface, seen in figure 55(a), is meant to resemble the joystick on a 2D display. The device plays a loud beeping sound and resets itself to the zero position if the device detects that the human has let go of the slider. The finger controlling the slider does not have to be on the button because only the width-wise coordinate is monitored. The Discrete Buttons controller, seen in figure 55(b), sends the maximum positive or negative command when the respective button is pressed; at any other time the command is zero. The final, Tilt controller can be seen in figure 55(c). When this interface is enabled, the touchscreen device measures the roll angle of the device to determine the command. The operator sees a button moving while the device is being tilted. The maximum command value is reached when the device is tilted $\pm 50°$. The maximum command given from each of the touchscreen controllers was scaled to the maximum command from the physical joystick.

5.3.3 Assumptions and Limitations

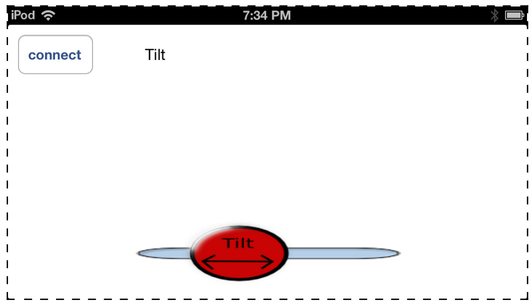
All subjects were relative novices, meaning they did not have extensive experience with tracking tasks of this kind. In general, novice operators exhibit lower performance and more variability in performance than highly-trained operators. This study is intended to investigate the performance of an "average" human operator with the different interfaces. It is less concerned with the performance of highly-specialized operators (such as professional crane operators, racecar drivers, and aircraft pilots), who would be more likely to adjust abnormally quickly to new conditions, or possibly to be hindered by previous training due to negative transfer [49].



(a) Slider UI



(b) Discrete Buttons UI



(c) Tilt UI

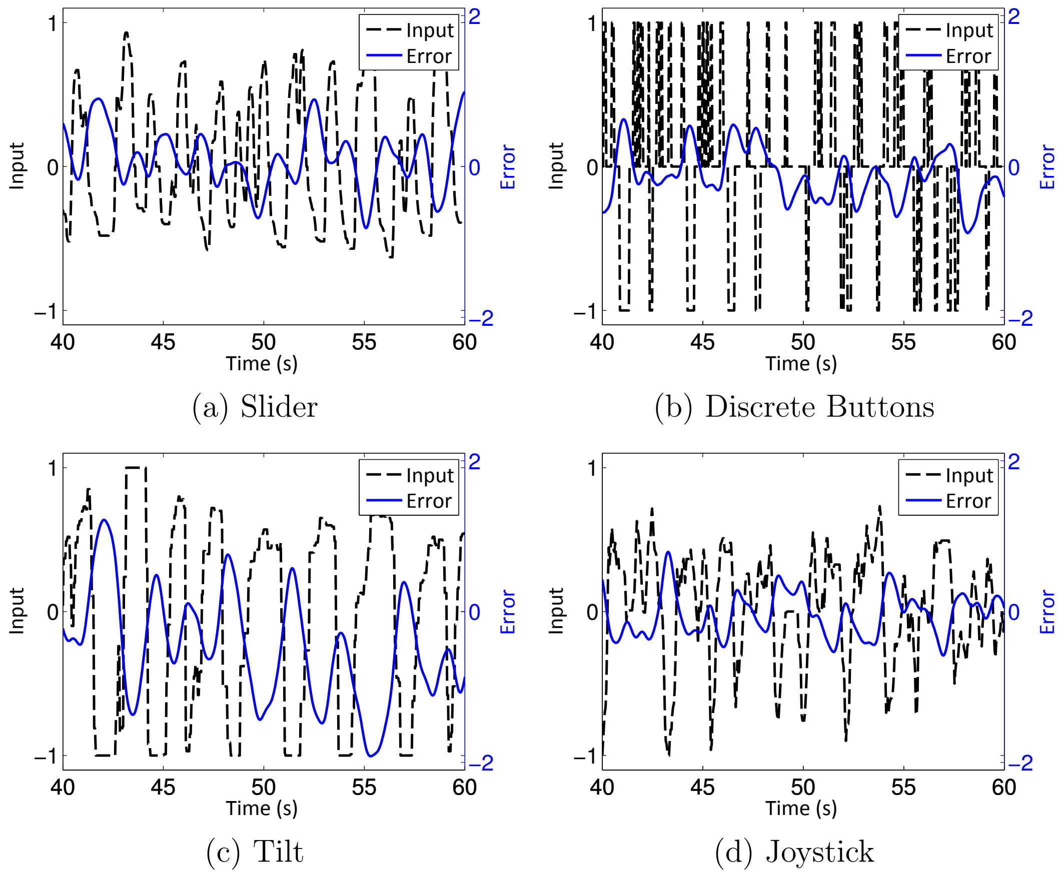
Fig 55: Touchscreen interfaces

5.4 The Crossover Model

According to [24] the human in the loop adapts his behavior to the plant's characteristics, which results in a Human-Machine transfer-function in the region of the crossover frequency w_c:

$$G(s) = G_h \cdot G_p = \frac{Ke^{-\tau s}}{s}, \tag{6}$$

where $s = jw_c$, G_h is the effective transfer model of the human behavior as a linear feedback controller, G_p is the plant of the controlled system, τ is the effective delay of the system, and $K = \omega_c$ represents the open-loop gain. The crossover frequency provides a measure of the frequency band the human can follow. The output of the Human-Machine system is only based on the difference between the reference position and the actual position of the $e(t) = r(t) - y(t)$, the open-loop gain K, and the effective time delay of the open-loop system τ. The cursor dynamics shown in Figure



(a) Slider (b) Discrete Buttons

(c) Tilt (d) Joystick

Fig 56: Typical responses to error

54 are described by the transfer-function:

$$G_p(s) = \frac{1}{s(s + \frac{b}{m})}, \tag{7}$$

where b and m are the plant's mass and damping coefficient respectively. The transfer-function of the human can be described as:

$$G_h(s) = Ke^{-\tau s}(1 + T_z s), \tag{8}$$

where K is the effective gain of the human and T_z is a zero of the transfer function [24]. The parameters in (7) are known, but those in (8) vary somewhat from person to person.

5.5 Results

Figure 56 shows typical ways that the operators used the interfaces. The solid blue line shows the difference between the target and the cursor and the dashed black line shows the response from the human. The way people tried to minimize error differs from one interface to another. It can be seen from Figure 56(b) that the command sent out with the Buttons controller is very different from every other method; however, the error was kept roughly at the same level compared to the other interfaces. It can also be seen that the joystick allowed for much faster and more precise reaction when compared to the Slider and the Tilt controllers.

5.5.1 Tracking Performance

The tracking performance is quantified by the root-mean-squared (RMS) tracking error during the measured 100 second test period:

$$e_{rms} = \sqrt{\frac{1}{T}\int_0^T (e(t))^2 dt}, \tag{9}$$

where e_{rms} is the tracking error, T is the trial duration, and $e(t)$ is the difference between the target and the cursor. Figure 57 shows the mean tracking performance for each of the interfaces with one standard deviation above and below the mean. As expected, the joystick was the best performer, followed by the Discrete Buttons controller, the Tilt, and finally the Slider. The results are not surprising, as the joystick is a familiar device and offers some haptic feedback. The Tilt controller produces slower response to error because the entire device has to be tilted precisely, and haptic feedback is limited. The slider performed the worst mainly because the operators were not sure what command it was issuing. This effect is discussed further in Section 5.5.2.

Two tests were used to determine statistical significance between the RMS tracking errors: a one-way analysis of variance (ANOVA) and Tukey's honestly significant difference test (HSD). It was found that the difference between the Tilt controller and the Buttons controller was not statistically significant (p=0.058). The other comparisons gave p values well below 0.05.

