Effects of Type and Strength of Force Feedback on the Path of Movement in a Target Selection Task

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Abstract. New flight deck technologies being developed under the proposed NextGen National Airspace System will require precise and efficient input from flight crews. The benefits of force feedback for these types of inputs in terms of a reduction in overall movement times have been shown in the past; however, an important component of input efficiency is the path taken by the cursor. The present study investigates the effects of multiple levels of two types of force feedback (gravitational and spring forces) on the path of movement for a target selection task. Mean square error from an ideal straight line path and cursor speeds in terms of the distance from the target were measured. Results suggest that increasing the gravitational force has an effect on path error at short distances and produces higher cursor speeds as the target is approached.

Keywords: Haptic and Tactile interaction, Multimodal interaction, Force Feedback, Input Devices.

1 Introduction

The proposed upgrades to the National Airspace System (NAS) being developed under the Next Generation Air Transportation System include the integration of additional automation into the flight deck which is designed to allow pilots to modify their route and downlink to ATC for approval [1]. This type of GPS based self-routing is intended to increase NAS efficiency by allowing for more direct, point to point, routing. At the same time, it will help to reduce air traffic controller workload by allowing pilots to consider traffic and weather in their modified routes thus aiding the controller in maintaining separation assurance. In order to accomplish this goal, new onboard technologies are needed in the modern flight deck.

Instrumentation such as the NASA Ames FDDRL Cockpit Display of Traffic Information (CDTI which includes a Route Assessment Tool (RAT), is intended to improve pilot traffic awareness by providing them with traffic displays, real time

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conflict alerting, and a graphical user interface [2]. However due to the inherent instability of the cockpit environment, the limited cockpit real estate, and the increased complexity of CDTI inputs, traditional cockpit input devices may prove to be too error prone and inefficient for flight planning. Moreover, these devices place additional demands on the pilot's visual channel and may increase the amount of head down time. Therefore, new inputs methods which are optimized for CDTI tasks are needed. In this paper, we describe work on an input device that provides force-feedback information to the pilot to improve the efficiency of CDTI inputs and relieve some of the visual demands made on the pilot.

1.1 Force Feedback

In a series of experiments, we have been developing and testing force feedback mechanisms for improving inputs to the CDTI, for example, elastic force in path stretching [3] and attractive force in target selection [4]; [5]; [6]. The targeting task is a fundamental task that is often performed on the CDTI. The operator selects a target on the screen by moving the cursor from its current position to the desired target location and then clicks on the target. This type of task resembles the movements utilized in research on Fitts' Law, where the efficiency of the movement is determined by movement time. Previous research has demonstrated that the use of certain types of force feedback, such as an attractive force, produces faster and more accurate selection of targets even when compared to traditional mouse inputs (e.g. [7]; [8]; [9]).

In an effort to better understand how force feedback affects specific portions of the target selection task, Akamatsu and MacKenzie [10] divided the task into two discrete phases, the approach phase and the selection phase. The approach phase begins as soon as the movement is initiated (i.e., a start location is clicked) and ends once the cursor breaches the target boundary. The selection phase begins at the end of the approach phase and ends when the target is clicked. Akamatsu and Mackenzie showed that a friction-based force feedback model reduced the time spent in the selection phase but had no effect on the time spend in the approach phase. They reasoned that the friction force allowed for faster stopping times because it provided the participants with multisensory feedback regarding target entry, and participants were able to more quickly stop their movement and select the target.

Hwang, Keates, Langdon, and Clarkson [11] showed that an attractive gravity based force model reduced the time spent in both the approach phase and the selection phase of movement for motion-impaired users. The authors concluded that this reduction in time spent in the approach phase of the task was due in part to an increase in cursor speed caused by the attractive force, although cursor speed was not specifically measured in their experiment.

Presently, an input device that is capable of force feedback differs significantly from an optical mouse, making it difficult to compare efficiency gains produced by force feedback to standard mouse performance. Rorie et al. [5] evaluated the impact of the input device itself and how force feedback may mitigate some input device problems. Participants performed a target selection task using a traditional mouse and a 3D force feedback input device called the Novint Falcon with and without a force modeled with a combination of gravitational and spring force. Results showed that without the force active, the Novint Falcon movement times were 40-50% slower than a traditional mouse. However, when force feedback was utilized, task selection performance met or exceeded that of a traditional mouse despite the fact that participants had much more experience using a mouse than they did the Novint Falcon [5].

