

Research Issues on Mobile Haptic Interface for Large Virtual Environments

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Abstract:

The mobile haptic interface is a novel solution for providing haptic sensations in a large virtual environment where a user can walk around. The feasibility of mobile haptic interface has been demonstrated by several research groups, but a number of challenging issues still remain in order to fully integrate a mobile haptic interface into advanced large visual displays. This paper presents a review on the current research status on mobile haptic interfaces and related engineering and evaluation problems. In addition, the design and performance of the mobile haptic interface being developed in the authors' laboratory are described briefly.

1. INTRODUCTION

At present, large visual displays which can provide immersive 3D virtual experiences are prevalent, including Head Mounted Display (HMD), stereo projector, CAVE™, and recent 3D TV. Research efforts to provide the sense of touch in such large virtual environments (VEs) have also been persistent. Approaches for this can be classified to two categories of a large haptic interface and a mobile haptic interface. Integration of a large manipulator-type force-feedback haptic interface into a large VE was pioneered by GROPE project as early as 1980s [1]. Several large manipulator-type haptic interfaces that have a workspace comparable to the human arm are commercially available now, and they are often used with large visual displays. Another similar but different class is to use a string-based haptic interface such as SPIDAR [2].

This paper is concerned with the other category, namely, Mobile Haptic Interfaces (MHIs). The MHI refers to a force-feedback haptic interface mounted on a mobile base [3]. An example is shown in Fig. 1 that presents the mobile haptic interface developed in the authors' laboratory (PoMHI; POSTECH Mobile Haptic Interface). The mobile base expands the workspace of the force-feedback interface by moving the entire system to a desired location, allowing (theoretically) an unlimited workspace. This advantage is especially useful for large immersive VEs in which the user can walk around to interact with virtual objects. Compared to other haptic interfaces used for large environments, the MHI has several distinctive advantages:

- 1) The MHI does not need to be "installed" to an environment, preserving the individual reusability of both visual display and haptic interface.
- 2) The MHI can provide higher-quality force feedback

because of the use of high-performance desktop force-feedback interface.

3) The MHI can be made not to interfere with the user's locomotion, as if it were non-existent, which is impossible for any haptic interfaces without self-mobility.

Attracted by the great potential of MHI, several groups have developed MHIs with diverse features. These efforts also unveiled more challenging issues for the MHI to be a mature level interface that is comparable to current commercial desktop force-feedback interfaces.

In this paper, we describe the architecture of MHI in Section 2. MHIs that have been developed so far and some design issues are briefly introduced in Section 3. Further research issues necessary to raise the status of MHI to the next level are discussed in Section 4 through Section 7. We conclude the paper in Sec. 8.

2. ARCHITECTURE

The overall architecture of MHI is illustrated in Fig. 2 using that of PoMHI (taken from [4]). Other MHIs, although they may have some specific differences, have similar structures. Thus, we describe the required components in a MHI based on Fig. 2. The primary components of any MHI are visual display, force-feedback haptic

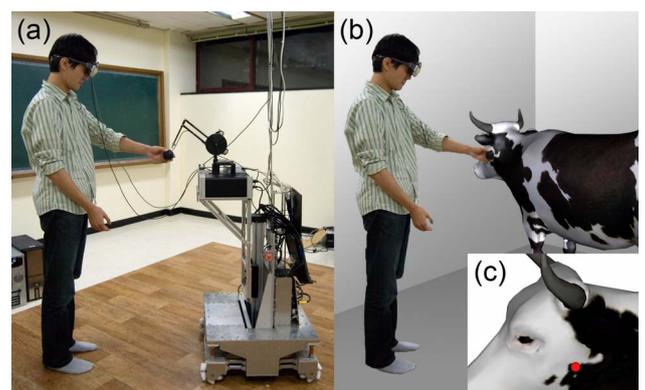


Fig. 1 (a) A user is touching a real-sized virtual cow (1.67 m × 0.46 m × 1.0 m; modeled with 9,593 faces) using the POSTECH Mobile Haptic Interface system. (b) The virtual environment that the user experiences. (c) An example of visual scenes displayed to the user via the HMD. The haptic tool is represented by the small red sphere, and the virtual environment boundaries are by the gray walls.

