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BILATERAL TELEOPERATION – HUMAN OPERATOR CENTERED APPROACH

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ABSTRACT

Bilateral teleoperation provides human operators with the ability to manipulate and receive force feedback from distant objects. Teleoperation is applied in various areas such as space robotics, handling hazardous materials, and surgery. Using teleoperated robots in space exploration reduces costs of assembly, maintenance, and repair tasks, as well as the risk that accompanies extra vehicular activity by astronauts.

Reliable and transparent feedback is important in space tasks due to their complexity. In measuring transparency it is important to consider how the human perception and action are affected by teleoperation. In this paper we review our findings about the effect of delay on human perception and action: subjects tend to overestimate the stiffness of elastic fields due to delay; this effect changes with probing strategy and with the joint that is used for probing; declarative and motor-related perception of stiffness are inconsistent. Based on these findings we proposed a multidimensional measure of transparency which takes into account perceptual, local motor, and remote transparency. We name the process of minimizing the perceptual transparencey as well as the remote transparencey – transparentizing.

We present our human-operator centered transparentizing approach and discuss its potential application to teleoperation in space exploration.

I. INTRODUCTION

Bilateral teleoperation provides human operators with the ability to manipulate objects at distant locations and receive force feedback sensation from the manipulated objects: the operator holds a local robot which determines the motion of a remote robot and continuously receives delayed force feedback. Since its beginning, back in the forties of previous century, teleoperation was applied in various areas such as operating space robots, handling hazardous materials, and surgery. Within the framework of teleoperation for space application the human operator and local device can be located at a ground control station or inside the space vehicle, and the remote device and environment are typically outside the space vehicle, in geosynchronous orbits or in deep space (figure 1).

Space exploration was considered over the years to be one of the most promising applications of teleoperation [1-3], since many astronautic targets are so far away that they must be explored by proxy, e.g.: pick up samples from lunar surface while remaining on Earth etc. Interestingly, it was the race to the moon which stimulated extensive research in teleoperation and revealed many of the control challenges imposed by inevitable delay in transmission [4]. Using teleoperated robots in space exploration can reduce costs of assembly, maintenance, and repair tasks, as well as reduce the risk that accompanies extra vehicular activity (EVA) by astronauts [5]. Moreover, space teleoperation spins off technology to terrestrial robots for various applications [2].

There are several considerations which distinguish space teleoperation from terrestrial applications of teleoperation. The typical tasks include servicing of satellites; satellite as

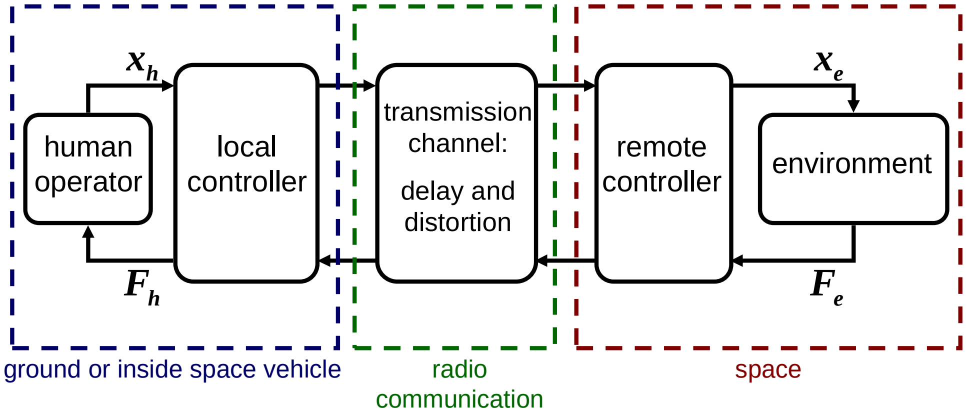

Figure 1: General scheme of a teleoperation system: human operator acts through a local controller, a channel, and a remote controller on the remote environment with delayed feedback. Dashed frames encapsulate subsystems at same locations.

assembly, repair, and construction; payload handling. These include subtasks such as removing and installing fastners, connection of umbillicals and fluid lines, module replacement, and adjustment of thermal blankets [2]. Microgravity should be considered both as advantage due to high manipulability of the slave, but also as disadvantage due to weird operator postures and the need for restraints for force reflecting controllers. Severe thermal and radiation conditions are important factor as well, but these are beyond the scope of this paper in which we focus on control related aspects of space teleoperation.

