Haptic Feedback Systems for Virtual Reality and Telepresence Applications

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***Abstract*— An overview of subjectively selected topics and research trends in the area of virtual reality and telepresence systems is given. The major focus is on haptic feedback devices allowing the operator to touch virtual and remote objects. The paper presents selected hardware developments and application studies in the haptic research area carried out at the Institute of Automatic Control Engineering, Technische Universität München.**

I. Introduction

Virtual reality (VR) and telepresence systems offer humans the possibility to interactively explore and manipulate artificial and remote environments. Examples are space robotics (Mars Pathfinder mission), telemanipulator systems for minimally invasive surgery (da Vinci, Zeus), surgical virtual reality training systems, and the intuitive and immersive exploration of virtual prototypes (e. g. digital mock-ups in automotive product development). In the majority of these systems only visual and audio feedback is used to present information to the operator. The interaction with the virtual or remote environment is done via pure input devices such as joysticks, mice, keyboards, and body or limb trackers. In recent years the additional use of haptic interfaces has received growing attention. These devices provide controlled force and torque feedback to the operator. The generated forces and torques are usually measurements from remote teleoperator environments or are computed in virtual reality haptic rendering engines as the result of virtual objects interacting with each other. This allows the operator to touch virtual and remote objects and to feel their weight and stiffness. The ability to physically interact with the environment drastically increases the realism and immersivity of the simulation. As haptic devices are used to read the operator's motion/force input and to react with a corresponding force/motion output they provide a bidirectional human-machine interface.

For the organization of the paper: Sec. II discusses the general structure of multi-modal VR and telepresence systems along with typical operation modes. In Sec. III haptic feedback systems are discussed and applications ranging from bimanual and mobile teleoperation to medical training simulation for skill transfer are presented in Sec. IV.

II. Multi-Modal VR and Telepresence Systems

The structure of a multi-modal telepresence systems is shown in Fig. 1. On the operator-site the human operator gives multi-modal command inputs to the human system interface (HSI) using motion, voice, or symbolic input devices. The commands are transmitted to the executing teleoperator on the remote-site across (communication or scale) barriers. The teleoperator is an executing robotic system such as a mobile service robot and is controlled according to the commands received from the human operator. Sensors mounted on the teleoperator measure the interaction between the teleoperator and the environment. Typically visual, acoustic, force, and tactile sensors are used. Measured data is transmitted back to the human operator and displayed using modality dependent hardware in the multi-modal HSI comprising multimedia and haptics.

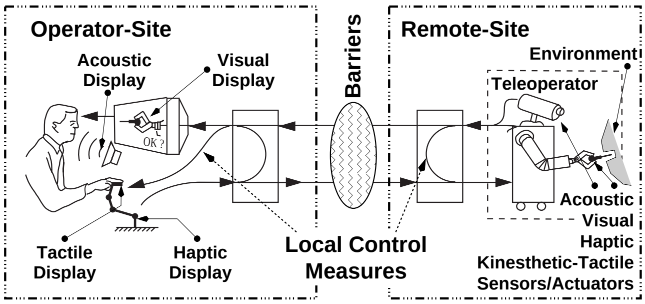


Fig. 1. Multi-modal telepresence system

One of the key issues in telepresence system design and operation is the degree of coupling between the human operator and the teleoperator. If the operator gives symbolic commands to the teleoperator by pushing buttons and watching the resulting action in the remote environment the coupling is *weak*. The coupling is *strong* for the haptic modality in a bilateral teleoperation scenario. Commonly, the motion (force) of the human operator is measured, communicated, and used as the set-point for the teleoperator motion (force) controller. On the remote site the resulting forces (motion) of the teleoperator in the environment are sensed, communicated, and fed back to the human operator through the force feedback channel of the multi-modal HSI.

The literature on telepresence systems distinguishes between *remote*, *shared*, *cooperative*, *assisting*, *semi-autonomous*, *symbolic* and *trading control*, see e. g. [3], [15], [16], [29], [85] and [19] for a detailed discussion.

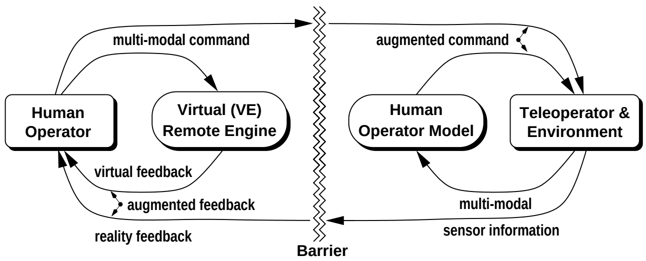


Fig. 2. Multi-modal control loops in telepresence systems.

The multi-modal control loop of telepresence systems is shown in Fig. 2. From the human operator the multi-modal command consisting of voice, haptic (force/motion), and symbolic input is transmitted across the (communication) barrier to the teleoperator. Simultaneously, the command is also input to a model of the teleoperator and remote environment implemented in a virtual environment for local feedback. Data measured by teleoperator sensors results in multi-modal feedback to the human operator across the barrier. Multi-modal feedback consists of 2D or 3D visual, mono/stereo acoustic, haptic (force, motion, tactile, temperature), and symbolic information. The remote local control loop using a human operator model increasing the autonomy of the teleoperator by implementing human task skill is also shown.

Multi-modal human system interaction with purely virtual environments has various important applications. Operator training is possible without risk for humans involved. A classical training application are flight simulators for pilot training, where the supported modalities have been visual feedback and acceleration emulation mainly. Medical applications like e. g. practice runs of complicated surgical procedures are being developed for surgeon training [84]. A system for multi-modal interaction with a virtual (possibly injured) human knee joint is [78]. Virtual environments are also being used to extract operator expertise, to transfer, and implement this knowledge for semi-autonomous local teleoperator control, see Fig. 2 and [15], [17], [23], [30], [56], [97].

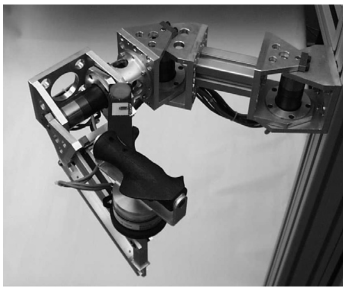
Feedback to the operator through the human system interface is often augmented, i. e. remote data is fused with supplemental data from a remote environment model. Augmentation on the remote site uses human control expertise from a human operator model to support local control of the teleoperator. Augmentation is possible for all mentioned human modalities, but most established are kinesthetic and (predictive) visual augmentation. In a bilateral kinesthetic teleoperation scenario local feedback has been used successfully to achieve stability (in fact passivity) of the communication link by interpreting it as a lossless two-port [2], [7], [50], [61]. Robust stabilization of these systems in the presence of communication unreliability as for instance caused by time-varying delay and packet loss is studied in [36]. A visual predictive display has been proposed using first a wire-frame and later a solid model image generated by computer graphics hardware, which is then blended or overlayed with the camera image from the remote site [12], [39], [49]. Work by our colleagues in Munich aims at photorealistic predictive displays [13], [14], [25], [73].

