Bimanual Haptic Telepresent Control Applied to Disposal of Explosive Ordnances – Concepts and Experimental Validation –

Günther Schmidt, *IEEE LF* and Alexander Kron

Institute of Automatic Control Engineering, Interactive Systems and Control
Group, Technische Universität München, Germany
gs@tum.de, alexander.kron@bmw.de

Abstract: *This paper presents a novel approach for performing disposal of explosive ordnances by application of bimanual haptic telepresent control technology. For improved task execution the proposed system enables an operator to perceive multimodal feedback, especially detailed kinesthetic feedback, from a remote task environment. Details of a developed experimental setup, comprising a two-handed human system interface and a corresponding two-arm teleoperator, are reported. In particular a novel structure adapting architecture for control of the display and manipulator is introduced. The usability and effectiveness of the developed bimanual telepresence system are demonstrated by focusing execution of demining operations in a remote environment as a highly relevant task scenario.*

Keywords: *Bimanual haptic telepresent control, tele-demining*

I INTRODUCTION

To date disposal of explosive ordnances is still requiring human experts to directly interact with the hazardous task environment. Relevant application scenarios are for example related to law enforcement, counter-terrorism measures and demining or removal of duds. To reduce the need for experts to directly operate under such life-threatening conditions, application of telerobotic technology is experiencing a growing interest in recent years [1, 2]. Currently, experts interact via remote control with the explosive out of harm's way, often perceiving visual feedback only from a mobile teleoperator, as indicated in Fig. 1a. Typically, the mobile platform comprises a single-arm manipulator with a gripper as end-effector for accomplishment of simple manipulatory tasks, e.g. [3]. This kind of telerobotic system enables execution of preparatory operations, e.g. object exploration, checking of the detonator mechanism as well as gripping and moving an object into some sort of safety area for final removal. However, despite of a remarkable reduction of the expert's risk by these preparatory operations, the expert eventually has to interact with the still armed object with his/her own hands. Tasks like unscrewing and excluding the detonator from the explosive always require the use of two hands or in case of teleoperation, a *bimanual manipulator system*. It is well-known that in addition to vision onto the object under inspection, experts feel a need for improved sensitiveness through feedback of additional sensory modalities, especially *touch and force*, i.e. haptic feedback.

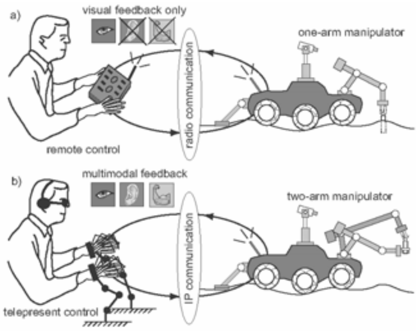

Figure 1
Disposal of Explosive Ordnances: (a) via state-of-the-art, (b) via novel telepresent control

Consequently, we propose the development of technologies to perform disposal of explosive ordnances by *telepresent control* as depicted in Fig. 1b. A corresponding telepresence system will enable an expert to perform necessary disposal operations from a control station located in a safe environment using in addition to visual some sort of haptic display for inputting control commands over an IP communication link to the remote teleoperator. The manipulator is equipped with multi-sensory components, for collecting *multimodal data* and sending it back to the expert, as well as with two manipulator arms for execution of more complex tasks. The focus of this paper is on the development and control of a bimanual haptic master-slave arm system, whereby the bimanual manipulator could become part of a disposal robot when mounted on a suitable mobile platform.

II BIMANUAL TELEPRESENCE SYSTEM

For purposes of advanced remote manipulation, a novel telepresence system is proposed, comprising detailed two-handed force feedback at wrist and fingers as well as a two-arm manipulator.