It is clear that the properties of the channel transmitting the information from the local to the remote side and back may influence the system quality. For example, ground-space teleoperation is far more complicated challenge than teleoperation from inside the space vehicle due to the large distance that the information has to travel in the former case. An obvious advantage of teleoperation over various autonomous control solutions for space robotics is the exploitation of human perception, judgment, decision, dexterity, and training [6]. However, while channel properties have been analyzed, the influence of the human operators and their perceptual and motor capabilities has been largely overlooked.

In our approach to teleoperation we aim to utilize the adaptive responses of the human operator to generate perceptually transparent and functional teleoperation systems. In such systems, the operator’s intentions will be accurately executed in the remote environment, and the remote environment will be accurately perceived by the operator. A broad range of applications will benefit from these enhancements in telerobotics and telepresence technologies of the future, e.g. by performing space vessels maintenance tasks without the need for space walk, but also by handling hazardous materials from safe distance, by performing complicated surgical procedures and everyday rehabilitation activity without the need in patient transportation, and by adding a personal touch to standard telecommunications.

A prominent and unavoidable charachteristic of bilateral teleoperation systems is delay between movements of the operator and force feedback. The effect of delay on teleoperation was studied quite extendively and reviewed in [4, 7]; however, most of the studies there do not deal with bilateral teleoperation with direct force feedback. The influence of delay on haptic perception of mechanical stiffness was recently addressed [8-12]. It was found that subjects tend to overestimate stiffness with delayed forces [8] and that shifting the location of contact with elastic force field also modified perception of stiffness [9]. More recently we found that the effect of delay on perception depends on the way in which a surface is probed by repeated contacts [11] and the joints that are most used in probing motions [10, 12]. We also found inconsistency between declarative and motor-related perception of stiffness [9]. Such inconsistency was reported in other tasks [13, 14].

Based on these findings, we suggested that a multidimensional measure of transparency [15] which consists of the following three components:

(i) *Perceptual transparency:* The human operator cannot distinguish between the system and an ideal channel.

(ii) *Local motor transparency:* The movement of the operator would not change if the teleoperation system was replaced by an ideal channel.

(iii)*Remote motor transparency:* The movement of the remote robot would not change if the teleoperation system was replaced by an ideal channel.

Based on our results concerning the different roles of perception and action in haptic estimation [9], we hypothesize that for a wide family of teleoperation channels it is possible to obtain perceptually transparent teleoperation (i) and remote motor transparency (iii) without local motor transparency (ii). In practice, perceptual and remote motor transparencies are simultaneously attainable by changing either the local or remote controllers, or the human operator by means of training.

The remainder of this paper is organised as follows. A survey of recent studies of applications of teleoperation systems for space research is presented in section II followed by a survey of the effect of delay between force and position on perception and action of human operators in section III. Our approach for transparent teleoperation is reviewed in section IV, and a discussion finalizes the paper in section V.

II. TELEOPERATION FOR SPACE APPLICATIONS

With the growing use of satellites and the development of space stations the need for construction, maintenance, and repairs in near and farther space has considerably increased in the last decades. Even though some of the tasks can be successfully performed by astronauts during EVA these missions are expensive and dangerous. Thus, there is great economical as well as risk reducing motivation for development of telerobotic devices for teleoperation in space and ground-space teleoperation.

The first teleoperated devices in space were not bilateral in the sense that there was no force feedback transmitted back to the operator from the remote device. Examples of such teleoperators are the 20m Space Shuttle Remote Manipolator System (SRMS) that was developed by the Canadian Space Agency and carried aboard the US space shuttle, and the Space Station Remote Manipulator System (SSRMS) [16]. Both these systems are controlled from within the space vehicle by a human operator and designed to work with very large payloads (>10000kg) for assembly, satellite deployment and retrieval, and moving astronauts in EVA.