Rorie et al. [6] examined the effects of different types and amounts of force feedback on CDTI target selection task by using a combination of two force feedback models. The first was an attractive force feedback model similar to that used by Hwang et al. [11], and was based on a modified version of Newton's gravity equation, where the magnitude of the force was inversely proportional to the distance between the cursor and the center of the target while the cursor was outside of the target boundary. The second was a spring-force feedback model, and was based on a standard spring equation, where the magnitude of the force was proportional to the distance between the cursor and the center of the target while the cursor was within the boundary of the target. Results showed that mean approach time was inversely related to the magnitude of the gravity force, but that the reduction in movement time decreased logarithmically with the magnitude of the force. Gravity force at high levels was most effective for small targets and at short target distances. Selection time, on the other hand, was affected only by the spring force feedback. Thus, these findings suggest that there is an ideal combination of gravity and spring force feedback levels, which would optimize device stability and overall movement time.

Although a benefit of force feedback in terms of shorter approach and selection times was found by Rorie et al. [6], an explanation of the cause of this effect requires an analysis of the path of movement [11]. Therefore, in the present study we investigated the path of movements in Rorie et al. [6], specifically the path error and path speed to determine if the benefits were due to cursor speed or deviation from the straight line path to the target.

2 Method

2.1 Participants

Seven males and five females (M = 25.83 years old) from NASA Ames Research Center participated in this experiment. All participants were right handed, over 18 years of age, and had normal or corrected-to-normal vision.

2.2 Apparatus

The experiment used two input devices, a standard Logitech optical laser mouse and the Novint Falcon. The control-display ratio (i.e., gain) of the computer mouse was reduced to approximate the C-D ratio of the Novint Falcon. The Falcon is capable of position sensing and applying force feedback in three dimensions, with an operational workspace of 4” x 4” x 4”. For the purpose of this experiment, however, the device was restricted to movements in a horizontal plane parallel to the ground. The Falcon was also rotated and mounted on a stand to produce movement in the horizontal plane analogous to the mouse (*see Figure 1*).

The force feedback conditions were provided via the Novint Falcon. A modified version of Newton's gravitational law equation, shown in Equation 1 [4], was used to generate an attractive force, F_g, in the direction of the target's center, where d is the distance from the center of the target, r is the radius of the target and K_1 is the gain constant. When outside the target boundary (||d|| > r), this gravitational force (expressed in Newtons/Pixel^2) pulled the user toward the center of the target, with the strength of the force increasing as the cursor approached the target's center. The unit vector of the distance (d) was used to specify the proportion of the force that was to be output along both axes (x and y).

$$F_g = \frac{K_1}{\|d\|^2}\hat{d}, for\ \|d\| \geq r \tag{1}$$

A second force model provided stability when the distance between the cursor and the target center was less than or equal to the target radius, as shown in Equation 2.

$$F_s = K_2\ \|d\|\ \hat{d}, for\ d < r \tag{2}$$

F_s is the spring force in Newton-Pixels, and K_2 is the gain constant. When the cursor is inside the target (d < r), the spring force resisted movements away from the target's center. The combination of the two models, therefore, led participants to experience an attractive force toward the target when outside its boundaries, and resistance to exiting the target once inside its boundaries. Three values of gravitational force were tested, 100, 300 and 500 Newtons/Pixel^2, and two levels of spring force were tested, 0.1 and 0.3 Newton-Pixels. These values were selected after informal pilot testing.

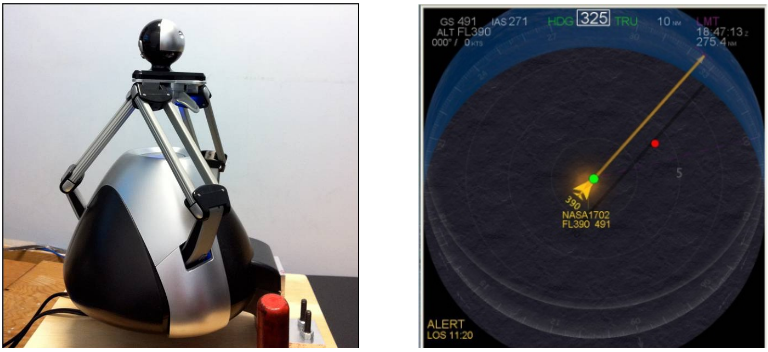

Fig. 1. Novint Falcon rotated 90 degrees (left) screen shot of the task (right)

2.3 Design and Procedure

The experimental design depended upon the input device. For experimental blocks with the Falcon, the design was a 2 (Target Size) x 2 (Target Distance) x 2

(Spring Force Level) x 3 (Gravitational Force Level) x 12 (Target Direction) repeated measures design. All five variables were manipulated and randomized within each experimental block. For experimental blocks with the mouse, a 2 (Target Size) x 2 (Target Distance) x 12 (Target Direction) repeated measures design was used since the mouse was not equipped with the spring or gravitational force models. For the mouse, all three variables were manipulated and randomized within experimental blocks. Participants completed 22 experimental blocks (20 blocks dedicated to the Falcon and 2 dedicated to the mouse), resulting in a total of 3,168 individual target selection trials.

