Visual Guidance for Encountered Type Haptic Display: A feasibility study

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ABSTRACT

Virtual/mixed reality leveraging an encountered type haptic display will suffer difficulty if virtual and real objects are spatially discrepant. We propose a new method for resolving this issue, visual guidance. The visual guidance algorithm is defined and described in detail, and contrasted with a previously explored approach. The feasibility of the proposed algorithm is experimentally verified.

Keywords: Haptic augmented virtuality, spatial discrepancy, encountered type haptic display, visual guidance.

Index Terms: Mixed/augmented reality; User interface design

1 MOTIVATION

One of the key applications for virtual/mixed reality systems is in haptic training [1] since these systems have several advantages over traditional real world systems. First, accidents due to a failed procedure or trainee error will not result in a real harm. Second, rather than reconstructing or reconfiguring real facilities for a new training scenario, a VR (virtual reality) system allows a designer to reconstruct or reconfigure the virtual facilities.

A recurring issue with this approach to training is ensuring that the user feels the resulting environment is plausible. By combining traditional haptic training with real tools for the trainee to interact with, we can create a plausible HAV (haptic augmented virtuality) environment for the trainee with a specific application. We categorized the combined environment as HAV because we added the geometric shape of a real tool onto a virtual haptic feedback device (e.g. force/torque feedback). One area where HAV can offer significant benefits is in a plant safety training simulator that may require plausible haptic sensations (e.g. click feeling for buttons, virtual torques during valve or lever turning, etc.) for a more immersive training experience.

In order to touch and manipulate these diverse tools, many different types of haptic devices must be provided to the trainee in many different poses, which is not an economical solution. One solution to this problem is the use of an active haptic technology: the encountered type haptic display paradigm [2][3] because in this paradigm, one robotic device can provide many real tools at many different poses by exchanging them [4]. A real tool, which a trainee tries to manipulate, is assembled with a robotic device while the trainee walks towards a virtual tool, then is moved to coincide with the virtual tool by the robotic device.

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Although some literature introduced encountered type haptic displays for tennis ball juggling [2] and for automobile control panel [3], the virtual tools were located within the workspace of the robotic device. However, the virtual plant facility has many virtual tools in a **wide** area, which means that the trainee has to walk/run to another place to manipulate a variety of tools whose positions/orientations, size, etc. are all different. Therefore, some virtual tools can't be reached by the robotic device because the effective pose range is limited by mechanical and safety aspects, resulting in **spatial discrepancy**, the definition of which will be detailed in the next section. A robotic device with larger workspace may solve the problem, but it is not an economical solution. This spatial discrepancy problem may also arise in automobile haptic repair training and electrical facility construction, which use diverse tools over a wide area.

The purpose of this paper is to propose the concept of the visual guidance approach to resolve the spatial discrepancy problem and then to validate the feasibility by a simple button pressing task as an example.

2 SPATIAL DISCREPANCY

In general, spatial discrepancy can be defined as a *pose, size, or shape difference between a visually perceived object in the virtual world and a haptically perceived corresponding object in the real world*.

Fig. 1 shows a typical spatial discrepancy due to the pose difference between the virtual and real buttons. In the context of the encountered type haptic display system for the haptic plant training system, the pose difference can occur when a real button that a robot holds cannot reach the pose of the virtual button. This could be due to the virtual button being outside of a reachable workspace of the robot that is used in the encountered type haptic display system. This is not necessarily a kinematic limit of the robot since the workspace of a robot may be limited for trainee safety or be constrained to ensure a stiff and robust haptic feedback [5].

We verified the negative impact of the spatial discrepancy on a targeting performance [6]. To counter this effect, simulations must ensure visual haptic colocation so that the visually perceived point of contact in the virtual world match the haptically perceived point of contact.

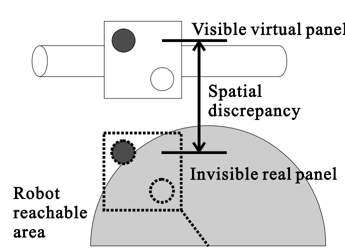

Figure 1: Typical example that causing the spatial discrepancy

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2.1 Previous Research – Redirected Touch

Redirected touching [7] is a technique by which "*virtual space can be warped to map a variety of virtual objects onto a single real object*" [8].

