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Kinesthetic Telepresent Control with Application to Defusing of Mines

- Concepts, Implementation and Evaluation

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Abstract: This paper presents a novel approach to support disposal of explosive ordnances by application of bimanual haptic telepresent control techniques. For improved task execution the proposed system enables an operator to perceive multimodal feedback, in particular detailed kinesthetic and tactile feedback, from a remote task environment. Details of the developed experimental setup, comprising stereo vision, a two-handed human system interface and a corresponding two-arm teleoperator, are presented. Furthermore a novel structure adapting scheme for control of the force feedback display and the manipulator arms is introduced. The usability and effectiveness of the bimanual telepresent control system are demonstrated by focusing and evaluating as a most relevant task scenario, the execution of defusing operations in a remote task environment.

1. INTRODUCTION

To date disposal or defusing of explosive ordnances is typically requiring a human expert to directly interact with the hazardous task environment. Relevant application scenarios are related to law enforcement operations, counter-terrorism measures and deactivation or removal of bombs and mines. To reduce the need for experts to directly operate under extremely life-threatening conditions, application of telerobotic technology is experiencing a growing interest in recent years, cf. (Hirose *et al.*, 1998), (Nguyen *et al.*, 2000), (Habib *et al.*, 2001). Currently, experts interact via remote control with the explosive out of harm's way by using visual feedback provided by a camera equipped mobile teleoperator, see Fig. 1a. The mobile platform comprises typically a single-arm manipulator with a gripper as end-effector for accomplishment of simple manipulatory tasks, cf. (Telerob, 2002). Such a type of telerobotic system enables execution of preparatory operations, e.g. object exploration, checking of the detonator mechanism as well as gripping and transferring an object into some sort of safety area for final removal. However, despite of a remarkable reduction of the expert's risk by those remote preparatory operations, the expert eventually needs to interact with the still armed object by use of his/her own hands. Tasks like unscrewing and excluding the detonator from an explosive always require the use of two hands or in case of teleoperation, a bimanual manipulator system. It is also well-documented that in addition to vision onto the object under inspection, experts feel a need for improved sensitiveness and immersiveness into the remote environment (RE) through inclusion of other sensory modalities, such as haptics, i.e. touch and force (kinesthetic).

As a consequence, this article proposes the development of techniques to perform handling of explosive ordnances by use of *telepresent control,* as depicted in Fig. 1b. A corresponding telepresence-based control system enables an expert operator to perform necessary operations from a control station located at a safe distance, using in addition to a visual display a more or less comprehensive haptic display system, cf. (Petzold, 2004).

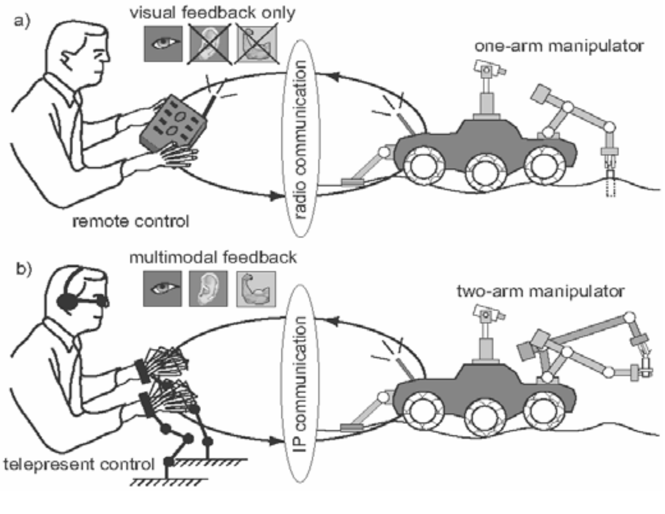
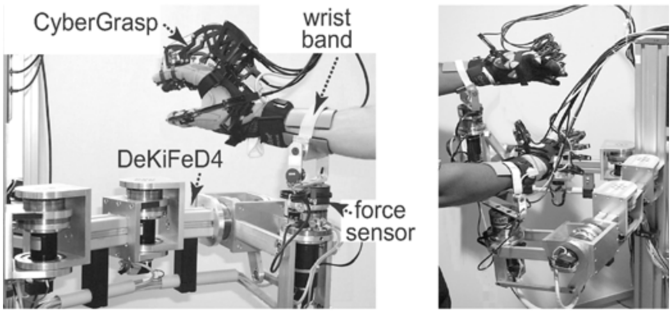