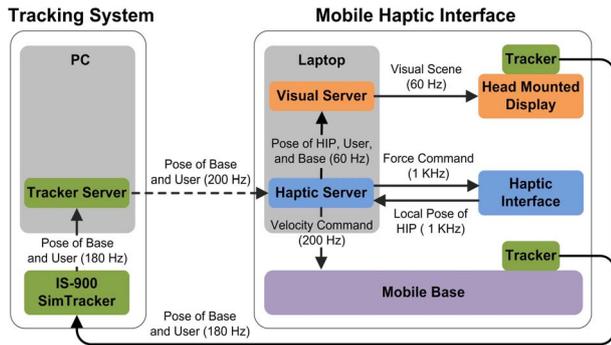


Fig. 2 System Structure of POSTECH MHI system. Solid and dotted arrows represent the direction of wired and wireless communications, respectively.

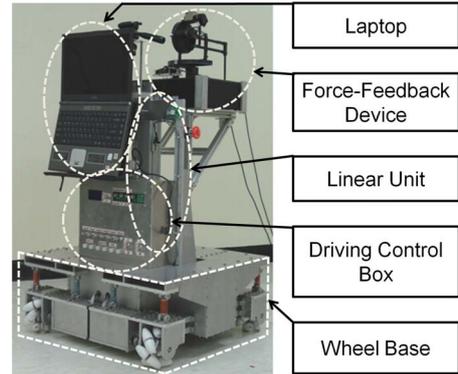


Fig. 3 Hardware Structure of POSTECH MHI.

3. HARDWARE AND RELEVANT ISSUES

interface, and mobile platform. Most of MHIs, but not all, also use a tracker of 3D position and orientation (pose).

In general, the visual display can be any of 2D or 3D displays, including small desktop monitor, large projection screen, HMD, CAVE™, and 3D TV. Those which can provide 3D immersive views are usually preferred. A separate workstation, or a cluster of workstations, is usually in charge of computing visual images for a 3D VE, and connected to the visual display.

The haptic interface can be any force-feedback device, either single or multiple of them, depending on system configurations. Haptic rendering algorithms for MHI are based on common ones for desktop force-feedback devices, including collision detection and response. Unique and challenging requirements also exist for haptic rendering using a MHI, owing to the mobility of the user and itself. In most occasions, one high-performance computer is sufficient for haptic rendering.

The mobile platform of a MHI can be any mobile robot, but one with omnidirectional and holonomic mobility is more adequate to track the user's locomotion. Both commercial and custom-built mobile robots have been used. Besides, a mechanism to move a force-feedback interface up and down is desired to expand the workspace in the vertical direction. A mobile robot usually also has a dedicated control machine.

The last component, which is also critical for the performance of MHI, is a tracking system. A MHI allows a user to freely walk and move. Thus, to follow the user, the MHI system should measure the user's pose and that of itself using an external tracking system or internal sensors in real-time. Virtual Reality (VR) research in the past has developed several kinds of high-performance trackers, such as magnetic, ultrasonic, hybrid (inertial and ultrasonic), and optical trackers. They are in the state of the art for visual VR, but often fall short of performance required for stable and high-fidelity haptic rendering using a MHI.

The four major components described above are usually connected through network and transmit information to each other. Each component has its own update rate, thus synchronization of data among the four components is another issue of critical importance.

Fig. 3 presents the PoMHI hardware that features with 3D workspace extension. As a force-feedback interface, the PoMHI uses a commercial PHANToM device (model 1.5). The omnidirectional mobile platform of the PoMHI has four custom-made Mecanum wheels, and moves the entire system to a desired 2D configuration. In addition, the linear lift unit expands the workspace of the force-feedback device in the height direction, encompassing the one-arm workspace of an adult. Our current system uses a HMD or a large screen for a visual display.

