Exploring the Impact of Visual-Haptic Registration Accuracy in Augmented Reality

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Abstract. In augmented reality (AR) systems featuring visual and haptic cues it is important to maintain a close match between the presented stimuli in order to create realistic environments. What is felt must match what is seen. However, this is a challenging task - AR systems inherently feature noise. This paper describes a study to explore the effect of disparities between visual and haptic cues in a targeting task in an AR environment. The results reveal that participants were highly sensitive to discrepancies between the modalities; performance degraded with registration errors of as low as 2 mm, suggesting this is practical limit for AR systems. Future work will explore how haptic rendering parameters such as cursor size and stiffness affect these results.

Keywords: Visual-haptic registration, Augmented reality, Perceptual threshold.

1 Introduction

Real environments naturally present users with rich, coherent multi-sensory cues: sights, sounds, and haptic sensations. Indeed, during everyday tasks such as object manipulation we inherently see, hear and feel diverse information pertaining to the same activities. Reflecting the importance and ubiquity of such cross-sensory experiences, a vibrant research community explores multi-modal perception. However, in virtual or augmented environments the coherence of multi-modal cues is not guaranteed. Indeed, one prominent research topic has been to manipulate combinations of cues delivered to vision, hearing and touch [1,2] in order to examine the effects and cast light on underlying perceptual processes. In the area of haptics, this issue has largely been discussed in terms of spatiotemporal visual-haptic object correspondence – the match between graphical and haptic representations of objects.

This issue is not purely theoretical. For example, in augmented reality systems, achieving a good spatiotemporal match between visual scenes, typically captured by a camera, and haptic information, typically rendered on a force-feedback device, is a challenging process. Numerous techniques have been described to match visual and haptic representations, including those based on optical reflection [e.g. 3 – 5] and on Head-Mounted Displays (HMDs) [6 – 8]. Optical reflection systems use a half-silvered mirror to integrate graphical and haptic representations so that a user can see

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both their own hand and digitally generated graphical scenes. On the other hand, HMD systems use cameras and tracking techniques to monitor head, hand and object position in order to generate appropriate visual and haptic feedback. Generally, increased levels of realism, comfort and ease of use have been attributed to optical reflection approaches [7] while improved performance in target acquisition tasks have been demonstrated in HMDs [8].

The vast majority of this work focuses on approaches to achieve close visual-haptic co-location. This paper argues that a pre-requisite for such development is identifying the required level of spatial correspondence for an effective, convincing and compelling perceptual experience. For example, several authors indicate their systems lead to registration errors of between 2 mm–3 mm between visual and haptic representations [3, 9]. Others suggest that when a high level of correspondence is not provided, task performance degrades [10]. Although the presence of such problems is acknowledged, the acceptable range of error in augmented reality systems has not been discussed. Therefore, this paper seeks to address this lack of knowledge by conducting a study to establish the perceptual threshold of visual-haptic registration errors. The results are intended to serve as preliminary requirements stipulating the necessary visual-haptic registration accuracy in augmented reality systems.

2 Visual-Haptic Registration Study

The objective of this paper is to determine the impact of disparities between visual and haptic cues. The results will be used as registration accuracy requirements that can inform the design of future systems that integrate visual and haptic feedback. In order to achieve this objective, an experimental platform that allowed precise manipulation of visual and haptic stimuli was developed and a user study conducted.

2.1 System Configuration

The experimental system is illustrated on the left side of Figure 1. Participants are seated in front of a 23 inch computer monitor and manipulate a PHANToM omni with their dominant hand. The graphical display is configured to exactly match physical dimensions: one mm of on-screen cursor movement is caused by one mm of movement with the haptic device in real environment. The exact spatial correspondence is common in visual-haptic AR systems, particularly in those based on silvered mirrors [3-5]. The right of Figure 1 shows the on screen display. It takes the form of still image depicting a simple scenario in which a box is situated in the center in an otherwise cluttered visual environment. The haptic box shown in Figure 1 was not visible during the experiments and was only used to render haptic feedback. Altering the position of the haptic box was used to generate discrepancies between visual and haptic cues.

