Design Issues of Mobile Haptic Interfaces

Norbert Nitzsche,* Uwe D. Hanebeck, and G. Schmidt
Institute of Automatic Control Engineering
Technische Universität München
80290 München, Germany
e-mail: Norbert.Nitzsche@ei.tum.de
Uwe.Hanebeck@ei.tum.de
Guenther.Schmidt@ei.tum.de

Received 31 January 2003; accepted 18 April 2003

As a novel approach to force-reflecting telepresence, the concept of *mobile haptic interfaces* (MHI) is presented. An MHI *actively* follows the locomotion of an operator, who is no longer bound to be stationary during teleoperation. Thus, operator locomotion can be used as an input for locomotion control of a real teleoperator or control of locomotion in a virtual environment while keeping the advantage of force-reflection. The article focuses on basic design issues and presents a prototype MHI for haptic exploration of extended virtual environments.

1. INTRODUCTION

1.1. Motivation

The objective of the type of telepresence system considered in this paper is to induce for a human operator (HO) the sensation of being present in an inaccessible extended target environment. A teleoperator replicates operator action in the target environment and collects sensory information that is fed back and displayed to the HO by means of appropriate displays. In other words, for the HO the displays represent the target environment (see Figure 1).

The feeling of presence, although no objective measure seems to exist, is typically created by visual and auditory feedback as well as force-reflection. In the case of an extended target environment, locomotion in the target environment becomes equally important for a comprehensive feeling of presence. The sensation of walking freely about in the target environment can be achieved most realistically by tracking HO locomotion in the operator environment and controlling teleoperator locomotion accordingly. In this case the HO can employ the entire set of natural senses for perception of locomotion which proves to be vital for localization and navigation.

To permit force-reflecting interaction with a

*To whom all correspondence should be addressed.

Published online in Wiley InterScience (www.interscience.wiley.com). • DOI: 10.1002/rob.10105

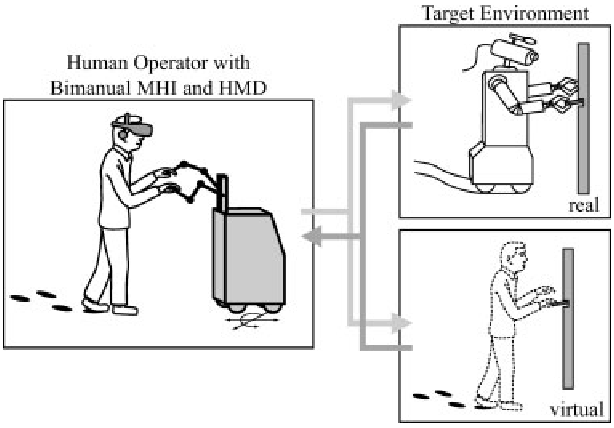

Figure 1. Mobile haptic interface (MHI) for force-reflecting interaction with extended target environments.

target environment while the HO is moving around, a haptic interface must be capable of covering the full workspace available to a free walking HO. For achieving this feature, a *mobile haptic interface* (MHI) is proposed as a novel approach to exploration and manipulation of extended target environments.

Extended area telepresence systems as considered in this article can be applied to tele-exploration and tele-manipulation tasks in extended target environments. Examples are telepresent visits to museums, castles or industrial facilities as well as interactive virtual interior design and composition. Usually, the execution of such tasks requires the HO's localization and navigation capabilities.

The application of MHIs is not limited to real target environments but can easily be extended to virtual environments (Figure 1). Experimental results presented in Section 4 of this paper have been obtained from application of the proposed telepresence system to a virtual target environment.

1.2. State of the Art

Current haptic interfaces are typically stationary devices with a workspace limited to the reach of a human arm,[1,2] resulting in the following restrictions with regard to applicability: (i) the HO must remain stationary and (ii) the workspace in the target environment is limited.

