Position and Force Augmentation in a Telepresence System and Their Effects on Perceived Realism

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ABSTRACT

Haptic assistance functions for a telepresence system are presented and assessed. These assistance functions are based on the augmentation of exchanged position and force data, and they are intended to increase the transparency of the telepresence system while maintaining stability. We present the concept and implementation of different assistance functions. Furthermore, we show the setup and results of a psychophysical experiment, which was designed to evaluate the effects of the assistance functions on perceived realism. As a result, the position assistance can increase stability and safety without negatively affecting transparency, and the force assistance can even increase the feeling of presence under certain conditions.

Keywords: telepresence, haptics, psychophysics, assistance

1 INTRODUCTION

Haptic telepresence and teleaction systems provide the human operator with a feeling of presence in a remote environment and the ability to perform complex tasks through the teleoperator. The two conflicting objectives in the design of a telepresence system are *stability* and *transparency*. While the former is necessary to prevent operator and technical systems from harm and damages and to allow an efficient execution of the desired task, the latter is desirable in order to convey a high degree of immersion into the remote environment to the human operator.

Both, stability and transparency, are affected by actuator and sensor deficiencies as well as time delay in the communication channel. The large number of telepresence control architectures, which have been proposed to guarantee stability or to improve transparency, for systems with non-ideal communication channel, are reviewed in an extensive survey by Hokayem & Spong [5].

As most of these approaches miss a high degree of transparency, one recent idea is based on an increase of the bandwith in delayed teleoperation systems by opening the loop between master and slave and coupling the master to a local model of the remote environment on operator site [2, 10, 12]. This shows that additional knowledge about the structure of the remote environment can help to increase stability and transparency.

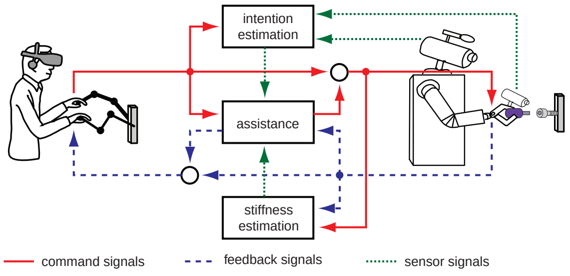

Figure 1: Concept of intelligent, assistive teleoperator

Yet, the moment of contact especially with stiff objects may still destabilize the overall system. To overcome this problem, different autonomous approaching functions were developed to guarantee an upper bound on the impact velocity [3, 9]. However, due to the combination of human-operated and completely autonomous behavior, these approaches neglect the human role in the teleoperation setup to some extent.

Thereby, combining the knowledge about the remote environment as well as the intended action of the operator can help to further increase stability and transparency. This insight leads to *Human-Machine Collaborative Telepresence Systems*, where intelligent local control loops on operator and teleoperator site are used to augment the interchanged position and force signals. The augmentation is based on models of the human operator and the remote environment. These models are used to predict position and force signals over a short horizon of time. The model parameters are continuously updated from the measured position and force data.

1.1 Proposed Method

We propose assistance methods for enhancing typical actions such as reaching movements and establishing contact between a tool and the environment. The proposed assistance concept works on a position-force architecture, i.e. position signals are sent from operator site to remote site, and force signals are returned in the opposite direction. Both signals are enhanced by appropriate models. The concept is illustrated in Fig. 1:

- *Position Assistance (PA):* based on a physiological model of human reaching movements, the intended action of the human operator is estimated by matching his position commands with the position of possible targets in the remote environment. It is assumed that possible targets can be identified and localized from the scene by additional sensors, e.g. an eye-in-hand camera. The model also yields an estimate of the future trajectory the human is going to follow. These estimates are used to calculate an optimized trajectory which mimics the intended movement, but avoids errors such as high impact velocities.

- *Force Assistance (FA):* a model of the remote environment is used to predict the interaction forces which occur during contact between teleoperator and remote environment. This model is implemented using two different identification methods for the environment. One of these methods is based on the mechanical stiffness of the touched object, the other on its rate hardness. Both quantities are estimated online from position and force measurements at the remote site.

