Development of Haptic Assistance for Route Assessment Tool of NASA NextGen Cockpit Situation Display

Eric Park[1], Jose Robles[1], Paul Sim[1], Ryan O'Connor[2], Martin T. Koltz[2], Gregory B. Armsdoff[2], Kim-Phuong L. Vu[2], Thomas Z. Strybel[2], and Panadda Marayong[3]

[1] Department of Computer Engineering and Computer Science
[2] Department of Psychology
[3] Department of Mechanical and Aerospace Engineering, California State University, Long Beach
eric.park@student.csulb.edu

Abstract. The NextGen Cockpit Situation Display (CSD), developed by NASA Ames's Flight Deck Display Laboratory, provides advanced flight control functionalities and traffic/weather displays to pilots [1]. Traditionally, the user operates with the CSD using a computer mouse and receives only visual feedback about the controlling actions. In this work, we integrate force feedback in the Route Assessment Tools of the CSD, where the user can manage the flight plan to resolve conflicts in real-time. A spring force, with a variable stiffness coefficient, was used to model the force feedback with its strength varying proportionally to the overall path length. Force display was provided as an indicator of the effort required to deviate from the optimal path to assist the user in decision making. The force feedback models were evaluated on a software testbed created on Microsoft Foundation Class with the Novint Falcon haptic-feedback input device.

Keywords: Multimodal interaction, Haptic feedback, NASA NextGen.

1 Introduction

To improve performance and to meet the current air traffic demands, modern aircraft flight decks have been increasingly automated, and much of the tasks performed by pilots are done by a computer or an embedded system. An example of such technologies is the volumetric Cockpit Situation Display (CSD) developed by NASA Ames's Flight Deck Display Laboratory. This software framework is designed to provide an enhanced visual display and advanced control functions to the pilot for use in real-time flight management. One of the most important tasks for a pilot is to plan routes in order to reach destinations safely and most efficiently, which may require the pilot to modify the aircraft's flight plan in real-time to avoid obstacles (i.e., weather) and traffic conflicts. The Route Assessment Tool (RAT) of the CSD allows the pilot to manage the aircraft's flight plan and utilize available information, such as relative aircraft positions and surrounding weather patterns, to resolve conflicts in real-time.

S. Yamamoto (Ed.): HIMI/HCII 2013, Part II, LNCS 8017, pp. 163–172, 2013.

In its current implementation, the user operates in CSD environment using a computer mouse and is only provided with visual feedback of his or her controlling actions. This creates a problem that can adversely affect a pilot's performance and manipulation accuracy because of certain flying conditions, such as turbulence. Our research group has explored a solution to the problem through the addition force displays with a Novint Falcon haptic-feedback input device. Addition of force feedback has been shown to improve the performance of object selection task [2-3]. With respect to movement time, the Falcon with force feedback offers a comparable performance as a mouse; however, it can outperform the mouse for selection of small target sizes and when making diagonal movements.

In this present work[1], we continue the integration of force feedback in the Route Assessment Tool (RAT) of the CSD. Using the RAT, the user can manage the flight plan and utilize available information, such as nearby aircraft positions and surrounding weather patterns, to resolve conflicts in real-time. We developed a force display to assist the pilot with the route manipulation task, as he/she modifies the route from the original path. With the implemented model, the strength of the force feedback varies proportionally to the change in the overall path length indicating the effort required to deviate from the optimal (or original) path. The force feedback provides augmented information, so the operator would still make the final decisions. The subsequent sections describe the prior work, the implementation of the force-feedback model, and a user study with a testbed system.

2 Prior Work

Haptic feedback has been previously known to be effectively utilized in various applications [4-13]. Semere et al. [4] performed user studies on teleoperated surgical procedures, and found that the presence of force feedback helped improve the surgeon's accuracy and efficiency, though the overall time of surgery was not significantly improved. In minimally-invasive surgery, Wagner et al. [5] observed that tactile feedback provided when the tool is making contact with tissues improves accuracy by reducing the amount of surgical mistakes such as accidental punctures. In teleoperated uninhabited aerial vehicles, Lam et al. [6] showed that force feedback reduces the number of vehicle collisions. Furthermore, Farkhatdinov et al. [7] conducted a user experiment study and found that variable gain for force feedback output in a teleoperated robot helped improve accuracy and the quality of manipulation by allowing smoother movements.