The German robotic technology experiment (ROTEX) is the first teleoperator that was operated in ground-space teleoperation mode [17, 18]. It was launched in 1993 onboard of the COLUMBIA space-shuttle [18], and was capable of performing preprogrammed motions as well as teleoperated motions under the operation of an astronaut with small delays or operator on the ground with large delays up to 7s. Its tasks included assembling a mechanical grid structures, connecting/disconnecting and electrical plug, grasping a floating object, and exchanging orbit replaceable unit (ORU). There was no force feedback in this teleoperation system at all, and due to stability problems with large delays in ground teleoperation the visual feedback was provided from a model and not the actual remote device, and the model was updated online using the feedback.

The engineering test satellite VII (ETS-VII) was launched by the national space development agency (NASDA) of Japan in 1997 [19-22]. It was the first free-floating space robot, and the first system that employed bilateral ground-space teleoperation with haptic feedback. Both model based [20, 21] and direct [19] bilateral teleoperation were tested in slope tracing and peg-in-hole tasks, and showed that even under delays as large as 7s kinesthetic force feedback is usefull and improves performance. In this system the forces were scaled by a factor of 5 in the transmission from the local to the remote devices.

The German ROKVISS – robotic component verification in the international space station – was mounted outside Zvezda, the Russian service module of the international space station [22-25]. For the first time in space teleoperation a direct radio link contact between onground and onboard controllers was used and allowed reducing round trip delay to 20ms. Delays of such small magnitudes allow perception of remote objects properties such as stiffness and viscosity [8], but the access to the onboard system was limited to 8 minute time windows when the ISS passed through the tracking space of the ground antenna. In these experiments telepresence (bilateral teleoperation), telerobotic (unilateral teleoperation), supervisory, and automatic modes were tested in several tasks, including surface tracking, peg-in-hole, and interaction with mechanical spring. They used wave variables [26] with prediction control in bilateral teleoperation mode and hybrid force and position control at the remote site. The ROKVISS demonstrated the readiness of space robots to on-orbit servicing applications and this direction is further explored in technology satellite for demonstration and verification of space systems (TECSAS) [22]. In ROKVISS transparency of teleoperation was defined for the first time for space teleoperation; according to their definition the operator should feel as directly operating in the remote environment. However, a quantitative measure for the extent of transparency was not provided.

In all these studies the distortion in perception of mechanical properties of the remote environment by the human operator due to delay was not addressed. In the following section we review our findings about the effect of delay on perception of mechanical properties.

III. PERCEPTION AND ACTION IN VIRTUAL DELAYED ENVIRONMENT

In the recent years the influence of delay on the perception of mechanical stiffness was addressed [8-12]. In all these studies a similar paradigm was used to assess the affect of delay on the perception of the stiffness of an elastic force field in bilateral force reflecting teleoperation. In a forced choice paradigm subjects were presented with two spring-like force fields and asked to identify the one that felt stiffer. In one field the force was proportional to the penetration beyond the boundary of the field, but in the second the force was proportional to the penetration 50ms earlier. Then their binary answers were used in order to extract the perceived stiffness of delayed and nondelayed force field with some reference level of stiffness, which was different depending on the experiment. The experimental methods are described in details in [8, 9, 11, 12] and here we will only present the results of these experiments without going deep into methodology issues. All these studies were performed in virtual reality setups, and therefore we could examine the effect of pure delay on perception and action of human operators without additional control considerations [26, 27]. In these setups subjects held the handle of a robotic device which applied forces that simulated the remote environment.

Subjects interacted with simulated spring-like force field (SLF): a position-dependent force field, which has the mechanical properties of a one-sided spring, i.e., the applied force is proportional to the penetration into the field. The ratio between the applied force and penetration is the stiffness of such a field. In the non-delayed case, the trajectory is a straight line (figure 2a). Introducing delay into the system causes this trajectory to become elliptical (figure 2b), i.e., force is no longer a single-valued function of position. During this movement, the local stiffness is some times lower and at other times higher than the non-delayed stiffness. The boundary of a linear spring-like field, such as the one described in Fig. 1 and 2b is a region where stiffness is ill-defined, i.e., the derivative of the force/position relation exhibits a sudden transition from zero to a non-zero value, and at the transition point it has different values along different directions.