1.2 Contribution

A psychophysical study of a 1 DOF telepresence system where position and forces are augmented by an intelligent assistance concept is presented. As a benchmark scenario the approach of a screw head

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with a screw driver is used. As the experiment is restricted to 1 DOF, only the temporal course of the approach and the interaction forces in the approach direction are subject to assistance. In a similar experiment [13], the effects of lateral positions and forces were investigated, but temporal effects were neglected, and no contact situations were investigated.

In the presented study, the effects of the proposed assistance concept on system stability and the perceived degree of immersion are analyzed. Specifically, the following hypotheses are investigated, whereby the respective assistance mode is compared to the unassisted teleoperation mode, unless specified otherwise:

- position assistance decreases the perceived realism
- force assistance increases the perceived realism for contacts with a stiff environment, but decreases the perceived realism for contacts with a compliant environment
- rate hardness-based prediction is preferred to stiffness-based prediction for contacts with a stiff environment
- the combination of position and force assistance has a significantly positive/negative effect on the perceived realism for contacts with a stiff/soft environment
- time delay intensifies the effects of position assistance and force assistance

2 ASSISTANCE CONCEPT

A bilateral telepresence system with position-force exchange is considered. The master device is under admittance control to render desired target dynamics with virtual mass and damping parameters. The damping parameter is hereby switched from a low value in freespace to a high value during contact. A constant time delay T_d is assumed in each direction, i.e. the round-trip time is $2\,T_d$.

In the following, two independently operating assistance modes are presented. The proposed *position assistance* (PA) modifies the arriving master position on the remote site, while the *force assistance* (FA) alters the delayed interaction forces on local site. The overall control architecture including human (H) and environment (E), master (M) and slave (S) devices, as well as the communication channel (CC) is shown in Fig. 2.

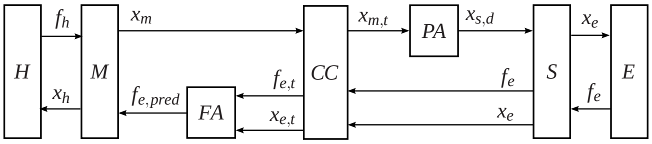


Figure 2: Overall control architecture

2.1 Position assistance mode

In the considered task, the transition from freespace to stable contact with a stiff object is most crucial for stability and transparency. When touching stiff remote objects, even small time delays may lead to large interaction force peaks with the environment, which may damage the teleoperator or the environment. Furthermore, the operator may get irritated due to the unexpected force feedback and bounce back away from the object. Oscillations of the teleoperator are the consequence, making stable contact impossible. Therefore, the proposed position assistance aims at minimizing kinetic energy and momentum of the slave at the moment of impact t_{hit}, which implies minimizing the impact velocity $v_{hit} = \dot{x}_s(t_{hit})$. Consequently, large force peaks are avoided, and stable contact is easier to accomplish. However, as a pilot study suggests, humans tend to touch objects with non-zero impact velocity. In telepresent scenarios, bad vision conditions may additionally lead to unintentionally high impact velocities. In order to solve the conflict between actual human behavior and the desirable behavior w.r.t. system stability, the approach trajectory is reshaped to enforce zero impact velocity. To this end, the duration of the movement $\hat{T}$ is estimated based on a model of the human-commanded trajectory and a new trajectory with identical $\hat{T}$, but with $v_{hit} = 0$ is calculated. By smoothly fading from the human commanded trajectory to the altered trajectory, the assistance is expected to not be noticed by the operator.

The assumed human-commanded slave trajectory from an initial position x_0 to the position of the screw x_w with constant final velocity v_{hit} is based on Hogan's minimum-jerk criterion for a point-to-point human arm movement [4],

$$\begin{aligned} x_{m,t}(t) &= x_0 + (x_w - x_0)\;(6\tau^5 - 15\tau^4 + 10\tau^3) \\ &\quad + v_{hit}\;(-3\tau^5 + 7\tau^4 - 4\tau^3),\ \tau = \frac{t - t_0}{T}. \end{aligned} \tag{1}$$

Hereby, the current time is denoted by t, the duration of the movement by T, and $\tau \in [0;1]$ represents a normalized time. Without loss of generality, the initial time t_0 is set to zero. It is assumed, that the duration T is the only unknown parameter in this model, as it varies not only between humans, but also between trials and is difficult to be kept constant by the human. A nonlinear recursive least squares algorithm is used to online estimate its value, denoted by $\hat{T}$. Upper and lower bounds on the parameter estimation are introduced to avoid instability of the algorithm.

