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Effects of haptic feedback, stereoscopy, and image resolution on performance and presence in remote navigation

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Abstract

Traditionally, the main goal of teleoperation has been to successfully achieve a given task as if performing the task in local space. An emerging and related requirement is to also match the subjective sensation or the user experience of the remote environment, while maintaining reasonable task performance. This concept is often called "presence" or "(experiential) telepresence," which is informally defined as "the sense of being in a mediated environment." In this paper, haptic feedback is considered as an important element for providing improved presence and reasonable task performance in remote navigation. An approach for using haptic information to "experientially" teleoperate a mobile robot is described. Haptic feedback is computed from the range information obtained by a sonar array attached to the robot, and delivered to a user's hand via a haptic probe. This haptic feedback is provided to the user, in addition to stereoscopic images from a forward-facing stereo camera mounted on the mobile robot. The experiment with a user population in a real-world environment showed that haptic feedback significantly improved both task performance and user-felt presence. When considering user-felt presence, no interaction among haptic feedback, image resolution, and stereoscopy was observed, that is, haptic feedback was effective, regardless of the fidelity of visual elements. Stereoscopic images also significantly improved both task performance and user-felt presence, but high-resolution images only significantly improved user-felt presence. When considering task performance, however, it was found that there was an interaction between haptic feedback and stereoscopy, that is, stereoscopic images were only effective when no force feedback was applied. According to the multiple regression analysis, haptic feedback was a higher contributing factor to the improvement in performance and presence than image resolution and stereoscopy.

Keywords: Haptic feedback; Teleoperation; Remote navigation; Mobile robot; Presence; Telepresence; User study

1. Introduction

Traditionally, the main goal of teleoperation has been to successfully operate a vehicle or mechanism over a distance, in a manner similar to performing the task in local space (Sheridan, 1992a). An emerging and related requirement is to match the subjective sensation or the user experience of the remote environment, while maintaining reasonable task performance. This concept is often called "presence" or "(experiential) telepresence."

Presence has been one of the most important goals of virtual reality (VR) as a critical component in creating a life-like experience (Steuer, 1992; Sheridan, 1992c). Likewise, one goal of a teleoperation system is to provide an experience (and not necessarily to accomplish a task). For instance, a Mars rover can be teleoperated both to perform critical tasks, and to provide people the experience of roaming Mars, preferably as if they were there. We believe that the interface for each situation is different, the former concentrating on task performance and the latter presence. Moreover, there is evidence from VR research that presence may affect task performance as well (Nash et al., 2000). The interface for the former can be improved by considering elements which enhance presence.

One important factor for presence is immersion (Slater and Wilbur, 1997; Bystrom et al., 1999). One natural method to achieve at least some degree of immersion is to

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use immersive displays (e.g., wide FOV visual, 3D sound, omni-directional/areal haptic feedback). During teleoperation, however, providing immersive displays to the operator may not be viable, because of the lack of "dispersed" sensors in the remote environment. Instead, VR research leads us to consider effects of multimodality and natural interaction design for enhanced presence (Witmer and Singer, 1998). Note that in many applications, these two factors are generally known to improve task performance (Mills and Noyes, 1999; Stanney et al., 2003). Thus we need to carefully choose the modalities appropriate for the task, and this requires an understanding of the interaction among our sensory modalities in processing information and performing motor tasks.

There are many elements in interaction design that may affect both presence and task performance, such as scene scale, viewpoints, haptic rendering algorithms, display qualities, etc. While research on teleoperation has sufficiently considered the effects of temporal delay on task performance (Ando et al., 1999; Allison et al., 2004), other such issues have generally not attracted as much attention as in VR. In VR, it is generally accepted, for instance, that only a certain minimum "level" of display quality is required to induce sufficient presence (Slater, 2002). While this "minimum" level is unknown and probably varies for different tasks, we posit that it is defined in terms of minimum task performance, that is, a display quality that enables the user to perform the minimum requirements of the application. An understanding of these issues will enable us to design an economic teleoperation interface that provides improved task performance or more realistic experience, through the consideration of these presence elements (e.g., multimodality and interaction design).

In our previous study (Lee, 2005; Lee et al., 2005), we proposed a force rendering scheme for remote navigation, using a mobile robot equipped with a laser range finder. We tested the effectiveness of haptic feedback through an experiment in a virtual environment with a simulator. This result was further verified through a smaller scale experiment in a real-world environment. Particularly, in the experiment with a real robot, we found that haptic feedback significantly affected both the operator performance and the user-felt presence, when sensory elements in other modalities were impoverished.

However, there remain further issues to be investigated regarding this effect. One is whether haptic feedback generated from low-fidelity depth information (obtained by low-fidelity range sensors such as a sonar array) can also have a significant effect. The other is whether the high fidelity of other sensory feedback can affect the effectiveness of haptic feedback, that is, whether using other high-fidelity sensory elements reduces or increases the effectiveness of the haptic feedback. In this paper, we seek answers to these questions.

This paper is organized as follows. In Section 2, the work related to this research is reviewed. Section 3 details the implementation of the new tele-navigation system used in the experiment, including the means by which our previous force rendering scheme is applied with a low-fidelity sonar ring, instead of laser range finders. Sections 4 and 5 describe the experimental procedure, and discuss findings and their analysis, respectively. Finally, in Section 6, this paper concludes with a summary and suggestions for future work.

2. Related work

2.1. Haptic navigation control of a mobile robot

Haptic feedback is usually used as a supplementary cue to help users understand and interact in virtual or remote real-world environments (Stone, 2000; Srinivasan and Basdogan, 1997; Sallnäs et al., 2000; Richardson et al., 2006; Robles-De-La-Torre, 2006). Particularly, in the area of telerobotics, control techniques exploiting haptic information have been extensively studied, to enable operators to perform tele-manipulation tasks intuitively (Bejczy and Salisbury, 1980; Hannaford et al., 1991; Daniel et al., 1996; Kazi, 2001; Williams et al., 2002; Peer et al., 2005).

Regarding mobile robot navigation, only a relatively small number of studies have focused on using haptic feedback. Elhajj et al. (2001) proposed an event-based direct control, in which the force fed back to the operator was calculated from the difference between the actual and desired velocities. For vehicle teleoperation, Fong et al. (2001) proposed the HapticDriver using the force cube primitives converted from the range information obtained by infrared sensors. In a haptic teleoperation system developed by Diolaiti and Melchiorri (2003), the force, calculated from the displacement of the haptic interface and the obstacle map, helped operators to follow a trajectory safely. With aims similar to those of Diolaiti and Melchiorri (2003), Jin et al. (2004) proposed a force rendering scheme based on the virtual impedance method (Arai et al., 1989; Ota et al., 1995). Hassan-Zadeh et al. (2005) proposed a shared impedance control scheme, and conducted a pilot experiment with two human operators to evaluate the effects of haptic feedback. Their experimental results suggested that the haptic information integrated with the visual information could result in an improved teleoperation.

Instead of calculating the force based on range information, Rösch et al. (2002) used force sensors. In their approach, the magnitude of the force directly measured by the sensors was reflected to a haptic joystick.

While several researchers developed various remote mobile robot navigation systems using haptic information (as described above), only a few actually showed the significance of haptic feedback in formal experiments. One experiment to investigate effects of haptic information on navigation control was conducted by Barnes and Counsell (2003) in a simulated virtual environment. According to their analysis, haptic feedback significantly improved the