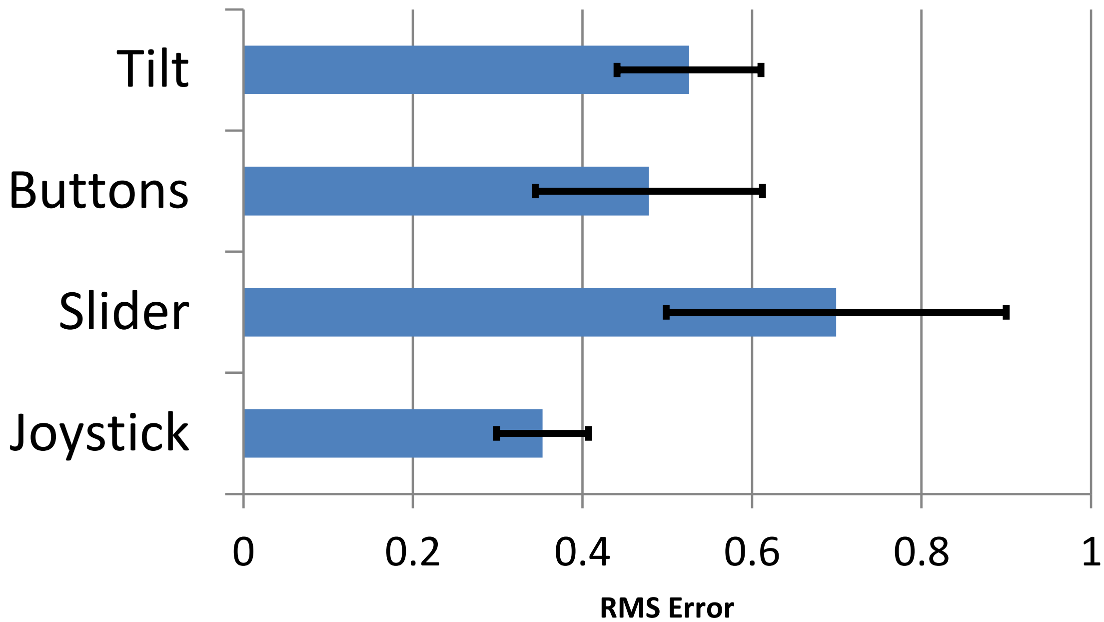


Fig 57: Results (mean ± standard deviation in all figures)

5.5.2 Qualitative Responses

Figure 58 shows how confident the users were in the command they were issuing. It can be seen that with the Slider UI they had little confidence in the command while they had high confidence in commands issued with the joystick, which was considered the best of the interfaces where the command can vary. Figure 59 shows how the operators compared the interfaces on the touchscreen device to the traditional joystick. The significance of that figure is that even when the quantitative performance is worse, people thought that the Discrete Button controller was as good as the joystick; this result is consistent with the results in [20]. The figure also shows that the results in Section 5.5.1 compare well with the assessment the operators gave for the interfaces.

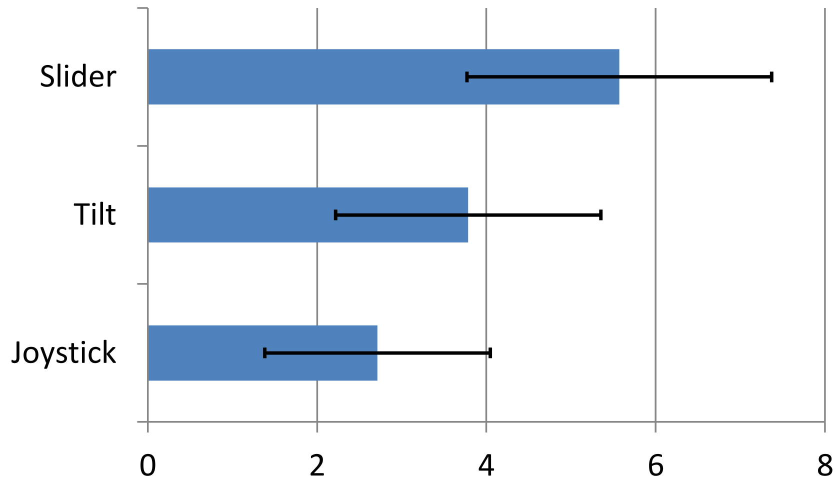


Fig 58: How confident were you in the command you were issuing?

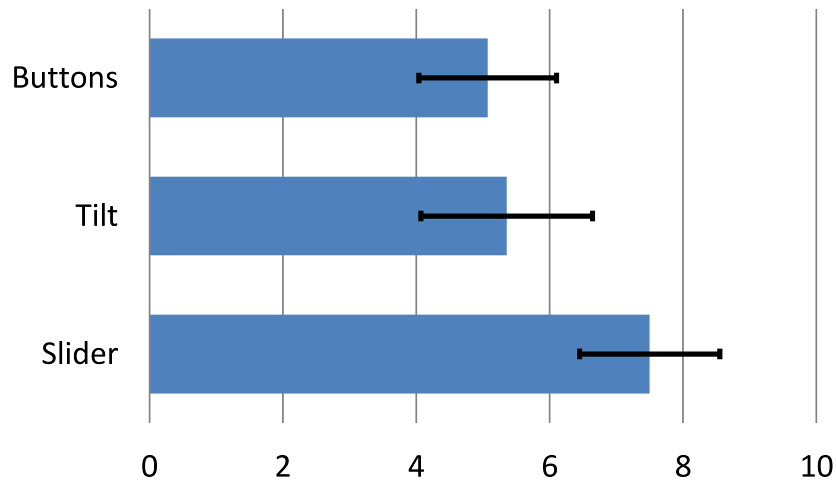


Fig 59: How did the interface compare to the Joystick? (1=much better 5=about the same 10=much worse)

5.5.3 The Parameters in the Crossover Model

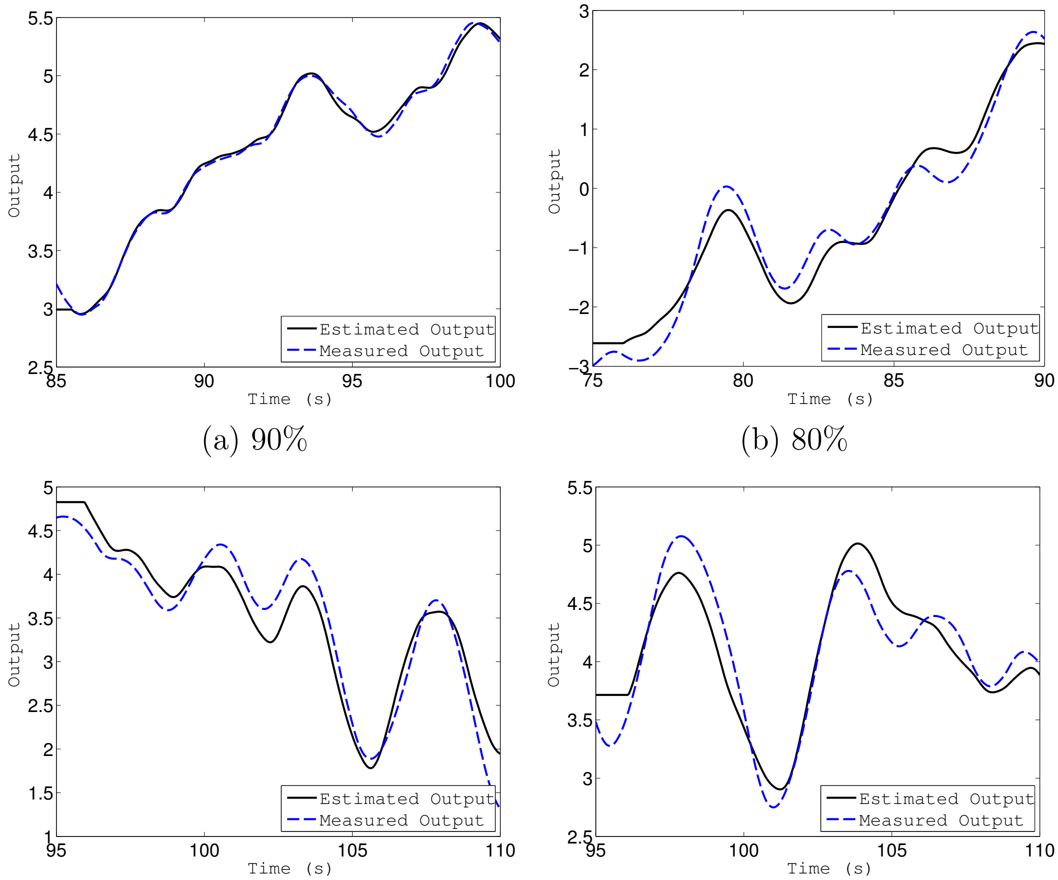
Using MATLAB's System Identification toolbox and its iterative prediction estimation (pem) algorithm, it was possible to determine the unknown parameters in (8). Because the human tracker is inherently nonlinear it is reasonable to evaluate the data in subsections of the 100 second test window. The best result was obtained when the data was broken into fifteen second sections with 5 seconds separating each group. The quality of the fit to the model was estimated based on the normalized mean square error given by:

$$Fit = 100 \cdot (1 - \frac{\|y_h - y\|}{\|y - \bar{y}\|}) \tag{10}$$

where y is the measured output, and y_h is the output of the estimated model. So a Fit of 100% is a perfect model and $-\infty$ is the worst possible model. Figure 60 illustrates how well the estimated models matched the actual data. The measured output is compared with the output of the system calculated with the estimated crossover model parameter for that subsection of data. It can be seen that 90% is nearly a perfect fit and 50% still gives a good estimation. To estimate the mean parameters in the crossover model, only data that matched better than 50% were taken into account. The parameters were then averaged per trial. The average results for the interfaces can be seen in Table 3. It can be seen that the Joystick has the largest gain, followed by the Discrete Buttons Controller, and then the Slider and the Tilt which are close to being equal. The transport delay is shortest for the joystick and the Buttons controller, while the Tilt and the Slider exhibit a lower value. The larger gain values and shorter time delays of the human test subject would allow higher frequencies to be tracked [24]. A larger time delay could be an effect of the operators needing more time to do mental computations due to the unintuitive interface. These results follow the ones given in Section 5.5.1 fairly well. These results indicate that given the same plant to control, the interface has an effect on the human-machine system's gain and delay constants.