III. Haptic Feedback Systems

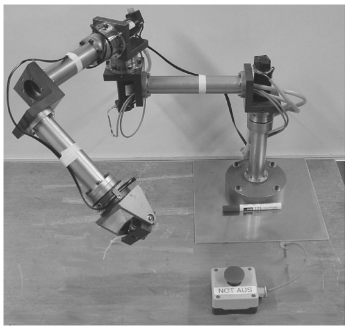
Haptic feedback systems have also been covered in recent survey articles [35], [58]. A brief overview on recent devices has been given in [59]. The most wide class of interfaces that achieved a highly convenient development status are passive designs providing kinesthetic feedback in small workspaces at moderate force levels. These displays are characterized by highly lightweight mechanical designs requiring no active force feedback control to provide a good backdrivability. Commercially available passive devices include the by far most widely used PHANToM family (see `www.sensable.com`, [60]). An example of interfaces with improved but still moderate force capability compared to common passive designs is the commercially available DELTA Haptic Device (`www.forcedimension.com`, [32]). It employs force sensing to compensate for the slightly increased dynamic properties. This class of interfaces shows an improved but still moderate output capability. Displays providing human matched force levels are uncommon. Two of the few examples are the Excalibur device [1] and the *Haptic*MASTER (`www.fcs-cs.com`, [95]). Both provide $100\,\mathrm{N}$ continuous force but in a rather limited workspace in 3 DOF only. For the realization of tasks requiring both, high force capability and large workspace, almost no adequate hardware solutions are available; usually standard industrial robots with force sensor are used. Disadvantages of these are very high dynamic properties and safety concerns when in contact with human operaors. For these reasons we have been developing suitable haptic display hardware in recent years discussed in the following.

A. Haptic (Force) Feedback Devices

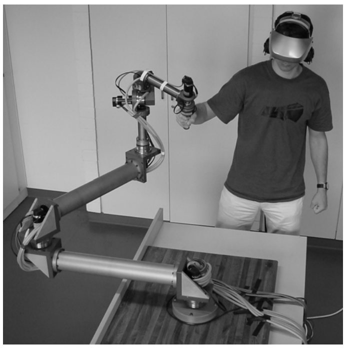
In our research we have developed a variety of versatile, universally applicable force feedback devices. In early work DeKiFeD3, a 3-DOF haptic display for maximum forces of $60\,\mathrm{N}$ in 3 translational directions, was employed for haptic telepresence (using the same kinematic structure), also in combination with tactile feedback on the finger-tip, see Fig. 3 (a) and [5], [40], [41], [43], [44]. This display was then extended to DeKiFeD4 by one active rotational joint to provide haptic feedback in 4 DOF, see e. g. [48]. In addition, the planetary gears have been replaced by harmonic drive gears largely improving the haptic feedback at interactions with stiff environments due to the higher torque capability and elimination of backlash.



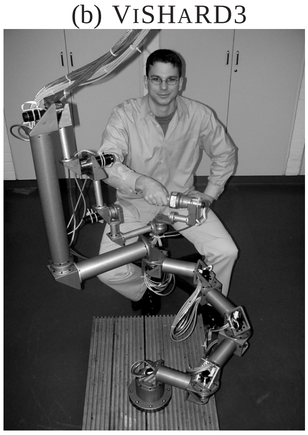
(a) DeKiFeD3



(b) VISHARD3



(c) VISHARD6



(d) VISHARD10

Fig. 3. Photos of haptic feedback devices DeKiFeD3, VISHARD3, VISHARD6, VISHARD10.

In later years the VISHARD[1] family - VISHARD3, VISHARD6, VISHARD10 - of high-performance, general purpose haptic feedback devices has been developed. Their comparatively high force/torque capability is provided by DC motors coupled to harmonic drive gears. VISHARD3 has 3 active rotational degrees-of-freedom (DOF) and 3 passive, freely rotating DOF, see Fig. Fig. 3 (b) and [31]. The human finger-tip can be placed on the end effector to allow pointwise interaction with the device. Force feedback is limited to 3 Cartesian directions in an increased workspace compared to DeKiFeD3. As a universally applicable, fully actuated haptic device with 6 DOF the VISHARD6prototype was developed mainly for virtual environment applications, see Fig. 3 (c) and [87], [88]. VISHARD6 has many advantages in terms of a large workspace, force capability matched to the human arm, see Tab. I.

The main design objective for a recently developed, novel hyper-redundant haptic interface VISHARD10is to provide a versatile haptic display with distinct advantages compared to existing solutions with respect to applicability for a variety of applications: large workspace free of singularities; high payload capability to accommodate various application specific end-effectors as e. g. surgical tools like drills [28] or scissors; to mount tactile stimulation actuators for combined kinesthetic and tactile feedback; offer redundancy to avoid user interference; provide dual-arm haptic interaction with full 6 DOF capability (again redundancy facilitates collision avoidance between the two arms), see Fig. 3 (d) and [90]–[94].

This versatility is advantageous as it provides a benchmarking testbed for the development and feasibility studies of novel haptic applications. When new applications are developed, which require a certain workspace or a certain maximum allowable force, the proposed redundant device can be constrained to these specifications by appropriate controller design; this includes the development of dedicated inverse kinematics algorithms adapted to the specific needs of the application. Once the new haptic application has been rudimentarily developed using VISHARD10 and the feasibility is verified, a tailored, highly specialized haptic display with specifications exactly matching the application requirements can be developed. The technical specifications of the VISHARD device family are given in Tab. I. It summarizes the worst case performance indices within the specified workspace.