The latter restriction can be removed quite easily by displacement of the target environment workspace. Such displacement can be achieved by an appropriate mapping of the operator workspace into the teleoperator's workspace or by teleoperator locomotion. With today's force-reflecting telepresence systems workspace displacement is commanded by means of auxiliary controls. Examples are mouse and joystick for position or rate control as well as various forms of reindexing.[2] These auxiliary controls translate stationary HO motion into locomotion with respect to the target environment, i.e., they do not allow proprioceptive (kinesthetic and vestibular) perception of locomotion. In other words, the desired sensation of locomotion in a stationary environment is replaced by the sensation of an environment moving with respect to the stationary HO. Psychological studies prove that incomplete or false proprioceptive cues result in deterioration of the natural orientation and navigation capabilities of a HO.[3]

Realistic locomotion interfaces allowing free locomotion do already exist for virtual reality applications. Such interfaces enable interactive visual exploration but do not allow force-reflecting interaction with an extended target environment. With realistic locomotion interfaces, in contrast to the above mentioned auxiliary controls, the HO can perceive locomotion not only visually but also partly by means of kinesthetic and vestibular stimuli. Realistic locomotion interfaces comprise omnidirectional treadmills,[4,5] programmable footplatforms,[6] and tracking of free locomotion of the HO in the operator environment.[7–9]

Summarizing these findings leads to the conclusion, that current telepresence systems do *either* allow realistic haptic interaction *or* realistic locomotion, Table I.

Table I. Classification and comparision of existing telepresence systems and the proposed system.

		Telepresent Locomotion	
		none or abstract	realistic
Manipulation/Interaction	no force-feedback	• computer games • remote control • CAD-systems	• interactive visual exploration in VR
	force-feedback	• computer games • master/slave-teleoperation	• extended-workspace haptic interaction

1.3. Novel Approach

For the first time, simultaneous telepresent locomotion *and* telepresent haptic interaction are made possible by use of a MHI.

Complete and realistic perception of locomotion can be achieved with comparatively low effort by sensing and replicating HO locomotion. Up to now, free locomotion of the HO was contradictory to the restriction imposed by stationary haptic interfaces, which requires the HO to be stationary as well. This contradiction can be resolved by moving the haptic interface along with HO locomotion, thus making force-reflecting telepresence available in much larger workspaces than presently possible. Other approaches to haptic interfaces allowing operator mobility were discussed in ref. 10 together with their advantages and deficiencies.

The remainder of the paper is organized as follows: Section 2 details our approach to the development of a MHI. Research challenges arising from that approach are outlined in Section 3. The presentation of an experimental MHI setup together with a discussion of experimental results follows in Section 4.

2. MOBILE HAPTIC INTERFACE—SETUP AND REQUIREMENTS

The basic objective of a MHI is to provide realistic display of reaction forces and torques to the hands of the HO while at the same time actively following the HO's wide area locomotion. Hence, a MHI must comprise a mobile, e.g., wheel-based, platform, and manipulators for direct interaction with the HO's hands.

The platform must meet two contradictory requirements: (i) it must be sufficiently fast and maneuverable to follow HO locomotion and (ii) it needs to resist forces and torques applied by the HO without overbalancing. In addition, the platform should have omnidirectional kinematics to change the direction of motion without extensive maneuvering.

Since the manipulators of a MHI are in direct contact with the HO's hands, they must be capable to measure hand motions as well as to display forces and torques according to the mechanical properties of the target environment. The workspace of the manipulators should be of similar size as the workspace of the human arm. Thus, the platform with its higher inertia does not need to follow quick hand and arm motions, i.e., platform motion should be limited to following HO body locomotion.

In order to provide natural freedom of motion to the HO at all times, the platform must be continuously positioned such that optimal manipulability is achieved. For that purpose, the relative position and orientation of the platform with respect to the HO must be known. In addition, the absolute position and orientation of the platform or the HO with respect to a fixed coordinate system is required.

3. RESEARCH CHALLENGES

The general requirements regarding a MHI as stated in the preceding section pose a number of interesting questions which will be discussed next.

3.1. Transparency

A basic requirement of any haptic interface is transparent display of the mechanical impedance of a virtual or real target environment. This property can only be achieved by suitable feedback control.

Assuming linearity, mechanical impedance can be defined by the transfer function[11,12]

$$Z(s)=\frac{f(s)}{x(s)},$$

where f is the force resulting from a displacement x. Z can then be specified as

$$Z(s)=\frac{ms^2+bs+k}{1},$$

with m, b, and k being the mass, damping coefficient, and spring constant.

Transparency in this context denotes the ideal case when the impedance felt by the HO, i.e., $Z^*(s)$, equals the environment impedance to be displayed $Z_E(s)$. How close one can get to this ideal situation depends on three major factors:[11]

(i) the environment impedance Z_E itself,
(ii) the impedance of the haptic interface and
(iii) the control architecture chosen.