Fig. 1. Disposal of an explosive ordnance by (a) state-of-the-art remote control, (b) novel telepresent control

The human operator (HO) and the local haptic display are interconnected with the remote teleoperator by wireless communication. For purposes of implementation the mobile platform must be equipped with (i) multi-sensory components, for collecting and transmitting multimodal data at and to the local and remote site, and (ii) two manipulator arms with appropriate grippers for execution of more complex and delicate manipulation tasks. The focus of this paper is on the development and the control of a bimanual haptic master-slave arm system, whereby the bimanual manipulator approach is supposed to become part of a mobile disposal robot.



(a) (b)

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

2. BIMANUAL TELEPRESENCE SYSTEM

For purposes of advanced remote manipulation, a novel multimodal telepresence-based control system is presented, comprising stereo vision, detailed two-handed force and touch feedback at wrist and fingers as well as a two-arm manipulator.

2.1 Visual Feedback

Visual feedback rests upon a stereo image stream captured at the teleoperator site with a fixed stereo camera pair, see Fig. 3. Stereo images with 320x240 resolution are JPEG-compressed and transferred in packages to the operator site. Here, the stereo stream with 30 stereo frames/sec is unpacked, decompressed and interpolated to images with a 640x480 resolution. The stereo images are displayed to the HO by a standard head mounted display (HUD), see Fig. 7a. This type of passive stereo visualization allows visual perception of the RE and provides the HO a satisfactory impression of depth. In addition, the real video images are augmented by display of *virtual hints*, e.g. colored arrows, indicating dangerous manipulator situations as caused by upcoming telemanipulator collisions or workspace penetrations (Kron *et al.*, 2005b). Respective arrows are depicted within the images at the end-effectors or at individual telemanipulator joints. The virtual hints are generated by use of an algorithm that computes the perspective transformation of 3D world poses into image coordinates. Since the hints are displayed in both images for the left and right eye, they hardly disturb the stereoscopic view into the real remote scene.

2.2 Two-handed Force Feedback

The setup of the two-handed force feedback display, as shown in Fig. 2, rests upon a Wrist/Finger Haptic Display enabling combined force feedback perception at wrist and fingers (Kron, 2005a). The system comprises a non-portable high performance **D**esktop **Ki**nesthetic **F**eedback **D**evice (DeKiFeD4) coupled with the commercial hand force exoskeleton CyberGrasp from Immersion Corp, see Fig. 2a. The robotic arm enables proprioceptive inputs with 4 active degrees of freedom (DoF), i.e. 3 translations and 1 rotation, 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 the HO with kinesthetic stimuli enabling perception of object contact, stiffness, friction, and weight. 6 DoF force/torque sensors are located between the arms and the coupling with the operator's wrist.

The haptic glove has the capability to produce finger forces up to 10N for each finger. This type of finger force feedback proves to be adequate for perceiving fingertip to object contacts. Fig. 2a indicates, how the HO's forearms are attached to the DeKiFeD4s behind the wrist by means of a wrist band. Such a type of coupling allows the HO to make use of all passive DoFs of wrist motion, thus ensuring intuitive and natural hand motions. The two-handed input device (Kron, 2005a) is implemented by duplicating the Wrist/Finger Haptic Display with mirrored joint configuration for left- and right-handed use, see Fig. 2b.

2.3 Bimanual Teleoperator

Object manipulation in the RE is achieved by means of a two-arm teleoperator, see Fig. 3. By duplicating both DeKiFeD4s and adding two-jaw grippers as end-effectors, we designed a left- and right-sided **D**esktop **Ki**nesthetic **Te**leoperator (DeKiTop4) with 4 active DoFs each for positioning of the two-jaw grippers in the remote workspace.