Two other research groups have led the progress of MHI research. One group has led by M. Buss in the Institute of Automatic Control Engineering at Technical University of Munich, which presented a MHI for the first time. Their recent MHI is equipped with two 7-DOF robot arms (ViSHaRD7), which have larger workspace than that of human arm, for bimanual interaction [5]. A user wears a HMD to interact with the MHI.

Another group led by D. Prattichizzo at University of Pisa has been developing a MHI system that has a self-contained visual display (e.g., a monitor). This type of MHI does not require 3D trackers, since visual and haptic workspaces are calibrated off-line and remain fixed during operation. However, the estimation error of mobile platform pose via odometry can be quickly accumulated and noticed by the user. Their most up-to-date MHI uses two desktop haptic interfaces (PHANToM desktop) for two-point interaction in a large VE mounted on an omnidirectional mobile robot, but without a vertical lift [6].

Despite the progress, we need further improvements for MHIs with high usability. First, a user can easily outrun the current MHIs, as they are much slower. This is in part to guarantee the user safety, but it prevents realization of more exciting applications such as dynamic object simulation. It would be desirable to make the dynamics bandwidth of MHI closer to the human movement ability.

Second, a MHI inevitably makes more noise during the operation of mobile base and vertical lift, which prohibits a user's immersion to virtual experiences. Even though we do not have formal data for its annoyance level, this problem is obvious in actual uses. More quiet mechanisms are necessary to overcome this problem.

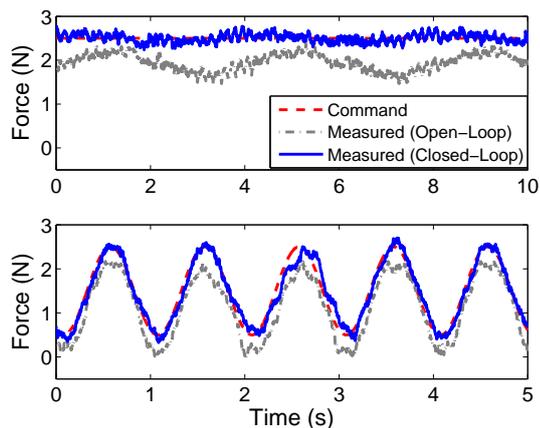


Fig. 4 Demonstration of the differences between force commands and measurements. In open-loop control, the effect of mobile base dynamics is mixed to the force delivered to a user, causing easily perceptible artifacts.

The last issue, but more fundamentally important to MHIs, is related to the fact that the dynamics of mobile platform may affect the force exerted to a user's hand, especially when the base moves with large and frequent acceleration/deceleration. Even though there exist related studies that provided general guidelines for mechanism and controller design to alleviate this problem [3][7], their application to real complex mechanisms are not very straightforward. In [4], we applied closed-loop force control using an additional force sensor attached at the tool tip, and could achieve substantial performance improvements in terms of the rendering quality of object surfaces (Fig. 4). However, it still remains a question how successful the current approaches could be for rendering of more delicate haptic properties such as friction and texture.

4. USER TRACKING AND MOTION PLANNING

In a large VE, a user can walk and turn to a virtual object of his/her interest for interaction. A MHI system needs to reason where the user wants to interact from limited sensor information and determine the goal configuration for MHI motion planning based on the deduced user intention. This is, however, an extremely difficult problem, and all MHI systems developed thus far uses simplified algorithms.