By choosing the slave trajectory with zero impact velocity as close to the human-commanded trajectory as possible, deviations between commanded and assisted trajectory can be kept small, avoiding confusion of the operator. It results a minimum-jerk trajectory with zero impact velocity and identical duration of movement

$$x_r(t,\hat{T}) = x_0 + (x_w - x_0)(6\tau^5 - 15\tau^4 + 10\tau^3),\ \tau = \frac{t}{\hat{T}}. \tag{2}$$

For a smooth transition from direct to assisted control of the teleoperator's position, the human-commanded and desired trajectories are merged, leading to an assisted slave trajectory

$$x_{s,d}(t) = (1-\alpha)\cdot x_{m,t}(t) + \alpha \cdot x_r(t,\hat{T}), \tag{3}$$

which is the modified controller input on teleoperator site. The sliding factor $\alpha \in [0;1]$ determines the degree of assistance, which is chosen to depend on the distance to the stiff object and, in an indirect way, on the estimated duration:

$$\alpha = \begin{cases} 0 & x_r(t,\hat{T}) \le x_0 \\ \frac{x_r(t,\hat{T}) - x_0}{x_w - x_0} & x_0 < x_r(t,\hat{T}) < x_w \\ 1 & x_r(t,\hat{T}) \ge x_w. \end{cases} \tag{4}$$

According to this function, α increases with decreasing distance to the remote object to guarantee convergence to the desired slave trajectory x_r and vice versa. As this sliding factor as well as the desired trajectory are continuously adapted to the human-commanded trajectory, the proposed position assistance is able to track changes in human behavior in a certain range.

In the presence of a known time delay in the communication channel, the proposed method is used for prediction. Again, the most critical point is the moment of impact, and with delayed vision feedback, it becomes even harder for the operator to exactly determine the moment of impact and to precisely drive the slave onto the desired trajectory. Predicting the known model of $x_{s,d}$ over a horizon of the time delay leads to an assisted slave trajectory, that forces operator and teleoperator devices to reach the position of the wall simultaneously, such that

$$x_m(t_{hit}) = x_s(t_{hit}) = x_w. \tag{5}$$

With this prediction mode, the reaching movement of the remote object is facilitated and the transition from unconstrained to constrained motion can be controlled more precisely. At the end of the approaching phase, the position assistance is switched off to allow penetration into the object. The switching moment is determined to minimize the position error between master and slave.

2.2 Force assistance mode

While the proposed position assistance focuses on the stabilization of impact, force assistance aims at improving the haptic impression of the remote object, which is mainly determined by the degree of transparency of the teleoperation system. According to Lawrence [7], transparency is defined as the ratio of the impedance displayed to the operator Z_t to the environment impedance Z_e:

$$\Gamma = \frac{Z_t}{Z_e}. \tag{6}$$

Perfect transparency, i.e. $\Gamma = 1$, implies a direct coupling between the operator and the remote environment. However, technical limitations, such as time delay in the communication channel or sensor deficiencies, degrade the maximum achievable degree of transparency. The idea of force assistance is to circumvent some of these restrictions by locally rendering the remote object on operator site. Using an online updated model of the remote object, local forces between master and virtual object are computed and replace the measured and delayed transmitted forces from the remote site. With this assistance, the control loop is closed locally during contact, relaxing the requirements on stability. In the enlarged stability region, parameter sets are included, by which an increased feeling of perceived realism is reasonable to expect.

2.2.1 Stiffness-based prediction

For the local rendering, the dynamics of the remote object have to be known. In a first approach, referred to as stiffness-based prediction (SbP) in the following, the assumed stiff object is modeled as a simple linear spring

$$f_e(t) = \begin{cases} -k_e(x_e(t) - x_w) & \text{if } x_e \geq x_w \\ 0 & \text{else} \end{cases} \tag{7}$$