Related to the NextGen CSD, Robles et al. integrated force feedback in object selection tasks [2], which Rorie et al. used to evaluate the effect of force feedback as compared to the performance of a computer mouse in a Fitts' law task [3]. A commercial haptic device, called the Novint Falcon, was used as the force-feedback input device. The results showed that the Falcon with force feedback produced faster

[1] This work is supported by NASA cooperative agreement NNX09AU66A, Group 5 University Research Center: Center for Human Factors in Advanced Aeronautics Technologies (Brenda Collins, Technical Monitor).

movement times than a mouse when moving the cursor in a non-vertical or non-horizontal line. There was no difference in performance with the two devices, though, when the movement was along a vertical or horizontal line. Thus, the Falcon with force feedback produced better movement time than a mouse for smaller targets. This finding is consistent with those obtained by other researchers [14]. Thus, the existing research suggests that there is a potential benefit for the use of force feedback to improve the efficiency of operator interactions with the CSD.

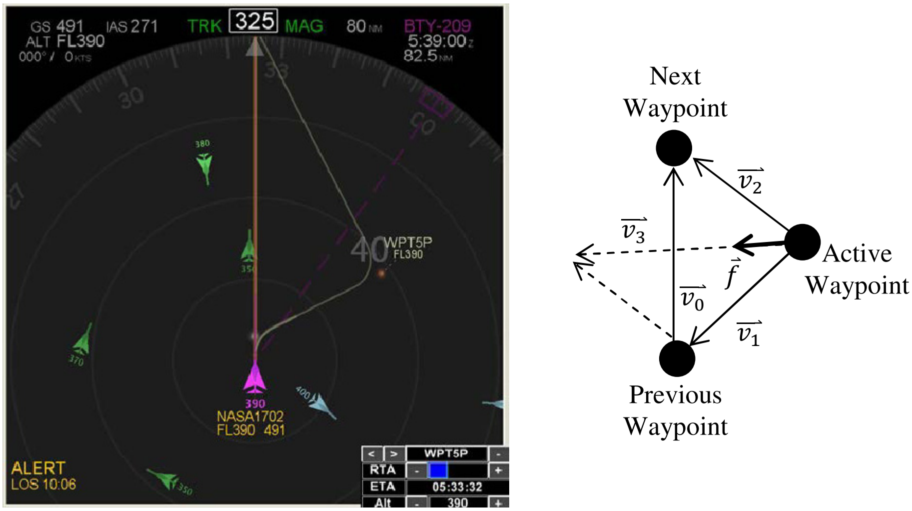

Fig. 1. (Left) A view of the CSD as the user moves a waypoint, shown by the orange dot labeled as WPT5P, through the Route Assessment Tools to create a new route shown by the gray curve. (Right) A vector diagram used for the force feedback calculation. A color version of the figure is available in the electronic copy of this paper.

3 Force Feedback Integration with the CSD

3.1 Force-Feedback Model for Route Manipulation

To extend the application of force display within the CSD functionalities, a new force feedback model was created for the route manipulation task that can be accomplished through use of the Route Assessment Tool (RAT). To modify an existing route using the RAT, the pilot creates a new (active) waypoint by clicking on a line representing an existing route. The path changes as the active waypoint is moved to a new position as shown in Fig. 1. As the user moves the active waypoint away from the original path, the overall distance increases and potential conflicts with nearby aircrafts and/or obstacles may arise. To warn the pilot of such changes, we developed a force model that simulates stretching of a rubber band to represent the action that occurs during route manipulation. The force model applies a linear spring force with a variable stiffness coefficient, which changes proportionally to the increase in the overall path length. The rise in the magnitude of the force display implies the effort required to deviate from the optimal (or original) path, which can be used as an indicator of undesirable outcomes, such as longer flight time and higher fuel usage.

Fig. 1 (right) illustrates the calculation of the output force, $\vec{f}$, in a simple scenario with one via point, shown as the *active* waypoint. $\overrightarrow{v_0}$ represents the original path, where $\overrightarrow{v_1}$ and $\overrightarrow{v_2}$ are the new path segments that are generated from moving the active waypoint. The magnitude of the force depends on the difference between the lengths of the new route and the original route, while the direction of the force is dictated by the sum of the vectors $\overrightarrow{v_1}$ and $\overrightarrow{v_2}$, as shown in Fig. 1 (right). The directional vector $\overrightarrow{v_3}$ was defined as.

$$\overrightarrow{v_3} = \overrightarrow{v_1} + \overrightarrow{v_2} \tag{1}$$

The increase in the overall path length can be calculated from

$$d = \|\overrightarrow{v_1}\| + \|\overrightarrow{v_2}\| - \|\overrightarrow{v_0}\| \tag{2}$$

Then, the output force can be computed from.

$$\vec{f} = kd\widehat{v_3} \tag{3}$$

where $\widehat{v_3}$ is the unit vector of $\overrightarrow{v_3}$ and a scalar k is introduced as an overall gain. As more path segments are created, the calculation of d is modified to include the entire path history.

