Human Interface Using the Rutgers Master II Force Feedback Interface

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Abstract

The research presented here investigated the effects of haptic display modalities on human performance in virtual environments. Force feedback information was presented through visual, auditory and haptic feedback modalities. Results show that haptic feedback greatly increases performance and reduces error rates compared with the open loop case. Redundant haptic information (two modalities at the same time) does not improve significantly the performance, but is very useful in order to increase sensitivity.

1 Introduction

Virtual reality is a computer generated immersive environment in which users have real-time, multisensorial interactions [1]. A key element is a sensing device for the hand equipped with haptic display. Such haptic interfaces have been developed in recent years [2], [3], [4], [5], [6] and [7]. Due to the presence of humans in the force feedback loop it is important to understand how people perceive events in synthetic environments and how they respond to them.

The work presented in this paper is a continuation of a previous study performed using the Rutgers Master I (RM-I) [8]. The task consisted of squeezing a ball (compressing 10% of its volume) while reaching a target by following a specified path. Results showed that when visual, auditory or force feedback were present, performance was increased by 33.3% (V: visual force feedback through LED bar graphs), 35.7% (A: auditory force feedback through headphones) and 52.3% (H: haptic feedback) respectively, as compared to the open loop case (N: with no force feedback). Redundant force feedback information (V and A) reduced ball deformation by 61.9% (H-V) and 69% (H-A). Task completion times were also reduced by about 30%. However, the test showed some drawbacks of the RM-I system. Although performance improved in closed-loop (using some feedback), the mean deformation for sensory substitution (V and A) and haptic feedback (H) was far from the desired value of 10% by 180%, 170% and 100%, respectively. The main reason is the low dynamic range (maximum-force/static friction) of the RM-I and reduced range of motion of its actuators. Due to the above limitation it was difficult for the user to feel small deformations, particularly for soft virtual objects. In those cases, sound proved to be useful in supplementing the small force feedback. Furthermore, the best results (lowest object deformation) were obtained when auditory redundant force information was presented to the user. The use of an external visual force representation (LEDs bar graphs) in addition to graphics overloaded the visual channel and increased the task completion time.

Recently, a new device, called "Rutgers Master II" (RM-II), has been developed [7], as shown in Figure 1. This device consists of a compact and portable position sensing and force feedback structure that fits in the palm. The RM-II uses light custom actuators with decreased dynamic range versus the RM-I. The present paper describes human factor tests performed to ascertain its usefulness in a virtual environment configuration.

2 Experimental configuration

The Rutgers virtual system has a client-server Ethernet-distributed architecture using three Unix workstations, as shown in Figure 2. A Sun 4/380 (to which the RM-II is interfaced) is dedicated to calculating object dynamics (collisions, grasping, gravity and object tossing). Updated information on object deformation and location is sent to

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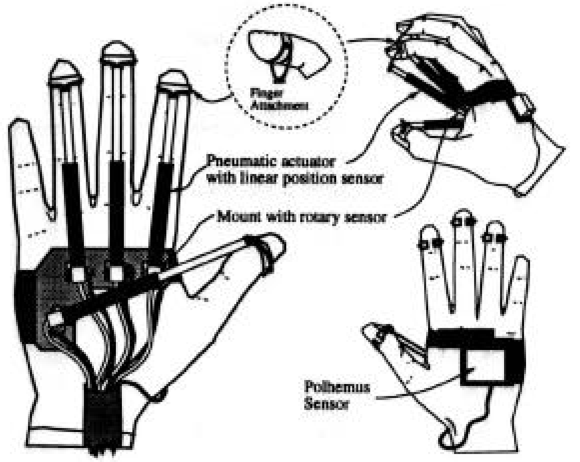

Figure 1. The Rutgers Master II, [7].

an HP-755 workstation dedicated to graphics rendering and display at rates up to 28 frames/second. A sound ID is sent from the Sun4/380 to a Sun ELC which displays the appropriate sound. Our experiments used a single 21 in. graphics display with stereo LCD shutter glasses.