B. Mechatronics and Control Issues

Haptic feedback devices are usually serial kinematic designs very similar to known robotic manipulator arm designs, although very different in the design criteria. Structural rigidity and positioning accuracy is not a key issue in haptics as compared to robotic manufacturing applications. More important is a good backdrivability to render unconstrained motion (e. g. free space simulations) where

[1] **V**irtual **S**cenario **Ha**ptic **R**endering **D**evice

TABLE I

TECHNICAL SPECIFICATIONS OF THE VISHARD DEVICE FAMILY

Property	VISHARD3	VISHARD6	VISHARD10
transl. workspace	$0.6 \times 0.25 \times 0.4\,\mathrm{m}$	$0.86 \times 0.3 \times 0.3\,\mathrm{m}$	$\varnothing 1.7 \times 0.6\,\mathrm{m}$
rot. workspace	not applicable	$360°$, $60°$, $360°$	$360°$ for each rotation
peak force	$86\,\mathrm{N}$	$178\,\mathrm{N}$	$170\,\mathrm{N}$
peak torque	not applicable	pitch, yaw: $54\,\mathrm{Nm}$ roll: $4.8\,\mathrm{Nm}$	pitch, yaw: $13\,\mathrm{Nm}$ roll: $4.8\,\mathrm{Nm}$
transl. velocity	$1.0\,\mathrm{m/s}$	$0.61\,\mathrm{m/s}$	$>1\,\mathrm{m/s}$
rot. velocity	not applicable	$2.96\,\mathrm{rad/s}$	
transl. acceleration	$14.7\,\mathrm{m/s^2}$	$7.5\,\mathrm{m/s^2}$	
rot. acceleration	not applicable	$38.6\,\mathrm{rad/s^2}$	
max. payload	$6.5\,\mathrm{kg}$	$7.5\,\mathrm{kg}$	$7\,\mathrm{kg}$
mass of moving parts	$\approx 5.5\,\mathrm{kg}$	$\approx 20\,\mathrm{kg}$	$\approx 23\,\mathrm{kg}$

no force generated by the natural device dynamics should be felt by the operator. A reduction of the acceleration and velocity dependent backdrivability is obtained by a reduction of the inertia and friction of the mechanical hardware, respectively. In case this is not possible due to other design considerations a further significant lowering of the dynamic properties can be accomplished by closed loop control.

To achieve a good backdrivability many haptic interface designs employ tendon transmission systems for motor torque amplification and the transmission of the actuator power over distances. This offers the possibility to mount the motors at the device base to lighten the interface structure. As no toothing is used these systems are virtually free from backlash and torque ripple. Although the torque ripple of gears has usually a comparatively low amplitude, its high frequency can cause a significant disturbance to the haptic sensation. On the other hand, tendon transmission mechanisms show a drastically reduced compactness and inferior stiffness characteristics when compared to gears. The price of communicating torque over distances with tendons is usually an increase in friction, additional and complex transmission dynamics [77], and a higher system complexity. Tendon mechanisms seem to be primarily rewarding for devices small in physical size and low DOF because in case of large devices the weight of the mechanical structure typically dominates over the actuator weight due to the requirements on structural rigidity.

Very different compared to industrial applications is the fact that the end-effector trajectories are not known in advance because the human operator may move the haptic interface freely. As a consequence, end-effector locations in the neighborhood of interior singularities[2] are not available for haptic interactions. Around these positions the dynamic properties of the robot degrade because high joint velocities only produce small end-effector velocities in certain directions. As motions along these critical directions cannot be foreclosed, because the end-effector is moved by the operator a will, interior singularities result in a significant impairment of the end-effector output capability regarding acceleration and velocity. This is different in common robotic manufacturing applications where these workspace areas can be used; dedicated path planning usually allows to drive the manipulator through interior singularities. Haptic applications also complicate the control of redundant devices. Due to the lack of a priori known trajectories no path inversion approaches can be applied to solve for the inverse kinematics problem.

The haptic simulation of a human's bilateral interaction with a virtual or remote environment requires the control of the motion-force relation between the operator and the robot. This control task shows similarities to manufacturing applications that implicitly require the control of the robot interaction force with the workpiece (e. g. assembly, polishing, grinding, handling flexible parts). In fact, haptic control often adopts algorithms that are originally motivated by industrial force control applications. Widely used approaches include impedance and admittance control, see [89] for an overview and experimental comparison of haptic control schemes with focus on VR applications. A discussion of telepresence control architectures is provided in [34], [57].

There are, however, two main differences between the industrial force and haptic control task: First, the end-effector typically contacts a very stiff environment in case of manufacturing applications whereas the haptic interface is grasped by a human operator providing a comparatively compliant connection. Accordingly, many stability problems of robot force control caused by low grip compliance do not apply for haptic control tasks. Second, the goal of common industrial force control tasks is the generation of a dedicated contact force. In case of impedance or admittance control the desired robot dynamics is freely chosen by the control designer to maximize the performance of the force controller. In other words, it is chosen as a means of satisfying a superordinated control goal. This is different at haptic control task where the generation of the motion-force relation between operator and device is the intrinsic control goal. The target impedance or admittance is specified by the virtual or remote environment and is usually subject to strong dynamical variations. As a matter of these facts, these control strategies have to be newly investigated in the haptic feedback application domain.

[2]Singularities are positions in space where the robot looses a DOF.

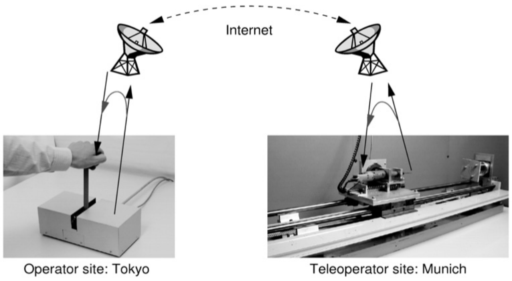


Fig. 4. Teledrilling over the internet.

IV. Application Examples

A. Teledrilling Munich-Tokyo[3]

The haptic global control loop in telepresence systems is usually closed over Internet communication. Overall control strategies have been surveyed in [19], [83]. Often it is required that the teleoperator switches control modes (e.g. from position to force control) depending on the environment contact state. In [4], [7]–[9], [19] this hybrid (discrete-continuous) control mode switching strategy is proposed for an example task of teledrilling; experimental results between Munich and Tokyo with $0.2 - 2\,\mathrm{s}$ round trip time delay in the Internet.

B. Tele-Manufacturing Munich-Berlin[4]

In recent experiments we have demonstrated a prototypical telemanufacturing — fixing a screw by telepresence — experiment, where a 7 DOF teleoperator arm is controlled by two 1 DOF force feedback devices over the Internet between Munich and Berlin, see [37], [38], [86].

C. Telepresence and Teleaction in full 6 DOF[5]

In order to enable intuitive telemanipulation in full 6 DOF a telepresence system using a 7 DOF teleoperator arm, the haptic input device ViSHaRD10 (cf. Sec. III-A), and a stereo vision systems has been set up. In order to combine these both devices a coupling-method for devices with different kinematic structures has been developed. In addition, the implemented control algorithms for haptic display and telemanipulator assure a stable interaction with the environment. In several experiments tracking of free space motion, haptic exploration of different materials as well as fixing a screw by telepresence has been successfully demonstrated, see Fig. 5 and [18], [74], [75].