Table 3: Comparison Between Interfaces

	$\overline{K}$	$\bar{\tau}$	$\overline{Fit}$
Slider	0.97	0.74	64.8
Buttons	1.13	0.54	67.2
Tilt	0.92	0.73	68.6
Joystick	1.21	0.53	72.9



(a) 90% (b) 80%

(c) 70% (d) 50%

Fig 60: Matching the model to the measured data

5.6 Discussion

The data indicates that the joystick is the best interface in highly dynamical control situations. However, it can also be seen that with the touchscreen controllers the operators were able to track the error fairly well even though the wrist is much more dexterous than the thumb. With the Buttons controller the operators exhibited the same transport delay as with the joystick, which is not surprising because it was easy to simply place the correct thumb down on the interface. The major drawback with that interface is that for small errors it seems unintuitive to issue a maximum amplitude command, and this is reflected in the fact that the Buttons controller has a lower gain to the error. The Tilt controller utilizes the dexterity of the wrists, but because the tactile feedback is not as good compared to the joystick, the interface performed worse. The Slider controller performed the worst out of the interfaces tested in this chapter but still managed to track the error quite well, because for most of the time only a coarse command was needed, and the operators managed to tell the far left of the screen from the far right. The operators had trouble when only a small command was needed, because it was hard for them to tell whether the command they were giving was in the correct direction.

5.7 Conclusions

A manual-tracking experiment was conducted to investigate operator performance using three different kinds of interfaces on a touchscreen device, and then comparing them with a physical joystick. It was found that the joystick was superior to the touchscreen device in terms of tracking error. In addition, the human operator exhibits the highest gain and a low time-delay using the joystick allowing to cope with error the best. However, the results indicate that the touchscreen devices were still capable of tracking error well and for systems with slower dynamics they could be a good solution as the primary controller.

Chapter VI

CONCLUSION

The touchscreen user interface is an inherently dynamic device that is becoming ubiquitous. The touchscreen's ability to adapt to the user's needs makes it superior to more traditional haptic devices in many ways. Most touchscreen devices come with a very large array of sensors already included in the package. This gives engineers the means to develop human-machine interfaces that are very intuitive to use.

This thesis presents research that was done to develop a good touchscreen interface for industrial crane control for users who do not have substantial experience. To generalize the research, testing also determined how touchscreen interfaces compare to the traditional joystick in highly dynamic tracking situations using a manual tracking experiment.

Three separate operator studies were conducted to investigate touchscreen devices for crane control. The data suggests that the touchscreen interfaces are superior to the standard Push-Button Pendent used commonly in industry. Data indicates that users feel safer, are more in control, and produce much faster completion times with the touchscreen devices. Two interface layouts, out of many tested, seemed to be the best in two very different operator studies.

In addition, based on the operator studies it can be seen that for simple tasks, rotating driving axes on a crane are not needed and the operators are able to cope with the standard fixed axes. However, when the task is more demanding, rotating axes and especially axes based on the orientation of the device, are superior to fixed control axes by making crane control more intuitive.

It is worth remembering that all of the operators who volunteered for the operator studies were novices. If these controllers were implemented in industry, then crane operators with experience might not adjust to these kinds of changes. No data was gathered on how experienced and highly skilled crane drivers would cope with these interfaces. Such data might be crucial before implementing this technology widely in industry. It was shown, however, that novice users have no problems with these interfaces.

A manual-tracking experiment was conducted to investigate operator performance using three different kinds of interfaces on a touchscreen, and then comparing them with a physical joystick. It was found that the joystick is superior to the touchscreen device in terms of tracking error. In addition, it was found that out of the interfaces implemented on the touchscreen device, the human operators performed best with a discrete button layout, which a caused the same overall transport-delay as the joystick but with a lower gain to the error. The results indicate that the touchscreen interface is a viable controller, and, for systems with slower dynamics, such interface could be a good solution as the primary controller.

In Appendix A this thesis shows that the touchscreen interface also shows great promise for allowing users to navigate through interactive textbooks. Nine widgets were developed for an interactive mechanical design textbook that is meant to be delivered via tablet computers. Those widgets help students improve their technical writing abilities, introduce them to tools they can use in product development, as well as give them knowledge in how some dynamical systems behave. In addition, innovative touchscreen applications developed for judging a design competition illustrate the way portable computing devices are changing the way we do things by making certain tasks less cumbersome and time more friendly.

Appendix A

TOUCHSCREEN USES IN EDUCATION

A.1 Introduction

The tremendous success of tablet computers such as the iPad and numerous smartphones has led to a revolution in portable computing. Many universities, high schools, and elementary schools are capitalizing on this revolution by generating curricula that exploit tablets – portable touchscreen computing devices such as the iPad. While these tablet devices have been available for only a short time, results are already showing that the devices offer interactive functions that improve learning.

Because the use of tablet computers in education is a very fresh topic, there is very little data published. Efforts to integrate iPads into classrooms have generally pursued two goals: to improve student motivation and to improve learning. Liu et al. developed an iPad-based signal-processing project to enhance an electrical engineering course at Arizona State, and found that the activity improved student, enthusiasm as well as learning outcomes [23]. Perez et al. found that student grades and student satisfaction improved when students were provided with iPads, even if those iPads had no particular software for the courses in which they were issued [35]. However, Perez did not evaluate learning outcomes in particular courses. Using tablet computers rather than iPads, Oostveen studied the work of students who were not in the sciences and obtained mixed results, suggesting that the way students interact with tablet devices is an important factor in their overall outcomes [29]. Weisberg reported a project in which undergraduate business students were given a variety of digital readers in order to compare their different experiences and outcomes with those of students using a traditional hard copy textbook [48]. Here again results were

Fig 61: Cover of an iBook

mixed, as students who used the different computer devices had outcomes that were similar to those seen in students who used traditional textbooks.

Findings indicate that students respond well to touchscreen tablet computers such as iPads when those devices offer some type of interactive capacity that addresses the students' course goals. At the time these studies were conducted, interactive projects had to be developed by hand, and interactive textbooks were not widely available. The problem that is revealed in these curriculum development efforts is that interactive textbooks must move beyond the static display of printed words, equations, and figures that are typically seen when traditional textbooks are converted for display on computer screens. Features that distinguish interactive textbooks include: embedded videos that can be viewed with the tap of a finger, picture slideshows, user-controlled simulations, and interactive forms that accept user input and provide immediate feedback. Like all components of textbooks, such interactive elements must illuminate the course material, and they must do so in a new way. Because the concept of an interactive textbook is still relatively new, instructors must develop their own interactive materials as best they can, without "industry" standard procedures.

An interactive textbook offers many capabilities, and it requires both authors and

Fig 62: Chapter Format

students to reconsider how a book looks and works. Figure 61 for example shows an iPad opening up the interactive textbook discussed in this chapter. Figure 62 shows the format of the opened book. The figure shows the first page of Chapter 1 of the textbook. Near the bottom of the page are small figures that preview the next several pages of the chapter. The user is able to jump ahead several pages by simply touching one of the small icons showing the next pages. At the very bottom of the screen is a row of dots that allow the user to jump to other chapters. The next section of this chapter describes how a textbook can take advantage of the interactive capabilities provided by the iBooks environment. Section A.3 documents and illustrates the features and advantages of such a book created for introductory mechanical design students. Section A.4 describes two applications that were developed to judge a mechanical design competition.

A.2 Team Development

The interactive book discussed in this chapter started as a traditional textbook that was written by Drs William Singhose and Jeffrey Donnell. Dr. Singhose is a mechanical engineering professor at Georgia Tech. He teaches courses in mechanical

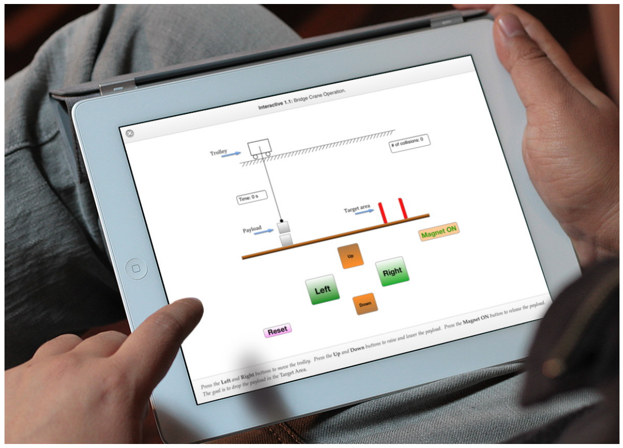


Fig 63: Interactive Bridge Crane Simulation

design, system dynamics, and controls. Dr. Donnell is the coordinator of the Frank K. Webb Program in Professional Communication. Dr. Donnell brings technical writing instruction and technical presentation instruction to the undergraduate and graduate classrooms and labs. He also teaches an advanced writing course that helps graduate students prepare thesis proposals, manuscripts for publication, and presentations for professional conferences. While these two authors were able to create a traditional textbook, they lack the skill set and time to develop and integrate interactive elements.