3.2 Implementation on a Testbed System

While the force-feedback model is currently being integrated into the CSD framework, we were first interested in evaluating the effect of the new force feedback model on the performance of a route manipulation task. To accomplish this, a testbed software was developed in the Microsoft Foundation Class. A static image of the 2D flight plan display of the CSD is used as the background. The task simulated a simplified route modification task with one waypoint and one obstacle. An obstacle is created as a circle in which its location and diameter can be changed depending on the experimental condition. The obstacle simulates a real obstacle that can occur during flight, such as a weather pattern or a nearby aircraft that must be avoided when creating a flight plan change. The new waypoint and the new route can be created by the same click and drag motion as with the CSD. A waypoint is created on the existing route by clicking on any location along the route. The user can then drag the waypoint to another location to create a new route. Fig. 2 (left) shows the new route, with the black circle denoting the active waypoint, and the white line showing the new route. The Novint Falcon is used as the force-feedback input device, as shown in Fig. 2 (right). The Novint Falcon is a 3D joystick that moves in 3 dimensions of force, with feedback up to 2 lbs. It has a position resolution of 400 steps per inch and a workspace volume of 4in x 4in x 4in, yielding the total resolution of 1600 x 1600 x 1600 steps. Since the task was two-dimensional in nature, a virtual unidirectional plane was programmed to limit the range of movement for the Falcon to a planar surface creating movement similar to using a computer mouse on a physical surface.

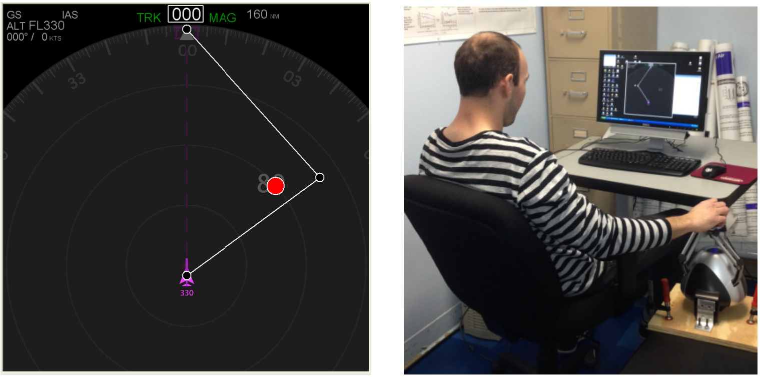

Fig. 2. (Left) the MFC testbed with the new route shown white line as created to avoid the obstacle shown as a red circle. (Right) User experiment apparatus with the Novint Falcon oriented to point upward, and its height is set at the level of the participant's armrest. A color version of the figure is available in the electronic copy of this paper.

4 Evaluation of the Effect of Force Feedback

4.1 User Experiment Overview

The experiment was conducted with the Falcon input device and baseline conditions using a Logitech laser mouse were included. Since the task was two-dimensional in nature, a virtual unidirectional plane was programmed to limit the range of movement for the Falcon to a planar surface. While the Falcon is typically oriented to accommodate hand motion in the plane parallel to the orientation of the visual display, in the present study, the device was turned 90 degrees to allow hand movement in the horizontal plane (i.e., perpendicular to the visual display.) This was done to maintain a similar form of manipulation relative to the mouse condition as well as to improve participant comfort while using the device. Buttons located on the Falcon's interchangeable grip allowed participants to select targets as they would with the mouse. The height of the grip was set at the level of the participant's armrest. Fig. 2 (left) illustrates the physical environment of the experiment. The start and obstacle icons were displayed using a screen shot of a CSD, where no traffic was present. The CSD display was 8" x 8", presented on a 17" x 11" computer monitor with 1680-pixel x 1050-pixel resolution. Participants sat roughly 20 in. from the computer monitor. The worktable was aligned with the height of the chair's armrests, so that movements in all conditions could be accomplished with the arm resting on the chair. An experimenter remained in the room with the participants for the duration of the experiment in order to field any questions and activate the program between trials.