Future work includes the extension of this system for bimanual manipulation. This requires further analysis of possible contact situations and the investigation of new stable control algorithms.

[3]The original work on teledrilling is by former members of the Institute of Automatic Control Engineering: H. Baier, G. Schmidt.

[4]The implementations and experiments between Munich and Berlin were performed by S. Hirche and B. Stanczyk, a former member of the Institute of Automatic Control Engineering.

[5]The experiments have been performed by K.-K. Lee, A. Peer, the 3rd author, and B. Stanczyk, a former member of the Institute of Automatic Control Engineering

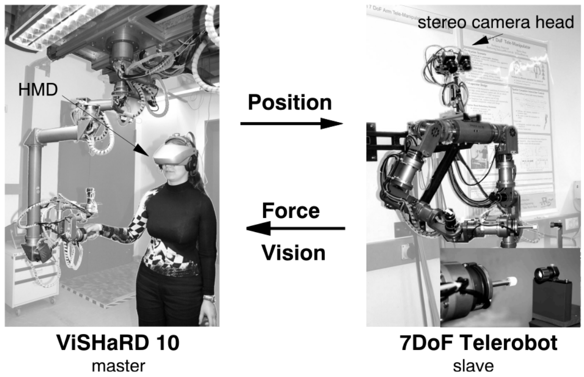


Fig. 5. Experimental setup: tele-screw-tightening

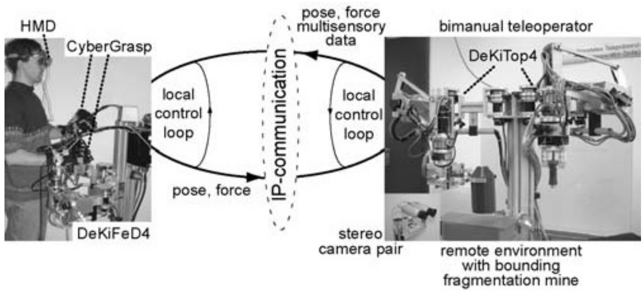


Fig. 6. Bimanual, haptic telepresence system; demining task example.

D. Stationary Bimanual Telepresence[6]

A bimanual haptic telepresence system has been proposed in our group, see Fig. 6 and [47], [48], [51], [52], [54], [55]. The system comprises a wrist/finger haptic display for generation of combined force feedback at wrist and fingers [53]; for wrist force feedback two DeKiFeD4 systems with 4 active DOF each (cf. Sec. III-A) are used; finger forces are generated using the hand force exoskeleton CyberGrasp from Immersion Corp. Another two DeKiFeD4 systems with two-jaw grippers as end-effectors are used on the remote site. Force/torque sensors measured the interaction forces at the human wrists and the environment reaction forces on both teleoperator systems. This bimanual telepresence system has been applied for a bimanual benchmark task, opening and closing of a remote flask [53], and a demining scenario, where person mines had to be defused [54], [55].

E. Mobile Telepresence[7]

In order to enable telepresence in arbitrarily large remote environments the telemanipulator has been mounted on a mobile base which can freely move around in the remote environment [18], [33], [75]. For maintaining a high degree of immersion in wide area telepresence it is crucial to convey a natural feeling of locomotion. This is achieved

[6]The first bimanual experiments were realized by A. Kron, a former member of the Institute of Automatic Control Engineering.

[7]Original work by N. Nitzsche and U. Hanebeck, both former members of the Institute of Automatic Control Engineering.

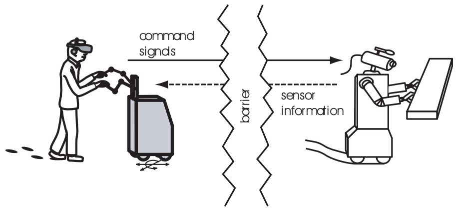


Fig. 7. Locomotion *and* force-reflecting teleoperation in extensive remote environments using a Mobile Haptic Interface (MHI) and a Mobile Teleoperator (MTO).

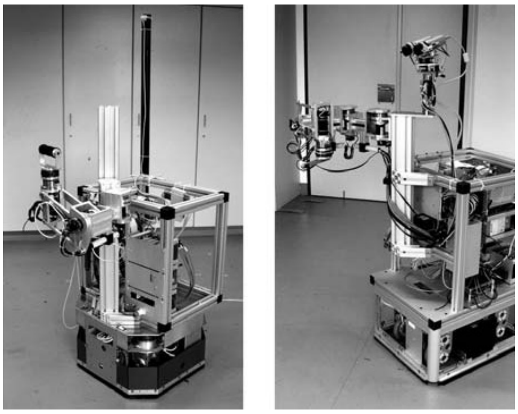


Fig. 8. Mobile Haptic Interface (MHI) (left) and Mobile Teleoperator (MTO) (right).

by also placing the haptic interface on a mobile base which allows to track operator motions and to reflect forces at the same time, see Fig. 7 and 8. The mobile haptic interface (MHI) can be used in wide area telepresence as well as in extensive virtual environments [62], [65], [70]. Related Work can be found in [6], [11], [20], [22], [24], [46], [72], [81], [96].

A problem which is common to both applications of an MHI is the limited workspace at the operator site. Techniques like scaling or indexing have been shown to considerably reduce the feeling of presence in the target environment (see [10], [21], [76], [82]). Using the concept of motion compression [63], [63], [64], [66]–[69], [71], [80] the path in the remote environment is transformed in such a way that it fits into the available operator space, see Fig. 9. As long as the curvature deviation between original and transformed path is kept below a certain threshold the operator cannot perceive compression artifacts.

In a current research project our institutes aims at developing and implementing a system enabling mobile and bimanual haptic tele-collaboration in 6 DOF as illustrated in Fig. 10 (see [18], [75])

F. *VR Knee Simulator*[8]

Virtual reality applications investigated at our research institute include medical training and education. Multi-modal training systems enable students and young medical doctors to practice medical interventions without a patient solving for time and performance constraints. The measurement of all actions during the simulation permits a systematic evaluation of the operator's progress and skill level.