Two-handed Force Feedback:
The setup of the two-handed force feedback display rests upon a Wrist/Finger Haptic Display enabling combined force feedback perception at wrist and fingers [4] (see Fig. 2). The system comprises a non-portable high performance **De**sktop **Ki**nesthetic **Fe**edback **D**evice (DeKiFeD4) coupled with the commercial hand force exoskeleton CyberGrasp from Immersion Corp. (see Fig. 2a).

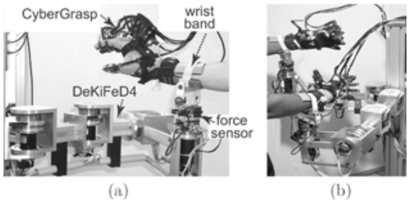

Figure 2
(a) Combined wrist and finger force feedback display, (b) two-handed force feedback display

The robotic arm enables proprioceptive inputs with 4 active[1] degree of freedoms (DoF) in the Cartesian space and perception of forces/torques for each DoF with up to 120N and 20Nm. The available force range is sufficient for providing a human operator (HO) with kinesthetic stimuli enabling perception of object contact, stiffness, friction, and weight. 6 DoF force/torque sensors are mounted behind the coupling with the operator's wrist.

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[1] 3 translations and 1 rotation

The haptic glove produces finger forces up to 10N for each finger. This type of finger force feedback proved to be adequate for perceiving fingertip to object contacts. Fig. 2a indicates, that the HO's forearms are fixed at the DeKiFeD4s behind the wrist by means of a strap. This type of coupling allows the HO to make use of all passive DoFs of wrist motion, thus ensuring intuitive and natural hand motion. The two-handed input device [4] is realized by duplicating the Wrist/Finger Haptic Display with mirrored joint configuration for left- and right-handed use (see Fig. 2b).

Bimanual Teleoperator:
Object manipulation in RE is achieved by means of a two-arm teleoperator (see Fig. 3). By duplicating both DeKiFeD4s and mounting two-jaw grippers as end-effectors, we designed a left- and right-sided **De**sktop **Ki**nesthetic **Te**leoperator (DeKiTop4), with respectively 4 active DoFs positioning the gripper.

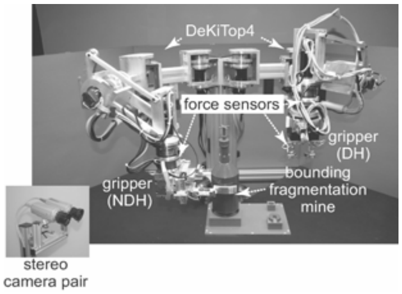

Figure 3
Bimanual Teleoperator with two-jaw grippers

Typically, bimanual coordinated tasks are accomplished by humans with asymmetric roles for both hands, referring to the well-known classification into a non-dominant (NDH) and dominant (DH) hand [5]. For that purpose, we designed a gripper with horizontally, the other with vertically arranged jaws. The first gripper is used for NDH's operation, such as maintaining an object in a stable position for manipulation by the DH, i.e. accomplishment of more dextrous and manipulatory actions. Both grippers are equipped with sensors measuring grasp forces. In addition, 6 DoF force/torque sensors are located between wrists and gripping devices. The gripper configurations ensure a sufficient workspace overlap.

Kinesthetic Control Architecture:
Development of kinesthetic telepresence systems requires to select appropriate algorithms for display (master) and manipulator (slave) control with the goals of robust stability and high fidelity kinesthetic feedback. In the literature several control architectures are proposed. A survey is given in [6]. The reported architectures are classified by the number of information channels used for data transfer between master and slave. Typically, force, pose or velocity information are transmitted.

In this work a bilateral control architecture extending the concept of *dual hybrid teleoperation* [7] is implemented for both left and right-sided kinesthetic master-slave subsystems (MSS). The idea underlying dual hybrid teleoperation is that for low environmental impedance[2] Z_e, indicating free motion, the master should act as a force source with position sensor, whereas the slave should behave as a position source

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[2] Z_e represents the relation between the force $F_e=F_{ss}$, the environment exerts on the manipulator, and its velocity $V_e=V_s$. Z_e is defined by the mechanical parameters mass m_e, damping b_e, and stiffness k_e, i.e. $Z_e(s) = F_e(s)/V_e(s) = m_e s^2+b_e s+k_e$.