Basically, two different approaches to the control of haptic interfaces are distinguished: impedance and admittance architecture.[11,13,14] In this paper, the focus is on the impedance architecture only. This architecture is characterized by a haptic interface, which displays forces in response to measured displacements of the interface endeffectors. In this case the interface usually operates in force control mode.

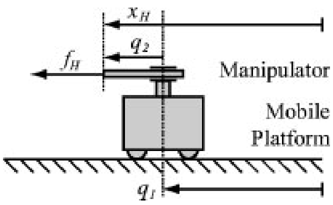

Figure 2. MHI with two redundant configurational degrees of freedom q_1 and q_2.

A MHI as proposed in Section 2 is a kinematically redundant system with the platform introducing comparatively high inertia. This makes the evaluation of transparency particulary interesting.

To exemplify the kinematic redundancy of the overall system consisting of a mobile platform and a manipulator, a simplified, one-dimensional system with two configurational DoF is considered, Figure 2. The kinematics of this setup are given by

$$x_H = q_1 + q_2,$$

where x_H denotes the hand or endeffector position and q_1, q_2 the configurational (joint) coordinates. The equations of motion expressed in configurational coordinates are

$$\begin{pmatrix} m_1 & 0 \\ m_2 & m_2 \end{pmatrix} \underline{\ddot{q}} + \begin{pmatrix} b_1 & -b_2 \\ 0 & b_2 \end{pmatrix} \underline{\dot{q}} = \begin{pmatrix} \tau_1 - \tau_2 \\ \tau_2 + f_H \end{pmatrix},$$

with m_1 and m_2 the two link masses, b_1 and b_2 the joint damping coefficients, τ_1 and τ_2 the joint forces and f_H the force exerted on the system's endeffector by the HO.

By use of the Jacobian matrix

$$\mathcal{J} = [\mathcal{J}_{ij}] = \left[\frac{\partial x_{H,i}}{\partial q_j} \right],$$

a simple explicit force feedback control law with an additional feedforward term can be formulated

$$\underline{\tau} = \mathcal{J}^T \{ f_{\mathrm{ref}} + K_F (f_{\mathrm{ref}} - f_{\mathrm{act}}) \}.$$

For nonredundant systems, this control law is sufficient and achieves good performance, whereas adopted for redundant systems, it will result in uncontrollable nullspace motion.[15]

This problem can be solved by a hybrid control structure, with some of the joint coordinates being position controlled, in order to eliminate the redundancy. In our example system comprising a platform and manipulator, the platform will be position controlled. If the manipulator itself is redundant, additional measures like nullspace damping are necessary for achieving stability. The objective of the position control then is to optimize the actual platform position with respect to a cost function as discussed in more detail in Section 3.4. For the simple one-dimensional example, the following cost function

$$L = q_2^2$$

is employed resulting from the assumption that the optimal configuration of the simplified model is specified by $q_2 = 0$.

Figure 3 shows the block diagram of the simplified model of a MHI with 2 configurational DoF together with a hybrid feedback controller and the impedance Z_E to be displayed.

For further analysis and simplification, the following assumptions are made:

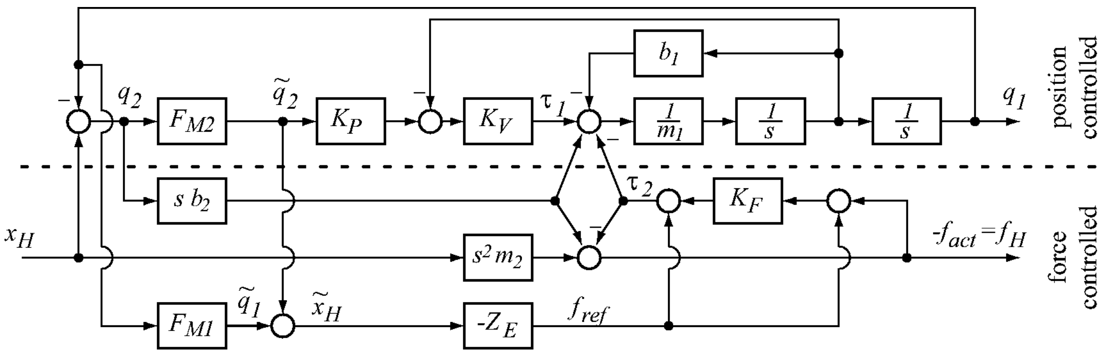

Figure 3. Block diagram of a MHI with two degrees of freedom (impedance architecture). F_{M1}—transfer function measurement q_1, $\tilde{q}_1$—q_1 measured, F_{M2}—transfer function measurement q_2, $\tilde{q}_2$—q_2 measured, K_V, K_P—velocity and position controller gains of platform, and K_F—force controller gain of manipulator.