A standard, Fitts' Law task was employed. On each trial, a green start circle (located in the center of the display) and red target circle (located at a specific direction and distance) was presented on a screen shot of the CDTI. The program had an 8" x 8" active display and was presented on a 50" x 29" computer monitor (pixel resolution: 1920 x 1080). Participants selected the green start circle to begin a trial and then moved their cursor as quickly and accurately as possible to the red target circle, clicking anywhere inside the target. After target selection, the start circle, along with the next target, appeared on the screen.

In order to determine cursor speed and path error, the cursor's position was recorded every 16 milliseconds. From the cursor position, we determined mean-squared (MS) error and average cursor speed towards the target during the approach phase. The approach phase was defined as movement of the cursor while outside the boundary of the target.

3 Results

MS error was determined by averaging the squared distance between the cursor and the straight line path to the target at each 16 millisecond interval. To determine cursor speed, the path to the target was divided into four quadrants and the average speed of the cursor in each quadrant was calculated by dividing the amount of time the cursor spent within each quadrant by the length of each quadrant (75 pixels for long distance trials and 25 pixels for short distance trials).

A 2(Target Distance) x 2(target size) x 3(Gravitational Force) x 2 (Spring Force) repeated measures ANOVA was performed for MS approach path error. Because the length of the path quadrants differed depending on the distance to the target, separate 12(direction) x 2(target distance) x 2(size) x 3(gravitational force) x 4(path quadrant) repeated measures ANOVAs were conducted on the cursor speed data for each target distance.

3.1 MS Approach Error

A significant main effect of target distance was obtained, with long target distances resulting in significantly higher MS error (M = 96.64, SE=5.92) than short target distances (M = 26.17, SE = 2.21), F (1, 11) = 191.275, $p < 0.001$. No significant main effects of gravitational force or spring force were found. However, a significant interaction between gravitational force and target distance was obtained, *F* (2, 10) = 8.89, *p* = 0.001. The effects of the gravitational force were only apparent for short target distances. As shown in *Figure 2*, the MS error for short target distances was significantly higher when the gravitational force was set at 100 Newtons/Pixel^2 (*M* = 121.508, *SE* = 4.861) than at 500 Newtons/Pixel^2 (*M* = 95.203, *SE* = 3.7), *p* = 0.001. It should also be pointed out that at long target distances the MS error for the trials in which the Falcon was used was greater than that of a traditional mouse, however for short target distances this difference in MS error was eliminated at high force values.

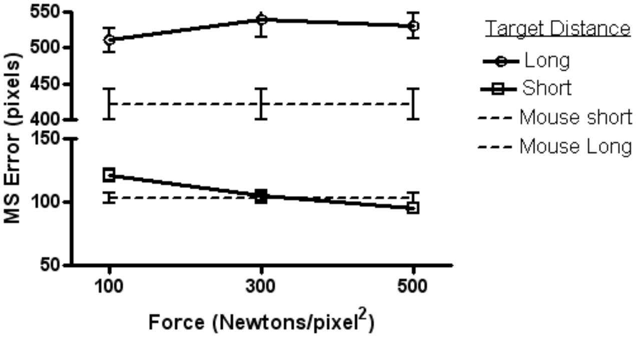

Fig. 2. MS approach error as a function of gravitational force and target distance compared to no-force mouse conditions

3.2 Cursor Speed

As mentioned earlier, the path was divided into quadrants and the average speed of the cursor was calculated for each. Separate ANOVAs were conducted for each target distance because the length in pixels of each quarter differed depending on the target distance.

For short target distances a significant main effect of gravitational force was obtained, *F* (2, 22) = 216.21, *p* <.001 as well as a significant main effect of path quadrant, *F* (3, 33) = 212.05, *p* < 0.001. As the force increased or as the cursor approached the target, cursor speeds increased significantly.

For short distances a significant interaction between gravitational force and path quadrant was found, *F* (6, 66) = 285.53, *p* < 0.001. Cursor speed was found to be equivalent through the first two path quadrants as the level of gravitation force varied. However, as shown in *Figure 3,* there was a significant difference in cursor speed at each level of force in the third and fourth quadrants. At higher levels of force participants decelerated the cursor less as they approached the target.

For long target distances, a significant main effect of force was also obtained such that higher levels of gravitational force resulted in significantly higher cursor speeds, *F* (2, 22) = 17.59, *p* < 0.001. In addition, a significant main effect of path quadrant was obtained; cursor speeds were significantly higher as the cursor neared the target, *F* (3, 33) = 243.09, *p* < 0.001.