with unknown stiffness k_e. This simple model is used, as for force assistance, only stiff objects are of interest, whose most important characteristic is their mechanical stiffness. Other factors such as damping play a minor role and are therefore neglected. Moreover, the identification process especially for damping becomes difficult due to almost zero velocities during contact and may deteriorate the stiffness estimation process. When contact is established, such that the measured interaction force on the slave site exceeds some specified threshold, the stiffness of the object is estimated online using a recursive least squares algorithm. The convergence time for a steel cube with an identified stiffness of $k_{e,steel} = 98.36 \cdot 10^3\ \frac{\mathrm{N}}{\mathrm{m}}$ is around $0.4\,\mathrm{s}$ for arbitrary penetration depth, while it is $0.5\,\mathrm{s}$ for a silicone cube with $k_{e,silicone} = 4.36 \cdot 10^3\ \frac{\mathrm{N}}{\mathrm{m}}$ for a penetration depth of $0.01\,\mathrm{m}$. With the estimated stiffness $\hat{k}_e$, locally rendered forces $f_{e,pred}$ are obtained according to

$$f_{e,pred}(t) = \begin{cases} -\hat{k}_e(x_m(t) - x_w) & \text{if } x_m \geq x_w \\ 0 & \text{else.} \end{cases} \tag{8}$$

Evaluating Eq. (6) for the proposed method, the resulting equation depends solely on the estimated stiffness of the remote object. Ideally, $\hat{k}_e$ converges to the true value or, at least, reaches a value below the just noticeable difference (JND) for stiffness, in which case perfect transparency is achieved. Taking the dynamics into account, the following behavior is expected. The master device may touch the virtual object earlier in time than the slave touches the remote object. During this period of time, no information about the stiffness of the object is available. The virtual model is therefore initialized with a large static stiffness parameter to avoid instability at the moment of first measurement.

2.2.2 Rate hardness-based prediction

The second approach for rendering the remote environment on operator site is based on Lawrence' finding [8], stating that rather the rate of change of force and position during impact is the deciding factor for the human perception of stiff virtual objects compared to a purely static relation between force and displacement. Hereby, rate hardness is defined as the ratio of initial force change to impact velocity

$$H_R = \frac{\dot{f}_e(t_{hit})}{\dot{x}_s(t_{hit})}. \tag{9}$$

By determining and displaying the rate hardness of the remote object to the operator, the human perception is taken into account for the haptic rendering. The derivative of the interaction force is approximated as

$$\dot{f}_e(t_{hit}) = \frac{f_e(t_{hit} + 2T_a) - f_e(t_{hit})}{2T_a}, \tag{10}$$

with T_a being the sampling rate. Furthermore, a haptic rendering method for large stiffness values is introduced in [8], which is uncritical concerning stability issues, as it is based on an appropriate replacement of stiffness by damping. By applying a low-pass filter to f_e to account for the limited bandwidth of electronics and actuators, a modified differential equation

$$\dot{f}_e(t) = -a f_e(t) + a d_e \dot{x}_s(t) + a k_e (x_s(t) - x_w) \tag{11}$$

is obtained for the remote object, with $\frac{1}{a}$ being the time constant of the low-pass filter. In the moment of impact, Eq. (11) simplifies to $\dot{f}_e(t_{hit}) = a d_e \dot{x}_s(t_{hit})$ and, thus, $H_R = a d_e$. In order to perceive this desired level of rate hardness, $H_R \geq k_e$ has to hold. Otherwise, a softer remote object is rendered with the introduced damping. As the condition $H_R \geq k_e$ is assumed to hold for the considered objects, the stiffness estimation, as described before, is superimposed with a rate hardness estimation, where $\hat{H}_R$ denotes the estimated value. Transformed into a damping term, a modified model for rendering the remote object can be set up:

$$f_{e,pred}(t) = \begin{cases} -\hat{k}_e(x_m(t) - x_w) - \frac{\hat{H}_R}{a}\dot{x}_m(t) & \text{if } x_m \geq x_w \\ 0 & \text{else.} \end{cases} \tag{12}$$

The corresponding force assistance mode is referred to as rate hardness-based prediction (RHbP) assistance in the following. Steady-state and dynamic behavior of the modified virtual object are supposed to be equivalent to the above described behavior except that the perception of the object to be stiff should be even more distinct.

3 EVALUATION METHOD

3.1 Experimental setup

Two identical linear actuators, Thrusttube modules 2504 from Copley Controls Corp., each equipped with an optical position encoder (resolution 1 μm) and a force sensor, as shown in Fig. 3, were used as teleoperation system.