The simplest approach is based on the measured position of a haptic interface tool in the local coordinate frame of the haptic device, without considering the global coordinate of a user (e.g., see [6]). This class of algorithms assumes that a user holds the device tool and the tool movements are direct reflections of the user's intention. Thus, the mobile base moves in a way to minimize difference between the current device position and the target device position (e.g., the center of haptic device workspace with the highest manipulability), all within the local coordinate frame of the haptic device. These algorithms have an apparent drawback. Since the motion planning of

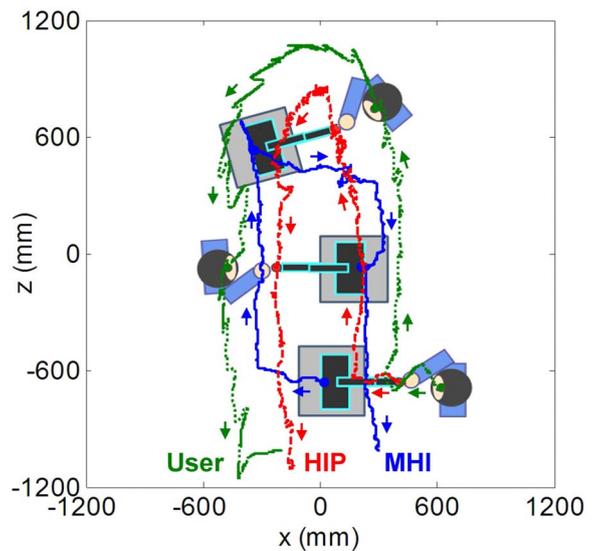


Fig. 5 Mobile base movements (blue solid line) during haptic rendering in POSTECH MHI.

MHI base does not consider the user's current pose, the MHI is under the risk of collisions with the user depending on the user's pose.

A more general approach is to explicitly measure the current pose of a user and a MHI using external tracking systems. Given the world coordinate of MHI, the haptic tool configuration in the world coordinate frame can be easily computed through kinematics conversion. Based on the three data, the next goal configuration of a mobile base can be determined using simple heuristics (e.g., see [4][8]). However, we note that this phase of mobile base movement planning may have critical influence on the overall usability of a MHI, and deserves more careful attention and further research.

Once a goal configuration of mobile platform is determined, computing appropriate motion commands is relatively straightforward. We can either use simple PD-based algorithms [6][8], or more general algorithms following the configuration space approach [4]. Robot motion planning algorithms using configuration spaces are mature, with a number of real-time algorithms with high extendibility. For instance, our PoMHI system relies on the potential-field based algorithm that is simple, fast, yet robust in geometrically simple configuration spaces (see [4] for details, and Fig. 5 for the example paths of PoMHI and user movements during haptic rendering). Such approaches also allow adding other objects in the workspace (e.g., the visual screens of CAVETM and the tracking boundaries of a tracking system) as obstacles for further user safety.

5. VISUO-HAPTIC CALIBRATION AND REGISTRATION

The tool configuration of a force-feedback device in the world coordinate frame is computed by successive coor-

dinate transformations. The measured configuration of the haptic tool in the local coordinate frame through digital encoders and the device kinematics are usually precise. This tool configuration is then transformed to the local coordinate frame of a mobile platform, and then to the world coordinate frame using the measured configuration of the mobile base from a tracking system. These last two transformations can suffer from large errors unless they are carefully calibrated, resulting in an inaccurate estimate of the tool coordinate.

Inaccurate estimation can result in a few critical problems especially for collocation of visual and haptic scenes. If the error is relatively static, the estimated tool configuration held by a user has an offset from its real configuration. Therefore, an error exists between the true tool configuration sensed by the user's sensorimotor system and the configuration displayed by a visual display, which is in turn sensed by the user's visual system. When the user cannot see his hand (e.g., with a video see-through HMD), the user may not notice the error unless it is fairly large because of relatively insensitive human kinesthetic perception of 3D position in space. When the user can see his hand (e.g., with an optical see-through HMD or in a CAVETM), however, the error makes the visual representation of the device tool (e.g., displayed by the HMD) from the real tool (e.g., seen through the HMD) have different configurations, creating an easily perceptible artifact. In the worst case, the user who is not touching any virtual objects in real can receive force feedback, or vice versa. If the error is dynamic, it can make the response force of the haptic device change abruptly, and may even cause rendering instability. This problem can be common to any MHI systems that use 3D trackers.