4.2 Experimental Design and Data Collection

Participants performed a simple waypoint selection task with both input devices: the Novint Falcon with three levels of force feedback and the Logitech computer mouse.

At the beginning of each trial, the predetermined route and an obstacle were displayed. Participants started a trial by clicking any point along the vertical predetermined route to select a waypoint; then, they clicked and dragged the waypoint around the obstacle as quickly as possible and released the waypoint to end the trial. Movement times were recorded for each trial. After the waypoint was released, the start point and obstacle stimuli for the next trial were presented. The task was therefore self-paced, as the trial did not begin until the start location was clicked.

Table 1. Levels of each independent variable

Variable	Levels
Target Size	10 pixels, 20 pixels (Radius)
Target Horizontal Distance	125 pixels, 250 pixels
Force Level	0, 10, 30, 50 mN/pixel

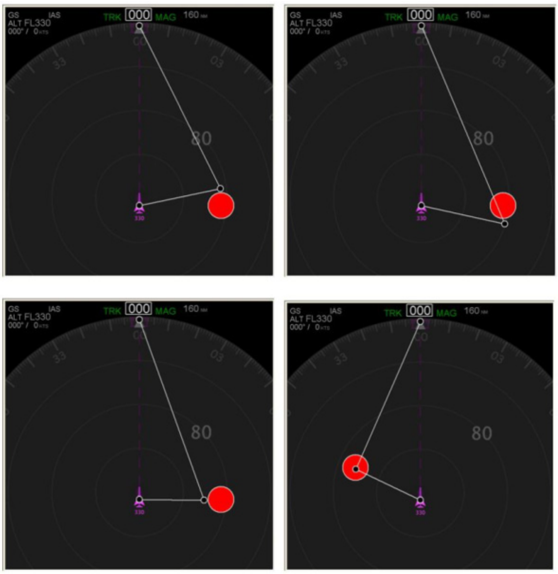

Fig. 3. Examples of inaccurate obstacle avoidance outcome

The predetermined route was always located at the center of the display at the beginning of each experimental trial. Obstacles varied in size and distance from the predetermined route for each trial. Two obstacle sizes of radii 10 pixels and 20 pixels, and two horizontal obstacle distances away from the predetermined route of 125 pixels and 250 pixels were used. Three vertical obstacle locations were used, however, since participants the starting location (i.e. they were allowed to place their starting waypoint anywhere along the starting route), vertical distance was not coded in the results. Each size, horizontal distance, and force combination was presented to the participant randomly, for a total 72 trials per test block.

The experiment employed a 2 (Target Size) x 2 (Target Distance) x 4 (Force Level) repeated measures design, as shown in Table 1. The order of presentation for the obstacle variables (i.e. size, and distance) and the force level were randomly generated for each participant. The dependent variables were movement time, recorded to the nearest millisecond, and overall accuracy. Accuracy was determined by two factors: obstacle overlap and horizontal waypoint placement (refer to Fig. 3). Obstacle overlap was considered inaccurate if the distance between the centers of the waypoint and obstacle was less than the sum of their radius. Horizontal waypoint placement was considered inaccurate if the inside edge of the waypoint (i.e. the side of the waypoint

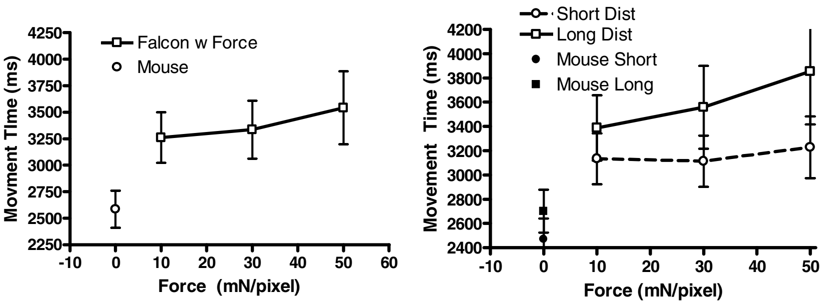

Fig. 4. Movement time comparison between computer mouse and Falcon with force feedback

nearest to the center) was placed on the inside of the vertical center line of the obstacle. Overall accuracy was the combination of these two accuracy metrics.