The Munich Knee Joint Simulation project addresses the problem that for the diagnosis of knee joint lesions more than 80 different clinical knee evaluation tests exist, which are difficult to practice due to limited access to real patients. Moreover, the procedure can be painful for the patient. To improve training and education the Munich Knee Simulator (MKS) with haptic, acoustic and visual feedback has been developed, see Fig. 11. A visual display provides insight into the geometry and kinematics of the knee joint and its anatomical structures. An acoustic display renders noise from inner structures of the knee joint when moving the leg and generates the sounds uttered by the virtual patient when pain occurs. The haptic display enables the user to move an artificial leg with realistic tactile and geometric properties and feel forces and torques appearing in an intact or pathological knee joint. Details on this system are given in [42], [45], [78], [79].

G. *VR Bone Drilling Training*[9]

Another project in the area of medical VR-training systems is bone drilling [26]–[28]. Bone drilling is necessary during many orthopedical operations, prior to insertion of pins and screws. The main problem of a bone drilling operation is heat generation. The friction that occurs during

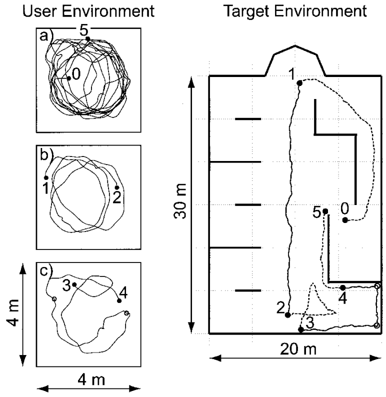


Fig. 9. Trajectories of a test run in user environment (left) and target environment (right) [68]

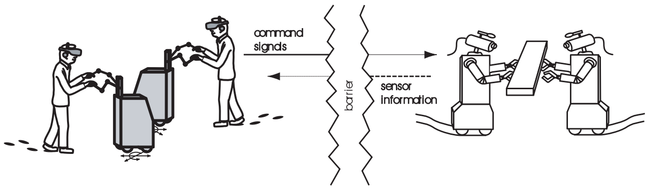


Fig. 10. Current research: mobile and bimanual haptic tele-collaboration in 6 DOF

[8]The work on the Munich Knee Simulator is by M. Frey, T. Pröll, R. Riener, all former members of the Institute of Automatic Control Engineering.

[9]The Bone Drilling teaching system has been realized by the 2nd author H. Esen and K. Yano of the Gifu University, Japan.

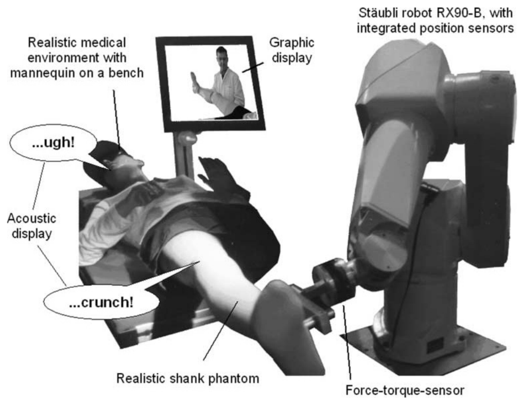


Fig. 11. Multi-modal Munich Knee Simulator [78]

a bone drilling process produces high temperature which may cause irreparable damages to the bone. For proper bone drilling surgeons have to gain the following core skills: recognizing the drilling end-point; applying constant and sufficient but non-excessive thrust force and feeding velocity. The multi-modal bone drilling training system developed by our research group enables teaching core skills of a bone drilling operation. The visual display contains a 3D skull model that is obtained from CT data and a model of medical drill. A haptic display enables the trainee to feel the interaction forces of the virtual drill with the skull model. Applying the correct force for drilling through haptic display lets trainee drill into the virtual skull. During the virtual drilling an appropriate drilling sound is provided to the trainee. Recently, the system has been extended for multi-user training purposes [26]. It is allows an expert to follow visually and haptically a trainee who performs a virtual bone drilling task. The expert can interact with the trainee and correct his/her operation.

V. Conclusions

An overview of the general structure of multi-modal telepresence and teleaction systems has been given. High-fidelity haptic (force) feedback devices as part of the human system interface are a crucial component of modern multi-modal telepresence systems. An overview of haptic devices developed in our work has been presented. Some of the mechatronic and control design issues of haptic interfaces differing largely from classical robot manipulator design because of humans interacting with them have been discussed. Several application examples of internet, mobile wide area, and bimanual telepresence as well as virtual medical training were summarized.

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References

[1] R.J. Adams, M. Moreyra, and B. Hannaford. Excalibur - a three axis force display. In *Proceedings ASME International Mechanical Engineering Congress and Exhibition*, 1999.

[2] R. J. Anderson and M.W. Spong. Bilateral control of operators with time delay. *IEEE Trans. on Automatic Control*, (34):494–501, 1989.

[3] R.J. Anderson. Autonomous, Teleoperated, and Shared Control of Robot Systems. In *Proceedings of the IEEE International Conference on Robotics and Automation*, pages 2025–2032, Minneapolis, Minnesota, 1996.

[4] H. Baier. Model-Based Teleoperation of a Drilling Machine in Uncertain Communication Barriers. Internal Report, Institute of Automatic Control Engineering, Technische Universität München, April 1997.

[5] H. Baier, M. Buss, F. Freyberger, J. Hoogen, P. Kammermeier, and G. Schmidt. Distributed PC-Based Haptic, Visual and Acoustic Telepresence System—Experiments in Virtual and Remote Environments. In *Proceedings of the IEEE Virtual Reality Conference VR'99*, pages 118–125, Houston, TX, 1999.

[6] H. Baier, M. Buss, F. Freyberger, and G. Schmidt. Interactive stereo vision telepresence for correct communication of spatial geometry. *Advanced Robotics, The International Journal of the Robotic Society of Japan*, 17(3):219–233, 2003.

[7] H. Baier, M. Buss, and G. Schmidt. Control Mode Switching for Teledrilling Based on a Hybrid System Model. In *Proceedings of the IEEE/ASME International Conference on Advanced Intelligent Mechatronics AIM'97*, Tokyo, Japan, Paper No. 50, 1997.

[8] H. Baier, M. Buss, and G. Schmidt. Stabilität und Modusumschaltung von Regelkreisen in Teleaktionssystemen. *at—Automatisierungstechnik*, 48(2):51–59, Februar 2000.

[9] H. Baier and G. Schmidt. Control Aspects of Closed-Loop Haptic Teleoperation. In *Proceedings of the 7th International Workshop on Robotics in Alpe-Adria-Danube Region (RAAD'98)*, pages 151–156, Smolenice, Slovakia, 1998.

[10] N. H. Bakker, P. J. Werkhoven, and P. O. Passenier. The effect of proprioceptive and visual feedback on geographical orientation in virtual environments. *Presence*, 8(1):36–53, 02 1999.