A.3 Interactive Features

The program iBooks Author, distributed at no cost by Apple, allows authors to easily insert interactive elements, generally described as "widgets," into their books. However, creating these interactive elements is a programming challenge. For example, if an interactive dynamic simulation is to be inserted, then there is no shortcut for creating the simulation. The dynamic mathematical model must generated, the interface must be developed, the real-time commands that are received through the interface must be integrated into the model, and then the output of the simulation must be reflected in the visual representation. The widgets discussed in this section were programmed in Apple's Dashcode environment. By default, Apple's iBooks author lets users insert 3D models, picture galleries, video files, interactive multiple-choice or drag-to target questions, slideshows, and overlays just by dragging them into the book. The next sections describe the interactive features that were developed for the interactive mechanical engineering book.

A.3.1 Widget Classifications

In this thesis the widgets are divided into three categories where very distinct challenges are addressed. The first category includes real-time interactive simulations of physical systems. The reason for these widgets is to give students better understanding of how physical systems behave. The users can be asked to either change some parameters in the setup or to control parts of the system. The second category, Interactive charts, contains widgets that introduce tools that are used when designing products. These widgets ask the students to complete tasks and they get the evaluations. Another way to utilize this category of widgets is to have the students use the widgets on their own design tasks and have the option to save the results. The third category contains widgets that help the students improve their technical writing abilities. Users can either browse the instructions on how technical documents need to be written or do exercises designed to help produce meanignful and concise sentences and sections.

A.3.2 Real-Time Interactive Simulations

Figure 63 shows an interactive real-time simulation of a bridge crane. Near the bottom of the screen are buttons that allow the user to move the overhead trolley of the crane. They can move it left or right. They can also raise and lower the crane payload by pushing the **Up** and **Down** buttons. The goal of the simulation is to give the user a “hands-on" experience in driving a crane. They quickly learn that it is difficult to control the payload because it swings every time a **Left** or **Right** control button is

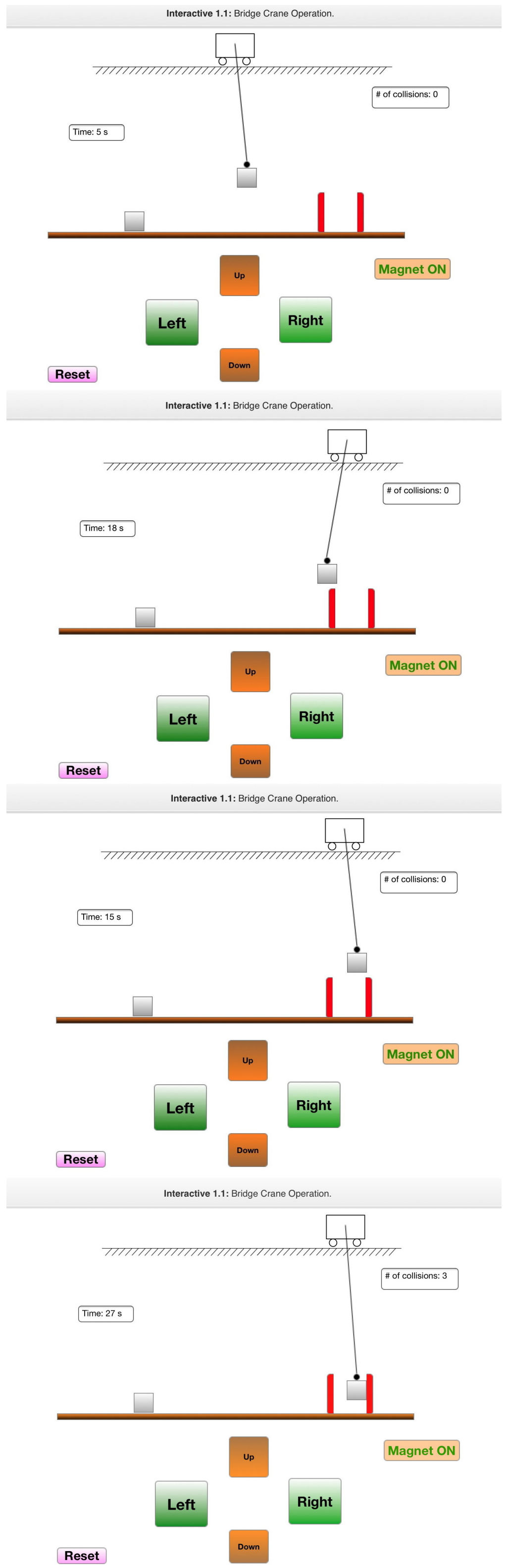


Fig 64: Progression of Crane Simulation

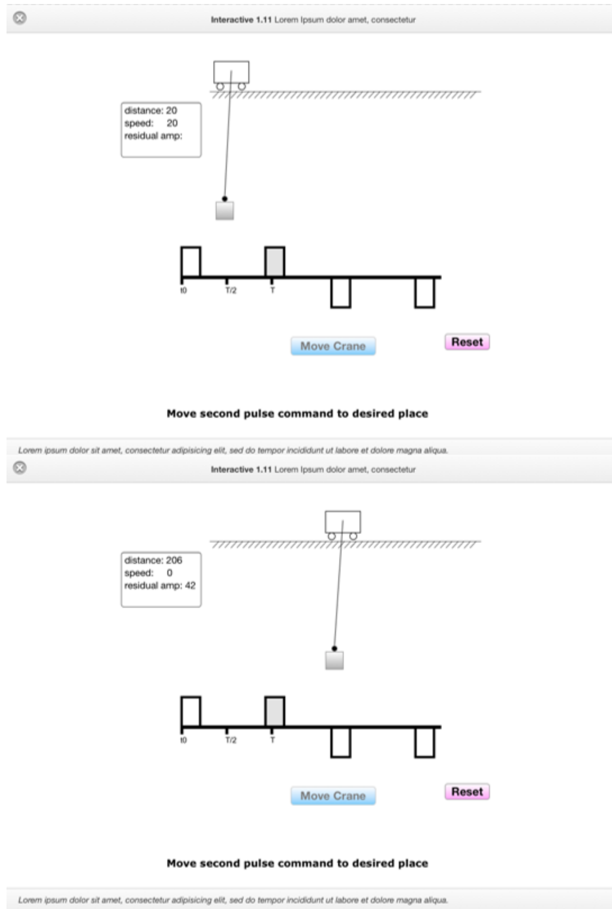


Fig 65: Command shaping example

pushed. The instructions that go along with the simulation challenge the user to pick up the payloads and safely deposit them in the area between the two red walls shown on the right side of the simulation screen. A progression of one such trial is shown in Figure 64. With a little practice the user can usually develop the skill to control the payload swing and safely lower the payloads into position. To help users monitor their progress, the widget displays the time it has taken for the students to do the tasks, and it also shows the number of collisions that have occurred.

Figure 65 shows a progression of a trial of a widget which is meant to teach students of a controls course how to handle the sway of the pendulum by adjusting the timing of a 2-pulse command an adjustment that represents input shaping. Once they have settled on a position they will press "**Move Crane**". The simulation will run and the

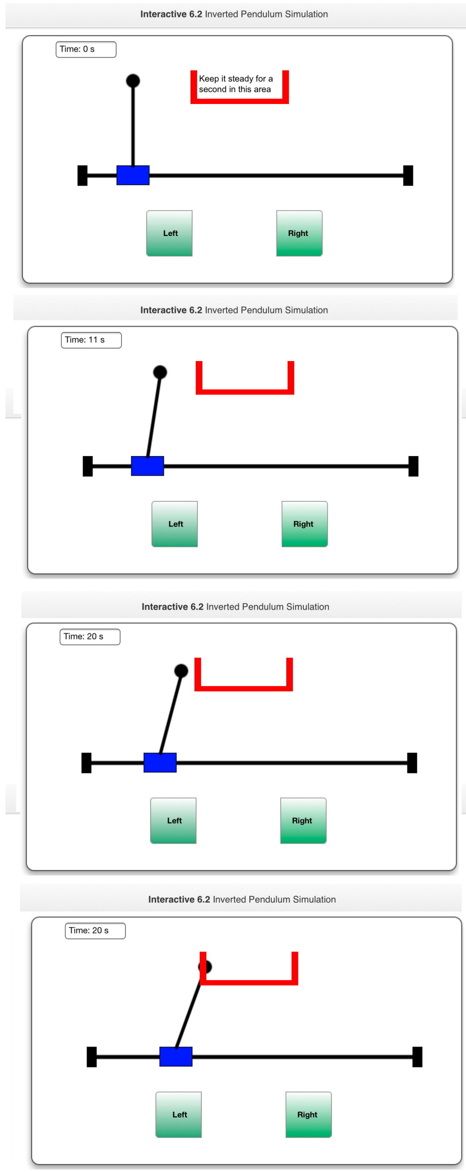


Fig 66: Progression of Inverted Pendulum Simulation

students will see how far the crane travels and the amplitude of residual vibration. During the motion, the display will shows how fast the crane is moving in real-time.