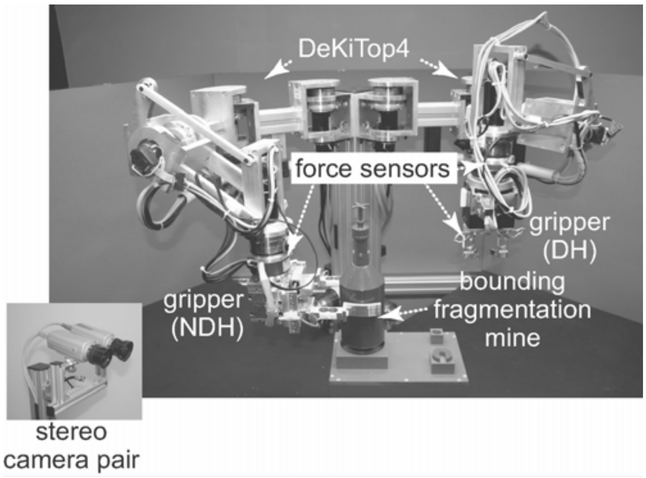


Fig. 3. Bimanual teleoperator with two-jaw grippers and a stereo camera pair fixed in the remote environment

Bimanual coordinated tasks are typically accomplished by humans with asymmetric roles for both hands, referring to the well-known classification into a non-dominant (NDH) and dominant (DH) hand, cf. (Guiard *et al.*, 1987). Based on those findings, one gripper was designed with horizontally and the other with vertically oriented jaws. The horizontal gripper supports NDH operations, such as maintaining an object in a stable position for manipulation by the DH, i.e. for purposes of accomplishing more dextrous and manipulatory actions. Both grippers are equipped with sensors measuring grasp forces. In addition, 6 DoF force/torque sensors are located between the wrists and gripping devices. The gripper configurations ensure a sufficient workspace overlap.

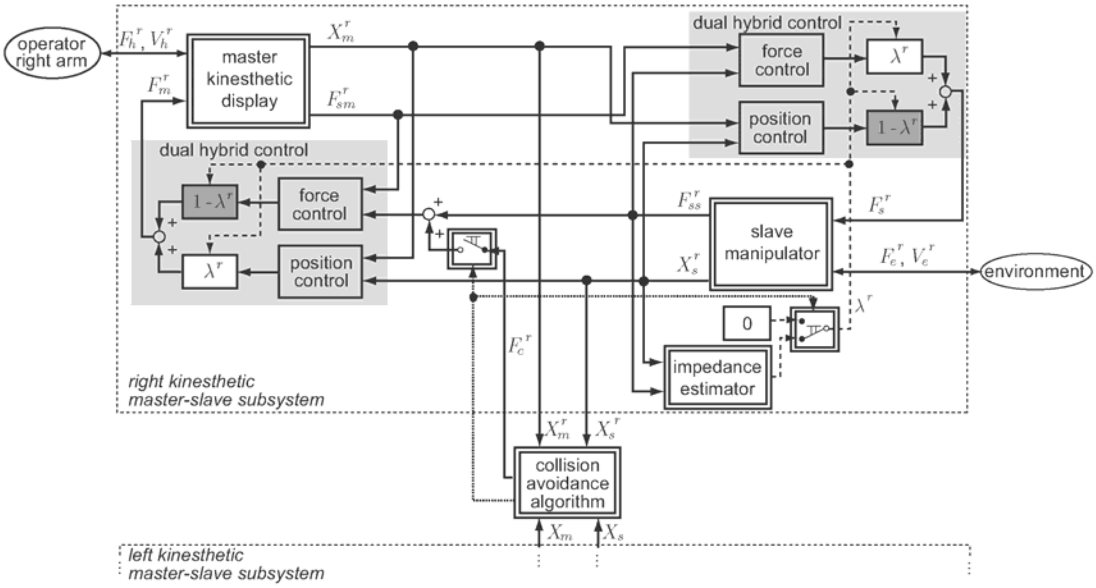


Fig. 4. Bilateral structure adapting control scheme of the kinesthetic master-slave subsystem, with details shown for the right operator arm