Six students from California State University, Long Beach participated in the experiment. They were paid 30 dollars at the conclusion of the study for two, one-hour sessions and an addition half hour session over three days. All six of the subjects were male, reported being right handed, had a lot of experience with a standard computer mouse and limited previous experience using the Falcon. Each participant completed a practice block on the first day of testing with the Falcon. The practice block consisted of two trials of each combination of the variables. Each test block took an average of seven minutes to complete. Upon completion of a block, participants were provided with a brief rest period before starting the next block. Participants completed three to ten test blocks per day, depending on device condition, in a single session lasting about 60 minutes. All blocks for one device were completed before moving to a new device, with the order of device blocks partially counterbalanced.

5 Results and Discussion

5.1 Movement Time

We found a marginally significant main effect of force, $F(2,10) = 5.728$, $p = .06$, such that movement time tended to increase with the amount of force feedback (10mN/pixel M = 3261 ms; SEM = 238.3 ms; 30 mN/pixel; M = 3335 ms; SEM = 273.1 ms; 50 mN/pixel; M = 3541.3 ms; SEM = 344.4 ms). Movement time for the mouse was lower overall as seen in Fig. 4 (left). We also found significant main effects of distance, $F(1,5) = 10.69$, $p = .02$, and size, $F(1,5) = 6.71$, $p = .05$. Movement time increased with distance (short: M = 3158 ms; SEM = 224.3 ms; Long: M = 3600 ms; SEM = 347 ms). With respect to the target size, the participants took longer to position behind smaller targets than larger targets (10-pixel targets: M = 3430; SEM = 287.3 ms; 20-pixel targets: M = 3328 ms; SEM = 282.8 ms).

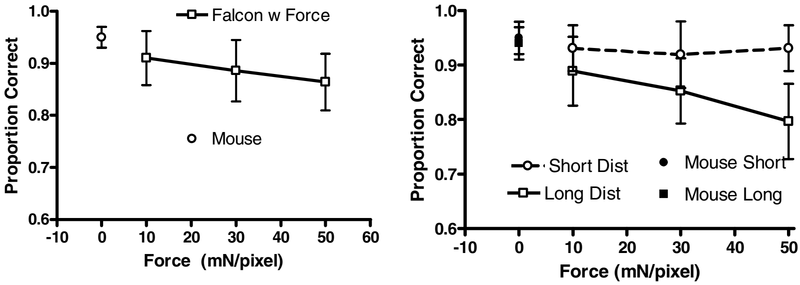

Fig. 5. Accuracy comparison between computer mouse and Falcon with force feedback

We also found a significant interaction of force and distance, $F(1,5) = 6.71$, $p = .01$) as shown in Fig. 4 (right). For the short distance, the level of force feedback had little impact on movement time, but for the long distance movement time increased almost linearly with the amount of force. For all force feedback levels, movement times were longer than that obtained with a mouse. The increase in movement time with the presence of force feedback was expected for an object avoidance task where the amount of force feedback increases proportionally to the deviation from the preferred path. That is, as the distance to the target increases (or with higher gain), the user is required to exert more effort to resist the force feedback to make the route modification. This finding suggests the use of low force feedback could reduce the negative effect on movement time.

5.2 Accuracy

A significant main effect of force, $F(2,10) = 6.54$, $p = .01$, and distance, $F(1,5) = 13.6$; $p = .01$) was found. Accuracy decreased overall with force feedback

(10 mN/pixel: $M = .91$ $SEM = .05$; 30 mN/pixel: $M = .89$, $SEM = .06$; 50 mN/pixel $M = .86$; $SEM = .05$) as seen Fig. 5 (left). Accuracy also decreased overall with distance (*Short*: M = .93, $SEM = .05$; Long: $M = .85$, $SEM = .06$). We also found a significant interaction between force and distance, $F(2,10) = 4.175$, $p = .05$, which can be seen in Fig. 5 (right). With force feedback, the accuracy was the highest at the short distance. At the long distance, accuracy decreased with force feedback. Accuracy at the short distance was about equal to the accuracy of using a mouse similar to the movement time results, too much force feedback decreased accuracy, as the user needed to overcome the force feedback to make the route modification. Since the force model for route manipulation increased proportionally to the overall path length, the amount of force feedback will be generally low when the obstacle is closer. Again, these findings suggest that an appropriate level of force feedback can be applied to yield similar accuracy performance to a mouse.

