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How to Design a Haptic Telepresence System for the Disposal of Explosive Ordnances

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Abstract

At the Technische Universität München (TUM) an experimental telepresence system is developed enabling the disposal of explosive ordnances (EOD) without any risk for the user. Most current EOD-systems enabling user control of remote environments are single-armed configurations and display only visual feedback. In contrast to this, the presented telepresence system constitutes of an intuitive bimanual interface and displays visual as well as force feedback to the user. In order to generate guiding design principles, two operator consoles were set up and evaluated experimentally.

1 Introduction

The threatening of blasting compositions to harm military and civil population is more present these days than ever. To dispose explosive ordnances, most of the time direct human interaction is required inevitably. Though robots are available for basic operations during the explosive ordnances disposal (EOD), they do not suffice for all required actions [3]. This is mainly due to the poor interaction between the human operator (HO) and the robot. Usually, the operator controls the robot by supervising the robot's actions via a monitor screen remotely (see Fig. 1). As the monitor screen does not provide any depth cues, it is very difficult to determine the exact spatial positions of remote objects as well as of the robot end-effector. Besides, current control panels do not provide an intuitive interface. Smooth movements of the manipulator afford a lot of training and even expert users are not able to accomplish all the tasks needed for an EOD because of the following reasons: First, most manipulators are designed to be single-armed configurations. As almost all human interactions are two-handed they cannot be mapped onto a single manipulator in an optimal manner. Second, present systems usually do not display force feedback to the HO which in consequence diminishes a sensitive interaction in the remote environment. Especially for visually hidden operating areas this turns out to be a major drawback. To improve current EOD-systems, a more sophisticated bimanual interaction, experiencing haptic (*force* and *touch*) feedback, seems to be necessary [5]. Therefore, telepresence technology is highly suggestive for developing EOD-systems [1, 3].

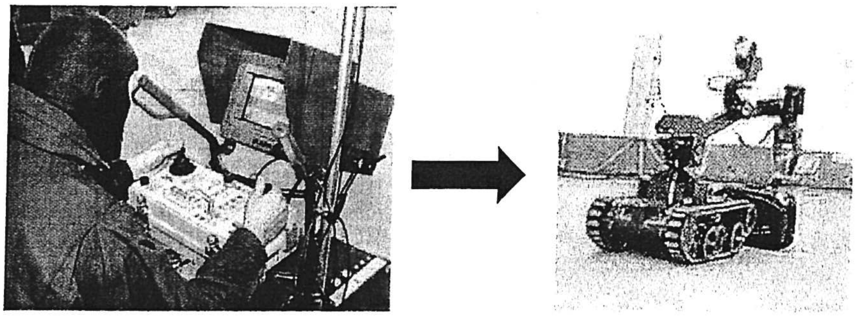

Figure 1: EOD with the commercially available single-armed TeleRob vehicle [7].

Telepresence is characterized by a high-fidelity human-system interface which enables the HO to feel '*present*' in a remote environment. To guarantee familiar and intuitive manipulations, force feedback devices play a major role for the design of such an interface. As the human hand is a very complex organ, the devices vary extremely in size, shape, and function. Some devices track finger motions and display grasping forces to the user (e.g. CyberGrasp, from Immersion, Corp. [2]). Other devices present contact forces or the weight of objects (e.g. PHANToM-Series from Sensable Technologies [6]).

At the TUM two telepresence EOD-systems for the disposal of a remote bounding fragmentation mine are developed (Section 2). In order to gain a deeper insight in how to design a haptic telepresence EOD-system, both setups were evaluated experimentally (Section 3, 4).

2 Telepresence Setup

2.1 Teleoperator

The teleoperator consists of two manipulator arms each providing 4 degrees of freedom (DoF) (3 translational and 1 rotational) in motion [3, 4]. For the manipulation task the end-effectors are equipped with two-jaw grippers; whereas one is arranged vertically for task execution of the dominant hand, the other one is arranged horizontally accomplishing the non-dominant hand's operations (see Fig. 2). The shared workspace of both arms is cube shaped with 60 x 20 x 30 cm³. The maximum gripper opening is 9 cm. Both arms are equipped with force/torque sensors that measure contact forces as well as the gripping forces while picking up and holding objects.