[11] F. Barbagli, A. Formaglio, M. Franzini, A. Giannitrapani, and D. Prattichizzo. An experimental study of the limitations of mobile haptic interfaces. In *Proc. Int. Symp. on Experimental Robotics*, Singapore, 2004.

[12] A.K. Bejczy, W.S. Kim, and S.C. Venema. The phantom robot: Predictive displays for teleoperation with time delay. In *Proceedings of the IEEE International Conference on Robotics and Automation*, pages 546–551, Cincinnati, Ohio, 1990.

[13] T. Burkert and G. Färber. Photo-realistic scene prediction. In *Proceedings of the IEEE International Conference on Mechatronics and Robotics, MechRob2004*, Aachen, Germany, 2004, *Special Session on Telepresence and Teleaction*.

[14] T. Burkert, J. Leupold, and G. Passig. A photorealistic predictive display. *Presence: Teleoperators and Virtual Environments*, 13(1):22–43, 2004.

[15] M. Buss. *Study on Intelligent Cooperative Manipulation*. PhD thesis, University of Tokyo, Tokyo, June 1994.

[16] M. Buss and H. Hashimoto. Skill Acquisition and Transfer System as Approach to the Intelligent Assisting System—IAS. In *Proceedings of the 2nd IEEE Conference on Control Applications*, pages 451–456, Vancouver, British Columbia, Canada, 1993.

[17] M. Buss and H. Hashimoto. Motion Scheme for Dextrous Manipulation in the Intelligent Cooperative Manipulation System—ICMS. In V. Graefe, editor, *Intelligent Robots and Systems*, pages 279–294. Elsevier Science, Amsterdam, 1995.

[18] M. Buss, K.K. Lee, N. Nitzsche, A. Peer, B. Stanczyk, and U. Unterhinninghofen. Advanced telerobotics: Dual-handed and mobile remote manipulation. In R. Aracil, C. Balaguer, M. Buss, M. Ferre, and C. Melchiorri, editors, *Advances in Telerobotics: Human Interfaces, Control, and Applications*. Springer, STAR series, 2006, *to appear*.

[19] M. Buss and G. Schmidt. Control Problems in Multi-Modal Telepresence Systems. In P.M. Frank, editor, *Advances in Control: Highlights of the 5th European Control Conference ECC'99 in Karlsruhe, Germany*, pages 65–101. Springer, 1999.

[20] C. Cruz-Neira, D. Sandin, and T. A. DeFanti. Surround-screen projection-based virtual reality: The design and implementation of the CAVE. In *Proc. of the ACM SIGGRAPH*, pages 135–142, Anaheim, California, 1993.

[21] R. P. Darken. Spatial orientation and wayfinding in large-scale virtual spaces II. *Presence*, 8(6):iii–vi, 12 1999.

[22] R. P. Darken, W. R. Cockayne, and D. Carmein. The omni-directional treadmill: A locomotion device for virtual worlds. In *Proc. of the ACM UIST*, pages 213–222, Alberta, Canada, 1997.

[23] N. Delson and H. West. Robot programming by human demonstration: Subtask compliance controller identification. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems IROS*, pages 33–41, 1993.

[24] N. Diolaiti and C. Melchiorri. Haptic tele-operation of a mobile robot. In *Proc. of the IFAC Symposium on Robot Control*, Wroclaw, Poland, 2003.

[25] C. Eberst, N.O. Stöffler, M. Barth, and G. Färber. Compensation of time delays in telepresence applications by photo-realistic scene prediction of partially unknown environments. In *Proceedings of the IASTED International Conference on Robotics and Applications RA'99*, pages 163–168, Santa Barbara, CA, 1999.

[26] H. Esen, A. Sachsenhauser, K. Yano, and M. Buss. Multi-user virtual environments with haptic feedback for training purposes. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2006. in review.

[27] H. Esen, K. Yano, and M. Buss. A control algorithm and preliminary user studies for a bone drilling medical training system. 2003. IEEE International Workshop on Robot and Human Interactive Communication.

[28] H. Esen, K. Yano, and M. Buss. A virtual environment medical training system for bone drilling with 3 DOF force feedback. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 3631–3636, 2004.

[29] C. Fischer, M. Buss, and G. Schmidt. HuMan-Robot-Interface for Intelligent Service Robot Assistance. In *Proceedings of the IEEE International Workshop on Robot and Human Communication (ROMAN)*, pages 177–182, Tsukuba, Japan, 1996.

[30] H. Friedrich, J. Holle, and R. Dillmann. Interactive Generation of Flexible Robot Programs. In *Proceedings of the IEEE International Conference on Robotics and Automation*, pages 538–543, Leuven, Belgium, 1998.

[31] M. Fritschi. Development of a Training Simulator for Prostate Cancer Diagnosis Simulation. Diploma thesis, Control Systems Group, Faculty of Electrical Engineering and Computer Science, Technische Universität Berlin, 2002. in German.

[32] S. Grange, F. Conti, P. Rouiller, P. Helmer, and C. Baur. Overview of the Delta Haptic Device. In *Eurohaptics'01*.

[33] U. D. Hanebeck and N. Šaldic. A modular wheel system for mobile robot applications. In *Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 17–23, Kjongju, Korea, 1999.

[34] K. Hashtrudi-Zaad and S.E. Salcudean. Analysis of control architectures for teleoperation systems with impedance/admittance master and slave manipulators. *International Journal of Robotics Research*, 20(6):419–445, 2001.

[35] V. Hayward, O.R. Astley, M. Cruz-Hernandez, D. Grant, and G. Robles-De-La-Torre. Haptic interfaces and devices. *Sensor Review*, 24(1):16–29, 2004.

[36] S. Hirche. *Haptic Telepresence in Packet Switched Communication Networks*. PhD thesis, Institute of Automatic Control Engineering (LSR), Technische Universität München, 2005.

[37] S. Hirche, B. Stanczyk, and M. Buss. Transparent Exploration of Remote Environments by Internet Telepresence. In *Proceedings of the International Workshop on High-Fidelity Telepresence and Teleaction, jointly with the IEEE conference HUMANOIDS'2003*, Munich, Germany, 2003.

[38] S. Hirche, B. Stanczyk, and M. Buss. Haptic tele-assembly over the internet. In *Proceedings of the EuroHaptics'2004 Conference*, pages 417–421, Munich, Germany, 2004.

[39] G. Hirzinger. Rotex–the first robot in space. In *Proceedings of the ICAR International Conference on Advanced Robotics*, pages 9–33, 1993.