In the first step towards exploring the effect of delay on perception of mechanical stiffness it was found that subjects tend to overestimate delayed stiffness, and that this effect is enhanced with increasing delay, and reversed if direction of delay is reversed (namely force precedes position) [8]. In this experiment subjects moved their entire arm including shoulder, elbow, and wrist joints and were free to cross the boundary of the elastic field as much as they liked.

More recently [11] we explored the effect of crossing the boundary of elastic force field on perception of delayed stiffness. We found that when subjects did not cross a boundary – i.e., when their hand remained inside an elastic field all the time – they tended to underestimate the delayed stiffness (figure 3a left, and 3b), whereas when they did cross the boundary they overestimated delayed stiffness; therefore, the outcome of the estimation depends on the boundary crossing.

To account for these results we proposed a computational model of stiffness perception that describes haptic perception as an active process that combines the operation of a force control system and of a position control system operating concurrently [11]. When moving without crossing the boundary, our best model for estimation of stiffness was the slope of force over position regression of the explorative movement data in the force-position plane. Probing inside the boundary as well as occasionally crossing the boundary resulted in a weighted sum of the regression slopes of force over position (FP) and the inverse of position over force (PF), which yield underestimation and overestimation respectively. According to this model the perceived stiffness is

$$\hat{K} = \alpha \hat{K}_{PF} + (1-\alpha)\hat{K}_{FP} \tag{1}$$

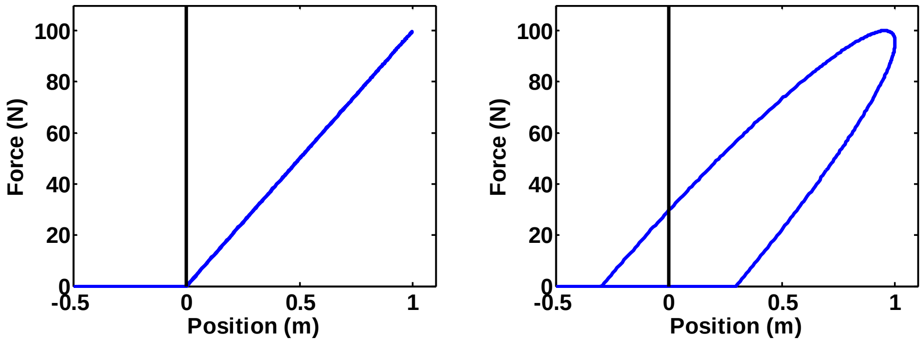

Figure 2: Force position trajectory in contact with a spring-like field without (a) and with (b) delay. In the case of a delayed spring-like field (b), the operator first penetrates the field without force feedback, and only after the delay does the force increase gradually. As the operator reverses the movement direction, the force continues to increase for the duration of the delay and then decreases. The horizontal line denotes the position of the boundary. In both trajectories, the probing movement begins and ends outside the field. We designate such movement as "probing a spring-like field with boundary crossing".

where α is the boundary crossing ratio, namely $\alpha = 0$ when moving only inside the field, and $\alpha = 1$ when each and every movement included crossing of the boundary inside and out. We further explored perception of delayed stiffness in experiments where we used orthopedic splints in order to constraint the probing movement to a movement with a single joint without changing the grip of the robotic handle [12]. The subjects did not have access to the boundary of the elastic force field in these experiments, and therefore we expected to observe underestimation of stiffness due to delay. Indeed, such underestimation was observed; however, we found a proximodistal gradient in the amount of underestimation of delayed stiffness in the transition between probing with elbow and wrist joints, as depicted in figure