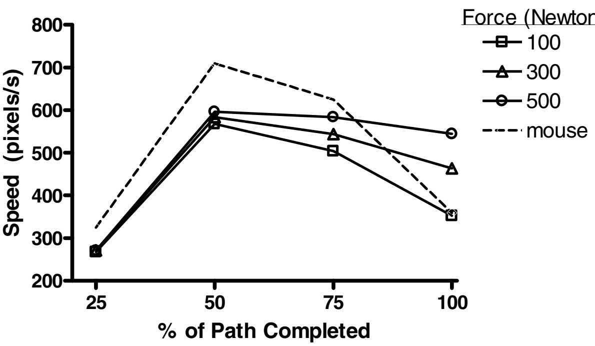

Fig. 3. Average cursor speed within each path quadrant by gravitational force at short target distances. Dotted line shows average cursor speed for mouse movements.

For long target distances a significant interaction was found between gravitational force and path quadrant, F (6, 66) = 67.34, $p < 0.001$. As shown in *Figure 4,* differences among cursor speeds were found only in the fourth quadrant. That is, there were no differences in cursor speed in the first three quadrants as gravity varied. In the last quadrant a significant increase in target speed was shown with increases in gravitational force levels.

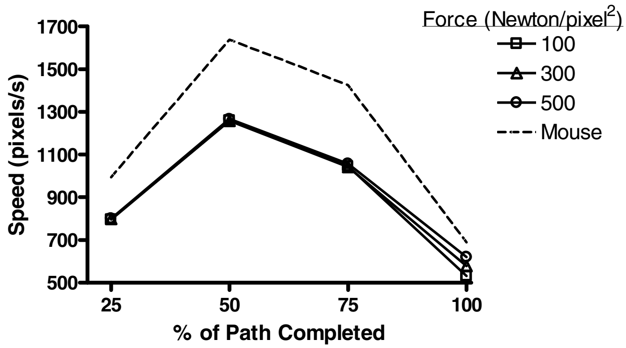

Fig. 4. Average cursor speed within each path quadrant by gravitational force for long target distances. Dotted line shows average cursor speed for mouse movements

In both Figures 3 and 4, the speed attained by the mouse movements is also shown. At both distances, it appears that movements of the mouse consisted of rapid accelerations and then decelerations, compared to the Novint Falcon. For the Falcon, the maximum speed was much lower than the mouse. At short distances, however, higher force levels produced faster speeds at the target boundary, which may account for the equivalence in movement times at these values. This is less evident in Figure 4 at long distances because the attractive force affected target speed for a smaller portion of the movement path. Looking at the results of the cursor speed it can be seen that compared to the mouse, the Falcon with force feedback initially accelerated less quickly. Moreover, these higher cursor speeds did not result in extra path error and at some target distances and levels of gravitational force, path error was comparable to that of the mouse.

4 Discussion

Previous research on force feedback applied to Fitts' Law target selection tasks have shown benefits in reduced movement time with the application of various force feedback models (e.g., [11]). The results shown by Rorie et al. [6] supported previous work and provided for a better understanding of how varying the levels of force feedback could be used to modulate performance gains. The present study showed that the performance gains due to the addition of force feedback can be explained by, increased cursor speed and in some cases decreased path error.

In both cases, however, we found that the effects of the gravitational force on approach error and speed tend to be significant only when the target distance is short. One reason for this outcome may be that when target distances are long, the cursor spends more time outside the effective range of the gravity force. That is, there is essentially no force effect while the cursor is significantly far away from the target. On short distance trials the cursor is under the effects of the gravitational force for a proportionally larger segment of the overall movement. This means the benefits of gravitational force on path error and cursor speeds are accrued for more of the total path. It is important to note however that the reduction in path error may only be necessary as the cursor approaches the target as it is more critical in this area to have increased accuracy for target selection.

In the real world, interaction with a CDTI will not be as simple as the task used in the present study. Future studies will need to address the impacts of distractor targets and obstacles that a pilot in a modern day cockpit will need to deal with. It is also necessary to investigate the use of other force feedback capable input devices. The Novint Falcon requires a significant amount of real estate to operate correctly and therefore is not suitable for the tight space in an aircraft cockpit. It can be seen however that the effects of a gravitation force feedback model can be a powerful tool for increasing the performance of an input device [5]. Finding a force feedback capable device which is suitable for use in the cockpit and has baseline (no force) performance comparable to a mouse is an important avenue for future work. The addition of force feedback models to such a device may result in performance that far exceeds that of a mouse, providing an accurate and efficient input method for tomorrow's NextGen flight decks.

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