1. $F_{M1}(s) \approx 1$: exact measurement of q_1, e.g., by localization of the platform position,
2. $F_{M2}(s) \approx 1$: exact measurement of q_2, e.g., by encoder, and
3. $b_2 \approx 0$: zero damping in the second joint.

The impedance felt by the HO Z^* as defined by

$$Z^*(s) = \frac{f_H(s)}{x_H(s)}$$

is then given by

$$Z^*(s) = Z_E(s) + \frac{m_2 s^2}{1+K_F}.$$

This expression does not depend on the dynamics of the position controlled platform. The transparency of the interface is exclusively determined by the force controlled sub-system, i.e., the manipulator. In other words, the platform is not perceived haptically by the HO.

While assumption 2 can be fulfilled easily, assumptions 1 and 3 are focal points in the development of a MHI. Both will be discussed in more detail in the following subsections.

3.2. Platform Localization

As stated in Section 3.1, localization of the platform should be realized such that $F_{M1} \approx 1$ is satisfied. What this condition means in terms of specific values for absolute and relative accuracy is still under investigation. The following numbers are currently the basis for our research:

(i) absolute accuracy: 100 mm,
(ii) relative accuracy: 1 mm,
(iii) signal band width: 1 kHz.

These demands cannot be achieved by means of a single measuring method. Therefore, several measuring systems as well as methods for sensory data fusion must be applied. Odometry and dynamic system models are employed for achieving the desired *relative* accuracy together with sufficient bandwidth. In addition, localization methods based on optical, magnetical, or acoustic sensor systems provide the desired *absolute* accuracy.

As already mentioned in Section 2, both the HO's and the platform's position and orientation must be measured. The HO can either be localized with respect to a world fixed coordinate system (${}^0T_B$) or a platform fixed system (${}^PT_B$) (Figure 4). The first method requires additional sensors which cover all the HO's workspace. The alternative method can be realized by using sensors onboard the platform and the manipulator.

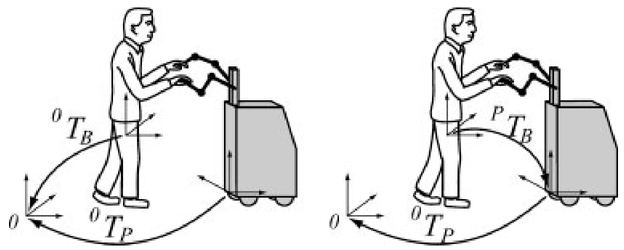

Figure 4. Localization of the HO: world fixed (left) and platform fixed coordinate sytems (right).

A rather elegant approach is to exclusively use the sensors of the manipulator for determining position and orientation of the HO's trunk. By evaluation of the manipulator joint angles, the position and orientation of both the HO's hands can be calculated. Due to the redundancy in the kinematical chain hand–arm–trunk–arm–hand it is not possible to directly calculate the position and orientation of the trunk from the previously mentioned information. Assuming a simple arm model with 7 DoF leaves a two-dimensional null-space for this kinematic chain. This redundancy can be resolved by introducing additional conditions based on maximum manipulability and/or minimum energy consumption.

3.3. Decoupling

Studying the simplified MHI in Section 3.1 led to the conclusion that the dynamic properties of the platform become imperceptible to the HO if the damping coefficients coupling platform and manipulator become zero. Two basic approaches to reduce damping exist and must be combined if necessary. First, damping in the manipulator joints can be reduced by choosing a suitable actuator and transmission design. Second, decoupling can be achieved by control. Full decoupling by control, however, requires precise knowledge of the corresponding system parameters.

3.4. Optimal Platform Control

As already mentioned, the MHI is a kinematically redundant system. Redundancy provides the opportunity to satisfy additional conditions which can be expressed as cost functions for purposes of optimization.

