TELE-ASSEMBLY IN WIDE REMOTE ENVIRONMENTS

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ABSTRACT

Telepresence offers considerable advantages in the remote execution of maintenance assignments. In this work a telepresence system is presented that allows to perform assembly tasks in remote and extensive environments. This system comprises a telemanipulator with two anthropomorphic 7-DOF arms controlled by a hyper-redundant 10-DOF haptic display. Dexterous manipulation capabilities are achieved by employing 3-finger grippers at the teleoperator site and data gloves at the operator site. An omnidirectional mobile platform provides the teleoperator with locomotion abilities. The platform motion is controlled via a specifically designed 3-DOF pedal. In this paper a description of the overall teleoperation system is given, and details and results of an experiment involving locomotion, navigation and dexterous manipulation are presented.

1. INTRODUCTION

Telepresence systems can be used to perform tasks in distant, dangerous or badly accessible environments. Many application scenarios like disaster operations, rescue and maintenance tasks involve exploring an unknown terrain, moving to the operational area, and finally conducting some sort of manipulation task. This mode of operation requires a highly integrated telepresence system capable of moving freely around, performing dexterous manipulation tasks, and conveying multimodal feedback to the operator site.

Nowadays several bimanual telemanipulation systems exist to perform complex manipulation tasks in the remote environment, but most of them still exhibit severe limitations of several kinds: Either they are limited to a few DOFs and/or relatively small workspace, so that full spatial immersion is not achieved, e.g. [1–4], or they suffer from the inability to display stiff environments or to mount task specific end-effectors. Only a few more advanced telemanipulation systems operating in 6 DOF and using haptic interfaces as well as telemanipulators with human scaled workspace are known. In [5] as well as in [6, 7] a teleoperation system with 7 DOF exoskeletons used as haptic input devices and 7 DOF humanoid telemanipulators are presented. But as working with exoskeletons is very fatiguing these systems are very limited in their performance (the entire range of human arm movements is restricted and long time operations are not possible because of the high weight of the system, see [8]).

Similarly different interfaces for the control of mobile robots have been investigated in the past. The most common input device is a joystick or some kind of haptic interface for the operator's hand [9]. However, joystick control is not appropriate for setups where the operator needs both hands for telepresent manipulation. In these cases the joystick can be substituted by a pedal which is operated by foot [10]. Other approaches are based on gesture or speech recognition. These systems offer only indirect control and thus do not allow fine positioning of the mobile robot (e.g. [11]).

Issues created by an integrated solution of telepresent bimanual manipulation and locomotion are mostly neglected. To the authors' best knowledge only [6, 7] deal with such a system using exoskeletons and a motion base as human system interfaces and a humanoid robot as telerobot. But as far as known the problem of contemporaneously locomotion and manipulation of various objects is not solved yet for humanoid robot systems, which restricts the applicability of the overall telemanipulation system.

Here we present an integrated telepresence system with visual, acoustic and haptic feedback which allows telemanipulation with two arms in full 6 DOF. The telemanipulator is placed on a mobile platform, therefore it can move around and operate in an arbitrarily large remote environment allowing simultaneous manipulation and locomotion.

In the following section a description of the overall teleoperation system is given. Subsection 2.1 describes the kinesthetic input and slave devices as well as their bilateral coupling. Subsection 2.2 continues with the description of a multi-fingered telemanipulation system, which enables dexterous manipulation tasks. Subsection 2.3 deals with the stereo vision system. Subsection 2.4 covers the mobile base and the control pedal used to move the teleoperator around in the remote environment. Finally details and results of an experiment involving locomotion, navigation and dexterous manipulation are presented.

2. DESCRIPTION OF TELEOPERATION ROBOTIC SYSTEM

A schematic overview of the complete teleoperation system is given in Fig. 1. Basically systems for haptic telemanipulation, systems which enable locomotion in the remote environment, as well as visual and auditory systems can be distinguished. In the following these different components of the overall teleoperation system will be described in more detail.

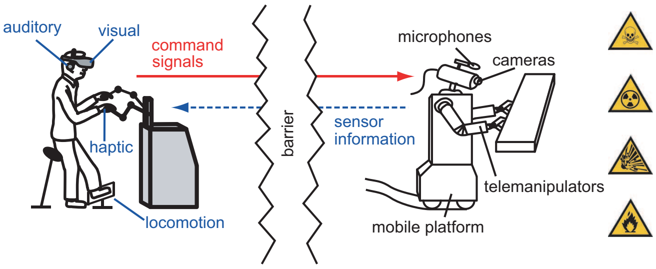


Fig. 1. Teleoperation robotic system

2.1. Telemanipulation Master and Slave Devices

Accomplishing complex telemanipulation tasks requires master and slave devices, which allow to manipulate in full 6 DOF. In the following a hyper redundant haptic interface, a redundant 7DOF telemanipulator, as well as the coupling between both devices will be presented.

