

# High Fidelity Telepresence Systems: Design, Control, and Evaluation

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**Abstract.** An overview of subjectively selected recent topics and research trends in the area of modern telepresence and teleaction is given. Multi-modal telepresence systems are to enable human operators to become present and active in remote or inaccessible environments through a communication network and a suitable telerobotic system. The major challenges of such a multimodal telepresence system like stabilizing measures, and transparency, e.g. in the case of time-delay (latency) in the communication network, are discussed. A practical implementation of an integrated mobile and bimanual multi-user telepresence and teleaction system as well as some exemplary experiments are presented. Furthermore, it is discussed how the performance of telepresence systems can be improved by using psychophysical knowledge of human perception.

**Keywords.** *Telepresence, Multimodality, Psychophysics*

## I. Introduction

Multi-modal telepresence and teleaction systems include classical teleoperation and telemanipulation systems. An important issue is the combination of telepresence and teleaction, allowing the human operator to perform actively in remote environments. Here, remote environments include possibly distant and/or scaled physical environments, virtual environments—VEs and augmented realities.

One of the central issues in modern telepresence systems is multi-modality in the *human-system interface—HSI* accompanied by appropriate sensing techniques at the teleoperator site comprising theoretically all the human senses. In current technical applications most important and only partly realized are the visual, auditory, and haptic — i.e. kinesthetic, tactile and temperature — senses.

Application areas of telepresence and teleaction systems are countless, to name only a few: tele-programming, tele-installation, tele-diagnosis, tele-service, tele-maintenance, tele-assembly, tele-manufacturing, miniature or micro mechatronics, inner and outer space operations, tele-teaching, tele-medicine, tele-surgery, tele-shopping, etc.

Haptic (force and tactile) feedback systems are one of the key elements in modern telepresence and virtual environment systems. Telepresence systems are most often operated with Internet communication, which means that the haptic control loop is closed over an unreliable communication channel posing additional challenges for control architectures.

Related overview articles addressing telepresence, haptics, and Internet control are [15, 16, 29, 36, 72]; see also a special section in Presence [10, 41, 58, 65–67] and a forthcoming book about telepresence [3]. Sections II, III, and IV discuss the general structure of multi-modal telepresence systems, the design of an integrated mobile and bimanual multi-user telepresence/teleaction system, and psychophysical aspects, respectively.

## II. Multi-Modal Telepresence Systems

The structure of a multi-modal telepresence system 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.

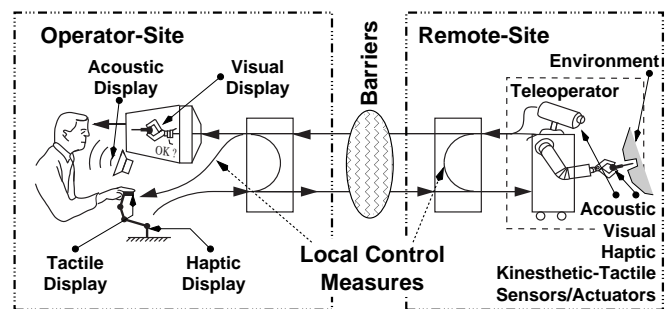


Fig. 1: Multi-modal telepresence system

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. [2, 11, 12, 25, 74] and [15] for a detailed discussion.

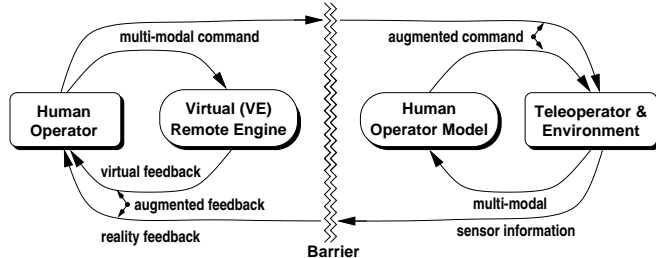


Fig.2: Multi-modal control loops in telepresence systems.

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 [73]. A system for multi-modal interaction with a virtual (possibly injured) human knee joint is [68]. 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 [11, 13, 20, 26, 48, 85].

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 feed-

back has been used successfully to achieve stability (in fact passivity) of the communication link by interpreting it as a lossless two-port [1, 5, 44, 50]. 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 overlaid with the camera image from the remote site [8, 35, 43]. Work by our colleagues in Munich aims at photorealistic predictive displays [9, 10, 24, 62].

