Unlimited Workspace - Coupling a Mobile Haptic Interface with a Mobile Teleoperator

Thomas Schauß, Ulrich Unterhinninghofen, and Martin Buss

Abstract A teleoperation system extends cognitive and manipulatory skills of a human to a remote site. Hereby, the dimensions of the haptic interfaces and telemanipulators typically limit the achievable workspace. In some application scenarios, however, an unrestricted workspace is desirable. Therefore, we develop and discuss two different coupling schemes for a wide-area teleoperation system. The schemes are implemented on a complex system composed of two haptic interfaces and two telemanipulator arms mounted on mobile bases. Aside from haptic feedback also visual and acoustic feedback are presented in an appropriate way. Experiments show the benefits and drawbacks of the different schemes, and conclusions on appropriate coupling schemes for different circumstances are given.

1 Introduction

Although autonomous robots have come a long way in the past years, they are not yet capable of performing complex tasks in unknown, unstructured environments. Using a haptic teleoperation system, an operator can control a robot located at a remote site. Thus, the benefits of robots and the cognitive skills of humans can be merged.

Since its invention in the 1940s, teleoperation has been a field of active research. While most hardware and control architectures are focused on low-power, small-workspace applications, e.g. telesurgery and microassembly [2], teleoperation also has many important applications in human scale environments, e.g. disaster recovery and remote maintenance. In these applications, the used workspace matches or even exceeds the workspace of the human arm.

Thomas Schauß, Ulrich Unterhinninghofen, and Martin Buss
Institute of Automatic Control Engineering, Technische Universität München, D-80290 München, Germany, e-mail: schauss@tum.de, ulrich.unterhinninghofen@tum.de, and m.buss@ieee.org

Among the various techniques for haptic interaction in large-scale environments [3], only mobile haptic interfaces and force exoskeletons can provide a truly unlimited workspace. However, the latter are cumbersome and fatigueing due to their heavy weight. Design and control guidelines for mobile haptic interfaces have been developed in [5] and extended in [1]. We have shown how to optimally position a bimanual mobile haptic interface in order to maximize manipulability and workspace in [8]. A full teleoperation system for a single arm based on a mobile haptic interface and mobile teleoperator has been examined in [4].

In this work, a haptic teleoperation system for applications in extensive environments is presented. The system comprises a mobile haptic interface and a mobile teleoperator, which are both designed to enable bimanual manipulations in six degrees of freedom. The mobile haptic interface consists of two large-scale haptic interfaces which are mounted on an omnidirectional mobile base. The design of the mobile teleoperator is similar such that two anthropomorphic robot arms are mounted on top of a mobile base.

The focus of this paper lies on the interconnection scheme between mobile haptic interface and mobile teleoperator. Two different approaches are presented and compared regarding their performance for different applications. In Sec. 2, the interconnection schemes are described. Sec. 3 offers on overview of the employed hardware components. The design and the results of the performance experiments are presented in Sec. 4. The paper concludes with Sec. 5, where a summary and an outlook on future work are given.

2 Proposed Methods

In Fig. 1, the components of the teleoperation system are depicted along with the associated coordinate systems. The position and orientation of the mobile haptic interface, i.e. the master, ${}^0T_M$, the mobile teleoperator, i.e. the slave, ${}^0T_S$, and the human operator ${}^0T_H$ are expressed in a common world coordinate system Σ_0. The end-effector poses of the right and the left haptic interface are denoted ${}^0T_R$ and ${}^0T_L$, and the respective interaction forces[1] are denoted ${}^0F_R$ and ${}^0F_L$. Analogously, the end-effector poses of the robot-arms on slave side are ${}^0T_R^*$ and ${}^0T_L^*$, while the forces are ${}^0F_R^*$ and ${}^0F_L^*$.

A typical teleoperation system aims at synchronizing master and slave poses as well as master and slave forces. Assuming that no transformation, e.g. scaling, occurs between master and slave coordinates, this aim can be expressed for right and left end-effectors by the four equality relations:

$$ {}^0T_R = {}^0T_R^* \qquad {}^0T_L = {}^0T_L^* \qquad {}^0F_R = {}^0F_R^* \qquad {}^0F_L = {}^0F_L^* \tag{1} $$

[1] Throughout this paper, forces represent generalized forces, i.e. translational forces and rotational torques.