The book also contains an interactive simulation of the inverse of a crane - an inverted pendulum. This simulation is used to illustrate the difficulty of controlling such unstable systems over and beyond the difficulty of controlling a crane. The simulation is used in connection with pictures and videos of a commercially-available inverted pendulum - the Segway Personal Transporter. The instructions that explain the inverted-pendulum simulation challenge the user to move the inverted pendulum to the middle of the screen and maintain it balanced within a target area delineated by red walls. A progression of such a simulation is shown in Figure 66. This hands-on experience is virtually impossible to master - the pendulum usually falls over in a short period of time. This experience provides a nice complement to the crane simulation.

These simulations are critical for interactive textbooks, because they realistically represent engineering concepts, while providing entertaining interactions for the users of the textbook. The development of such interactive simulations must be a top priority for authors of engineering textbooks.

A.3.3 Interactive Charts

Introductory mechanical design classes try to teach students basic methods to understand design problems, develop conceptual solutions, and evaluate the potential solutions that they generate. To guide students through these fundamental steps, the course usually teaches the students a number of charts and matrix tools. Students often feel that these tools are uninteresting and lack utility, in part because the textbooks and examples cannot provide interactive experiences to support the students' learning. In order to more actively engage the students with classroom material concerning these types of design tools, several interactive charts were developed. These interactive displays require the user to enter information, and then the chart gives them feedback on their choices. Here again, the students actively interact with the chart, and by doing so they develop a better understanding of the classroom topic.

One of the interactive charts is a morphological (morph) chart. That is a fundamental tool for generating large numbers of conceptual designs. Figure 67 shows an interactive morph chart. The chart is filled with conceptual designs for an aerial lift that allows people to work at elevated heights. It lists the required product sub-functions

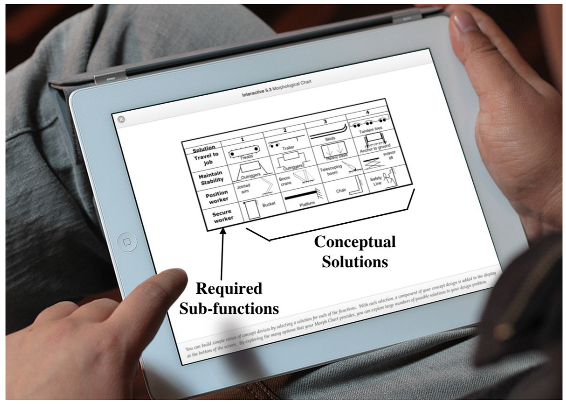


Fig 67: Interactive Morphological Chart - Initial

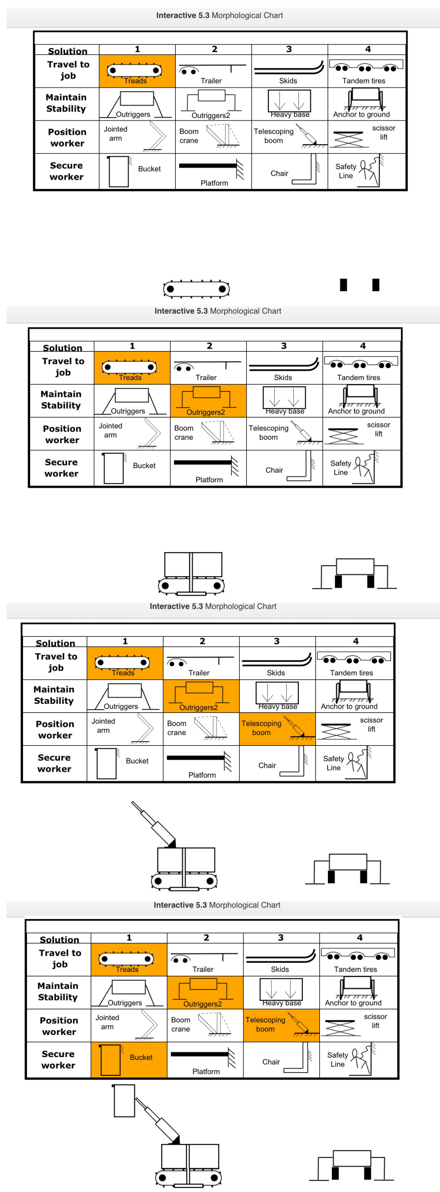


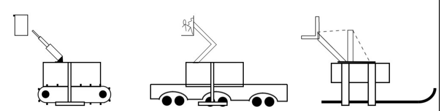
Fig 68: Interactive Morphological Chart

	Design your machine	Design your machine	Design your machine
Criteria	1	2	3
Payload Capacity			
Workspace Size			
Platform Oscillation			
Tip-over stability			
Ease of Transport			
Ease of Use			
Total	0	0	0
Relative total	0	0	0

4=very good, 3=good, 2=satisfactory, 1=just tolerable , 0=unacceptable

Reset

Fig 69: Interactive Evaluation Matrix - Blank



Criteria	1	2	3
Payload Capacity	3	4	2
Workspace Size	4	3	2
Platform Oscillation	2	3	3
Tip-over stability	3	4	3
Ease of Transport	4	1	2
Ease of Use	3	2	2
Total	19	17	14
Relative total	3.17	2.83	2.33

4=very good, 3=good, 2=satisfactory, 1=just tolerable , 0=unacceptable

Reset

Fig 70: Interactive Evaluation Matrix - Completed

in the first column on the left, and it shows graphical representations of potential solutions for each sub-function in the columns to the right of each sub-function.

After concepts have been entered into a morphological chart, they can be combined in various ways to create conceptual designs for the entire product. Many alternative designs should be created in the early stages of the conceptual design process, and the morph chart makes it easy to create various combinations from the conceptual designs in the chart. The chart allows the user to click on any design in each of the sub-function rows. When the design concept is selected, that component of the design appears at the bottom of the page. As the user selects concepts from each row, the figure is updated with the selected sub-function design. Figure 68 shows one such progression through the chart and the associated drawing construction at the bottom of the page. Using this tool, the user can rapidly create a large number of different conceptual designs.

When several conceptual designs have been created, the design team needs to evaluate them based on how well they meet the customer needs. A simple tool to perform this comparison is simply a chart that adds up how well each design satisfies the customer needs. These charts are generally referred to as Evaluation Matrices. Figure 69 shows the interactive evaluation matrix developed for the book. Across the top are boxes where candidate designs are entered. The rows below the concepts are labeled with customer needs such as: Payload Capacity, Workspace Size, and Ease of Use. The user enters values for each criterion, and the chart automatically tabulates the evaluation totals. An example of a completed interactive evaluation matrix is shown in Figure 70. Here, we see that by integrating a morphological chart widget with an evaluation widget, students are actively moved through the critical design and evaluation steps of a simple design project.

Figure 71 shows a function tree widget looks. A function tree is a figure that shows the dependencies between functions of a system. When the students touch a block on the chart, all the possible options that can go to that space become highlighted. Pressing on any of the choices will place the chosen guess in the function tree. Once all the fields have been filled the students can verify their answers by pressing the "Evaluate" button. A message saying whether the chart is correct will appear, and

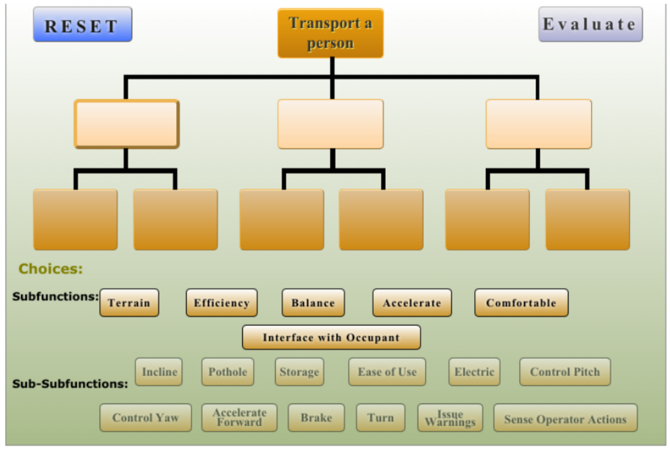


Fig 71: Function Tree - Blank

the fields that are wrong are colored red. The student can make adjustments. If the student has been wrong five consecutive times the correct answer will be displayed for ten seconds.