On one device, the handle of a screw driver was mounted as master endeffector. The participant grasped the handle and moved it away from his or her body towards the target object. The initial distance between the endeffector of the teleoperator and the first point of contact was 8 cm. Cylindrical steel pins were used as screw driver heads which were installed both at the local and at

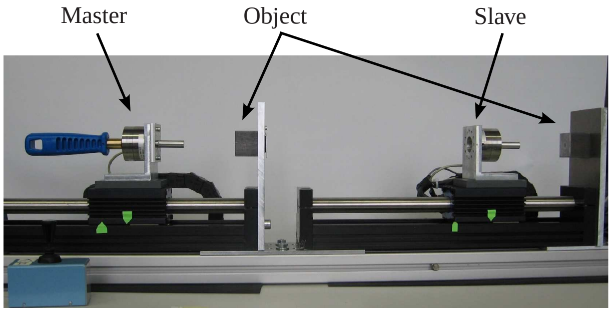


Figure 3: 1-DOF telemanipulation system

the remote site of the teleoperation system. This was done so that beside a telepresent operation mode of the system direct contact between tool and object could be presented to participants to serve as reference stimulus and control condition. For maximal external validity of the experimental evaluation, it was aimed to hide any visual cues from the participants which could provide hints about the current operation mode of the system and the mechanical properties of the touched object. It was therefore decided to visualize a virtual reality scenario which was presented through a head-mounted display (HMD) with SXGA resolution and a frame rate of 30 Hz. The virtual scene was composed of an anthropomorphic robot arm equipped with a hexagon screw driver and a wall with the target screw, as shown in Fig. 4. By tracking the head orientation and adjusting the viewing perspective accordingly, participants were able to freely look around the virtual scene.

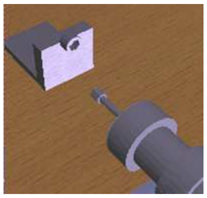


Figure 4: Virtual reality scene used as visualization tool in the experiment

3.2 Experimental design

The influence of the position– and force-based assistance functions on the attribute “perceived realism” was evaluated using the method of paired comparison (forced choice) within a 2 (position assistance) × 3 (force assistance) mixed-subjects experimental design. In this design, participants were presented with a reference stimulus and were then asked to decide which one of two further presented stimuli felt most like this reference stimulus. Position assistance was manipulated on two levels (on / off), force assistance on three (SbP / RHbP / off). A non-mediated (“real”) condition, in which the teleoperator was omitted, and the physical contact was established on the local site, served as reference and control condition. A systematic combination of all variable levels plus the control condition yielded seven experimental stimuli, see Tab. 1.

	position assistance	no position assistance
rate hardness-based prediction	S1	S4
stiffness-based prediction	S2	S5
no force assistance	S3	S6
real condition	RS	

Table 1: Experimental stimuli.

Each stimulus was systematically contrasted with every other stimulus, thus yielding 21 pairs of stimuli for participants to judge. A steel cube and a silicone cube were used as contact targets in a hard contact condition and a soft contact condition, respectively. Participants rated each pair of stimuli in both contact conditions. In addition, participants were randomly assigned to one of two groups. In one group, a time delay of 10 ms ($T_d = 10\,\mathrm{ms}$) was specified for the communication channel, whereas in the other, a time delay of near 0 ms ($T_d = 0\,\mathrm{ms}$) was assumed. The sequence in which the pairs of stimuli were presented was varied for each participant using the Latin square method. Furthermore, the order in which the two wall pieces were presented was also randomized. Since the virtual reality was identical for all trials, the visual feedback that participants received of their performance via the HMD provided no visual cues regarding the actual wall stiffness. Prior to the experiment, each participant was asked with which hand they typically operated a screw driver, and either a right or a left arm was visualized in the virtual scenario, accordingly.

3.3 Procedure

Participants were placed in front of the experimental apparatus and were given the opportunity to familiarize themselves with the device and their task before the first experimental trial began. For each trial, the task was to repeat the same movement, i.e. to make contact with the target using the virtual screw driver, three times. First, participants were always presented with the non-mediated reference condition. Then they were asked to repeat this movement twice, whereby each time a different setting was presented, see Tab. 1. After each trial, participants were asked to decide which one of the latter two stimuli felt most like the reference stimulus. Each participant conducted 42 trials in total, i.e. 21 per cube.