2.4 Control Architecture

Development of a kinesthetic telepresence systems requires selection of appropriate control algorithms for display (master) and manipulator (slave) with the objectives of robust stability and high-fidelity force feedback. In the literature several control architectures were proposed for this purpose. A survey is given in (Sulcudean, 1998). The reported architectures are classified by the number of information channels adopted for data transfer between master and slave. Typically, force, pose or velocity information is transmitted.

In this work a bilateral control architecture extending the concept of *dual hybrid teleoperation* (Reboulet *et al.*, 1995), (Kron *et al.,* 2006) is implemented for both the left- and right-sided kinesthetic master-slave subsystems (MSS).

The basic idea underlying dual hybrid teleoperation is that low absolute values of environmental impedance Z_e indicate free motion. In this case the master should act as a force source with position sensor, whereas the slave should behave as a position source with force sensor. On the other hand, high Z_e values indicate hard environmental contact. In this case the master should act as a position source with force sensor, while the slave represents a force source, exerting forces on the environment inputted by the HO at the master, and feeding back measured slave positions.

Here Z_e represents the relationship between the force $F_e=F_{ss}$, the environment exerts on the manipulator, and the manipulator velocity $V_e=V_s$. In the linear case Z_e is defined by an impedance function with the mechanical parameters mass m_e, damping b_e, and stiffness k_e, i.e.

$$Z_e(s) = F_e(s)/V_e(s) = m_e\, s + b_e + k_e/s \tag{1}$$

The varying causalities of master and slave arm operations are taken into account by changing the structure of local control algorithms depending on information from an on-line *environmental impedance estimator*. Fig. 4 illustrates the proposed control scheme with focus on the right kinesthetic MSS, where system variables with a superior index 'r' or 'l' indicate affiliation to the right or left subsystem. Local control algorithms of the master and slave arm sum up force and position control commands weighted by a normalized factor $\lambda\in[0,1]$, with λ changing according to the impedance estimator's output. Free motion (Z_e: low) is indicated by a λ-value close to zero, leading to a force controlled master and a position controlled slave. A hard contact (Z_e: high) 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.

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

$$\begin{aligned} F_m &= \lambda(K_{dm}K_{pm}(X_s - X_m) - K_{dm}sX_m) \\ &\quad + (1-\lambda)K_{fm}(\widetilde{F}_{ss} - \widetilde{F}_{sm}) \end{aligned} \tag{2}$$

$$\begin{aligned} F_s &= (1-\lambda)(K_{ds}K_{ps}(X_m - X_s) - K_{ds}sX_s) \\ &\quad + \lambda K_{fs}(-\widetilde{F}_{sm} + \widetilde{F}_{ss}) \end{aligned} \tag{3}$$

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

If communication latency between display and manipulator is < 5 msec (which is the case for communication in local area networks and over short distances) delay effects can be neglected in control analysis. Under this assumption on-line estimated λ-values become simultaneously available for further processing both at the operator and teleoperator site. Thus, reliable on-line identification of λ remains to be a key task for achieving proper adaptation of the control structure.

For impedance estimation a reduced, i.e. 1st order, impedance model is introduced, given by

$$\hat{Z}_e = \hat{b}_e + \hat{k}_e / s \quad . \tag{4}$$

$\hat{b}_e$ and $\hat{k}_e$ denote damping and stiffness values estimated on-line by a recursive least squares method, utilizing 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 impedance' measure $\tilde{Z}_e$ is defined by computing the absolute value of (4) at the fixed frequency $\omega=\omega_u=20$ rad/s, denoting the upper bound of the frequency range of human kinesthetic perception, cf. (Lawrence *et al.*, 1994).

$$\tilde{Z}_e = \left|\hat{Z}_e\right\|_{\omega=\omega_u} = \sqrt{\hat{b}_e^{\,2} + \frac{\hat{k}_e^{\,2}}{\omega_u^{\,2}}} \quad . \tag{5}$$

Remark: Since the actual frequency ω is not known, it is replaced here by the fixed frequency ω_u. For this reason the resulting impedance measure is denoted as 'virtual'.