A.3.4 Interactive Technical Writing Widgets

One of the biggest challenges for young engineers is to document and describe their progress in a proper and suitable manner. To help in this educational process widgets were developed that show how to complete project reports and how proper sentences should look in an engineering document.

Figure 72 shows a widget where the student can view an example report. The pages can be changed with the "**Forward**" and "**Back**" buttons at the bottom of the screen. The student has the ability to get details on how the different paragraphs and sections need to be written by pressing on them. Figure 73 shows an example of how an auxiliary page explains the format and content of the report.

Figure 74 shows a sentence composition widget; it presents a sentence and then the student must identify the correct fragments of the sentence that will go together. Figure 75 shows a sentence correction widget, which asks the students to identify

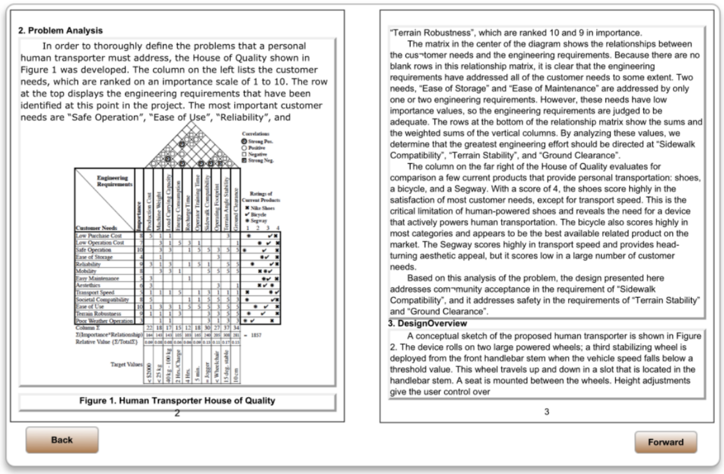


Fig 72: Pages of a Report

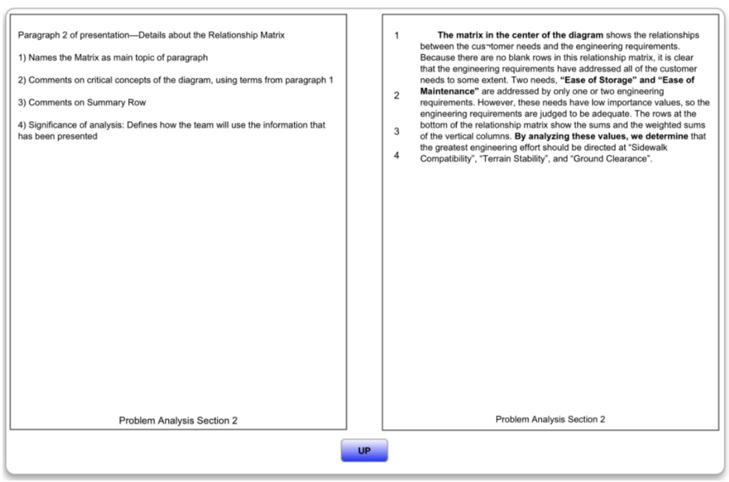


Fig 73: Details About One Section

needless words. Once the student has touched the words, they become crossed out. In both of these widgets the students will get a message saying either "Try again!", "There is a better answer", or "Correct." To move between sentences there are arrows on the sides of the widget. Five example sentences have been programmed into the widgets. None of the widgets introduced here, however, provides the desired amount of interaction, and consequently they have not been tested with students.

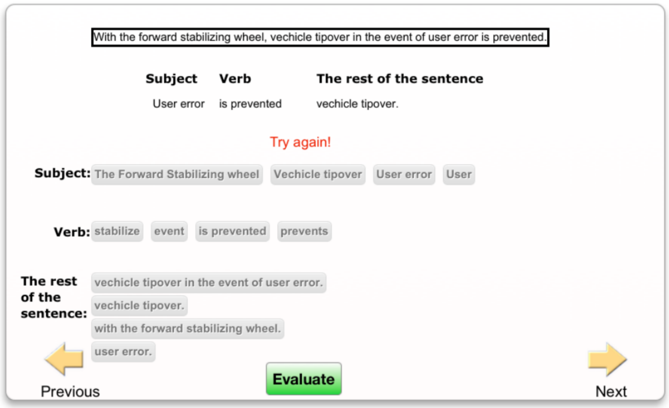


Fig 74: Sentence Composition Widget

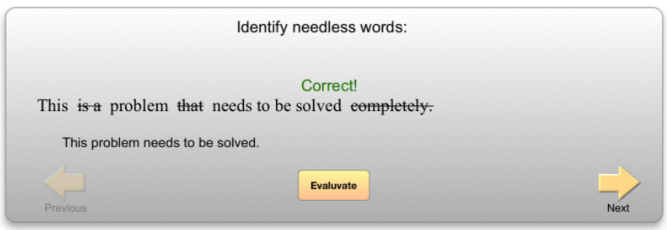


Fig 75: Sentence Correction Widget

A.4 Applications for Judging a Mechanical Design Competition

Each semester there is an undergraduate design competition for Mechanical Engineering students at Georgia Tech taking the "Creative Decisions and Design" class. In the fall and spring semester more than 200 students are divided into 60 to 70 teams. Before the competition gets underway, judges from both industry and academia give their assessments of the student's creations. The judges originally used paper forms to record their evaluations. After the scores were collected, a team of teaching assistants had to type them into a computer program, which was both error prone and tedious.

A solution to this problem was to create an application that can be seen in Figure 76. The judge inserts the scores by pressing on an evaluation field corresponding to the team they are evaluating. Then the judge chooses the proper score from a stepper field that pops up. There are ten teams simultaneously listed on the screen, which can

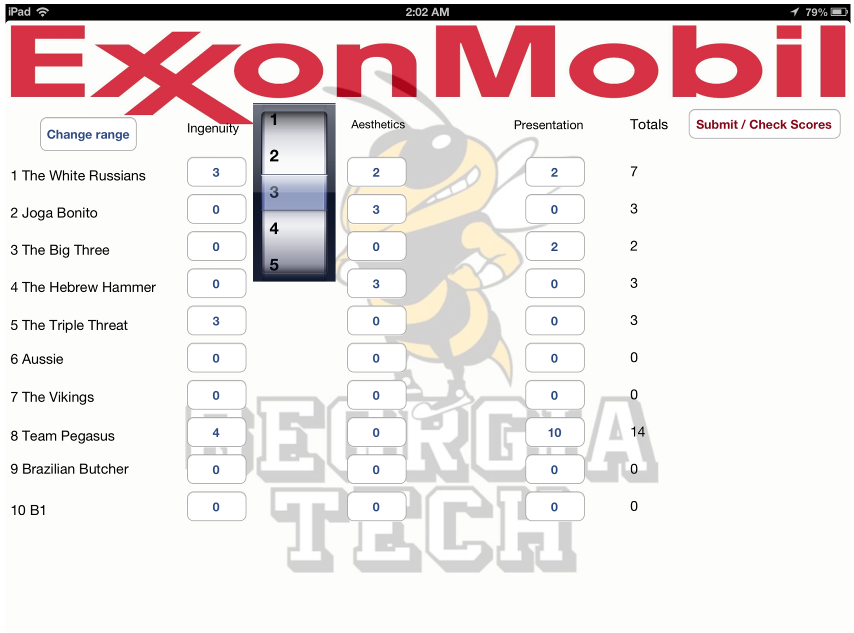


Fig 76: Judging Application

be changed by pressing the "Change range" and choosing the range of teams that is required. After all the scores are inserted the judge presses the "Submit/Check Scores" button upon which a window appears that shows all the scores inserted. If everything is correct, then the judge presses "Send", and the scores are sent via e-mail to the main data-recording computer. The scores can be easily copied to a preferred spreadsheet program to see the average scores the teams received. The applications can be altered to show the organization the judge is representing (Exxon Mobil in case of Figure 76).