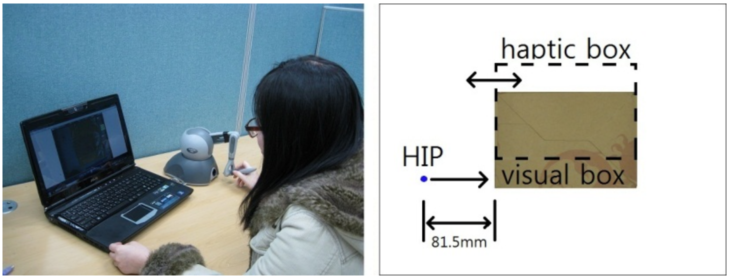

Fig. 1. System configuration for experiments

2.2 Experimental Procedure

Trials in the experiment were simple: participants observed the still image of the box while manipulating haptic device. A cursor representing the haptic interaction point (HIP) with radius of 1.5 mm was overlaid on top of the image. The participants' task was simply to reach and touch the edge of the box. A haptic wall was simulated around the box edge; its precise location was manipulated to create different levels of registration error, or offsets between the presented visual and haptic cues. To create the simplest possible scenario, participants' movements were constrained to single dimension: horizontal (x-axis) motions. Haptic cues in the form of a proportional controller served to constrain movements in y and z-axes.

At the start of each trial, forces were applied to move the HIP to an initial position, 81.5 mm left of the visual representation of the box. After this position was reached, participants' task was to move the HIP rightward towards the box. The precise experimental instructions were selected to be modality neutral; participants were told to "go to the edge of the object as fast and accurately as possible". Trials ended when participants showed stationary movement for 500 ms.

The visual cues remained the same throughout the experiment. Registration errors were simulated via variations in the position of the haptic wall. Specifically, 11 different haptic wall positions were studied. These ranged from 10 mm to the left of the visual representation (negative) to 10 mm to the right (positive), at equidistant intervals of 2 mm. The experiment was primarily intended to explore participant performance in situations where perfect registration, or the match between the haptic and visual information, was expected but not found. We believe this scenario simulates a realistic AR scenario in which users operate under the assumption that haptic cues will match to visual objects, but unpredictable system errors means this does not occur. In order to simulate this process, trials were organized into sessions of five. In four trials in each session, perfect visual-haptic registration was presented to users. In the fifth, randomly sequenced trial, a haptic offset was presented. Each of the 11 registration positions was presented to each participant five times, leading to a total of 275 trials (including 220 trials with perfect registration). The experiment took approximately 1 hour to complete. Participants took two rest breaks to counteract fatigue.

2.3 Experimental Results

A total of seven subjects completed the experiment. One was female and six were male. Ages ranged between 26 and 31. Six were right handed, one was left handed.

Representative velocity (calculated with the finite difference method with a windowing size of ten) and position profiles are shown in Figure 2 these depict single trials but are illustrative of the data captured across the study. Generally speaking, the data follow trends reported in the literature on general goal-directed movement [11]. Each targeting movement is characterized by an early ballistic phase: rapid accelerations followed by precise decelerations that lead to a rapid convergence at the target site. After the ballistic phase is complete, a correction phase commences if the results of the ballistic phase are considered inadequate. Three behaviors can be observed across the different registration levels. The first of these takes place with registration levels of 0 mm and -2 mm. In these cases, there is no observable correction phase, suggesting ballistic targeting movements were perceived to reliable and accurate. The second can be seen with registration levels of between -4 mm and -10 mm. In these cases, participants collided with the haptic box in advance of their expectations, truncating their ballistic targeting movement. Typically, they then entered a correction phase in which they pushed through the haptic wall to reach the graphically presented edge. This behavior suggests registration errors were easily perceivable and even disruptive. Finally, with registration errors of between 2 mm and 10 mm, participants encountered the haptic wall beyond the visual boundary. The traces show participants falling through the visual boundary at the end of their ballistic movement, and then correcting to reach the visual edge by moving back along their path. Once again, this behavior strongly suggests the registration errors were perceivable to participants.

In order to quantify these observations, an objective analysis was conducted using the index of error correction effectiveness (IECE) [12]. IECE is intended for characterization of targeting trajectories and has previously been employed to calculate the impact of visual monitoring during such processes. It is defined as