[40] J. Hoogen. Development of an Experimental System for Kinesthetic Feedback in Telepresence Systems. Internal Report, Institute of Automatic Control Engineering, Technische Universität München, May 1998.

[41] J. Hoogen. Ein Experimentalsystem zur Erzeugung von kinästhetischem und taktilem Feedback in Telepräsenzsystemen. In *VDI/VDE-GMA-Fachbericht zum VDE-Kongress 1998*, pages 65–74, Stuttgart, Germany, 1998.

[42] J. Hoogen. *Control of an Industrial Robot for the Haptic Interaction with a Virtual Knee Joint*. PhD thesis, Institute of Automatic Control Engineering (LSR), Technische Universität München, 2005. in German.

[43] J. Hoogen, M. Buss, and G. Schmidt. Kraftregelung eines haptischen Displays zur kinästhetischen Interaktion mit virtuellen und realen entfernten Umgebungen. In *VDI Berichte 1552 Robotik 2000 — Leistungsstand, Anwendungen, Visionen, Trends —*, pages 477–482, Berlin, 2000.

[44] J. Hoogen, P. Kammermeier, and M. Buss. Multi-Modal Feedback and Rendering in Virtual Environment Systems. In *Proceedings of the 8th International Workshop on Robotics in Alpe-Adria-Danube Region (RAAD'99)*, pages 221–226, München, Germany, 1999.

[45] J. Hoogen, R. Riener, and G. Schmidt. Control aspects of a robotic haptic display for kinesthetic knee joint simulation. *IFAC Journal on Control Engineering Practice*, 10(11):1301–1308, 2002.

[46] H. Iwata. Walking about virtual environments on an infinite floor. In *Proc. of the IEEE Virtual Reality Conference*, pages 286–293, Houston, Texas, 1999.

[47] P. Kammermeier, A. Kron, M. Buss, and G. Schmidt. Towards Intuitive Multi-fingered Haptic Exploration and Manipulation. In *Proceedings of the International Workshop on Advances in Interactive Multimodal Telepresence Systems*, pages 57–70, Technische Universität München, München, Germany, 2001.

[48] P. Kammermeier, A. Kron, J. Hoogen, and G. Schmidt. Display of holistic haptic sensations by combined tactile and kinesthetic feedback. *Presence: Teleoperators and Virtual Environments*, 13(1):1–15, 2004.

[49] W.S. Kim. Virtual Reality Calibration and Preview/Predictive Displays for Telerobotics. *Presence*, 5(2):173–190, Juni 1996.

[50] K. Kosuge, H. Murayama, and K. Takeo. Bilateral Feedback Control of Telemanipulators via Computer Network. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems IROS*, pages 1380–1385, Osaka, Japan, 1996.

[51] A. Kron, M. Buss, and G. Schmidt. Exploration and Manipulation of Virtual Environments using a Combined Hand- and Finger Force Feedback System. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems IROS*, pages 1328–1333, Takamatsu, Japan, 2000.

[52] A. Kron and G. Schmidt. A Bimanual Haptic Telepresence System – Design Issues and Experimental Results. In *Proceedings of the International Workshop on High-Fidelity Telepresence and Teleaction, jointly with the IEEE conference HUMANOIDS'2003*, Munich, Germany, 2003.

[53] A. Kron and G. Schmidt. A bimanual haptic telepresence system - design issues and experimental results. In *Proceedings of the Workshop on High-fidelity Telepresence and Teleaction, jointly with the conference HUMANOIDS*, Munich, 2003.

[54] A. Kron and G. Schmidt. Bimanual haptic telepresence technology employed to demining operations. In *Proceedings of the EuroHaptics'2004 Conference*, pages 490–493, Munich, Germany, 2004.

[55] A. Kron, G. Schmidt, B. Petzold, M. Zäh, E. Steinbach, and P. Hinterseer. Disposal of explosive ordnances by use of a bimanual haptic telepresence system. In *Proc. of the IEEE Int. Conf. on Robotics and Automation, ICRA*, New Orleans, LA, 2004.

[56] Y. Kunii and H. Hashimoto. Tele-teaching by human demonstration in virtual environment for robotic network system. In *Proceedings*

of the IEEE International Conference on Robotics and Automation, pages 405–410, Albuquerque, New Mexiko, 1997.

[57] D.A. Lawrence. Stability and transparency in bilateral teleoperation. *IEEE Transactions on Robotics and Automation*, 9(5):624–637, 1993.

[58] S.D. Laycock and A.M. Day. Recent developments and applications of haptic devices. *Computer Graphics Forum*, 22(2):117–132, 2003.

[59] J. Martins, J. Savall. Mechanisms for haptic torque feedback. In *Proceedings of the First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 611–614, 2005.

[60] T.H. Massie and J.K. Salisbury. The PHANTOM haptic interface: A device for probing virtual objects. In *Proceedings of the ASME Winter Annual Meeting, Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*.

[61] G. Niemeyer and J.E. Slotine. Towards Force-Reflecting Teleoperation Over the Internet. In *Proceedings of the IEEE International Conference on Robotics and Automation*, pages 1909–1915, Leuven, Belgium, 1998.

[62] N. Nitzsche. *Weiträumige Telepräsenz: Unbeschränkte Fortbewegung und haptische Interaktion*. PhD thesis, Munich, Germany, 2005.

[63] N. Nitzsche, U. D. Hanebeck, and G. Schmidt. Mobile haptic interaction with extended real or virtual environments. In *Proc. of the IEEE International Workshop on Robot-Human Interactive Communication*, pages 313–318, Bordeaux/ Paris, France, 2001.

[64] N. Nitzsche, U. D. Hanebeck, and G. Schmidt. Extending telepresent walking by motion compression. In *Tagungsbeiträge, 1. SFB-Aussprachetag, Human Centered Robotic Systems, HCRS*, pages 83–90, Karlsruhe, Deutschland, 2002.

[65] N. Nitzsche, U. D. Hanebeck, and G. Schmidt. Design issues of mobile haptic interfaces. *Journal of Robotic Systems*, 20(9):549–556, 06 2003.

[66] N. Nitzsche, U. D. Hanebeck, and G. Schmidt. Mobile Haptische Schnittstellen für Weiträumige Telepräsenz: Idee und Methodik. *at Automatisierungstechnik*, 51(1):5–12, 01 2003.

[67] N. Nitzsche, U. D. Hanebeck, and G. Schmidt. Motion compression for telepresent walking in large-scale remote environments. In *Proc. of SPIE, AeroSense Symposium*, Orlando, Florida, 2003.

[68] N. Nitzsche, U. D. Hanebeck, and G. Schmidt. Motion compression for telepresent walking in large target environments. *Presence*, 13(1), 02 2004.