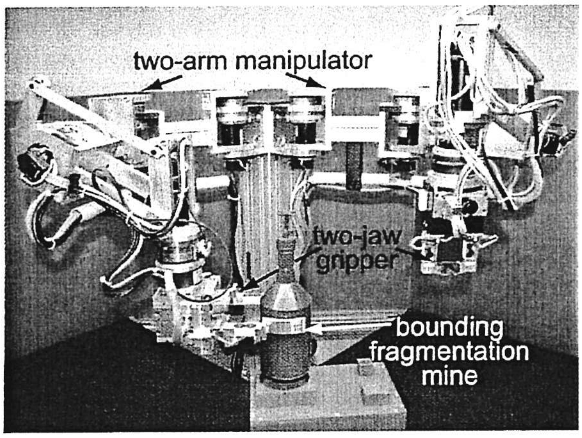

Figure 2: Bimanual teleoperator system.

2.2 Operator Side

For the operator side two different setups are realized: setup *A* (see Fig. 3) resembles to the manipulator kinematically and provides 4 DoF of motion and active force feedback by the same SCARA configuration as the teleoperator [4]. The grippers of the telemanipulator are replaced by clamps by which the wrists of both arms are linked to the haptic display. Thus, the operator perceives appearing contact forces at his/her wrist. A force/torque sensor which is integrated below the clamps enables the implementation of a dual hybrid control architecture [4] displaying teleoperator forces one-to-one. For the grasping procedure a CyberGrasp exoskeleton [2] for each hand is applied so that the user can perceive gripping forces. Consequently, the overall force transmission is done in a parallel manner by a combined finger-wrist display.

For setup *B* (see Fig. 3) two PHANToMs (Desktop and 1.5 / 6DoF) are used as input devices enhanced by two-finger gripping masters so that the operator can perform grasping procedures. As PHANToM devices do not provide integrated force measurement, a force-pose control architecture is implemented to display the weight of objects as well as the occurring contact and gripping forces. In order to display hard environmental contacts, the PHANToM devices are made compliant by local impedance control [3]. Despite of the adjusted manipulator compliance, the achieved force capability is still less than the magnitude of the measured contact forces. Therefore, the displayed forces are scaled appropriately and in consequence the maximum forces are lower compared to setup *A*. Force transmission occurrs exclusively at the fingertips. As the PHANToMs are desktop devices, the operator performs the teleoperation sitting in front of the system console.

In order to ensure natural motions, users are encouraged to reconfigure their workspace during the teleoperation: By switching a pedal the communication between display and teleoperator is disconnected and the input devices can be repositioned; a succeeding switch reconnects the user and the teleoperation continues. During this operating mode the telemanipulator might reach its limits of the workspace. Therefore, manipulator motions coming close to constraints in joint space are augmented by mapping virtual arrows into real stereo video images. In addition, an user is supported by augmented force feedback pushing him/her back into the workspace smoothly [3]. The same kind of augmentation is applied to avoid any collision of both manipulator arms.

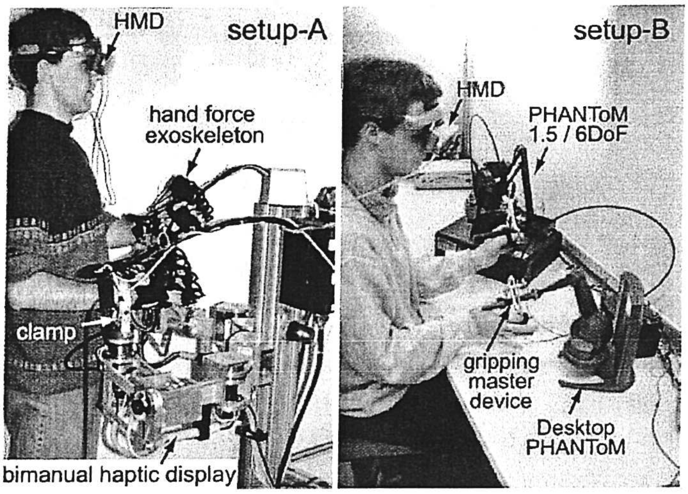

Figure 3: Operator side for setup A and for setup B.

Instead of a conventional visualisation by video-streaming, a stereoscopic view is implemented in both setups. The scene is recorded by a stereo camera setup with fixed view position and focus. On operator side the stereo images are displayed by means of a Head Mounted Display (HMD). The three-dimensional appearance by stereo-view ensures a reliable depth estimation of the scene.