2.1.1. Haptic Interface

In order to enable intuitive telemanipulation the hyper redundant haptic display VISHARD10 (**Vi**rtual **S**cenario **Ha**ptic **R**endering **D**evice with **10** actuated DOF) is used as a human system interface. Its main characteristics are a very large workspace free of singularities, a high payload capability to accomodate various application specific end-effectors, 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 [12–16].

2.1.2. 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 [17–19]. Like many other technical design solutions which have been inspired by nature, an anthropomorphic bimanual redundant telemanipulator has been designed. 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 [20–22]. 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 [23]. 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 [23–26].

2.1.3. Telemanipulation Control Structure

The complete teleoperation control loop, a two channel control architecture, consists of the local controllers on the master and slave site, human and environment impedances, kinematic transformations, and the communication channel.

Fig. 2 shows the simplified teleoperation control structure assuming perfect position tracking. Desired positions $\boldsymbol{x}_m$ are sent to the teleoperator and the interaction forces $\boldsymbol{f}_d$ between the teleoperator and the environment are fed back to the operator site.

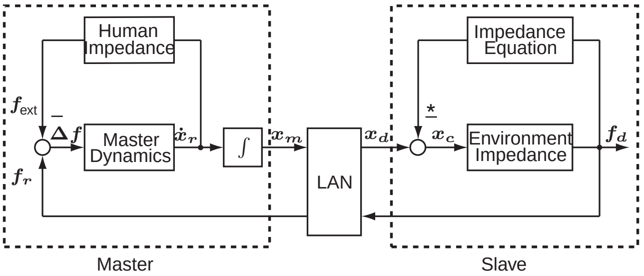


Fig. 2. Simplified teleoperation control architecture

2.2. Multi-fingered telemanipulation

In order to perform complex manipulation tasks the telemanipulator is equipped with two three-finger robotic grippers, which can be used as a universal tool to grasp and manipulate objects. Using such universal grippers instead of specific tools allows to operate in highly variable, unstructured, unknown or dynamic working environments. As a part of a telemanipulation system the grippers are controlled by a human operator. On this account human hand and finger motions are measured using a data glove system and mapped to the grippers. Sensed interaction forces are fed back to the operator and displayed through a haptic display, an exoskeleton. Since human hand and grippers have different kinematic structures, appropriate mappings for forces and motion between the finger and the hand are required. Fig. 3 shows the resulting system architecture. In the following their components should be presented in more detail.

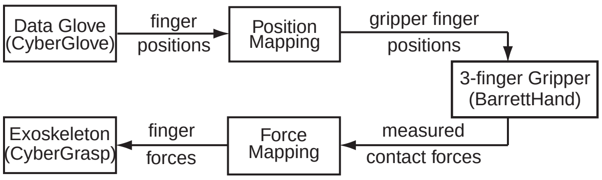


Fig. 3. System architecture of the multi-fingered telemanipulation system

2.2.1. *Grippers*

Two *BarrettHands* (BH) from Barrett Technology Inc. were used [27] as grippers. The *BarrettHand* has three fingers with four actuated degrees of freedom. Each finger consists of two coupled joints driven by a single DC brushless servo motor. In addition two fingers can rotate synchronously and symmetrically about the base joint in a spreading action. Each finger is equipped with a strain gage joint torque sensor, for measuring the torque externally applied about the distal joint over a range of +/-1 Nm. Real time operation of the motors is assured by a low level velocity controller. The high level controllers as e.g. impedance control are realized on the PC using MATLAB/Simulink Real-Time Workshop and RTAI Linux.

2.2.2. *Data Glove System and Position Mapping*

To capture finger and hand motions the data glove system *CyberGlove* from Immersion Corporation, see [28], is used. The data glove is equipped with 22 sensors located over or near the joints of the hand and wrist. A resistive bend-sensing technology is used to transform hand and finger motions into real-time digital joint-angle data. These joint angles are the input for a kinematic human hand model which computes the fingertip positions of the human hand. These fingertip positions are then mapped to the BH-fingertip positions by using an appropriate fingertip mapping algorithm (see [29]), which projects the human hand workspace on to the BH workspace. Finally an analytical inverse kinematic algorithm allows to compute appropriate joint angles for the gripper fingers, which can be set by the local BH controller. Using this mapping algorithm simple pick and place manipulation tasks can be performed.