3.4 Participants

An opportunity sample of 35 participants took part in the experiment. One person’s data set had to be excluded from further analysis. The remaining sample (N = 34) was comprised of nine women and 25 men (mean age = 25 yrs, std. deviation = 4 yrs). Three participants were left-handed. There were no significant group differences in age or 3D computer gaming experience between the two time delay groups ($t(32) = 0.39$, $p > .05$; $t(17,17) = 1.06$, $p > .05$, respectively).

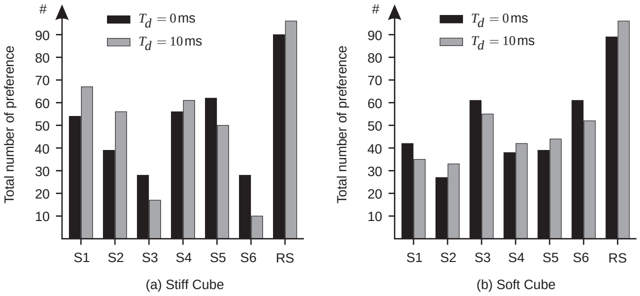
4 EVALUATION RESULTS

4.1 Manipulation check

In all four experimental conditions, i.e. the two time delay and the two contact conditions, the control condition was preferred the most, thus confirming that participants judged the experimental stimuli with reference to the real stimulus setting. Furthermore, Kendall’s concordance coefficient W showed significant agreement between raters for all four subgroups ($N = 17$) while calculated consistency coefficients confirmed that raters demonstrated a high degree of consistency in judgment. Fig. 5 shows the total number of preferences expressed for each experimental stimulus in the hard and soft contact conditions, respectively.

4.2 BTL model test of fit

The data were further analyzed using the Bradley-Terry-Luce (BTL) model for pair comparisons, see [1]. The BTL model is extended to the case in which there are several preference matrices, one for each of the four subgroups. First, it was tested whether the multinomial model with all 21 comparisons explained the data significantly better than a restricted BTL-model with seven parameters, using a maximum likelihood estimation. If not, the restricted model could be accepted as it explains the data with fewer parameters. As Tab. 2 shows, the analysis revealed that, for all four



(a) Stiff Cube

(b) Soft Cube

Figure 5: Total number of times a setting was preferred

subgroups (N=17), the BTL-model with seven parameters showed good model fit as the respective multinomial models were rejected.

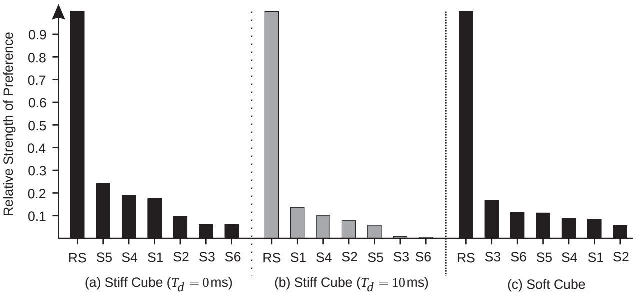
Hard contacts	$T_d = 0$ms	$\chi^2(14) = 9.68, p = 0.79$
	$T_d = 10$ms	$\chi^2(14) = 9.74, p = 0.78$
Soft contacts	$T_d = 0$ms	$\chi^2(14) = 12.87, p = 0.54$
	$T_d = 10$ms	$\chi^2(14) = 10.09, p = 0.76$

Table 2: BTL model test.

4.3 Group differences in judgments of stimulus realism

In order to assess whether there are group differences in judgments of realism depending on time delay in the communication channel, further model tests were conducted for each cube separately using a "conjoint" approach in which a general model with 12 variable parameters was compared to a restrictive model with only six free parameters. For the hard contact condition, but not the soft contact condition, the analysis found that the general model (df=12) explained significantly more variance than the restrictive model (df=6). That is, only for the soft contact condition, a model could be accepted that did not assume differences in judgments of realism between the two time delay groups. For the hard contact condition, the restrictive model had to be rejected in favor of a general model which takes time delay in the communication channel into account.

The relative strengths of preferences for contact settings are displayed in Fig. 6. The most preferred settings are normalized to one. Note that preferences of soft contacts were combined into one preference matrix, since there were no significant differences between the two time delay groups.