3 Experimental Evaluation

It is obvious that both systems differ in more than one dimension. Though both setups are able to display contact forces as well as gripping forces, they vary at least in three features: Setup *A* corresponds better to the kinematical configuration of the teleoperator and distinguishes by providing higher force feedback, whereas setup *B* is designed without a tight system linkage and therefore enables a more natural activation of the limbs. As these variations could not be held constant or controlled during the experiment much emphasis was put on a structured qualitative interview with which user requirements were explored thoroughly. The experimental evaluation was guided by the following hypotheses:

H1 Higher force feedback will reduce the applied contact forces in the remote environment and will decrease the distance error of the gripper when grasping objects. In consequence users who prefer setup *A* will experience this system to be more transparent and sensitive for the task at hand (*amount of haptic feedback*).

H2 By a tight system linkage a natural presentation of force feedback is diminished. In consequence users who prefer system *B* will experience that interface to be more realistic and classify those interactions to be more sensitive (*presentation of haptic feedback*).

H3 The kinematical correspondence of teleoperator and operator is less important than the amount or the presentation of the haptic feedback. For this reason the commanded trajectories will not differ and both setups will reveal the same degree of motion efficiency.

H4 A haptic augmentation of occurring constraints in the workspace will be perceived as useful and will not increase the operator's mental load.

3.1 Experimental Procedure

The disposal of a fragmentation mine of the type PROM (see Fig. 4) served as experimental scenario. The task required the following operations: First, the mine had to be gripped by the non-dominant hand and a retaining pin had to be picked up by the dominant hand. Next, the retaining pin had to be put on the detonator so that the mine was covered and the detonator could be unscrewed without any risk. Finally, both the detonator and the corpus of the mine were to be stored separately. The whole experimental procedure requires bimanual activity: While the non-dominant hand held and stabilized the gripped object, the dominant hand performed all sensitive procedures. According to the participants unscrewing the detonator was judged to be the most demanding operation followed by inserting the retaining pin; correspondingly longer completion times were recorded for these two subtasks.

Mainly, experienced EOD-experts from the German Armed Forces were recruited as participants. As the participants were not accustomed to telepresence technology, a sufficient training period was provided. The experiment was conducted as a within-subject design, so that every of the 20 participants performed the defusing task with both setups; serial and positioning effects were avoided by a balanced design.

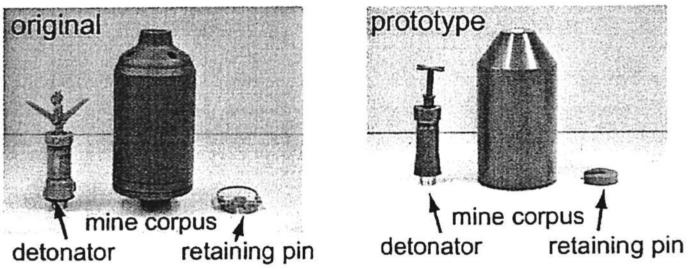

Figure 4: Assembly parts of a fragmentation mine of the type PROM served as experimental scenario - original (left) and experimental reproduction (right).

3.2 Experimental Results

When asking the participants to decide for one setup two-thirds (67%) of the users chose setup *A* whereas one third (33%) preferred to work with setup *B*. The subjective choice could be backed up by objective criteria as the participants required less reconfiguration of the workspace when teleoperating with their preferred system. As supposed, both groups accounted for their decision to be more sensitive for the task at hand. While according to the first group this was due to the displayed gripping and contact forces, the second group appreciated the available gripping masters and the way how input movements where performed (see Fig. 5).