2.2.3. *Exoskeleton and Force Mapping*

In order to provide force feedback to the human operator the *CyberGrasp* system, an exoskeleton from Immersion Corporation, see [30], is used. The exoskeleton is attached to the back of the hand and guides force-applying tendons to the user's fingertips. Desired force values are sent to the local force controller provided by the manufacturer. Since each finger is only equipped with one tendon only pull- but no push-forces can be applied. Similar to the position mapping algorithm, also a simple force mapping algorithm has been implemented: As the position mapping is designed as finger-to-finger mapping, the measured interaction forces can be directly fed back to the corresponding human finger.

2.3. Vision

The stereo vision system consists of two CCD firewire cameras placed on a 3DOF pan-tilt-roll head, see [31] for technical details. The recorded video streams are displayed on the head mounted display (HMD) carried by the human operator. Efficient low-latency real-time video is made possible by the use of a UDP-based, MPEG-4-compressed transmission approach using the XviD-codec (www.xvid.org). Requesting independently encoded frames in case of packet loss on the network ensures error resilience. The HMD is additionally equipped with a built in tracker (based on a hybrid technology of inertia and ultrasonic tracking), which is used for controlling of the camera head motion, such that the user can look around in the remote environment just by turning his/her own head.

2.4. Locomotion

2.4.1. *Mobile Base*

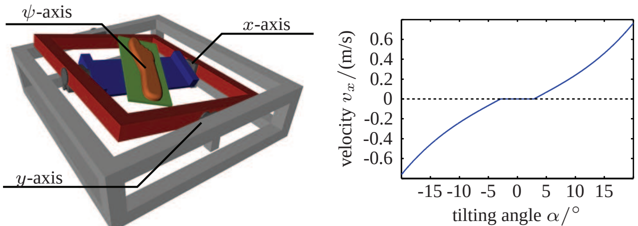
The mobile base enables the user to move the teleoperator in the remote environment. In order to make these movements intuitive the mobile platform must have locomotion capabilities similar to those of a human. Therefore we use an omnidirectional platform, which is operated in velocity control mode. Because the operator uses both arms to control the telemanipulator arms the desired velocity is input via a pedal.

The omnidirectional mobile base possesses four independently driven and steered wheels. The controller of the platform solves the redundancy of the platform and is optimized to generate smooth motions without preplanned paths. A more detailed description of the platform can be found in [32].

2.4.2. *Control Pedal*

As the operator uses both arms and hands to control the telemanipulator arms, the mobile base of the teleoperator cannot be commanded in a classic way by means of a joystick. Instead, a 3-DOF pedal has been designed allowing the operator to adjust the velocity of the mobile base using his/her foot.

A schematic view of the pedal is depicted in Fig. 4a. The roll-, pitch-, and yaw-axis intersect in a single point in order to increase the ease of use. A small deadband zone and a progressive velocity curve have been implemented (Fig. 4b) allowing smooth control of the platform.

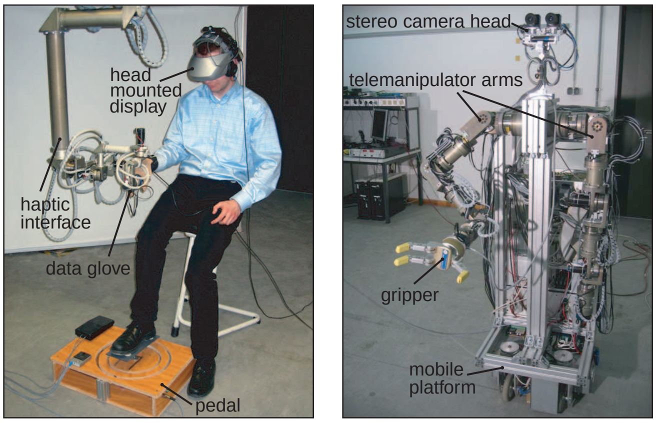


a) b)

Fig. 4. a) Schematic view of the 3-DOF control pedal b) Mapping from pedal angle α to velocity component v_x

3. EXPERIMENTAL RESULTS

The experimental setup consists of a stationary human system interface and a mobile teleoperator, see Fig. 5. The mobile teleoperator is equipped with telemanipulator arms, a three-finger gripper (BarrettHand) and a stereo camera head. To allow teleoperation in wide remote environments all these components are mounted on a mobile platform. The stationary human system interface comprises a data glove system (CyberGlove), a haptic display (VISHARD10), a head mounted display, as well as a control pedal. Due to the still missing coupling mechanism between human hand and end effector of the haptic interface no exoskeleton for finger force reflection is used in this experiment and the gripper is only position controlled by using a data glove. This missing coupling mechanism must be able to disconnect the human arm from the haptic interface in case of emergency. The required electro-mechanical mechanism is still under construction, experiments with finger force reflection will follow in the near future.



a) b)

Fig. 5. Setup: a) stationary human system interface, b) mobile teleoperator

In all our experiments the master and slave devices (haptic interface, telemanipulator arm, data glove, gripper, control pedal, mobile platform) communicate over the UDP network with a sampling rate of 1kHz, which is the same as used for the local loop controllers. The stereo camera system provides stereo images with a resolution of 640x480 pixels and a frame rate of approximately 30 fps, which allows a good visual impression of the remote environment.