To be free from such visuo-haptic synchronization errors, we need careful calibrations. The transformation between the coordinate frames of a haptic device and a mobile base is usually stationary, thus it can be relatively easily calibrated using standard kinematics calibration procedures available in robotics literature. The last transformation issue is related to the insufficient performance of a tracking system, and this needs more careful attentions and treatments.

The currently available 3D tracking systems are tailored to track user movements for interaction with visual VEs. Their performance can fall short of requirements for haptic rendering which is usually more stringent than that of visual rendering. For example, the accuracy of the state-of-the-art 3D trackers is in the order of mm, but that of a desktop haptic interface is in the order of 10 μ m. Furthermore, the tracker output usually has an update rate in the order of 100 Hz. This rate is fine for visual rendering, but can cause significant problems for haptic rendering, especially by introducing a lag in collision detection, which adversely affects haptic rendering stability.

More sophisticated estimation techniques, therefore, need to be applied to the tracker output. Odometry information from a mobile platform can also be helpful for improving the estimation. In our MHI [4], we use a pre-

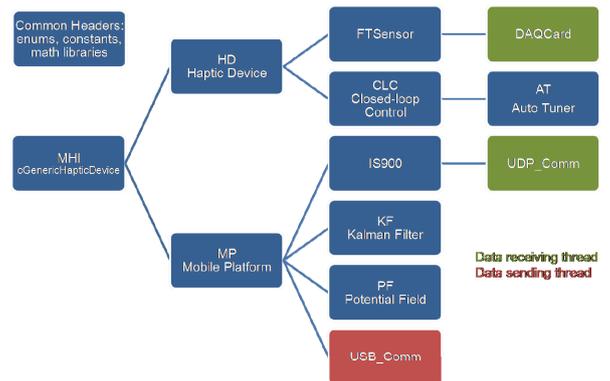


Fig. 6 Additional class hierarchy incorporated with CHAI 3D in POSTECH MHI.

dictor obtained in off-line and an on-line Kalman filter. This allows for an accuracy level of 5 mm. Although this performance is very close to the best that we can achieve from the current sensing hardware, it is clear that the accuracy level is not good enough for haptic rendering where even fine surface textures can be rendered. We need much more improved sensing hardware and algorithms for this challenging issue.

6. HAPTIC RENDERING ALGORITHMS

The last technical topic, which involves much more challenging issues than the previously described, is related to haptic rendering of virtual objects using a MHI. In general, we desire to use for a MHI haptic rendering algorithms for a desktop force-feedback device with no modification, or slight modification if necessary. However, haptic rendering with a MHI includes several critical issues that may degrade rendering fidelity. They are outlined in this section.

First, as explained earlier, position sensing of a haptic interface tool in the world coordinate frame may not have high accuracy, due to the 3D tracker errors. This can cause problems in haptic rendering of fine surface features and properties, such as friction and textures. To our knowledge, none of the related research has demonstrated successful rendering of such features; all of them have focused on rendering object shapes, including ours.

Second, we need an effective remedy to remove the effect of mobile platform dynamics on the final force delivered to a user, or at least mitigate the effect to an imperceptible level. Although some open-loop hardware design guidelines and plausible closed-loop force control approaches have shown some potential, their applicability to more difficult rendering situations, such as virtual objects including friction and textures and fast-moving dynamic virtual objects, is still questionable.

Third, we also need a general haptic rendering library for a MHI. At present, our rendering software is integrated into CHAI 3D, a stable and reliable open-source haptic rendering library that supports multiple OS platforms and haptic interfaces. The hierarchy of classes added to CHAI 3D is shown in Fig. 6. During this development, we faced

many delicate issues. For instance, update rates of the sensors are all different, so synchronization of the sensor readings for haptic rendering requires careful signal processing and estimation. Multiple threshold managements for sensor data transmission, position estimation, collision detection, force computation, and visual rendering are also of technical difficulty.

Lastly, all of the above three complexities can have effects on haptic rendering stability. Theoretical analysis and empirical verification for this has not been studied systematically.