Redirected touching can direct a trainee to a real tool by warping a virtual space such that predetermined virtual buttons in virtual world are mapped to real buttons. Even though the redirected touching may be applied successfully to some training situations, it has following characteristics and limitations: Firstly, a tradeoff made by the redirected touching approach is the visual/proprioceptive discrepancy between a person's real and virtual hand motion. This means inconsistent hand pose and velocity between what the trainee sees and how internal sense of body posture (i.e., proprioception) feels although the virtual and real hands press the target buttons at the same time. This discrepancy can be disturbing and thus can be disruptive and distracting to the trainee. Secondly, both adaptation to the warped virtual space before training and re-adaptation to the real world tasks after a long training duration (e.g. one block of experiment (6 target rings = 66 targets)) are necessary to mitigate performance degradation such as decreased throughput, increased error rate, task completion time, and trajectory variation.

However, in the proposed HAV environments using the encounter type haptic display system, the spatial discrepancy may be generated in a random fashion. Some virtual objects may not be reached by the real objects due to reachable workspace limitation of the robot or due to safety consideration. But other virtual objects may not have any spatial discrepancy. Therefore, additional training to adapt to the warped virtual space as required in the redirected touching technique cannot be applied in the proposed HAV environments using the encounter type haptic display system.

3 Visual Guidance

If there is a spatial discrepancy between real and virtual tools, such as buttons, the proposed visual guidance method guides the trainee hand to the real button by gradually moving the visually presented virtual button towards the real button as the trainee reaches their hand towards the virtual button. During this gradual movement of the visible virtual button, the trainee tries to reach the moving virtual button because there is no other visual cue for the button. Therefore the proposed solution is named "**Visual guidance**".

3.1 Applying Visual Guidance

(i) Compute the spatial discrepancy ($\bar{p}_{SD}$, shown in Fig. 2) between the real ($\bar{p}_{r,object}$) and the virtual objects ($\bar{p}_{v,object}$) by getting the external tracker information and by accessing the virtual world as,

$$\bar{p}_{SD}(t) = \bar{p}_{r,object}(t) - \bar{p}_{v,object}(\mathrm{t}). \tag{1}$$

(ii) Compute a vector of targeting from the user hand ($\bar{p}_{r,hand}$) to the virtual object by getting the external tracker information as,

$$\bar{p}_{r,targeting}(t) = \bar{p}_{v,object}(t) - \bar{p}_{r,hand}(\mathrm{t}). \tag{2}$$

The timing of the hand reaching to the virtual object and the timing of visual guidance to the real object must be same to make the real hand encounter the real object. This means,

$$t_1 = \frac{|\bar{p}_{r,targeting}(t)|}{|\bar{v}_{r,haad}(t)|} = t_2 = \frac{|\bar{p}_{SD}(t)|}{|\bar{v}_{v,object}(t)|}, \tag{3}$$

where the velocities of the real hand and the virtual objects are,

$$\bar{v}_{r,haad}(\mathrm{t}) = \frac{\Delta\bar{p}_{r,haad}(t)}{\Delta t}, \bar{v}_{v,object} = \frac{\Delta\bar{p}_{v,object}(t)}{\Delta t}. \tag{4}$$

(iii) Compute the displacement of the virtual object by combining eqs. (3) and (4) as,

$$|\Delta\bar{p}_{v,object}(t)| = \frac{|\bar{p}_{SD}(t)|}{|\bar{p}_{r,targeting}(t)|}|\Delta\bar{p}_{r,haad}(t)|. \tag{5}$$

(iv) Compute the position of the virtual object by using eq. (5) as,

$$\bar{p}_{v,object}(\mathrm{t}) = \bar{p}_{v,object}(\mathrm{t}-1) + |\Delta\bar{p}_{v,object}(t)| \times \frac{\bar{p}_{SD}(t)}{|\bar{p}_{SD}(t)|}. \tag{6}$$

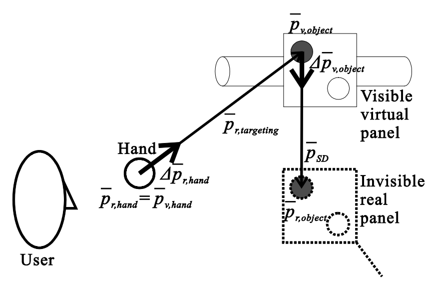


Figure 2: Coordinate relationship for the visual guidance

4 Feasibility of Visual Guidance

In order to check the feasibility of the proposed visual guidance, this section presents an experiment configuration, conditions, a design, procedures, as well as results and their analysis. The experiment is similar to the work of redirected touching [6].