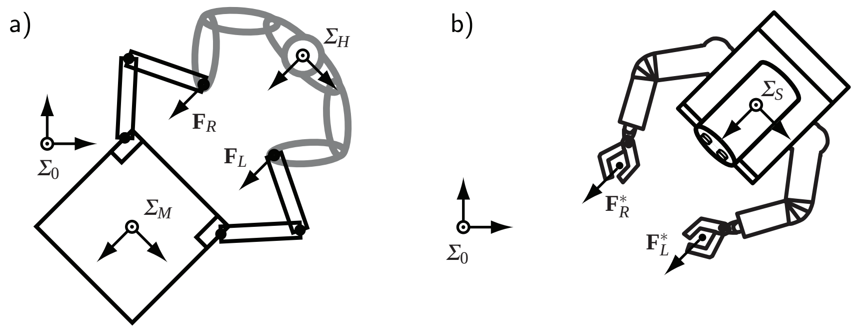

Fig. 1 Definition of coordinate systems of a) master side and b) slave side

As haptic interfaces and robot arms are mounted on mobile bases, the end-effector poses and interaction forces are expressed relative to the coordinate system of the mobile base on master side Σ_M and slave side Σ_S, respectively. Thus, the signals on master side become ${}^{M}T_R$ and ${}^{M}T_L$ as well as ${}^{M}F_R$ and ${}^{M}F_L$. Likewise, the signals on slave side are locally expressed by ${}^{S}T_R^*$ and ${}^{S}T_L^*$ as well as ${}^{S}F_R^*$ and ${}^{S}F_L^*$.

Both mobile devices have redundant degrees of freedom. When the poses of left and right end-effectors are given, this does not yield a unique solution for the pose of the mobile base. Any solution which produces the desired end-effector position in world-coordinates is equally valid:

$$ {}^{0}T_M \, {}^{M}T_R = {}^{0}T_R = {}^{0}T_R^* = {}^{0}T_S \, {}^{S}T_R^* \qquad {}^{0}T_M \, {}^{M}T_L = {}^{0}T_L = {}^{0}T_L^* = {}^{0}T_S \, {}^{S}T_L^* . \quad (2) $$

There are different criteria which can be used to find the desired pose of the mobile bases ${}^{0}T_{M,d}$ and ${}^{0}T_{S,d}$. In general, the optimization criteria must take the different dynamic capabilities of the mobile bases and the haptic interfaces or robot arms, respectively, into account. As the mobile bases carry the whole system weight, their maximum velocity and acceleration are comparatively low. On the other hand, the workspace of the mobile base is theoretically unrestricted, whereas the workspace of the haptic interfaces and the robot arms is limited. Consequently, large-scale motions with low dynamics must be assigned to the mobile bases, whereas fast, small-scale motions must be performed by the haptic interfaces or robot-arms.

For the mobile haptic interface, two optimization methods for finding the optimal pose of the mobile base are discussed in [8]. Below, similar methods for the mobile teleoperator are presented.

2.1 Coupling Schemes

In this section, two methods for the mobile teleoperator which determine the optimal pose of its mobile base are discussed. The operating principles are depicted in Fig. 2.

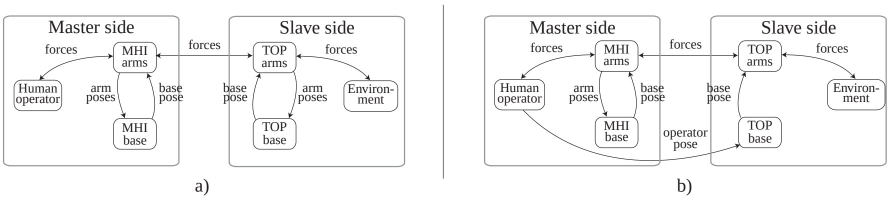

Fig. 2 Coupling schemes for mobile haptic interface and mobile teleoperator. In scheme a) only the end-effectors are coupled and the position of the mobile base on slave side is optimized, whereas in scheme b) the mobile base is positioned depending on the tracked position of the operator.

One method uses an optimization scheme in order to determine the pose of the mobile base as a function of the end-effector poses (Fig. 2a)). The second method relies on tracking the body of the human operator and replicating its position by the teleoperator (Fig. 2b)).