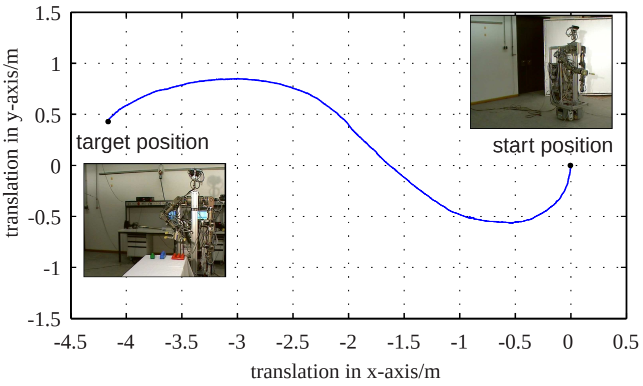


Fig. 6. Path of the mobile platform from start to target position

The experiment carried out involves locomotion, navigation and dextrous telemanipulation tasks and can be split into two major parts. While the first part concentrates on locomotion and navigation, the second part represents a classical telemanipulation experiment.

At the beginning the teleoperator is placed at an arbitrary position in the experimental hall (see Fig. 6, start position) and the human operator is asked to navigate the teleoperator to the location of the telemanipulation setup (see Fig. 6, target position) and to position the platform in an adequate manner relatively to this setup. Fig. 6 shows the path from start to target position recorded during this experiment. It should be noted that the path is very smooth, which indicates a good navigation performance of the system.

Subsequently the human operator is asked to perform a telemanipulation experiment, which can be summarized as follows:

- pick up toy brick at one location,
- move brick to target,
- align brick with target,
- join brick with fixed brick at target position,
- retract hand from target.

Fig. 7 shows a sequence of snapshots taken during the experiment. As it can be seen in these pictures, the experiment was successfully performed. For a full length video, see *http://www.lsr.ei.tum.de/movies*.

4. CONCLUSION

In this paper a telepresence system is presented which is capable of performing dexterous telemanipulation tasks in wide

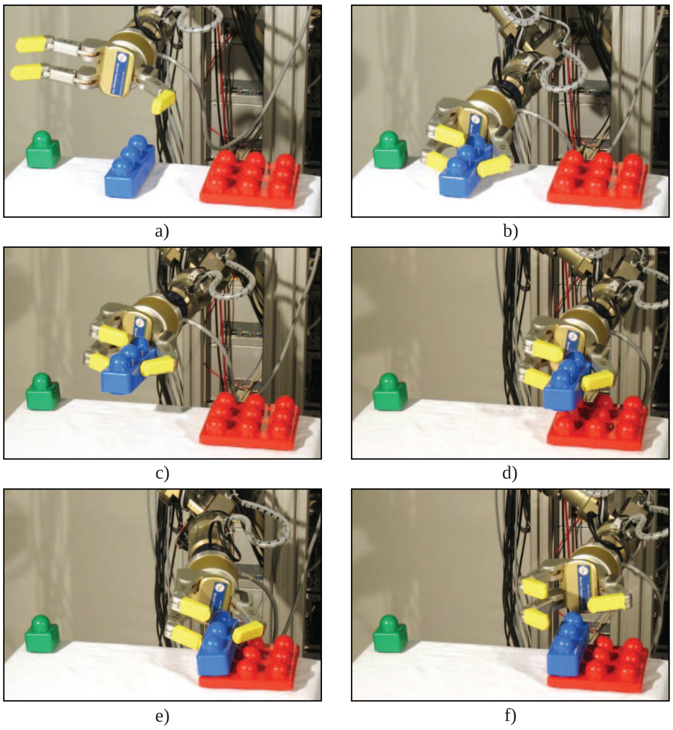

a) b) c) d) e) f)

Fig. 7. Experimental task: a) initial position, b) pick up toy brick at one location, c) move to target, d) align brick with target, e) join brick with fixed brick at target position, f) retract from target

remote environments. The successful completion of a complex experiment including locomotion of the teleoperator, navigation, and an assembly task using a robotic hand shows the versatility of the developed telepresence system. In the future experiments using two hands to address control issues related to closed kinematic chains as well as experiments using a bimanual mobile human system interface to improve the perception of locomotion will be conducted.

Acknowledgments

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