### III. Integrated Mobile and Bimanual Multi-User Telepresence and Teleaction

Existing telepresence systems show deficits with respect to workspace, manipulability, and performance. These deficits can partly be ascribed to a limited workspace of haptic display or telemanipulator. Moreover, most telepresence systems are limited to a few degrees of freedom necessary for a specific task, which makes intuitive manipulation very difficult.

The demand on intuitive manageability of a telemanipulation system results inevitably in a bimanual, mobile and kinematically redundant system. Enhancing such a system by further adding a multi-user mode enables to perform collaborative telemanipulation tasks. Our institute aims at developing and implementing such a high-definition telepresence system, see Fig. 3. In order to realize such a system the following research areas can be distinguished: A) stationary bimanual telepresence/teleaction in full 6 DOF, B) integrated mobile, bimanual telepresence/teleaction, C) multi-user mobile telepresence/teleaction. In the following these research topics and the current state of our research are briefly discussed.

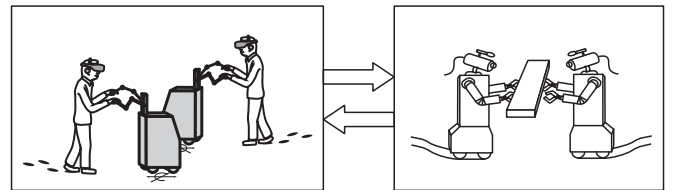


Fig.3: Mobile and bimanual haptic tele-collaboration

#### A. Stationary bimanual telepresence and teleaction in full 6 DOF

In order to enable intuitive telemanipulation the hyper redundant haptic display ViSHARD10 (**V**irtual **S**cenario **H**aptic **R**endering **D**evice with **10** actuated DOF) is used as a human system interface, see Fig. 4. Its main characteristics are a very large workspace free of singularities, a high payload capability to accommodate various application specific end-effectors as e.g. surgical tools like drills [27] or scissors, foreseen redundancy to avoid kinematic singularities and user interferences and the possibility for dual-arm haptic interaction with full 6 DOF (again redundancy facilitates collision avoidance between the two arms). In order to provide an effective

compensation of disturbances due to friction and to be able to render inertia and mass, admittance control has been implemented for this device. An appropriate inverse kinematic algorithm enables a reasonable redundancy resolution. Further details about the design concept, the kinematic model, and the control of ViSHARD10 can be found in [79–83].

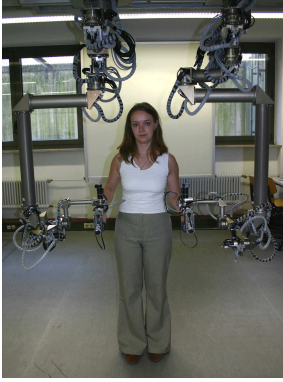


Fig.4: Bimanual haptic display ViSHARD10

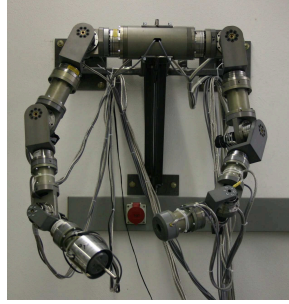


Fig. 5: Dual arm telemanipulator

The superior manipulation-dexterity of humans is a result of the kinematic redundancy of human arms and the ability to adapt their compliance to the current task. As many technical design solutions being inspired by nature, an anthropomorphic bi-manual redundant telemanipulator has been designed, see Fig. 5. The telemanipulator consists of two identical, human-scaled arms. Each arm consists of two spherical joints with 3 DOF at shoulder and wrist, each, and one revolute joint at the elbow, which results in 7 DOF, see [75, 76, 78]. The redundancy of the slave is efficiently utilized to fulfill additional kinematic or dynamic tasks, e.g. to avoid singularities or joint limits and to increase the structural stiffness of the arm in contact situations [14]. During telemanipulation, the telemanipulator has to handle interactions with unstructured rigid environments. For such reasons, a control algorithm that guarantees compliant behavior during contact is applied, see [14, 63, 64, 77].

In order to combine these both devices to a bimanual telemanipulation system 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. 6 and [14, 63, 64].