Calibration experiments with the MSS need to be performed in advance for identification of the maximum detectable $\tilde{Z}_{e,\max}$ for the case of contacts with high stiffness objects. With $\tilde{Z}_{e,\max}$ known, the required weighting factor λ is eventually computed by

$$\lambda = \tilde{Z}_e / \tilde{Z}_{e.\max} \qquad \in [0,1] \quad . \tag{6}$$

A detailed analysis of stability and performance of the adapting control scheme is presented in (Kron, 2005a). As indicated in Fig. 4, the basic control scheme is augmented by a manipulator *collision avoidance algorithm* overriding control structure adaptation, if necessary (Kron, 2005a).

3. APPLICATION SCENARIOS

For evaluation purposes the proposed bimanual telepresence control approach has been applied to various application scenarios. In the following we will focus two scenarios.

3.1 Opening and Closing of a Wide-necked Plastic Flask

Besides its practical relevance this scenario was chosen as a benchmark test for studying basic HO performance in bimanual telemanipulation *with* and *without force feedback*. In contrast to the haptic interface presented in Fig. 2, a strapped-down version was employed here. The HO's hands operated the two-arm force feedback display by use of simple handles attached to the force/torque sensors, see Fig. 5a.

For the task under consideration the required manipulation procedure is as follows: A plastic flask in the RE is gripped and moved with the NDH from its initial location on a table into free space. Next the flask cap is gripped and unscrewed by the DH. The cap is placed onto the location defined by the flask's initial position, see Fig 5b. After this the cap is once again picked by the DH, placed on top of the flask and screwed down. As a last step the flask is placed by the NDH back into its start location.

The two-handed manipulation procedure was performed both *without* and *with* force feedback .

As performance indicators (PI) for the remote operation we considered among others *task completion time T,* a measure of *average contact forces* I_c, and a measure of the *length of the manipulation trajectory* I_m

$$I_c = \int_0^T (|f_c^x| + |f_c^y| + |f_c^z|)\, dt / T_c \tag{7}$$

$$I_m = \int_0^T \sqrt{\Delta x_{m,x}^2 + \Delta x_{m,y}^2 + \Delta x_{m,z}^2}\, dt \tag{8}$$

with $f_c = [f_c^x, f_c^y, f_c^z]$ the contact forces between endeffector and environment, and $T_c < T$ the sum of time intervals with non-zero forces. $\Delta x_m = [\Delta x_{m,x}, \Delta x_{m,y}, \Delta x_{m,z}]$ denotes the incremental translatory Cartesioan motions during task execution... In Table 1 superior indices 'R' and 'L' indicate measures or PIs for the right and left hand, respectively.

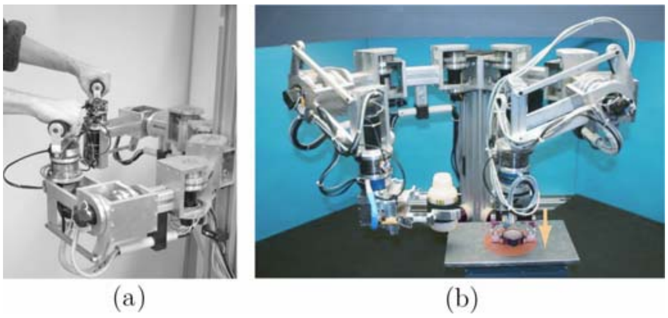

(a) (b)

Fig. 5. Benchmark scenario: (a) strapped-down hand-arm kinesthetic display, (b) NDH holds flask and DH places unscrewed cap onto the table

3.2 Deactivation of a Mine

A more delicate and more complex telemanipulation task is given by defusing of a remote bounding fragmentation mine of type PROM-1, see Fig. 7c. For evaluation purposes a mine mock-up, as depicted in Fig. 7b, has been developed in close cooperation with experts from the Pioneer Training Establishment of the German Armed Forces in Munich. The prototype device comprises the mine body and a removable detonator. The latter is equipped with on-board force measurement for indication of a virtual detonation and red LEDs are triggered in case of contact forces >25N.