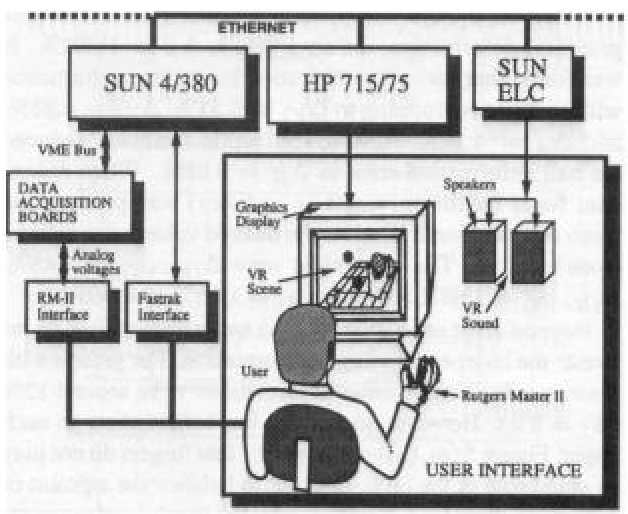

Figure 2. System architecture, [7].

The RM-II provides both hand gesture measurements and force feedback to four fingers. A Polhemus Fastrack measures the wrist 3D position. The main structure consists of four custom-made pneumatic cylinders with embedded position sensors. The pressure in the cylinder chamber determines the force applied by the piston directly to the fingertip (through the finger attachment). A maximum force of 16.38N with a resolution of 0.05N can be obtained.

The interface box displays virtual force feedback: (1) haptically through the feedback actuators using a compact 1/4 HP-60psi compressor; (2) Visually through four sets of twenty LEDs located on the front panel; and (3) auditory through headphones with a frequency range of 35-3,500Hz (proportionally to the deformation).

The experimental virtual environment is composed of black walls with perspective grids, a virtual hand, and a deformable ball (target). Visual cues such as projection of object "shadows" or graphical visual bar graphs can be introduced in the environment to improve both depth and haptic perception. The volume of the virtual room is about $1m^3$. The environment was programmed using the Starbase Graphic Library [9] with Gouraud shading. Four bar graphs, proportional to the level of the force feedback computed, can be displayed directly onto the screen. Four virtual forces (F_i) were calculate individually, according to the simple Hooke's law ($F_i = k\Delta x_i$). Here Δx_i represents the deformation at the contact point between fingertip i and the ball and k is the ball stiffness.

3 Human factor experiment

The two goals of this experiment were the following: (1) Investigate the effect of pseudo force feedback (visual and auditory feedback) and redundant presentation of haptic information on a dextrous manipulating task performance using the RM-II; and (2) compare the performance of RM-I and RM-II when achieving the same task.

Eight groups of eight subjects each (32 males and 32 females) were used for this experiment. The first group (N) performed the manipulation task using only graphical deformation feedback, the second group (V1) had graphics and visual force feedback through the interface LED bar graphs, while the third group (V2) had graphics and visual force feedback through bar graphs displayed onto the screen. The fourth group (A) had graphics and auditory force feedback, and the fifth one (H) had graphics and haptic force feedback from the RM-II. The three other groups had redundant force feedback added to graphics and haptic force feedback. The sixth (H-V1) and seventh (H-V2) groups had visual force feedback through the interface LED bar graphs and through bar graphs displayed onto the screen, respectively. The last group (H-A) had redundant auditory force feedback. The RM-II was worn in all experiments.

The first four subjects of each group had a yellow virtual ball (high stiffness) while the last four subjects had a red ball (low stiffness). All groups performed the task using the RM-II and the stereoscopic display. The haptic interface was energized only for the groups with haptic feedback (H, H-V1, H-V2 and H-A).

3.1 Experimental Protocol

Subjects were instructed to reach and pick up a virtual ball (red or yellow) at location "A", then move it to "C" going through location "B" (see Figure 3). They had to apply a low, stable amount of deformation (10% of the sphere radius) and keep the vertical projection of the ball between the two corresponding lines. The task had to be completed in less than 15 seconds, however, subjects were told that the most important thing was to control the amount of deformation.

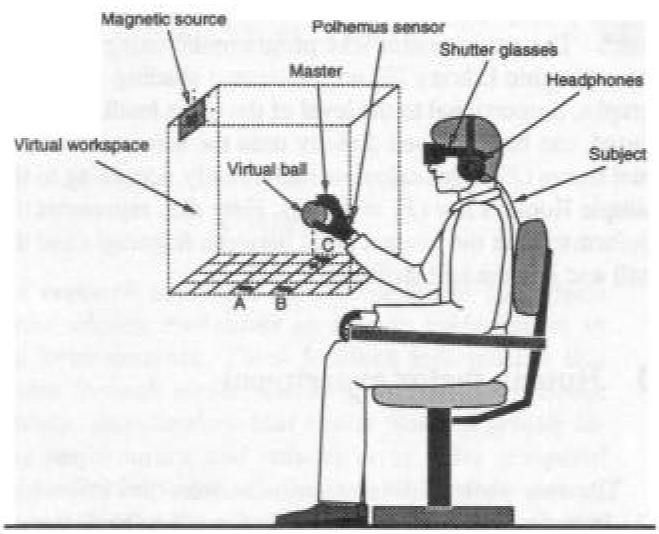

Figure 3. Experimental system configuration, [8]

Subjects had no explicit information about the relationship between the different force feedback and the percentage of deformation required (10%). The amount of deformation on fingers was recorded after every loop and the task completion time was noted (time to move the ball from location "A" to "C") after each trial.