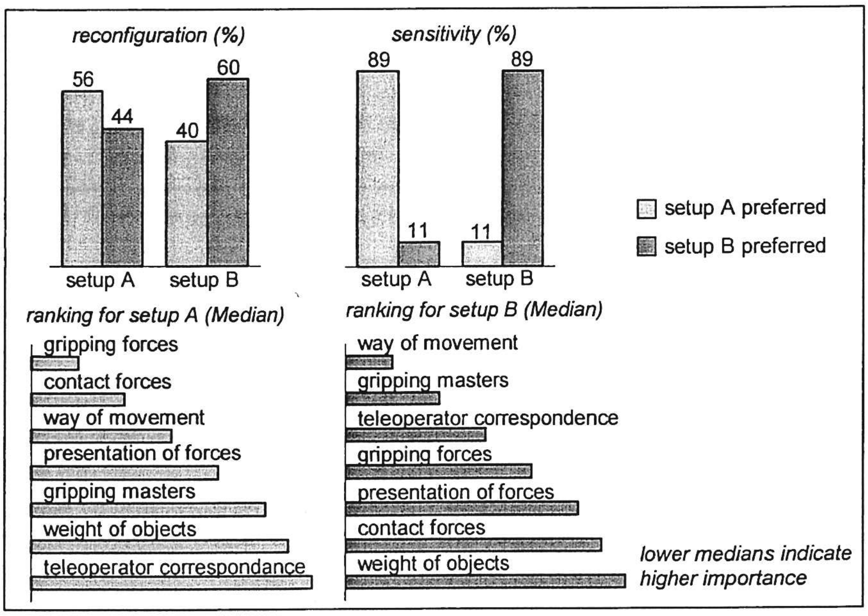

Figure 5: Participants reconfigured the dominant workspace less often when working with the setup *that they preferred, and that they judged to be more sensitive. While for system A the appearing forces were regarded to be important, for system B the kind how movements were executed was preferred.*

H1: In order to evaluate the objective value of higher displayed contact and gripping forces, both systems were compared according to the applied contact forces in the remote environment. Besides, the occurring error between gripper distance input at the operator side and the measured distance at the end-effectors was assessed (see Tab. 1). The assumption that contact forces which are displayed one-to-one to the user would reduce the applied contact forces in the remote environment was supported by a t-test. Furthermore, the percentage distance error, both for the non-dominant and the dominant hand, turned out to be significantly lower when working with system *A*. As a lower distance error indicates that the gripped object was felt more precisely, it is comprehensible when two-thirds of the participants classified system *A* to be more sensitive.

	mean		*standard error*		*t-test (sign. level)*
	A	*B*	*A*	*B*	
non-dominant contact forces [N]	6.0436	6.7716	0.1136	0.5367	1.327 (0.196)
dominant contact forces [N]	2.7388	4.2984	0.0974	0.2002	7.004 (0.001)**
non-dominant distance error [%]	34.80	84.36	3.52	3.79	9.581 (0.001)**
dominant distance error [%]	39.44	67.96	3.51	3.67	5.614 (0.001)**

Table 1: Comparison of appearing contact forces and gripping error for system A and B; highly significant results are marked by asterisks.

H2: Whether the activation of the limbs is natural or not can only be judged in comparison with an identical direct interaction. For this reason further 20 participants were recruited and asked to perform the defusion task in a real physical environment. The manual task was executed twice whereby the participants interacted once similar to setup *A* and once similar to setup *B*. In both conditions the participants were instructed to concentrate on their haptic sensation so that they would be able to assign the appropriate percentage values to the demanded limbs (see Tab. 2). When the participants were interviewed after the teleoperation they were also asked to express the perceived activation by percentages. As setup *A* provides a less natural stimulation, it is likely to expect that the gathered percentage contribution will differ from the manual benchmark data set whereas there would be no difference for the percentage contribution of setup *B*.

Actually, a chi-square test revealed that the participants favouring setup *A* did not differ from the manual benchmark data set, neither for setup *A* nor for setup *B* (I, III). In contrast to this, the participants preferring setup *B* differed in both teleoperation settings from the manual benchmark data set (II, IV). Thus the participants favouring setup *A* seemed to be more robust towards the perception of haptic feedback: they were not aware of the altered presentation of haptic feedback displaying interaction forces in a parallel manner at wrist and finger and tended to fuse sensed force feedback into realistic perceptions. In contrast, the participants favouring setup *B* recognized a different haptic stimulation in setup *A*. Though their recordings for setup *B* also differed from the manual benchmark data set, they demonstrated sensation of the higher stimulation of the fingertips that has been especially characteristic for this setup. In consequence the participants who preferred setup *B* turned out to be particularly sensitive towards the presentation of force feedback at the fingertip performing precision grasps and for this reason it is comprehensible that they decided for setup *B*.