Coupling of End-Effectors Only

The first proposed coupling scheme (Fig. 2a)) consists of optimizing the pose of the base of the mobile teleoperator (${}^0T_S$) with respect to the end-effector poses (${}^0T_R^*, {}^0T_L^*$). Different optimization criteria can be considered. The base can e.g. be positioned, so that the two telemanipulator arms have a maximum distance from their respective workspace boundaries or so that the velocity manipulability is maximized. Here, the maximum distance of the end-effectors from the center of the respective workspace is minimized, thereby approximately optimizing the workspace of the telemanipulator arms.[2]

Using this scheme, the pose of the mobile teleoperator (${}^0T_S$) is independent of the pose of the human operator (${}^0T_H$). A disadvantage of this scheme is that locomotion of the operator does not directly result in movement of the mobile base on teleoperator side, and movement of the mobile base on teleoperator side can occur without locomotion of the operator. Therefore, the relative pose of the end-effectors on local side (${}^HT_R^*, {}^HT_L^*$) and remote side (${}^ST_R^*, {}^ST_L^*$) is not necessarily equal, also not in steady state. Thus, a negative effect on task performance and feeling of immersion can be expected. An advantage of this scheme is that the pose of the operator (${}^0T_H$) does not have to be tracked, making an expensive wide-area tracking system unnecessary.

[2] This approximation only takes into account the translational DOF of the telemanipulator arm. The optimization problem for 6 DOF in Cartesian space or 7 DOF in joint space is non-convex and thus not solvable in real-time.

Coupling of Body and End-Effectors

An alternative coupling scheme is depicted in Fig. 2b). Hereby, the mobile teleoperator (${}^0T_S$) is controlled in such a way that it tracks the pose of the operator (${}^0T_H$).

Locomotion of the operator then directly results in movement of the mobile teleoperator. Using this scheme, the point of view and movement of the camera is expected to more closely follow the operators locomotion. In steady state, the pose of the mobile teleoperator (${}^0T_S$) will be identical to the pose of the human operator (${}^0T_H$). Then, also the relative pose of the end-effectors on local side (${}^HT_R^*, {}^HT_L^*$) and remote side (${}^ST_R^*, {}^ST_L^*$) becomes identical. This scheme is expected to provide superior task performance and a higher degree of immersion. However, reaching the workspace limits or a configuration with a low manipulability could occur more easily, as the mobile platform on teleoperator side is not controlled to optimize these criteria. Furthermore, tracking of the human operator (${}^0T_H$) is necessary to determine the control input for the mobile teleoperator.

2.2 Control Structure

In Fig. 3, the interconnection of the involved subsystems is depicted. The teleoperation system is realized as position-based admittance control architecture. The forces on master side (${}^MF_R, {}^MF_L$) and on slave side (${}^SF_R^*, {}^SF_L^*$) are transformed into the world coordinate system by means of the poses of the respective mobile base (${}^0T_M, {}^0T_S$). The transformed forces are summed and fed into two independent admittance equations which implement the desired mass, damping, and optionally stiffness. The outputs of the admittance equations are a desired pose for right and

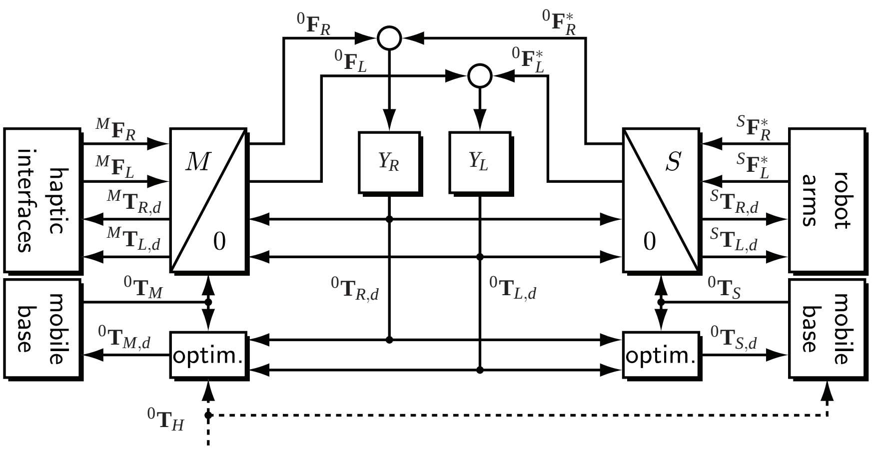

Fig. 3 Overall control structure of the wide-are teleoperation system with position based admittance control. The dashed line indicates the optional tracking data of the operator pose.

left end-effector in world-fixed coordinates ${}^{0}T_{R,d}, {}^{0}T_{L,d}$. These poses are used in two ways. On the one hand, they are transformed back into the local coordinate systems of mobile haptic interface and mobile teleoperator, where they form the control inputs to the haptic interfaces and robot arms, respectively. On the other hand, they are used for determining the optimal pose of the mobile base. Depending on the optimization strategy, additional inputs such as the body pose of the human operator ${}^{0}T_H$ are integrated.