Subjects were seated so that the eye-monocular display distance was approximately 60 cm. The RM-II was fitted on their right hand, and stereo glasses were worn. Then after a quick calibration of their hand, subjects had one trial to familiarize themselves with the limits of the virtual room and the sensory force feedback. Subjects performed the task in 10 trials with 15 seconds rest periods in between.

Experimental room illumination was maintained low in order to increase the contrast between the display and the immediate surroundings.

3.2 Results

Figure 4 shows the manipulation task mean deformation for all groups for both RM-II and the former human factor tests using RM-I. The error rate is defined as: $\Delta_j = |10\% - d_j(\%)|$, where d_j represents the percentage of deformation recorded for each group j.

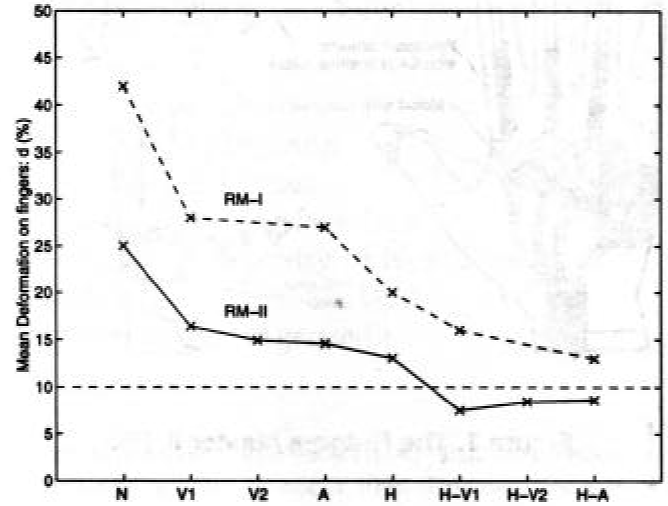

Figure 4. Manipulation task mean error for different force feedback modalities N: None, V: Visual, A: Auditory and H: Haptic.

When the system has no force feedback other then just graphical deformation, the error rate is $\Delta_N = 15.02\%$. It was found that sensory substitution increases performance with error rates dropping to $\Delta_{V1} = 6.51\%$, $\Delta_{V2} = 4.93\%$, and $\Delta_A = 4.37\%$. Moreover, haptic feedback reduced the ball deformation error to $\Delta_H = 3.02\%$. When redundant force feedback (visual or auditory) was present, the mean deformation fell below the desired value but remained close to 10%. The error rates were $\Delta_{(H-V1)} = 2.48\%$, $\Delta_{(H-V2)} = 1.66\%$ and $\Delta_{(H-A)} = 1.38\%$, respectively.

Beyond error rates, there is also an important field of interest: the independent finger deformation. For groups with sensory substitution, mean deformations were around 15% ($\Delta_j = 5\%$). However, looking to the deformation on each finger, Figure 5 (a), (b) and (c) shows that fingers do not play an equal role in the task. In order to balance the amount of deformation on each finger, haptic feedback is appropriate (Figure 5 (d)). The thumb presented a very small deformation due to the kinematic constraints. That is the spherical object located in the center of palm which makes the thumb travel a longer distance before it applies 10% deformation. In this way, users rely more on information coming from the other three fingers. Introduction of redundant haptic information (Figure 5 (e) and (f)) improves the balance of independent finger deformation giving the best results.