Where did you sense contact forces in…		*benchmark (%)*	*teleoperation (%)*			
				A preferred		*B preferred*
setup A:	fingertip	46.75		46.39		38.89
	phalanx	31.50		34.17		46.67
	palm	8.50		8.33		4.78
	wrist	13.25		11.11		9.66
chi-square-test			*I)*	0.58 (0.90)	*II)*	11.23 (0.01)*
setup B:	fingertip	50.56		38.06		53.33
	phalanx	30.22		41.67		36.67
	palm	6.11		6.10		0.56
	wrist	13.11		14.17		9.44
chi-square-test			*III)*	7.51 (0.06)	*IV)*	27.55 (0.01)*

Table 2: Comparison of a manual benchmark data set with the two teleoperation settings according to the activation of the limbs.

H3: For gaining a robust mental model of the telepresence system it might be favourable when the operator console corresponds to the kinematical configuration of the telemanipulator. To assess the motion efficiency both setups were compared in terms of their telemanipulator's trajectories (see Tab. 3). As assumed, in average a t-test revealed no significant difference between both setups. Solely, the motor demanding unscrewing operation profited by a similar kinematical configuration and was performed more efficiently when working with setup *A*. In consequence, the hypothesis has to be specified: Whereas a kinematical correspondence does not seem to be relevant in general, it becomes more important when the task difficulty increases and when rotational movements are demanded. The participants themselves ranked the kinematical correspondence to be rather unimportant (see Fig. 5).

manipulator trajectory [m]	*Mean*		*standard error*		*t-test*
	setup A	*setup B*	*setup A*	*setup B*	
1) gripping mine	0.0055	0.0229	0.0053	0.0117	1.356 (0.187)
2) gripping safety pin	0.6553	0.5364	0.0457	0.0546	-1.670 (0.103)
3) inserting saftey pin	1.2275	1.4756	0.2134	0.3335	0.627 (0.535)
4) unscrewing detonator	2.0896	5.7882	0.1804	0.5253	6.659 (0.001)**
5) storing mine	0.1333	0.1519	0.0281	0.0294	0.459 (0.649)
6) storing detonator	0.6663	0.7711	0.0621	0.0872	0.979 (0.335)

Table 3: Comparison of setup A and setup B in terms of motion efficiency for the dominant input.

H4: All participants classified the reconfiguration of the workspace to be helpful. Besides, the majority of the users (81%) appreciated the haptic augmentation of occurring constraints of the teleoperator and solely a minor part (19%) classified the force display to be an additional cognitive burden. Likewise, two-thirds (67%) of the participants stated that they made use of the forces provided additionally, although it has to be mentioned that one third (33%) drew the conclusion that they could not interpret the augmentation intentionally. Their interpretation difficulty is also mirrored in the recorded data as these participants afforded slightly more reconfiguration procedures compared to the others. When taking a closer look at the input behaviour, these users also tended to apply higher contact forces with the telemanipulators at the remote environment and for this reason seemed to be less sensitive towards haptic feedback (contingency coefficient: 0.71). The augmented force display might also be less useful when working with setup *B* as here higher contact forces were applied, too. In addition, due to the support with a lower amount of haptic feedback by setup B in comparison to setup A, participants demonstrated less sensitiveness for the augmented force feedback.

4 Conclusion

Two haptic telepresence systems were compared in terms of their usability for EOD whereby especially setup *A* was accepted by expert users. In order to state the reasons for the acceptance more generally, the following design principles could be derived: (A) Though being favourable it is not essentially necessary that force feedback activates the limbs in the same way a direct manipulation does. The majority of the users was not even aware of the different haptic presentation. (B) The telepresence system should be able to display high contact and gripping forces. Thus, the distance error when gripping objects can be diminished and lower contact forces will be applied when interacting with the remote environment which in consequence prevents damages of the telepresence system. (C) A kinematical correspondence of operator console and telemanipulator must not be overestimated and will yield only benefit when difficult tasks have to be executed (e.g. rotations). (D) In most cases it is recommendable to augment occurring limitations of the teleoperator's workspace not only visually but also haptically. The design principles (A-D) are proposed for novel designs of haptic telepresence systems employed to remote controlled EOD. Presently, at the TUM bimanual haptic devices and telemanipulators with full movability in 6 DoF are under development enabling more advanced teleoperated task execution in future.

5 Acknowledgments

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