3 Setup

Two identical omnidirectional non-holonomic mobile bases are used in this work. Each mobile base is composed of four independently driven and steered wheels mounted on a rectangular frame. The bases are capable of carrying a payload of up to 200 kg. The underlying controller allows independent translational and rotational movement. For more details on hardware and control of the mobile bases, see [5].

On master side, two ViSHaRD7 haptic interfaces are mounted on the mobile base. Each haptic interface has one translational and six rotational joints, resulting in seven actuated DOF. A half-cylinder with a radius and height of approx. 0.6 m and therefore most of the workspace of a human arm is covered. Peak forces of up to 150 N can be output at the end-effectors making it possible to convincingly display stiff remote environments. The kinematic structure is especially designed to decouple translational and rotational DOF. This is beneficial for the optimization of the manipulability of the haptic interfaces as presented in [8]. For more details on mechanical design and control of the ViSHaRD7, see [6].

Two anthropomorphic seven DOF telemanipulator arms are mounted on the mobile base of the slave side. As for the haptic interfaces, each arm is scaled to approximately cover the workspace of a human arm, and a payload of 6 kg can be held in any configuration. For details on design and control of the teleoperator arms, see [7].

In addition, a stereo camera and two microphones are mounted on a pan-roll-tilt base on the mobile teleoperator. The video and audio stream is presented to the operator over a Head Mounted Disyplay (HMD). Thus, a 3D-view and stereo sound of the remote site can be presented to the operator. On operator side, the commercial acoustic tracking system IS-900 by InterSense Inc. is used, which allows measuring the pose of multiple objects in six DOF. Specifically, the position and orientation of mobile base, operator body, and operator head are determined.

4 Results

Two experiments were performed to evaluate the coupling schemes given in Sec. 2. As tracking of the operator position is necessary for the scheme in which the mobile

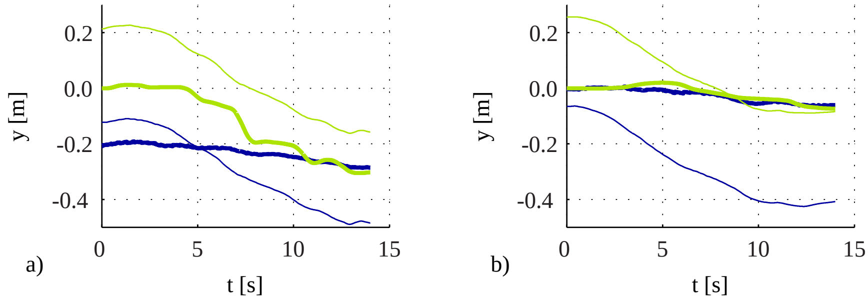

Fig. 4 Experimental results for manipulation while standing still for a) Coupling of the end-effectors only and b) Coupling of body and end-effectors. The bold dark/blue line depicts the position of the operator body while the bold light/green line depicts the base position of the mobile teleoperator. The thin blue and green line are the position of the right and left end-effector respectively. Results are given in the common world coordinate system. ${}^{0}T_{S}(t=0)$ is chosen to be the identity matrix.

base position is coupled to the operator position, a more sophisticated optimization scheme is used for the mobile haptic interface. This takes the operator position and his workspace boundaries into account, see [8].

The first experiment consists of a manipulation task while standing still. The operator picks up an object to his left (positive y-direction), moves it to the right, and places it down. Hereby he does not move his body more than necessary. Fig. 4 shows the recorded data for the experiment. As can be seen, the body of the operator only moves slightly in both experiments. In Fig. 4a) the case is depicted where only the end-effector positions are coupled. The mobile base is controlled to maintain a symmetric position with respect to both end-effectors[3]. In contrast, Fig. 4b) shows the method where operator body and mobile base are directly coupled. Only little deviation of the base position is observed in this case. This results in a more natural relative end-effector position. However, the right arm is near the workspace boundaries at the end of the experiment.

In the second experiment, the operator moves forwards a given distance and then backwards again to his starting position. While moving forwards, the operator holds his hands close to his body. While moving backwards, he extends his arms. In Fig. 5a) results are illustrated for the case where only end-effector positions are coupled. Again, the movement of the mobile base does not directly dependent on the movement of the operator body. This has the advantage that the end-effectors are far from the workspace boundaries as long as the operator does not move too fast. However, as can be seen well at the turning point, even large position changes of the operator do not result in base movement if the hands are kept still. This results in an unnatural feeling of locomotion as proprioception and visual cues are incon-

[3] The high velocity between second 7 and 8 is caused by the non-holonomic base, which must first adjust the steering angle of the wheels before it can accelerate appropriately.