(a) Stiff Cube ($T_d = 0$ms) (b) Stiff Cube ($T_d = 10$ms) (c) Soft Cube

Figure 6: Relative Strength of Preference

4.4 Perceived realism of stiff contacts

Using the respective BTL-models, the different assistance modes were examined for significant differences in preference probability. Based on our hypotheses, a number of comparisons were made to investigate the effects of position assistance, stiffness– and rate hardness-based prediction, as well as possible interactions between position assistance and the two force assistance modes on preference judgments. In order to compensate for multiple comparisons, the accepted significance level was adjusted with Bonferroni corrections and set to $p < .007$. The results of the different comparisons for both time delay groups are presented in Tab. 3.

Comparison	$T_d = 0$ms	$T_d = 10$ms
S4 vs. S6	$\chi^2(1) = 15.50$, $p < .007$	$\chi^2(1) = 65.97$, $p < .007$
S5 vs. S6	$\chi^2(1) = 22.63$, $p < .007$	$\chi^2(1) = 43.64$, $p < .007$
S4 vs. S5	$\chi^2(1) = 0.73$, $p = .39$	$\chi^2(1) = 3.00$, $p = 0.08$
S3 vs. S6	$\chi^2(1) < 0.001$, $p > .99$	$\chi^2(1) = 2.18$, $p = .14$
S1 vs. S6	$\chi^2(1) = 13.42$, $p < .007$	$\chi^2(1) = 79.91$, $p < .007$
S2 vs. S6	$\chi^2(1) = 2.53$, $p = .12$	$\chi^2(1) = 65.71$, $p < .007$
S1 vs. S2	$\chi^2(1) = 4.42$, $p = .04$	$\chi^2(1) = 3.04$, $p = .08$

Table 3: Preference comparisons

With regard to the comparisons made, only one difference presented itself between the two time delay groups. For both groups (each $N = 17$), force assistance was found to significantly improve perceived realism as both rate hardness-based prediction (S4) and stiffness-based prediction (S5) were significantly more often judged as more realistic compared to the telepresent stimulus without assistance functions (S6). When only force assistance was employed, there was no significant difference in preference between settings with rate hardness-based (S4) and stiffness-based prediction (S5). This did not change, when position assistance was added to both (S1, S2). The position-based assistance function on its own did not significantly decrease perceived contact realism as the experimental setting without any assistance (S6) was not significantly more frequently preferred over the setting that used the prediction algorithm (S3). When combined with position assistance, rate hardness-based prediction (S1) was still preferred to the unassisted setting (S6). However, there was some evidence pointing to a possible interaction of position assistance and stiffness-based prediction in their effects on preference ratings depending on time delay in the communication channel. With a time delay of 10 ms, position assistance showed no significant deteriorative effect when combined with stiffness-based prediction as this setting (S2) was still significantly preferred to the unassisted setting (S6). However, without time delay, the setting in which position assistance was combined with stiffness-based prediction (S2) showed no significant difference in preference to the unassisted setting (S6).

4.5 Perceived realism of soft contacts

The same statistical procedures were applied to preference ratings of contacts with the silicone cube. Since there were no significant differences between the two time delay groups, ratings of soft contacts were combined into one preference matrix ($N = 34$). As with hard contacts, position assistance showed no significant effect on perceived realism (S3-S6: $\chi^2(1) = 0.01$, $p = .92$). On the other hand, both stiffness and rate hardness-based prediction showed a significant effect on preference ratings (S5-S6: $\chi^2(1) = 8.64$, $p < .007$; S4-S6: $\chi^2(1) = 9.22$, $p < .007$). With soft contacts, however, the stimulus without any force assistance was significantly more frequently preferred over stimuli with either mode of force assistance present. In other words, both force assistance modes significantly decreased the probability to be preferred to other stimuli in terms of realism. When position assistance was combined with either stiffness or rate hardness-based prediction, the unassisted mode was still significantly preferred to either one (S2-S6: $\chi^2(1) = 28.51$, $p < .007$; S1-S6: $\chi^2(1) = 13.90$, $p < .007$). Again, there was no significant difference in preference between the settings with stiffness-based and rate hardness-based prediction (S4-S5: $\chi^2(1) = 0.01$, $p = .92$) which did not change when position assistance was added (S1-S2: $\chi^2(1) = 2.91$, $p = .08$).