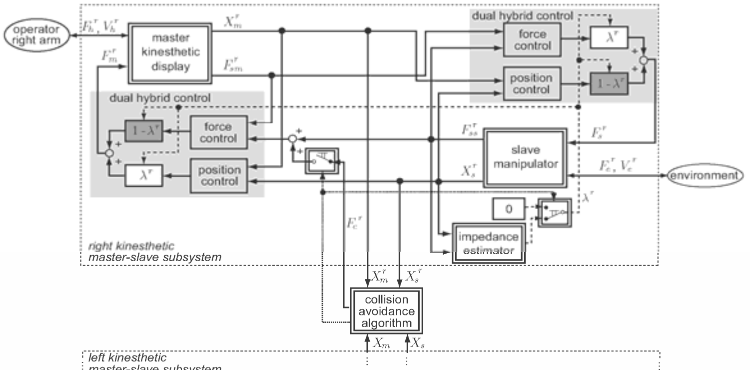

Figure 4

Bilateral control scheme of the kinesthetic master-slave subsystem for the right operator arm

with force sensor. If Z_e is high, indicating hard environmental contact, the master should act as a position source with force sensor, whereas the slave represents a force source exerting forces on the environment the operator is inputting at the master and sending back measured slave positions. The varying causalities are achieved by changing local control algorithms depending on an on-line environmental impedance estimator. Fig. 4 illustrates the control scheme with focus on the right kinesthetic MSS[3]. Master and slave local control algorithms add force and position control commands weighted by a normalized factor $\lambda \in [0,1]$, which differs according to the impedance estimator's output. Free motion ($Z_e \downarrow$) is indicated by a λ close to zero, leading to a force controlled master and a position controlled slave. A hard contact ($Z_e \uparrow$) results in $\lambda=1$, which corresponds to a position controlled master and a force controlled slave. The control algorithms are based on Cartesian explicit force control and state-space position control algorithms.

For a single Cartesian DoF the local control laws are described by

$$F_m = \lambda(K_{dm}K_{pm}(X_s - X_m) - K_{dm}sX_m) \quad (1)$$
$$+(1-\lambda)K_{fm}(\tilde{F}_{ss} - \tilde{F}_{sm})$$

$$F_s = (1-\lambda)(K_{ds}K_{ps}(X_m - X_s) - K_{ds}sX_s) \quad (2)$$
$$+\lambda K_{fs}(-\tilde{F}_{sm} + \tilde{F}_{ss})$$

with X_m, the display position, X_s, the slave position, F_m the display, and F_s the manipulator force generated by actuators, F_{sm} the measured force, which the display exerts on the operator, and F_{ss} the measured force, the environment exerts on the manipulator.

Assuming ideal communication[4] between display and manipulator ensures that an on-line estimated λ is simultaneously available at the operator and teleoperator site. Thus, a reliable on-line identification of λ turns out to be the key problem for achieving proper adaptation of the control architecture. For impedance estimation, a reduced 1st order impedance model is introduced, given by

$$\hat{Z}_e = \hat{b}_e + \hat{k}_e s \quad (3)$$

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[3] A system variable with a superior index 'r' or 'l' indicates its affiliation to the right or left MSS.

[4] In this work the communication latency is assumed <5 ms - typical for communication in local area networks - and insofar delay effects are neglected.