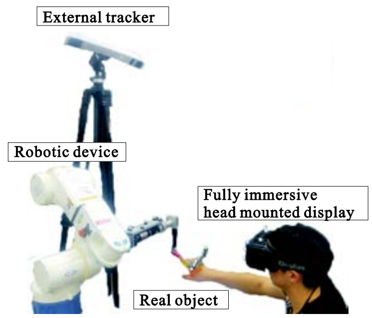
4.1 Experimental Configuration

As seen in Fig. 3(a), our experimental hardware includes the real object (real button), the external tracker (PST Iris), the fully immersive HMD (Oculus DK2), and the robotic device (Denso robot arm). The real button provides the feeling of a button click when the user presses it. The PST Iris tracks the poses of the user's head, hand, and real button. The Oculus DK2 provides a full immersion visual display of the virtual world. Finally, the Denso robot arm moves the real button on demand during the experiments to generate an artificial spatial discrepancy. As seen in Fig. 3(b), the experiment was performed with a complex virtual plant facility containing virtual pipes, virtual valves/levers, and a virtual panel intended to resemble a real training situation.

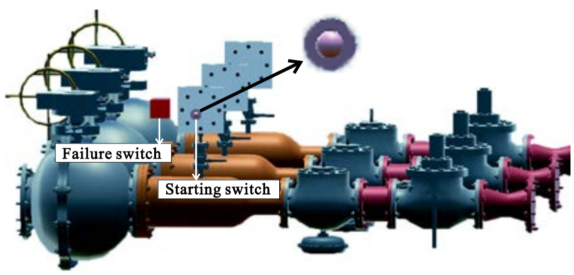
4.2 Experimental Conditions

The experiment was designed to validate the effectiveness of visual guidance with a different amount of spatial discrepancy along three primary axes.

The magnitudes of spatial discrepancy were varied from -30 mm to 30 mm with an increment of 10 mm along three primary axes. Artificial spatial discrepancies were generated by translating/rotating the real button rather than the virtual button.



(a) Hardware configuration



(b) Virtual environment setup

Figure 3: Developed plant safety training simulator

4.3 Experimental Design

The experiment was composed of 7 sessions for training and 19 sessions for the main experiment, each of which contained 8 individual button press trials, for a total of 56 trials ((2 non-zero spatial discrepancies × 3 axis + zero spatial discrepancy) × 8 buttons) for training and 152 trials ((6 non-zero spatial discrepancies × 3 axis + zero spatial discrepancy) × 8 buttons) for the main experiment. Subjects completed the full experiment in approximately 40-50 minutes (10 minutes for training and 30 minutes for the main experiment), allowing for a short break after every 4 sessions to prevent fatigue. During the training sessions spatial discrepancies of -10, 0, and 10 mm were displayed along the three orthogonal axis.

Each session consisted of all 8 buttons being pressed in a consistent order. However, each trial presented a randomly selected spatial discrepancy along randomly chosen primary axis to prevent adaptation. During the experiment, each button presented all spatial discrepancies along every axis exactly once. This ensured random sampling of all conditions, and guaranteed that all conditions were tested.

4.4 Experimental Procedure

Participants were sitting in front of the robotic device for the experiment and wore a finger tracking marker on their dominant hand for hand tracking. The participants wore headphones to block audio cues from the robotic device, in addition to other audio interference during the main experiment.

To begin a trial, participants had to reach his/her fingertip, represented as a sphere in the virtual world, to a starting switch seen in Fig. 3(b) which guaranteed a consistent starting position.

Once the trial began, the task of the participants was "Press the red colored virtual button as quickly and accurately as possible. If you fail to press the real button, do not try to find the real button and retract your hand immediately. Then reach your hand to the failure switch on your left side (seen in Fig. 3(b))". The failure switch was employed to objectively measure the error rate.

The objective performance measurements include a task completion time and an error rate. The task completion time was defined as the duration from the beginning of a trial to the button pressing. The error rate was defined by dividing the total number of missing trials with the total number of trials.

5 Results

We had 10 participants, 9 male and 1 female. All were between the ages of 21 and 31. One participant was excluded for analysis because he reported that he felt strange throughout the whole experiment, even for zero spatial discrepancy. Figs. 4 and 5, showing the raw experimental results, are present below.