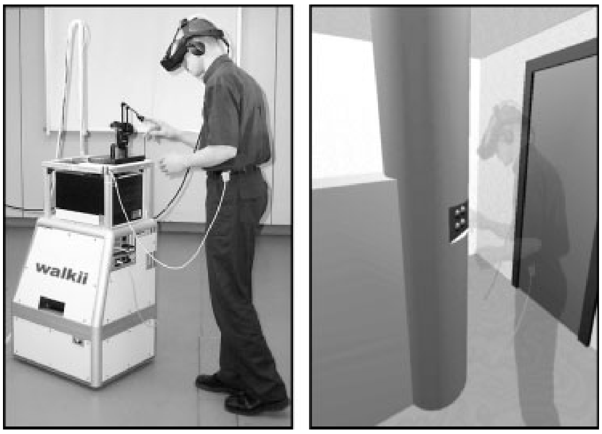

Figure 5. Prototype of a MHI (left) for one-fingered exploration of a virtual room (right).

One objective of a MHI is to provide maximum freedom of motion to the HO. Hence, a measure for manipulability of the MHI should be included in the cost function. If the platform's position and orientation is controlled such that the manipulability of the manipulator is maximized, the platform will follow the HO's motion.

As mentioned in Section 3.2, localization of the platform is, among other methods, based on odometry. Odometry, however, does only work with high accuracy if the platform paths are sufficiently smooth. Therefore, optimal platform control must also take into account path radii or curvature.

In order to optimally position the platform according to the defined cost functions and subject to kinematic and kinetic constraints imposed by the platform itself, a predictive behavior of the platform proves to be essential. Cost functions are not to be optimized instantaneously but over a (moving) time horizon reaching into the future. For that purpose future HO motion needs to be predicted.

Short-term prediction can be achieved by dynamic models of human locomotion. Long-term prediction is based on methods of intention recognition.

4. PROTOTYPE MOBILE HAPTIC INTERFACE

4.1. Implementation Issues

For evaluation of the ideas, requirements, and methods presented above, a first experimental setup was designed and implemented, as shown in the photo in Figure 5. With this extended area human-system-interface one-fingered haptic exploration of virtual environments with a floor space of 3 m by 3 m is possible.

The HO can move around freely in this workspace and he/she perceives an equivalent change of position and orientation in the virtual environment. Visual feedback from the virtual environment is provided as a stereoscopic view presented by a head mounted display (HMD). Forces resulting from touching objects in the virtual environment are displayed to the tip of the HO's index finger.

The MHI comprises a mobile, omnidirectional platform[16] and the commercially available haptic interface PHANToM Premium 1.0.

To record the HO's position and orientation a magnetic tracking system[17] is employed with one sensor at the HO's head and another at the hip. Position and orientation of the HO's head are fed into the visual rendering engine to generate a stereoscopic view of the virtual environment consistent with the HO's head position in space. The hip sensor provides additional information about position and orientation of the current workspace of the HO's hand.

A simple optimization algorithm uses the current configuration of the PHANToM and the current position and orientation of the HO with respect to the platform to compute command values for the platform position controller. Due to this algorithm the platform follows the HO's locomotion as well as the HO's hand motion. The goal of this algorithm is to always position the platform such that the manipulability of the PHANToM is maximized and that the platform faces towards the HO.

The forces resulting from exploration of the virtual environment are rendered by a simple haptic rendering algorithm. Collision detection is based on geometrical primitives like planes, cylinders, and spheres. Contact forces are calculated from the penetration depth according to a spring-damper-system. Due to its simplicity, the algorithm can run at a sampling frequency of 2 kHz for virtual environments modeled with about 500 surfaces on a Pentium IV PC (2.0 GHz).

Since platform localization by magnetic tracking runs with 50 Hz only, a dynamic observer for estimation of the platform position and orientation was applied, which provides position and orientation data synchronous with the haptic rendering loop.

4.2. Experimental Results

The basic functionality and the usability of the proposed MHI is demonstrated and evaluated by an

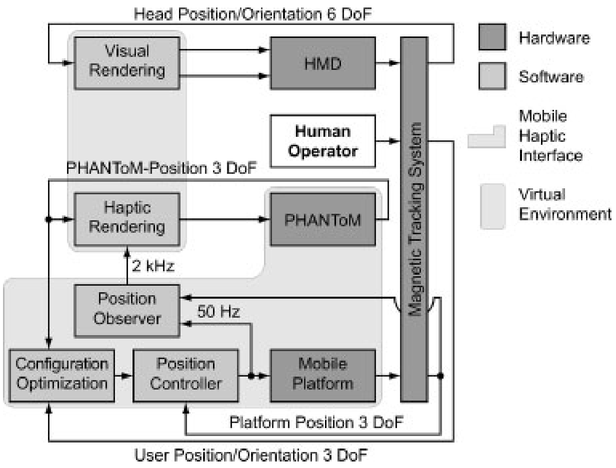

Figure 6. Hardware and software components of the extended area telepresence system.