6 Conclusions

In the present paper, we report a new force-feedback model that was developed for the route manipulation task of NASA Flight Deck Display Research Laboratory's volumetric cockpit situation display. The effect of force feedback on the performance (movement time and accuracy) was evaluated in a user study using a testbed system and the Novint Falcon haptic device as the input device. During the experiment, the users were asked to modify the aircraft's current flight path to avoid an obstacle. Based on the experimental results, the amount of force feedback provided had a significant effect on both movement time and accuracy. Force feedback increased the overall movement time and decreased accuracy as compared to the performance with a mouse. With the route manipulation task, the force feedback model implemented was designed to be used as an indicator of the change to the overall path. As the force increases to resist the user's motion away from the optimal path, the adverse effect of force feedback on performance is anticipated, as found in prior research [15]. Thus, the effect on movement time may not be the most suitable dependent measure to use in evaluating of the true benefit of the force feedback model. The experimental results, however, support the notion that appropriate selection of force feedback level can provide comparable accuracy to a mouse, and may lead to a better performance. To further evaluate the effect of force feedback for route manipulation, obstacles with more complex geometry that will require modification of multiple route segments should be employed. Qualitative factors including the efficiency of the modified path with respect to flight time and fuel cost should also be considered in future studies.

References

1. NASA Flight Deck Display Research Lab, `http://humansystems.arc.nasa.gov/groups/FDDRL`
2. Robles, J., Sguerri, M., Rorie, C., Vu, K., Strybel, T., Marayong, P.: Integration Framework for NASA NextGen Volumetric Cockpit Situation Display with Haptic Feedback. In: IEEE International Conference on Robotics and Automation, pp. 1033–1037 (2012)

3. Rorie, R., Bertolotti, H., Strybel, T.Z., Vu, K.-P., Marayong, P., Robles, J.: Effect of force feedback on an aimed movement task. In: Landry, S. (ed.) Advances in Human Aspects of Aviation, pp. 633–642. CRC Press, Boca Raton (2012)
4. Semere, W., Kitagawa, M., Okamura, A.: Teleoperation with Sensor/Actuator Asymmetry: Task Performance with Partial Force Feedback. In: Proceedings of the 12th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, pp. 121–127 (2004)
5. Wagner, C., Perrin, D., Howe, R., Vasilyev, N., del Nido, P.: Force Feedback in a Three-Dimensional Ultrasound-Guided Surgical Task. In: Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems 2006, pp. 43–48 (2006)
6. Lam, T., Mulder, M., van Paassen, M.: Haptic Interface in UAV Tele-operation using Force-stiffness Feedback. In: Proceedings of the 2009 IEEE International Conference on Systems, Man, and Cybernetics, pp. 835–840 (2009)
7. Farkhatdinov, I., Ryu, J., An, J.: A Preliminary Experimental Study on Haptic Teleoperation of Mobile Robot with Variable Force Feedback Gain. In: IEEE Haptics Symposium 2010, pp. 251–256 (2010)
8. Hwang, F., Keates, S., Langdon, P., Clarkson, P.: Multiple Haptic Targets for Motion-Impaired Users. In: Proceedings of CHI 2003 Conference on Human Factors in Computing Systems, pp. 41–48 (2003)
9. Abbott, J.J., Marayong, P., Okamura, A.M.: Haptic Virtual Fixtures for Robot-Assisted Manipulation. In: Thmn, S., Brooks, R., Durrant-Whyte, H. (eds.) Robotics Research. STAR, vol. 28, pp. 49–64. Springer, Heidelberg (2007)
10. Dennerlein, J.T., Martin, D.B., Hasser, C.: Force-Feedback Improves Performance For Steering and Combined Steering-Targeting Tasks. In: Proceedings of CHI 2000, pp. 423–429 (2000)
11. Martin, T., Ambrose, R., Diftler, M., Platt Jr., R., Butzer, M.: Tactile gloves for autonomous grasping with the NASA/DARPA Robonaut. In: IEEE International Conference on Robotics and Automation, pp. 1713–1718 (2004)
12. Rizzo, D., Messeri, L.: The Effect of Haptic Feedback in a Remote Grasping Situation. In: AIAA (2004)
13. Chaehyun, L., Adelstein, B.D., Seungmoon, C.: Haptic Weather. In: Proceedings of Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, pp. 473–474 (2008)
14. Akamatsu, M., MacKenzie, I.: Movement characteristics using a mouse with tactile and force feedback. International Journal of Human-Computer Studies, 483–493 (1996)
15. Marayong, P., Okamura, A.M.: Speed-Accuracy Characteristics of Human-Machine Cooperative Manipulation Using Virtual Fixtures with Variable Admittance. Human Factors 46(3), 518–532 (2004)