Table 1. Sample Performance Values for Scenario 4.1

PI	T(sec)	I_c^R	I_c^L	I_m^R	I_m^L
manually	14	-	-	-	-
without force	146.14	4.13	7.2	2.65	1.47
with force	**103.42**	**2.98**	**5.86**	**2.22**	**1.19**

For the object under consideration the standard defusing procedure is as follows (compare also Fig. 6): First the mine is gripped by the NDH. Next, the DH grasps the retaining element for saving the detonator. Mounting of the retaining element is followed by unscrewing of the detonator from the mine body. In a last step, the unscrewed detonator and the mine body are positioned into fixtures by peg-in-hole type operations.

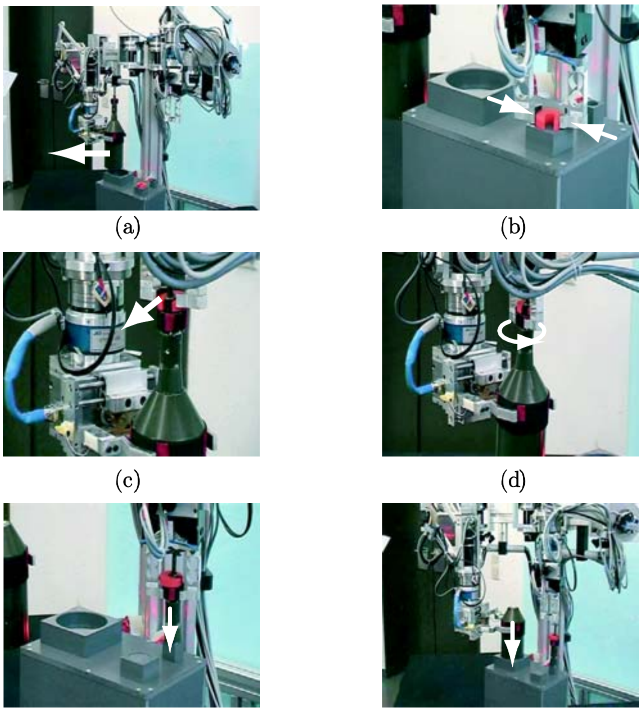

(a) (b) (c) (d) (e) (f)

Fig. 6 Disposal of a bounding fragmentation mine: (a) grip mine, (b) grip retaining element, (c) save detonator, (d) unscrew detonator, (e) place detonator, and place m

4. DISCUSSION

4.1 Flask Manipulations

Table 1 shows that average task completion time T (8 subjects involved) for telemanipulation *without* force feedback was 146 sec and *with* feedback 103 sec. This means that force feedback leads to a considerable improvement in performance. On the other hand, both numbers need to be compared to an average completion time of about 10 sec for the case of *direct manual execution* of the same manipulation task. A comparison indicates that both completion times turn out to be about 15 times or 10 times longer than in the manual case.

Table 2. Degree of Limb Activation for Scenario 4.2

Contact forces	manually		teleoperated	
distribution [%] at	$\bar{x}$	σ_x	$\bar{x}$	σ_x
shoulder	24.3	19.3	18.3	19.6
Elbow	21.3	16.1	21.3	16.3
Wrist	23.8	15.8	25.8	13.4
Finger	30.8	17.6	34.8	19.5
χ^2-test	0.54		(0.760)	
Grasp forces	manually		teleoperated	
distribution [%] at	$\bar{x}$	σ_x	$\bar{x}$	σ_x
fingertip	46.8	15.0	47.5	21.7
Phalanx	31.5	16.1	36.0	14.6
Palm	8.5	8.8	6.9	8.8
Wrist	13.3	12.5	9.6	8.1
χ^2-test	0.49		(0.785)	

In the literature, telemanipulation systems are assessed as to provide 'satisfactory' performance, if teleoperated task execution is <10 times longer than an equivalent manual operation in a real physical environment (Hamel, 2003). On the other hand, a factor > 100 indicates an extremely 'low' performance. In addition, Table 1 shows that with force feedback considerably smaller average contact forces and lengths of the manipulation trajectories are achieved for both hands..