After the science-fair evaluation by the judges, the student-built machines battle head-to head to see which one is the best at performing the competition tasks. The head-to-head competition was originally scored by referees using paper forms. The people giving marks calculated the points by hand to announce the winner and then manually took the scores to the main scoring computer. The computer would then generate the next match-ups. This kind of approach was both error prone and caused time delays in a competition, which often ran late into the night. An application, seen

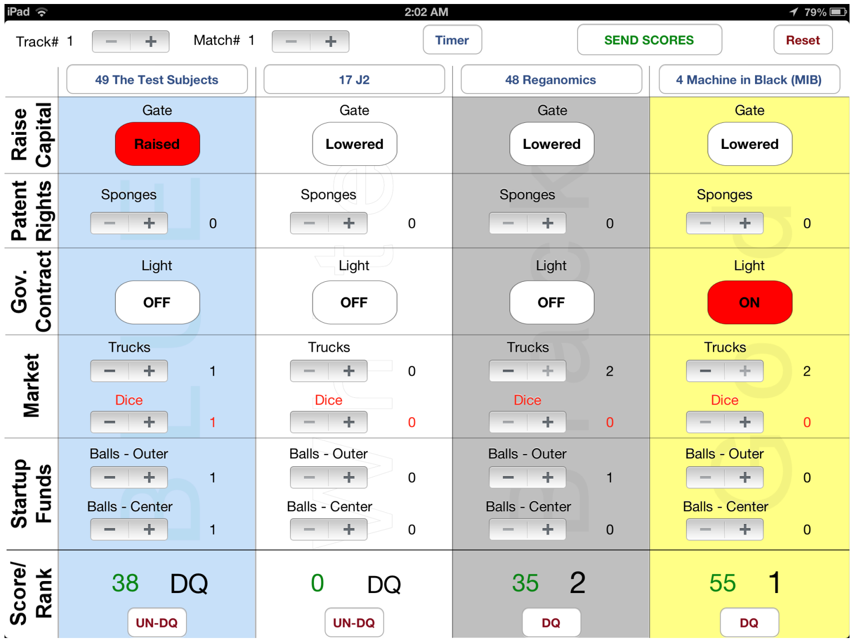


Fig 77: Competition Application

in Figure 77, was developed to streamline the competition-scoring process. All of the scoring categories are clearly labeled, and the program calculates the scores in real time as they are being entered. There are algorithms that also rank the teams. They even take into account teams that are disqualified and different levels of tiebreakers in case of equal scores. After the scores have been entered, the results of the match are automatically sent in a formated table to the main scoring system.

The judges must choose the table number and the current match number. In case of predetermined matches, the team names update automatically with the match number. If there are no more matches programmed in, then judges choose the team names after pressing on the designated button. Touching the "Timer" button causes a window to appear showing the countdown to the next match. This application has been estimated to save about thirty minutes during the night of the competition.

A.5 Future Work

A.5.1 Widgets

The current version of the textbook has a variety of interactive components that make it more valuable than the traditional words-and-figures version of the book. However, the interactive elements can clearly be improved using feedback from the users - just as any book can be improved with feedback.

The real time simulations need to have more configurable options added to them to make them more compelling. Among the areas that need the most improvement are the interactive charts and technical writing widgets. Because these are static displays, they are fundamentally less compelling than the real-time simulations that have been developed for this interactive textbook. As a first step towards more interactive language interaction, these widgets need to be expanded to provide more examples and challenges.

In addition, the interactive chart widgets should be made far more flexible in order to allow demonstrations of other examples. Students should also have the ability to apply those tools provided to their own projects. Furthermore, the users should have the option to save their work and share it across different platforms, in contrast to the current widgets, which confine the students to work inside the iBook.

A way to keep the widgets updated is to allow them to get extra examples or tasks form the Internet when the device has data connectivity. The instructors that use the textbook in their courses could also extract information about the use of the book by having the widgets send anonymous data to an assessment tool. This could also be an effective way of getting direct feedback from users.

A.5.2 Applications for Judging a Design Competition

The teams and challenges change every semester and require the programs to be reprogrammed and redesigned every semester. A solution to that problem would be to develop a program that reads all the information about the competition from some webpage, and then have the program update the application layout and scoring automatically. One alternative would be to build the applications straight on to the Internet, which would allow easier reprogramming and cross platform use.

The current state of the applications allows the results to be sent via e-mail. This step should be avoided in favor of automating the entire scoring process, with the scores being sent directly to the main scoring system. In addition, it may be helpful to build in a collaboration mode for competition judging, where multiple tablet computers would be used on one arena.

A.6 Conclusions

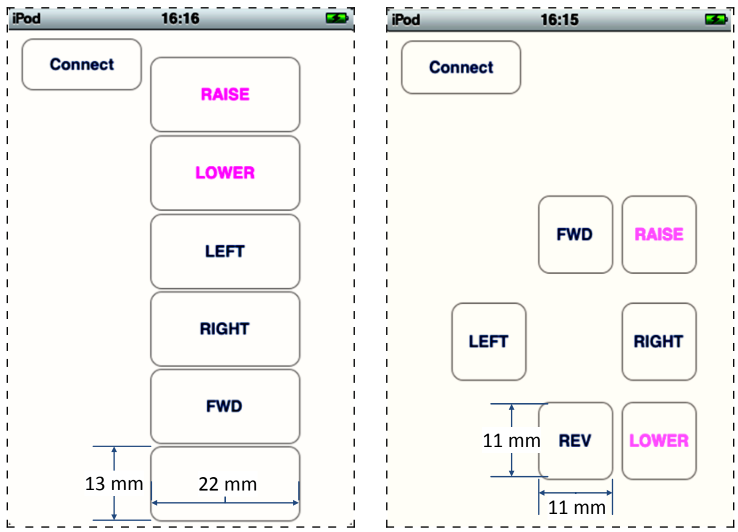
Interactive touchscreen textbooks can provide significant features that traditional textbooks cannot. In addition to the already built in widgets some important interactive features that authors of a design textbook have to write themselves: real-time simulations controlled by the user, interactive charts, technical writing widgets. The widgets thus far developed, however, need a lot of work put in to make them functionally and visually appealing to users.

Innovative touchscreen applications developed for judging a design competition illustrate the way portable computing devices are changing the way we do things by making certain tasks less cumbersome and more time friendly. These applications need further developed to make the entire judging process automated.

Appendix B

INTERFACE DESIGNS

B.1 Pendent Layouts

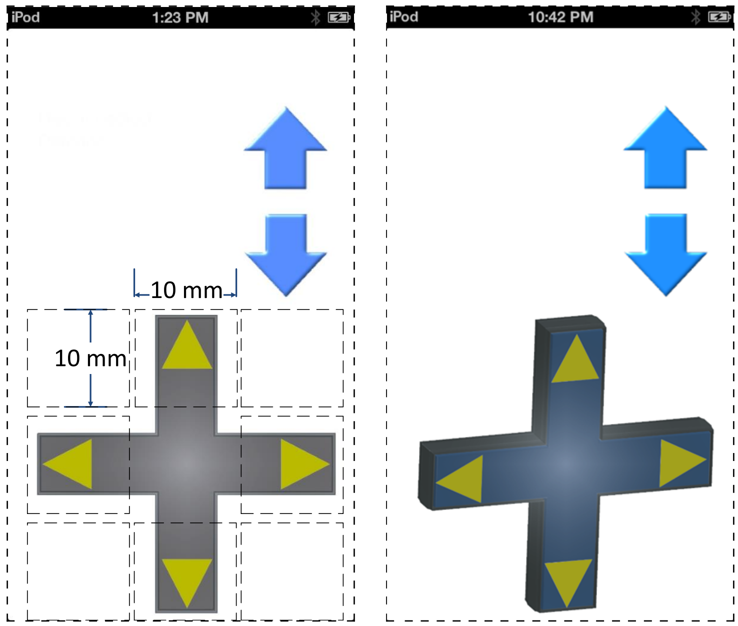


(a) Pendent

(b) Diamond-Pattern Pendent

Fig 78: Pendent Designs

The two pendent layouts seen in Figure 78 were designed to be the most basic interfaces and to test whether the users performed worse with them than with the actual pendent. The buttons were made as big as possible on the Pendent UI seen in Figure 78(a). The buttons on the Diamond-Pattern Pendent were laid out and were made to be big enough so that all of them could be reached by an operator using only one thumb. When a button was pressed it changed color to provide feedback to the user. Multiple buttons can be pressed at the same time.