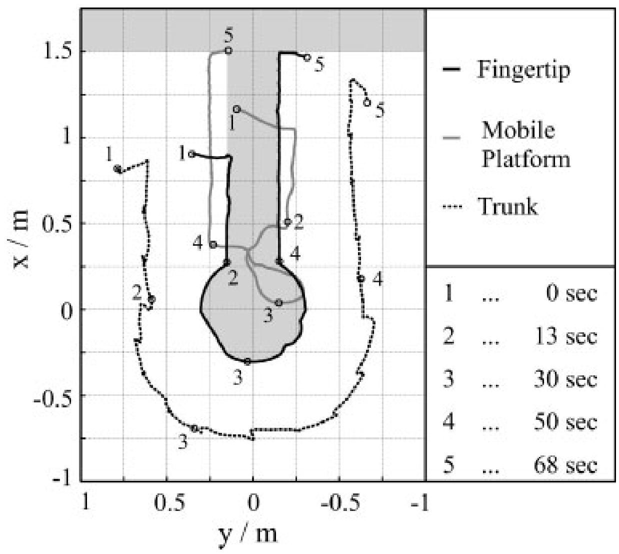

Figure 7. Motion trajectories: A test person is exploring a wall and a pillar (shaded area) in a virtual room. Numbered circles mark synchronous points of the trajectories.

experiment with the objective to explore a virtual room both visually and haptically, Figure 5. The room considered in the experiment is square with an edge length of 3 m. It comprises a cylindrical pillar with a diameter of 0.6 m and a connecting wall of 1.5 m height. The pillar shows two flattened surfaces with knobs resembling rivet heads. The exploration experiment was performed by a few test persons with varying degrees of experience regarding virtual environments. The focus of the investigation was on two major aspects of usability: (i) following a global contour with one's finger tip by walking along the walls and around the pillar, and (ii) exploring fine local structures such as the flat surfaces with the knob pattern.

Typical motion trajectories of one test person and of the MHI during *contour following* are shown in Figure 7. The plots represent user motion in both the physical and the virtual world. The HO's trunk trajectory indicates clearly that the user is walking around freely. Free physical locomotion of the user can only be achieved by a haptic interface that is capable of covering all the workspace accessible by the free walking user. If the workspace is not to be limited by the haptic interface, such an interface must be mobile and move along with the user. Even test persons, who had experienced high quality virtual reality simulations before, reported a very good feeling of immersion. This results mainly from the fact that for the first time users were able to walk *and* touch simultaneously. Other experiments, as reported in ref. 10, prove that global contours are more easily recognized by users if they can walk around freely rather than sitting in front of a display and controlling motion with some auxiliary device, such as mouse or joystick.

The finger tip trajectory shown in Figure 7 resembles the contour of the virtual walls and the pillar as the HO moves his/her finger along the object surfaces. It is noteworthy that the finger tip never does penetrate those objects rendered as solid. Such behavior can hardly be achieved by wearable haptic devices without an external base.[18] Test persons reported that the contact with the walls and the pillar feels realistically hard whereas free motion and motion in tangential direction to solid surfaces was experienced as realistically smooth and unresisted.

The investigation of the ability to *explore fine local structures* by use of the MHI was directed to an analysis whether the rather coarse platform motion would inhibit a realistic sensation of small structures. As reported by the test persons, small structures could be explored with great realism when the platform remained stationary. However, during repositioning of the platform, a disturbance was felt creating the sensation of the knobs being in motion. This behavior is attributed to inaccuracies in platform localization resulting in inaccurate finger motion detection. Such shortcomings can, however, be remedied both by smoothing platform motion and by improving the quality of platform localization.

5. CONCLUSIONS

This paper discussed the concept and related design issues of a novel haptic interface, which enables a HO to freely walk around and haptically interact with extended real or virtual target environments. By presenting visual and haptic information consistent with both user hand motion and user locomotion the proposed MHI proves to be a significant step towards higher degrees of telepresent immersion.