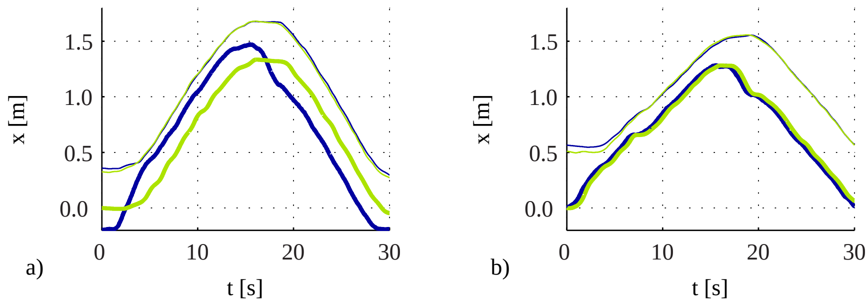

Fig. 5 Experimental results for walking for a) Coupling of the end-effectors only and b) Coupling of body and end-effectors. The bold dark/blue line depicts the position of the operator body while the bold light/green line depicts the base position of the mobile teleoperator. The thin blue and green line are the position of the right and left end-effector respectively. Results are given in the common world coordinate system. ${}^{0}T_S(t=0)$ is chosen to be the identity matrix.

sistent. Complementary results are obtained by the second coupling scheme where the movement of operator and mobile base are closely coupled, see Fig. 5b).

5 Conclusion

The concept of a mobile haptic interface and a mobile teleoperator for teleoperation in extensive environments was revisited. Two schemes for coupling the two mobile devices were presented, where the differences lie in the positioning of the mobile bases. In the first mode, which can be implemented without expensive tracking systems, both mobile bases are controlled to a position, which maximizes the distance to the workspace limits of haptic interfaces and robot arms, respectively. In the second coupling mode, the position of the human body relative to his hands is used to derive the base position of the mobile teleoperator. Furthermore, the base position of the mobile haptic interface is optimized for fast manipulation tasks.

In summary, both schemes enable spatially unlimited teleoperation, but it was shown that additional tracking can enhance the operator experience. In contrast to other methods previously presented, these schemes do not sacrifice low operator fatigue for an unlimited workspace and high output capabilities.

Some open questions still remain that could be addressed in the future. It could e.g. be beneficial to combine the two coupling schemes, i.e. optimizing both relative body pose and workspace of the teleoperator. Furthermore, a general solution to avoid workspace limits while maintaining position tracking between haptic interfaces and teleoperator arms has not been developed yet for position-based admittance control schemes as the one presented here.

Acknowledgements This work is supported in part by the German Research Foundation (DFG) within the collaborative research center SFB453 "High-Fidelity Telepresence and Teleaction" and in part by the European Commission under Contract FP6 034002 ROBOT@CWE.

References

[1] Formaglio A, Prattichizzo D, Barbagli F, Giannitrapani A (2008) Dynamic performance of mobile haptic interfaces 24(3):559–575
[2] Hokayem FP, Spong WM (2006) Bilateral teleoperation: An historical survey. Automatica 42(12):2035–2057
[3] Künzler U, Runde C (2005) Kinesthetic haptics integration into large-scale virtual environments. In: Proceedings of the First Joint Eurohaptics Conference, and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2005.
[4] Nitzsche N, Schmidt G (2004) A mobile haptic interface mastering a mobile teleoperator. In: Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2004), vol 4, pp 3912–3917 vol.4
[5] Nitzsche N, Hanebeck U, Schmidt G (2003) Design issues of mobile haptic interfaces. Journal of Robotic Systems 20(9):549–556
[6] Peer A, Komoguchi Y, Buss M (2007) Towards a mobile haptic interface for bimanual manipulations. In: Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)
[7] Stanczyk B (2006) Developement and Control of an Anthropomorphic Teleoperator. PhD thesis, Technische Universität München, Lehrstuhl für Steuerungs- und Regelungstechnik
[8] Unterhinninghofen U, Schauß T, Buss M (2008) Control of a mobile haptic interface. In: Proc. IEEE International Conference on Robotics and Automation ICRA 2008, pp 2085–2090