$$\mathrm{IECE} = \frac{AE(ii) - AE(ec)}{AE(ii) + AE(ec)} \tag{1}$$

where *AE(ii)* is an absolute error at the end of *initial impulse* phase of targeting movement and *AE(ec)* is an error at the end of any subsequent *error correction* phase. Determination of *AE(ii)* is based on [12] while *AE(ec)* takes the form of a steady state error. Essentially, human hands experience unintentional tremor movements [13]; this work assumes that movements of 0.5 mm and below are due to tremor. From this assumption, the unintentional *AE(ii)* range can be calculated by adding/subtracting the value of hand tremor and/from the average *AE(ec)*. By using this *AE(ii)* range and the average *AE(ec)*, the unintentional IECE range can be obtained by (1). This aids interpretation as follows: conditions yielding IECE values inside the range exhibit little or no correction phases; those yielding values outside the range feature directed error correction by users due to perceivable errors between the visual and haptic cues. An IECE plot is shown in Figure 2. Across the study, the average *AE(ec)* and two reference IECE values were 0.934 mm (SD: 0.698 mm), 0.211, and -0.349, respectively. As shown in Figure 2 (D), registration values of 0 and -2 mm are inside this range, suggesting these two conditions result in perceptually coherent targeting processes. The relatively high standard deviations observed with registration values of 0 and -2 mm are due to the presence of negative IECE values. Data points where *AE(ec)* is larger than *AE(ii)* generally reflect only hand tremor or other unintended movements.

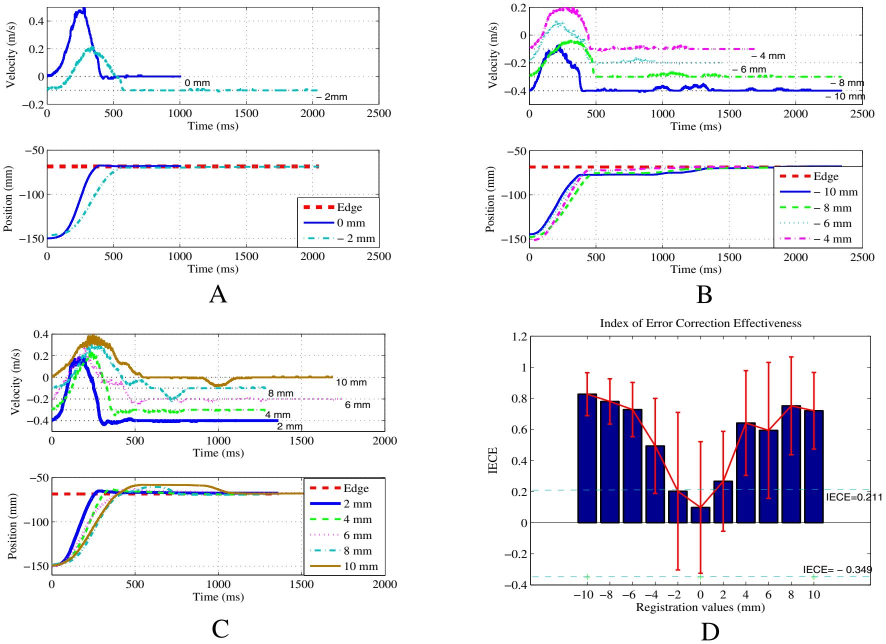

Fig. 2. Velocity and position profiles from representative trials when graphical and haptic cues are perceived as well aligned (0 and -2mm, A), when haptic cues are perceived as closer than visual cues to an users initial position (-4 to -10mm, B) and when haptic cues are perceived as further (2 to 10mm, C). In A, B, and C, each velocity profile is offset by 0.1 m/s to facilitate viewing. Also show IECE analysis for all 11 visual-haptic registration values (D).

3 Discussion and Conclusions

Augmented reality systems combining visual and haptic cues must work to ensure a close match between these modalities in order to create coherent and compelling experiences. This paper described an experimental study that manipulates haptic and visual correspondence in a targeting task. Data from velocity and position profiles suggests that acceptable registration errors between visual and haptic cues are below 2 mm, with a slightly higher tolerance for situations in which haptic cues preceded visual ones. The experiment also cast light on the role of haptic and visual cues in the task - subjects took advantage of the haptic feedback to achieve accurate targeting, for example by aiming their ballistic movements to stop against the rendered walls. This was particularly clear in cases in which the haptic wall was behind the visual wall – in these situations, participants clearly “fell” past the their intended visual targets. However, vision played a dominant role in error correction – despite the modality neutral instructions, whenever there was a perceivable discrepancy between the modalities they moved to the visual boundary to complete the trial. Future work on this topic will explore how different haptic parameters effect required registration accuracy. For example, haptic cursor size and boundary wall stiffness are likely to affect performance. By conducting such additional experimentation, we will be able to arrive at a complete description of the required registration accuracy for augmented reality systems featuring synergistic combinations of visual and haptic cues.

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