$\hat{b}_e$ and $\hat{k}_e$ are estimated on-line by a recursive least square method using the measured manipulator position X_s and its derivative V_s as input vector and the measured force F_{ss} at the manipulator as output. A *virtual*[5] impedance measure is defined by computing the absolute value of (Eq. 3) at the fixed frequency ω_u=20 rad/s, which is the upper bound of the frequency range of human kinesthetic perception [9].

$$\tilde{Z}_e = \left|\hat{Z}_e\right|\Big|_{\omega=\omega_u} = \sqrt{\hat{b}_e^{\,2} + \frac{\hat{k}_e^{\,2}}{\omega_u^{\,2}}} \qquad (4)$$

Experiments with the MSS are required to identify the maximum achievable $\tilde{Z}_{e,max}$ for contacts with typical high stiffness objects. With $\tilde{Z}_{e,max}$ known the required weighting factor λ is computed by

$$\lambda = \tilde{Z}_e \,/\, \tilde{Z}_{e.max} \qquad \in [0,1] \qquad (5)$$

A detailed stability and performance analysis of the adapting control architecture is given in [3]. Fig. 4 indicates, that a manipulator collision avoidance algorithm may override the control structure adaptation, presented in [3].

III APPLICATION SCENARIO

The proposed bimanual telepresence system has been applied to disposal of a remote bounding fragmentation mine of the type PROM-1 (see Fig. 5c). In cooperation with the Pioneer Training Establishment of the German Armed Forces in München, a mine prototype has been developed as depicted in Fig. 5b. It comprises the mine body and a screwable detonator, containing on-board force measurement for display of a virtual detonation and red LEDs set by contact forces >25N. Demining requires the following operating steps:

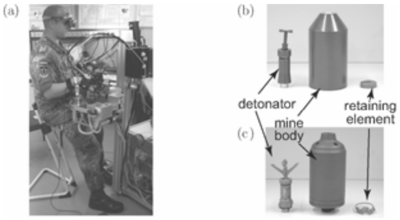

Figure 5
(a) demining expert operating with the telepresence system, assembly parts of prototype (b), of real PROM-1 (c)

First the mine is gripped by the NDH. The DH grasps the retaining element for saving the detonator succeedingly. Mounting of the retaining element is followed by unscrewing of the detonator from the mine body. Finally, the unscrewed detonator and the mine body are positioned into fixtures by peg-in-hole type operations.

IV EXPERIMENTAL RESULTS

The developed bimanual haptic telepresence system was checked for it's usability and performance for teleoperated demining in cooperation with experts from the German Armed Forces. As the participants were not accustomed to telepresence technology, a sufficient training period of about 25 min was allowed. 20 subjects (male, 25 to 40 years old) participated in the evaluation campaign. All participants were capable of interacting stably with the remote task scenario. Moreover, the subjects confirmed the experience of high fidelity kinesthetic perception performing free motion and hard contacts.

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[5] Given, that the actual frequency ω is not known in (Eq. 4) and that instead of ω the fixed frequency ω_u is assumed, this impedance measure is denoted as virtual.

Subjects stated, that the system allows accomplishment of hand motions, which are typical for direct demining operations.

While the task under consideration is performed by experts at a real physical mine within 60 sec, average task completion time of the subjects for teleoperated task execution were about 800 sec, i.e. about 13 times higher. Detailed force feedback at wrist and fingers results in strong operator immersion into the remote scenario. Gripping forces are required to feel contact with the object and for achieving a stable grasp. The unscrewing operation is improved by experiencing the torque between the screwed detonator and the mine body. Sensing of contact forces supports a successful insertion of the retaining element for saving the detonator as well as a proper accomplishment of peg-in-hole operations when placing the separated detonator and mine body.

Conclusions

This paper presented a novel bimanual haptic telepresence system with application to disposal of explosive ordnances. Details of the developed hardware setup and implemented control algorithms used are described. The specific application scenario under consideration has been tele-demining of a bounding fragmentation mine in a RE and its validation in an evaluation campaign with demining experts. The experts confirmed that the proposed haptic feedback technologies already enable realistic demining operations in RE. They recommended the proposed approach of bimanual haptic telepresence technology for an integration into future mobile telerobotic systems supporting deminers' work in the field.

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