Figure 6 shows the subject's learning process. It is notable that task learning does not present a fast decreasing behavior. It has to be noticed too, that the initial value (Trial

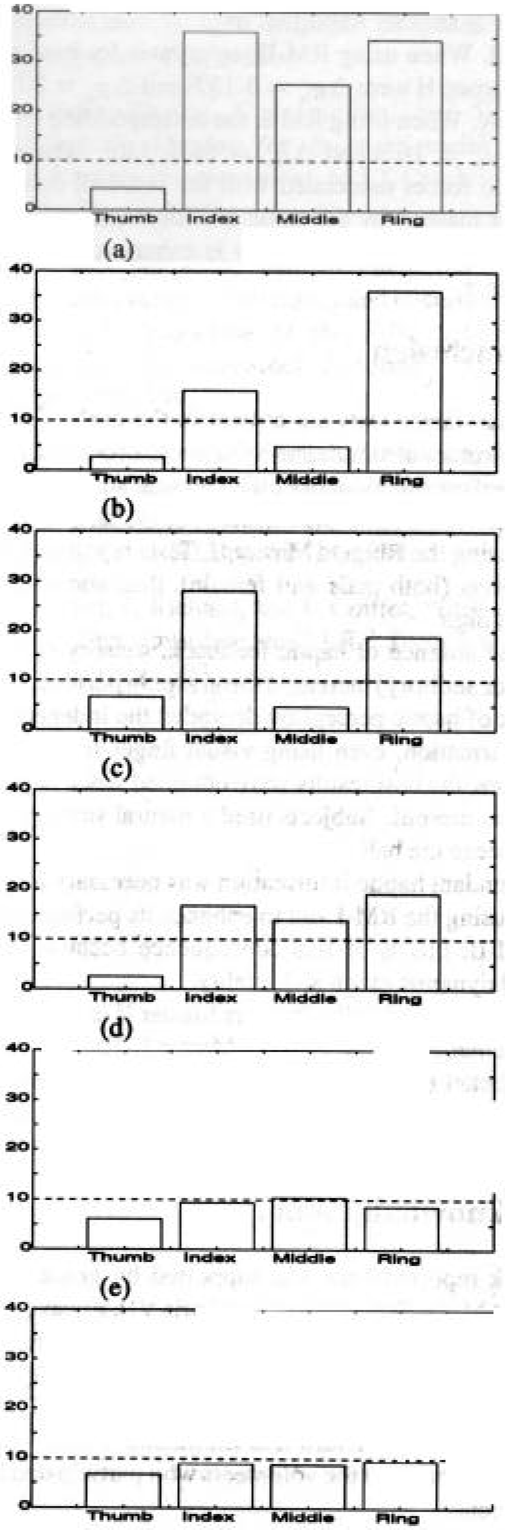

Figure 5. Independent finger deformation (%): a) None, b) Visual force feedback, c) Auditory force feedback d) Haptic feedback, e) Auditory and haptic force feedback, f) Visual and haptic force feedback.

#1) is already relatively close to the target value. The reason for this is that lower friction and higher resolution of the RM-II allow the user to have a good initial estimation. From there on (trials 2, 3 ... 10) the learning process is bounded in the neighborhood of 10%.

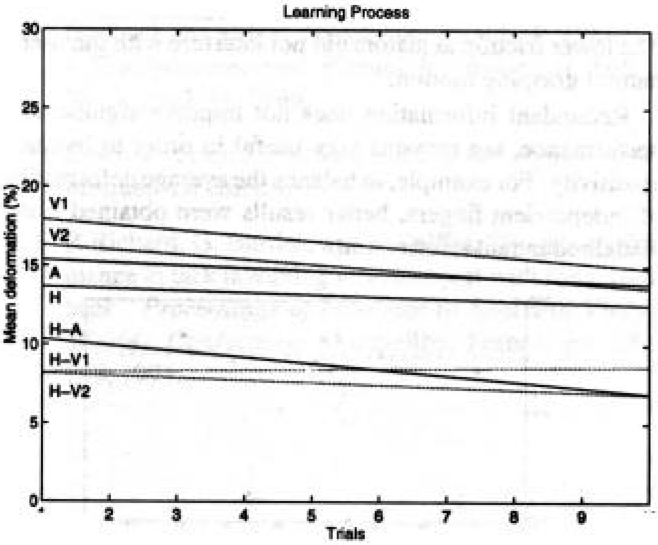

Figure 6. Manipulation task learning process for different force feedback modalities

The reason for this is that the way the subject estimates the target deformation is by first, fixing a mental 10% threshold on each finger articulations and then try to reproduce it during every trial. Thus, the deformation for each trial oscillates around the mean deformation (examples Figure 7). Furthermore, even if the difference in error rates between haptic and redundant force feedback was not too significant ($\Delta_H - \Delta_{(H-V2)} = 1.36$), the standard deviation of these oscillations decreased when redundant information was present. This was especially true when using visual force feedback for which subjects had explicit information about the deformation on each finger.