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

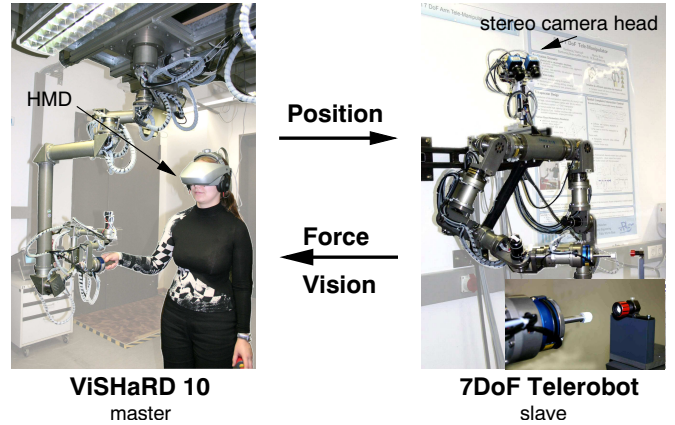


Fig.6: Experimental setup: tele-screw-tightening

### B. Integrated mobile, bimanual telepresence/teleaction

In order to enable telepresence in arbitrarily large remote environments the telemanipulator is mounted on a mobile base which can freely move around in the remote environment [14, 28, 64]. For maintaining a high degree of immersion in wide area telepresence it is crucial to convey a natural feeling of locomotion. This is achieved 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. 3. The mobile haptic interface (MHI) can be used in wide area telepresence as well as in extensive virtual environments [51, 54, 59]. Related Work can be found in [4, 7, 17, 19, 22, 37, 61, 70, 84].

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 [6, 18, 66, 71]). Using the concept of motion compression [52, 52, 53, 55–58, 60, 69] the path in the remote environment is transformed in such a way that it fits into the available operator space, see Fig. 7. As long as the curvature deviation between original and transformed path is kept below a certain threshold the operator cannot perceive compression artifacts.

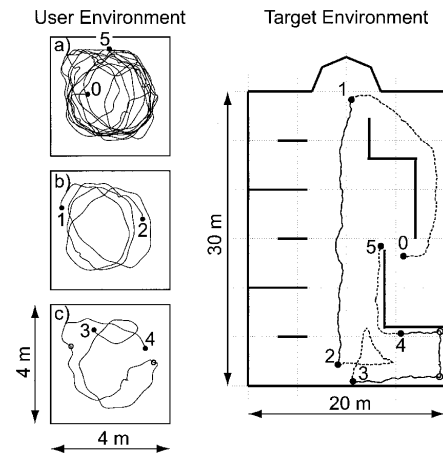


Fig.7: Trajectories of a test run in user environment (left) and target environment (right) [57]

### C. Multi-user mobile telepresence/teleaction

Finally the collaboration of multiple human operators in a telepresence and teleaction scenario is currently being investigated. Thereby the human operators interact with mobile haptic interfaces and control mobile teleoperators located at the remote site. The main research topics in this field are the development of control algorithms for collaborative telemanipulation and task sharing as well as the automatic collision avoidance between the teleoperators.

## IV. Telepresence and Psychophysics

### A. Dynamical model of human perception

Another way to improve telepresence systems is to take into account psychophysical aspects of human perception. Therefore, multimodal processes are described quantitatively by a systems theoretical model providing static, dynamical and statistical information. On the basis of a structural description [39] we investigate multimodal processes normally elicited within telepresence (haptic, visual and auditory). Thereby, we concentrate on crossmodal interactions and sensory processes [42, 45]. We use psychophysical models to develop data reduction algorithms and new kinds of transparency measures to be used in haptic telepresence [30–34, 49]. High fidelity telepresence systems like a multimodal bimanual human system interface or several tactile displays (shear force, thermal) serve as experimental testbeds [21, 23, 38, 40, 46, 47].

## V. Conclusion

An overview of the general structure of multi-modal telepresence and teleaction systems has been given. Typical control modes in multi-modal telepresence systems such as remote, shared, cooperative, assisting, trading, symbolic, semi-autonomous control were briefly discussed. A mobile and bimanual multi-user telepresence and teleaction system was presented and some of the challenging open research problems related to bimanual, mobile and collaborative telemanipulation were discussed. An interdisciplinary approach using psychophysical aspects of human perception to improve telepresence systems has been discussed.

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