[69] N. Nitzsche, U.D. Hanebeck, and G. Schmidt. Motion compression for telepresent walking in large target environments. *Presence: Teleoperators and Virtual Environments*, 13(1):44–60, 2004.

[70] N. Nitzsche and G. Schmidt. Force-reflecting mobile teleoperation. In *Proc. of RAAD'04*, Brno, ČR, 2004.

[71] N. Nitzsche and Günther Schmidt. A mobile haptic interface mastering a mobile teleoperator. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems IROS*, Sendai, Japan, 2004.

[72] J. Park and O. Khatib. Robust haptic teleoperation of a mobile manipulation platform. In *Proc. Int. Symp. on Experimental Robotics*, Singapore, 2004.

[73] G. Passig, T. Burkert, and J. Leupold. Scene model acquisition for a photo-realistic predictive display and its application to endoscopic surgery. In *MIRAGE 2005: International Conference on Computer Vision / Computer Graphics Collaboration Techniques and Applications*, pages 89–97, INRIA Rocquencourt, France, March 2005.

[74] A. Peer, B. Stanczyk, and M. Buss. Haptic telemanipulation with dissimilar kinematics. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 2483–2487, Edmonton, Canada, 2005.

[75] A. Peer, U. Unterhinninghofen, K.K. Lee, B. Stanczyk, and M. Buss. Haptic telemanipulation in extensive remote environments. In *Proceedings of the Joint International COE/HAM SFB-453 Workshop on Human Adaptive Mechatronics and High-Fidelity Telepresence*, pages 57–62, Tokyo, Japan, 2005.

[76] M.M. Popp, E. Platzer, M. Eichner, and M. Schade. Walking with and without walking: Perception of distance in large-scale urban areas in reality and in virtual reality. *Presence: Teleoperators and Virtual Environments*, 13(1):61–76, 2004.

[77] G.M. Prisco and M. Bergamasco. Dynamic modelling of a class of tendon driven manipulators. In *Proceedings of the 8th International Conference on Advanced Robotics*, pages 893–899, 1997.

[78] R. Riener, M. Frey, T. Pröll, F. Regenfelder, and R. Burgkart. Phantom-based multimodal interactions for medical education and training: the Munich Knee Joint Simulator. *IEEE Transactions on Information technology in Biomedicine*, 8(2):208–216, 2004.

[79] R. Riener, J. Hoogen, G. Schmidt, M. Buss, and R. Burgkart. Knee Joint Simulator Based on Haptic, Visual, and Acoustic Feedback. In *Preprints of the 1st IFAC Conference on Mechatronic Systems*, pages 579–583, Darmstadt, Germany, 2000.

[80] P. Rössler, U. D. Hanebeck, and N. Nitzsche. Feedback controlled motion compression for extended range telepresence. In *Proc. of the IEEE International Conference on Mechatronics & Robotics*, Aachen, 2004.

[81] H. Roth, K. Schilling, and O. J. Rösch. Haptic interfaces for remote control of mobile robots. In *Proc. of the IFAC 15th Triennial World Congress*, Barcelona, Spain, 2002.

[82] R. A. Ruddle and D. M. Jones. Movement in cluttered virtual environments. *Presence*, 10(5):511–524, 10 2001.

[83] S. E. Salcudean. *Control Problems in Robotics and Automation*, pages 51–66. Number 230 in Control for Teleoperation and Haptic Interfaces, Lecture Notes. Springer Verlag, Berlin, 1998.

[84] R.M. Satava and S.B. Jones. Virtual Environments for Medical Training and Education. *Presence*, 6:139–146, 1997.

[85] T. B. Sheridan. *Telerobotics, Automation, and Human Supervisory Control*. MIT Press, Cambridge, Massachusetts, 1992.

[86] B. Stanczyk, S. Hirche, and M. Buss. Telemanipulation over the internet: a tele-assembly experiment. In *Proceedings of the IEEE International Conference on Mechatronics and Robotics, MechRob2004*, Aachen, Germany, 2004.

[87] M. Ueberle and M. Buss. Design, Control, and Evaluation of a new 6 DOF Haptic Device. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems IROS*, pages 2949–2954, Lausanne, Switzerland, 2002.

[88] M. Ueberle and M. Buss. Design of a high performance 6 DOF haptic device. In *Proceedings of the 81t Mechatronics Forum International Conference*, pages 1201–1210, 2002.

[89] M. Ueberle and M. Buss. Control of kinesthetic haptic interfaces. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems IROS, Workshop on Touch and Haptics*, 2004.

[90] M. Ueberle and M. Buss. Design and control of a hyper-redundant haptic interface. In M.H. Ang and O. Khatib, editors, *Experimental Robotics IX: The 9th International Symposium on Experimental Robotics*, volume 21 of *Springer Tracts in Advanced Robotics*, pages 523–532. Springer, 2006.

[91] M. Ueberle, N. Mock, and M. Buss. Towards a Hyper-Redundant Haptic Display. In *Proceedings of the International Workshop on High-Fidelity Telepresence and Teleaction, jointly with the IEEE conference HUMANOIDS'2003*, Munich, Germany, 2003.

[92] M. Ueberle, N. Mock, and M. Buss. ViSHaRD10, a Novel Hyper-Redundant Haptic Interface. In *Proceedings of the 12th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, in conjunction with IEEE Virtual Reality 2004 conference*, pages 58–65, Chicago, IL, 2004.

[93] M. Ueberle, N. Mock, and M. Buss. Design, control, and evaluation of a hyper-redundant haptic interface. In R. Aracil, C. Balaguer, M. Buss, M. Ferre, and C. Melchiorri, editors, *Advances in Telerobotics: Human Interfaces, Control, and Applications*. Springer, STAR series, 2006, *to appear*.

[94] M. Ueberle, N. Mock, A. Peer, C. Michas, and M. Buss. Design and Control Concepts of a Hyper Redundant Haptic Interface for Interaction with Virtual Environments. In *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems IROS, Workshop on Touch and Haptics*, Sendai, Japan, 2004.

[95] R.Q. Van der Linde, P. Lammertse, E. Frederiksen, and B. Ruiter. The HapticMaster, a new high-performance haptic interface. In *Eurohaptics'02*, pages 1–5.

[96] 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(1):1–21, 02 2001.

[97] J. Yang, Y. Xu, and C.S. Chen. Hidden markov model approach to skill learning and its application in telerobotics. In *Proceedings of the IEEE International Conference on Robotics and Automation*, pages 396–402, Atlanta, Georgia, 1993.