4.2 Mine Defusion

The full-scale bimanual haptic telepresence system, as discussed earlier, was checked for its usability and performance in teleoperated deactivation in cooperation with experts from the German Armed Forces. As the participants were not accustomed to the use of telepresence control technology, each subject was allowed a sufficient training period of about 25 min. 20 subjects (male, 25 to 40 years old) participated in the evaluation campaign.

While the task under consideration was performed by experts at a real physical mine within 60 sec, *novice operators* needed about 800 sec and *trained experts* <400 sec for teleoperated task execution, i.e. a 14:1 or 7:1 ratio. Other evaluation results can be summarized as follows: All subjects were capable of interacting stably with objects in the remote task scenario. Moreover, the majority of subjects confirmed the experience of satisfactory kinesthetic perception when performing both, free motion and hard contacts. This result is to a great extent due to the efficacy of the proposed adaptive hybrid control scheme. Furthermore, subjects stated, that the system allows accomplishment of hand motions, which are similar to those applied in direct manual defusing operations.

Table 2 presents data from interviews with the subjects on an assessment of mean haptic sensations with respect to contact and grasp forces. Participants of the test were asked to assign appropriate percentage values of perceived limb activation during manual and teleoperated task execution.

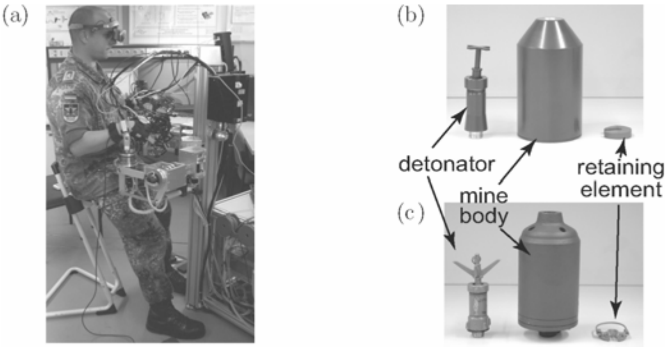


Fig. 7. (a) Defusing expert operating with the telepresence control system in the remote environment, (b) components of the mine mock-up and (c) of real PROM-1

A chi-square (χ^2) test revealed that participants accomplishing the teleoperation task did not differ in a statistically significant degree from the manual benchmark test. *Remark:* The chi-square test is a statistical hypothesis test comprising the following items of analysis: quality of fit, test for homogeneity, and test of independence.

Augmentation of visual feedback by detailed force feedback at wrist and fingers results in strong operator immersion into the remote scenario. Rendering of gripping forces allows the operator to feel contact with the object and to achieve a stable grasp. The unscrewing operation is improved by experiencing the torque between the screwed in detonator and the mine body. Sensing and rendering 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. Two video clips (http://) demonstrate both, expert-controlled manual and telepresent defusing operations.

5. CONCLUSIONS

This paper presented the basic concept of a novel bimanual haptic telepresence system with application to disposal of explosives. Details of the developed hardware setup, the developed control architecture and the adaptive control algorithms are presented. The specific application scenarios under consideration have been opening/closing of a flask and remote deactivation of a bounding fragmentation mine in a remote site about 500 m apart. The latter was validated in an evaluation campaign with defusing experts. The experts confirmed that the introduced visual and haptic feedback control technologies together with the two-arm manipulator system enable satisfactory realistic deactivation operations in a remote environment. They recommended the proposed approach of bimanual haptic telepresence control for integration into a future mobile telerobotic system, thus enhancing deminers' work performance in the field.

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