4 Discussion

The present experiments were aim at understanding how people perform a typical manipulation task using different force feedback modalities.

The study can also be used to compare the RM-I versus the RM-II haptic feedback devices. As in the study by Richard et al.[8], the smallest error rate corresponds to haptic-auditory (H-A) force feedback group, and average error rate for the group (H) is also reduced by about 50% as compared to the group (N). It is notable that results for all groups, decreased in the same manner (as shown Figure 4) for both RM-II and RM-I.

However, it is observed that performance for the open loop case ($\Delta_{N_{RMII}} = 15.02\%$) decreased by 53% as compared to the same group during the RM-I study ($\Delta_{N_{RMI}} = 32\%$). The main reason for this is the use of force feedback actuators with a higher dynamic range and larger range of motion. Because of this, it was easier for the user to interact with the object even when no haptic feedback was applied. The lower friction actuators did not interfere with the user's natural grasping motion.

Redundant information does not improve significantly performance, but remains very useful in order to increase sensitivity. For example, to balance the average deformation of independent fingers, better results were obtained using visual redundant information.

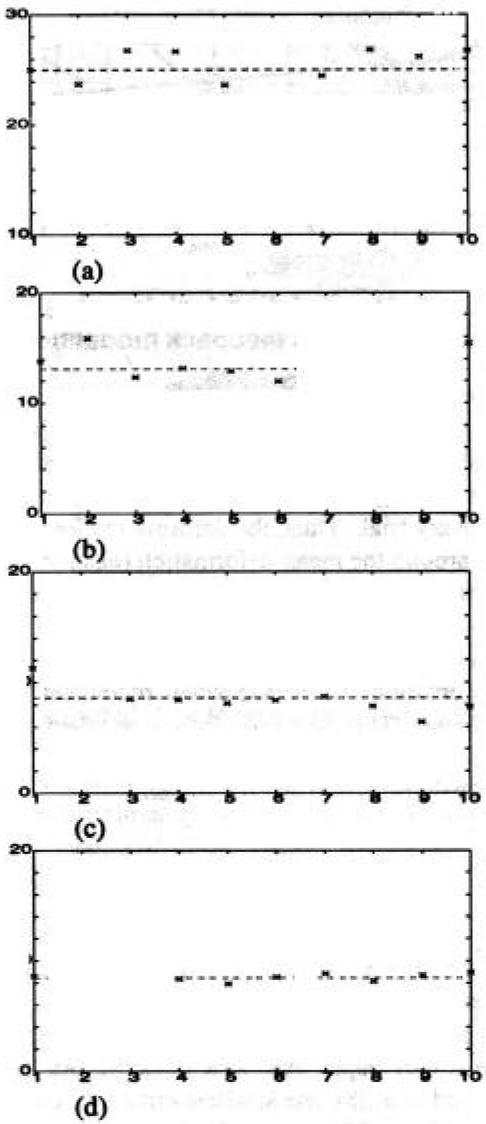

Figure 7. Manipulation task mean error (%) for each trial. a) Group N, b) Group H, c) Group H-A, d) Group H-V2.

There is another important improvement from the RM-I to RM-II. When using RM-II, error rates for hard and soft balls in group H were $\Delta_{H_h} = 3.13\%$ and $\Delta_{H_s} = 3.01\%$, respectively. When using RM-I, the corresponding error rates were $\Delta_{H_h} = 10\%$ and $\Delta_{H_s} = 25\%$, [10]. These results show that forces associated with the soft-ball deformation were not masked by the static friction when using RM-II. Thus the haptic display fidelity is enhanced greatly in the RM-II case.

5 Conclusion

Human factor tests are critical in the evaluation of virtual environment simulation systems in order to assess and improve their functionality . The present study investigated human performance for dextrous manipulation of a virtual object using the Rutgers Master II. Tests reported here used 64 subjects (both male and female), thus statistical confidence is high.

In the absence of haptic feedback, sensory substitution (visual or auditory) increased the grasping performance. But the lack of haptic perception degraded the independent finger deformation, even using visual finger force feedback. Therefore, the best results were obtained when haptic feedback was present. Subjects used a natural strategy to track and squeeze the ball.

Redundant haptic information was necessary to improve results using the RM-I and to enhance its performance. For the RM-II, this is of less consequence because of its increased dynamic range and fidelity.

Results show that the Rutgers Master II is a considerable improvement over the Rutgers Master I. The RM-II device allows better performance and a more natural grasp. This is important in order to increase performance in manipulation tasks and to enhance the user's sense of immersion.

Acknowledgments

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