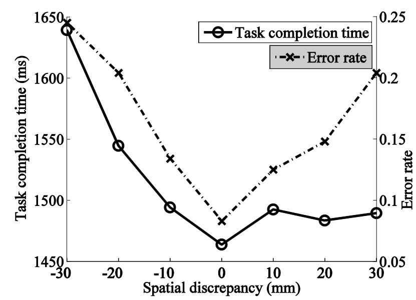


Figure 4: Performance measures with spatial discrepancies

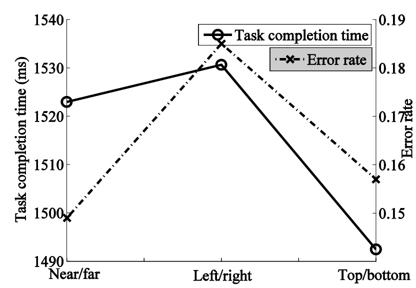


Figure 5: Performance measures along three orthogonal axis

To explore the differences in the data, a two-way RM-ANOVA (repeated-measure analysis of variance) was conducted for each experimental measure using SPSS with seven spatial discrepancies on three orthogonal axis. Table 1 shows the RM-ANOVA results while Table 2 shows the results of post-hoc pair-wise comparisons incorporating Bonferroni confidence internal adjustments for the variables of spatial discrepancy, where the RM-ANOVA main effects attained significance. However, the main interest of the current work is the statistically significant difference between the non-zero spatial discrepancies and zero spatial discrepancy. Therefore, we present only the results of comparison between them. Finally, the interaction plot for task completion time is shown in Fig. 6. Note that statistically significant differences are represented as follows; **$p < 0.05$*, $p < 0.01$**, $p < 0.001$*****.

Table 1: Statistical analysis for main and interaction effects

Measurements \ Variables	Spatial discrepancy	Axis	Spatial discrepancy * Axis
Task completion time (ms)	$F(6, 48) = 5.242$, **$p = 0.006$****	$F(2,16) = 1.183$, $p=0.331$	$F(12,96) = 5.547$, **$p=0.002$****
Error rate	$F(6, 48) = 2.647$, $p=0.087$	$F(2,16) = 1.322$, $p=0.294$	$F(12,96) = 1.927$, $p=0.128$

Table 2: Results of post-hoc pair-wise comparison for spatial discrepancies

Measurement	Post-hoc pair-wise comparison with zero spatial discrepancy: p-value					
	-30	-20	-10	10	20	30
Task completion time (ms)	0.161	1.000	1.000	1.000	1.000	1.000

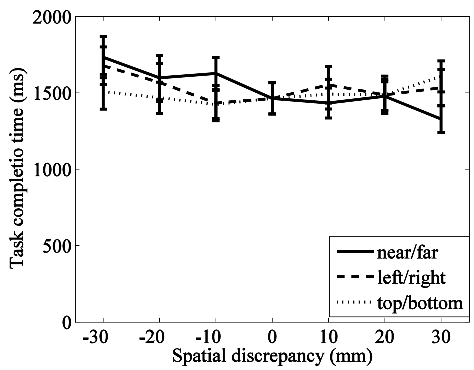


Figure 6: Interaction plots of the task completion time

6 Discussion

As seen in the 'Task completion time' of 'Spatial discrepancy' on Table 1, spatial discrepancy gives effects on the task completion time. As seen in the solid plot of Fig. 4, task completion time increased from a spatial discrepancy of -10 to -30 mm, but had consistent values from -10 mm to 30 mm. A probable explanation is that the negative discrepancies on the near/far axis increased travel distance, resulting in an increased task completion time. This is supported by Fig. 6. The task completion time gradually decreased from a spatial discrepancy of -30 to 30 mm along near/far axis.

As seen in the 'Task completion time' of 'Axis' on Table 1, on the other hand, there is no significant difference. In addition, as seen in the 'Error rate' row of Table 1, there is no effects on error rate with respect to the spatial discrepancy and the axis.

The 'Spatial discrepancy * Axis' column in Table 1 presents a statistically significant difference only for task completion time. As explained before, the significance was obtained due to a difference of the task completion time along the near/far axis.

Finally, as seen in Table 2 visual guidance obtained a statistically non-significant difference between non-zero spatial discrepancies and zero spatial discrepancy. This means that the task completion time was not significantly increased after applying the visual guidance.

The experimental results were comparable to the results of redirected touch [7]. There are however some differences; The visual guidance obtained non-significant differences for task completion time, while the redirected touch experiment obtained significant differences. In addition, the visual guidance obtained non-significant differences for error rate while the redirected touch obtained noninferiority.

7 Conclusion

This paper introduced the spatial discrepancy problem in an encountered type haptic display, then proposed a software solution called "visual guidance" to mitigate the issue. An experiment explored the feasibility of visual guidance with seven spatial discrepancies along three orthogonal axis. The efficacy of the visual guidance was tested by measuring objective performance, showed a feasibility that the visual guidance does not obtain statistically significant degradation measured objective performance. From the results we can conclude that visual guidance is a valuable algorithm to mitigate a spatial discrepancy problem in an encountered-type haptic display.

In the future, we will test the visual guidance approach effectiveness more comprehensively with larger spatial discrepancies. In addition, effect of the visual guidance on simulator sickness will be investigated more formally by using a SSQ (simulator sickness questionnaire). Since movement on virtual environment may generate simulator sickness.

Acknowledgements

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