(a) Design (b) “Reverse-Right” Pressed

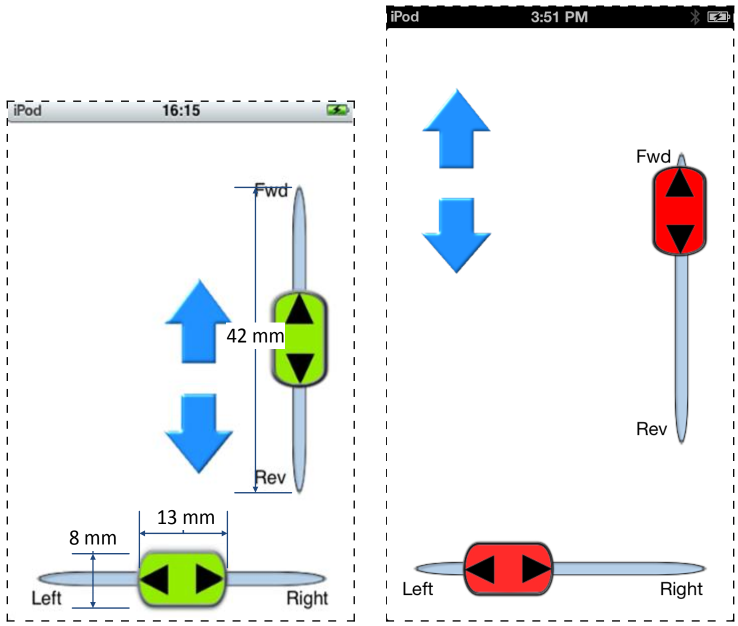
Fig 79: D-Pad With 3D Effects

B.2 D-Pad With 3D Effects

The D-Pad with the 3D effects was designed to give the operator a different kind of visual feedback about the command that has been issued. In addidtion to the 3D effect the D-Pad also changes color when any command is being sent. Figure 79 shows where the boundaries for the different commands are. All the areas that are outlined boxes but not on the D-Pad itself correspond to diagonal movements. The diagonal move can also be evoked when pressing two of the buttons on the D-Pad. Figure 79(b) shows how the interface will look when “Reverse-Right” is sent to the crane.

B.3 RC Control

The design for the RC Control UI gets its inspiration from controllers that are commonly used to control RC cars and model helicopters. The control over one axis is provided by one slider. Figure 80(a) show the design parameters of the interface. The buttons are located in the area where it is easy to reach them when using the right



(a) Design (b) 2 Sliders moved

Fig 80: RC-Control

thumb, and the buttons are also made big enough to be found easily. The sliders give the maximum velocity command when moved 22 mm from their default location at the center of the slider. The user can use both sliders at the same time, as can be seen in Figure 80(b). The sliders turn red when touched to provide feedback. When the touch event that is controlling the slider has ended the sliders return to their default position. The sizes of the interfaces in Figure 80 are different due to the different screen sizes that provided by different iPods.

B.4 Sliders

The Slider user interface combines the D-Pad and RC-Control. Although, traditionally in ergonomics it is advised not to separate controls on one axis to two different control actions, the Sliders interface was included in the operator study because sometimes in crane control it is important to have control over just one direction. For example when a crane must follow a trajectory that is close to a wall, isolating that control can

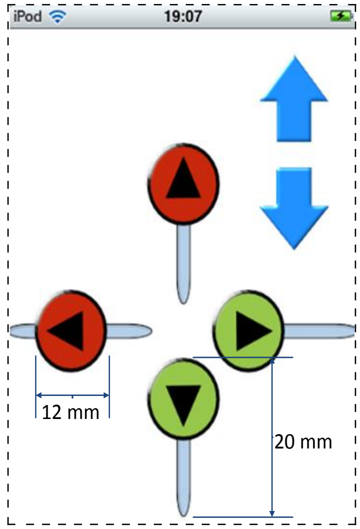
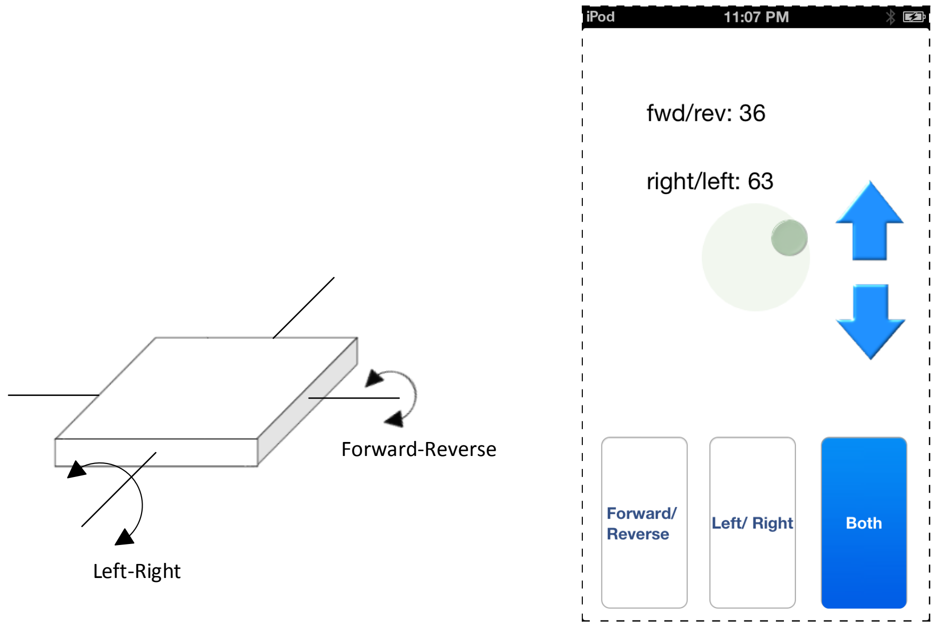


Fig 81: Sliders

reduce risk. Figure 81 shows the design specifications of the Slider UI. The controls are located in the area where the operator has the best reach with the thumb. When touched the slider's change color to provide user feedback. It is also possible to move multiple sliders at once. To give the maximum velocity command the individual slider has to be moved 20 mm.

B.5 Tilt

The operating principle behind the Tilt user interface is shown in Figure 82(a). The operator can control the "Left-Right" axis by twisting the forearm when the device is held in portrait position. The "Forward-Reverse" axis can be controlled by twisting the wrist front- and backwards. Figure 82(b) shows the interface layout. The user can choose which axes are in effect by pressing the respective buttons at the bottom. Once a button has been pressed the device will start to measure the angle from that position. To issue a maximum velocity command the device must be tilted $\pm$ 50°. An indicator on the screen, as well as a text display, shows what command is being issued. The example shown in Figure 82(b) shows the screen when the device is tilted



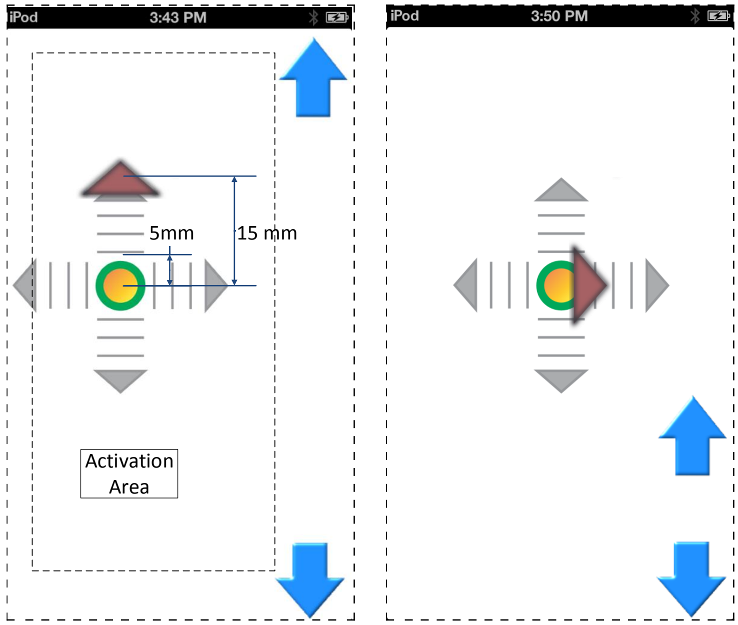
(a) Operation Principle (b) Example

Fig 82: Tilt

"Forward-Right."

B.6 Varying Home D-Pads

The Varying-Home D-Pads (Analog and Discrete) were designed as potential improvements to the D-Pad interface. The interfaces potentially offer the same kind of control as does the D-Pad but without the need for muscle memory on where the controls lie. Figure 83(a) show the design specifications for the Variable-Home D-Pads. The activation area covers most of the screen. When the operator places a finger close to the edge of the screen and wants to move towards that edge the operator will physically feel that the edge is reached, and the interface resets itself. After the initial touch the operator has to move the finger 5 mm towards one of the primary directions in order for it to be activated. Once a direction is active it cannot be reset until the touch event has stopped. The difference between the analog and discrete versions is that when the initial 5 mm threshold is reached with the discrete version, the maximum command will be issued until the touch has ended. With the analog



(a) Design (b) Example

Fig 83: Varying-Home D-Pad

version the operator will have the option of changing the magnitude from zero to maximum by sliding the finger. The finger does not have to be on the slider; only one coordinate is being monitored at a time. If the touch the finger reaches one of the hoist buttons while issuing the command, the button is not activated, and the velocity command is issued as if the button were not there. Figure 83(b) shows an example of a small "Right" command being issued. Figure 83(a) shows the maximum velocity in the "Forward" direction being issued.

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