Most of these issues are unique to MHIs, and need to be resolved for a MHI to present high-quality force feedback as desktop haptic devices do.

7. USABILITY

The last topic is concerned with the usability of MHI which must be evaluated in user experiments. Research for MHI has focused on the development of high-performance systems, but their usability in large VEs has been little explored (although see [9]). Such user-centered investigations should include various quantitative and qualitative performance indexes. For instance, various task performance measures (e.g., task completion time, task accuracy, and time on the target) can be measured for a number of manipulation and interaction tasks. Subjective user evaluations are also of importance, including easiness to learn, easiness to use, level of immersion, presence, and personal preference.

Furthermore, it would be of great significance to compare the user experiences of MHI to other force-reflecting solutions for large VEs such as large manipulator-type devices, string-based interfaces, and wearable approaches. In addition, comparative studies with software approaches for the exploration of large VEs using a desktop force-feedback interface (e.g., see [10]) would be also very interesting.

All of these studies would elucidate the utility of MHI in large VEs. This is one direction of research that our group will pay attention to in the future.

8. CONCLUSIONS

In this paper, we briefly reviewed the current research status of mobile haptic interface and discussed related research issues. The MHI is an exciting research topic that holds a great promise for enriching sensory experiences in large VEs, although it still has a number of challenging research issues to overcome. We envision that someday we may be able to play with a small home robot that can provide convincing haptic feedback along with a 3D TV that is becoming inexpensive and popular.

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REFERENCES

- [1] F. P. Brooks, M. Ouh-Young, J. J. Batter, and P. J. Kilpatrick. Project GROPE - Haptic displays for scientific visualization. In *Proceedings of the ACM SIGGRAPH Conference*, pp. 177–185, 1990.
- [2] N. Hashimoto, S. Jeong, Y. Takeyama, and M. Sato. Immersive multiprojector display on hybrid screens with human-scale haptic and locomotion interfaces. In *Proceedings of the International Conference on Cyberworlds*, pp. 361–368, 2004.
- [3] N. Nitzsche, U. D. Hanebeck, and G. Schmidt. Design issues of mobile haptic interfaces. *Journal of Robotic Systems*, vol. 29, no. 9, pp. 549–556, 2003.
- [4] In Lee, Inwook Hwang, Kyung-Lyong Han, Oh Kyu Choi, Seungmoon Choi, and Jin S. Lee, “System Improvements in Mobile Haptic Interface,” In *Proceedings of World Haptics Conference*, pp. 109-114, 2009.
- [5] A. Peer, Y. Komoguchi, and M. Buss. Towards a mobile haptic interface for bimanual manipulations. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 384–391, 2007.
- [6] M. de Pascale, A. Formaglio, and D. Prattichizzo. A mobile platform for haptic grasping in large environments. *Virtual Reality*, vol. 10, no. 1, pp. 11–23, 2006.
- [7] A. Formaglio, D. Prattichizzo, F. Barbagli, and A. Giannitrapani. Dynamic performance of mobile haptic interfaces. *IEEE Transactions on Robotics*, vol. 24, no. 3, pp. 559–575, 2008.
- [8] U. Unterhinninghofen, T. Schauss, and M. Buss. Control of a mobile haptic interface. In *Proceedings of the IEEE International Conference on Robotics and Automation*, pp. 2085–2090, 2008.
- [9] M. Buss, A. Peer, T. Schauss, T. Stefanov, U. Unterhinninghofen, S. Behrendt, J. Leupold, M. Durkovic, and M. Sarkis, Development of a Multi-modal Multi-user Telepresence and Teleaction Systems, *International Journal of Robotics Research*, 2009 (on-line first publication).
- [10] L. Dominjon, A. Lecuyer, J.-M. Burkhardt, G. Andrade-Barroso, and S. Richir, The “Bubble” Technique: Interacting with Large Virtual Environments Using Haptic Devices with Limited Workspace, In *Proceedings of the World Haptics Conference*, pp. 639-640, 2005.