Since the HO is no longer required to remain stationary in its local environment, a particulary simple and realistic locomotion interface can be implemented, by means of tracking the HO's physical locomotion. Effort and cost for the implementation of a MHI can be kept low by making use of existing mobile manipulator technology.

Investigations performed with the developed experimental setup impressively demonstrate the feasibility of mobile haptic interfaces and their positive impact on immersion into virtual and possibly real target environments. However, the experiments also reveal a need for further research to extend the capability and improve the usability of mobile haptic interfaces.

ACKNOWLEDGMENTS

This work was supported in part by the German Research Foundation (DFG) within the Collaborative Research Center SFB 453 on "High-Fidelity Telepresence and Teleaction."

REFERENCES

1. V. Hayward, Survey of haptic interface research at McGill University, Proceedings of the Workshop on Advances in Interactive Multimodal Telepresence Systems, München, Germany, 2001, pp. 91–98.
2. J.M. Hollerbach, Some current issues in haptics research, Proceedings of the IEEE International Conference on Robotics & Automation, San Francisco, California, 2000, pp. 757–762.
3. R.P. Darken, Spatial orientation and wayfinding in large-scale virtual spaces II, Presence 8 (1999), iii–vi.
4. H. Iwata, Walking about virtual environments on an infinite floor, Proceedings of the Virtual Reality Conference, Houston, Texas, 1999, pp. 286–293.
5. R.P. Darken, W.R. Cockayne, and D. Carmein, The omni-directional treadmill: A locomotion device for virtual worlds, Proceedings of the ACM UIST, Alberta, Canada, 1997, pp. 213–222.
6. http://www.sarcos.com/interpic_virtualinter.-html.
7. H. Baier, F. Freyberger, and G. Schmidt, Interaktives Stereo-Telesehen-Ein Baustein Wirklichkeitsnaher Telepräsenz, at Automatisierungstechnik 49 (2001), 295–303.
8. C. Cruz-Neira, D. Sandin, and T.A. DeFanti, Surround-screen projection-based virtual reality: The design and implementation of the CAVE, Proceedings of the ACM SIGGRAPH, Anaheim, California, 1993, pp. 135–142.
9. G. Welch, G. Bishop, L. Vicci, S. Brumback, K. Keller, and D. Colucci, High-performance wide-area optical tracking—The Hiball tracking system, Presence 10 (2001), 1–21.
10. N. Nitzsche, U.D. Hanebeck, and G. Schmidt, Mobile haptic interaction with extended real or virtual environments, Proceedings of the IEEE International Workshop on Robot-Human Interactive Communication, Bordeaux/Paris, France, 2001, pp. 313–318.
11. J. Hoogen, M. Buss, and G. Schmidt, Experimental results in control of an industrial robot used as a haptic display, Proceedings of the 1st IFAC Conference on Telematics Applications in Automation and Robotics, Weingarten, Germany, 2001.
12. H. Baier, M. Buss, and G. Schmidt, Stability and mode switching in closed-loop teleoperation systems, at Automatisierungstechnik 48 (2000), 51–59.
13. R. Riener, J. Hoogen, M. Ponikvar, R. Burgkart, M. Frey, and G. Schmidt, Multimodaler trainingssimulator für die orthopädie, at Automatisierungstechnik, 50 (2002), 296–303.
14. R.J. Adams and B. Hannaford, A two-port framework for the design of unconditionally stable haptic interfaces, Proceedings of the IEEE International Conference on Intelligent Robots and Systems, Victoria, Canada, 1998, 1254–1259.
15. O. Khatib, A unified approach for motion and force control of robot manipulators: The operational space formulation, IEEE J Robot Automat RA-3 (1987), 43–53.
16. U.D. Hanebeck and N. Šaldic, A modular wheel system for mobile robot applications, Proceedings of the IEEE/RSJ International Conference on Intelligent robots and systems (IROS), Kjongju, Korea, 1999, pp. 17–23.
17. http://www.ascension-tech.com.
18. C. Richard and M.R. Cutkosky, Contact force perception with an ungrounded haptic interface, Proceedings of the ASME IMECE 6th Annual Symposium on Haptic Interfaces, Dallas, Texas, 1997, pp. 15–21.