5 DISCUSSION

In this study, a number of position and force assistance functions were evaluated with respect to their influence on the realistic portrayal of haptic contacts with surfaces of differing stiffness in a telepresence system. Based on the literature, several hypotheses were formulated and experimentally tested.

Position assistance was speculated to reduce the perceived realism for two reasons: on one hand, the trajectory of the teleoperator before the impact is deliberately altered by the assistance algorithm and is, therefore, not in full accordance with the commanded trajectory; on the other hand, the change of the impact velocity, which is imposed by the position assistance scheme, is expected to affect the perception during the establishment of contact. The results, however, contradict these expectations and show that position assistance did not significantly affect the perceived realism, regardless of the stiffness properties of the contact surface. Apparently, the position deviations during the approach phase are too small and are built up too slowly to be perceived by the user [11]. Previous studies suggest that stiffness perception when mediated by tools relies primarily on kinesthetic rather than tactile information, e.g. [6], which could explain why the changed impact velocity is not noticed.

The force assistance concept was expected to increase the perceived realism for establishment of contact with stiff environments, because the stiff environment is rendered locally, thereby omitting the deteriorating and softening effects of the telepresent control loop. For soft environments, however, a degradation of the perceived realism was expected, because the stiffness estimation is initialized with a high stiffness value and adjusts to the true value only after a short transient. Both expectations were confirmed by the experiment. The two proposed force assistance schemes, stiffness-based and rate hardness-based prediction, both significantly increased perceived contact realism for stiff environments compared to a system-mediated contact situation in which no assistance functions were employed. When employed with compliant contacts, both forms of force assistance significantly reduced perceived realism as they momentarily portray a hard surface at point of contact before they adjust and simulate a soft object. This seems to affect perceived contact realism as it interferes with users' expectations.

A comparison of the two force assistance schemes, stiffness-based prediction and rate hardness-based prediction, was hypothesized to show a superiority of the rate hardness-based scheme for contacts with stiff environments. However, unlike other studies in the literature, see [8], we found no evidence for preference of rate hardness-based over stiffness-based prediction when employed on their own. This disagreement may be attributed to the different characteristics of the employed hardware. In contrast to the hardware used in [8], the experimental device used in this study was able to output a high degree of stiffness. It is therefore possible that rate hardness-based prediction is only superior to mechanical stiffness with devices that tend to render stiff surfaces softer.

For the combination of force and position assistance, a significantly positive effect was expected for stiff contact situations, as force assistance is thought to prevail possibly negative effects of position assistance. For soft contacts both assistance functions are assumed to significantly deteriorate the feeling of perceived realism, leading to an overall negative effect. Except for one comparison, these hypotheses are confirmed by the experiment. The combination of stiffness-based prediction and position assistance for stiff contacts without time delay failed significance when compared with the unassisted teleoperation mode. This effect may be further investigated in future studies.

It was expected that time delay does not change the effects of the assistance schemes qualitatively but quantitatively, such that the effects would be more prominent in trials with time delay than in trials without time delay. In general, this is confirmed by the experiment. The only exception can be found in conditions with a stiff environment when position and force assistance modes are combined. Apparently, the influence of this combination drops below significance level for the no time delay condition.

6 CONCLUSION

Under certain conditions, haptic assistance functions provide a means to increase the stability and perceived realism in a telepresence system beyond the level of unassisted systems. We presented two assistance concepts, which alter exchanged position and force signals such that high impact velocities and impact forces are avoided and the environment impedance is rendered more precisely on the local site. A psychophysical study was conducted to assess the influences of these measures on perceived realism. The tested task consisted in approaching a screw with a screw driver and establishing contact between both. Contrary to expectations, the position assistance does not deteriorate perceived realism. The force assistance concept increases the perceived realism as long as the stiffness of the contacted object does not differ too much from the initial value of the stiffness estimation.

The main challenge arising from the presented study consists in dealing with an unknown stiffness during the establishment of contact. Further research is directed towards an architecture which smoothly blends between classic stabilization techniques, such as wave variables, and the presented force prediction concept depending on the level of confidence of the stiffness estimation.

ACKNOWLEDGEMENTS

This work is supported in part by the German Research Foundation (DFG) within the collaborative research center SFB453 "High-Fidelity Telepresence and Teleaction".

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