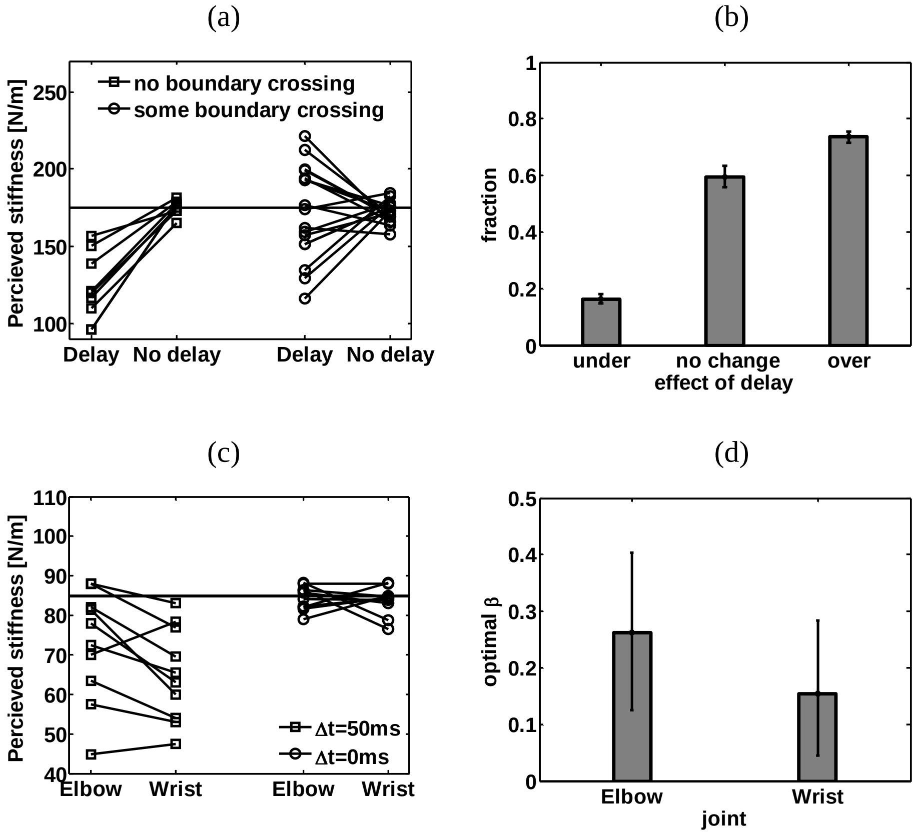

Figure 3: Experimental results of effect of delay on perception. (a) Perceived stiffness of SLF with nominal value of stiffness K=175N/m. Left – without access to the boundary of SLF all probing movements were conducted inside the field – all subjects underestimated delayed stiffness. Right – subjects could cross the boundary of SLF and showed mixed effect of delay on perception. (b) Fraction of probing movements which included a crossing of the boundary of SLF as a function of the perceptual effect reveals that increasing relative fraction of movements with boundary crossing during probing changes the effect of delay from underestimation to overestimation of stiffness. (c) Perceived stiffness of SLF with nominal value of stiffness K=85N/m. Left – when delay was introduced between force and position subjects underestimated the stiffness stronger when they used their wrist during probing movements rather than when they used their elbow. Right – without delay the stiffness of elastic force field was perceived correctly regardless to the joint that was used during probing. (d) Optimal proximity index is statistically significantly higher in elbow than in wrist probing condition.

2c. We followed the idea laid out in previous paragraph and equation (1) and tried to explain this perceptual effect by constructing a model that combines estimations of stiffness according to the slope of FP regression and the inverse of the slope of PF regression:

$$\hat{K} = \beta \hat{K}_{PF} + (1-\beta)\hat{K}_{FP} \qquad (2)$$

For each subject and for each probing joint condition we optimized the weight β in the range [0, 1] such that the model will yield answers as similar to the answers of subjects as possible; we found the optimal mixing weight was significantly graded along a proximodistal axis (figure 2d) and can be referred to as proximity index.

Our general hypothesis is that position and force control operate concurrently in the motor system, and are weighted according to demands opposed by the environment, such as boundary crossing, as well as according to the proximity of the joint that is involved in the probing movement. The weight of force control is increased with increasing boundary crossing ratio and with the proximity of the probing joint. Consequently, the perceived stiffness in such a system is a weighting between estimation of stiffness (impedance – e.g. regression of force over position), which yields overestimation, and inverse of estimation of compliance (admittance – e.g. regression of position over force), which yields underestimation. Therefore, a proximodistal gradient in underestimation of delayed stiffness, as well as transition between underestimation and overestimation of delayed stiffness according to the boundary crossing ratio are observed. Such proximodistal gradient is in line with converging neurophysiological evidence, as reviewed in [28]. This general hypothesis is depicted schematically in figure 4.

Several studies have reported inconsistency between perception and action [13, 14, 29, 30] in various tasks, such as grasping [14, 29], and placing a card into a slot [13, 31]. Dissociation between perception and action was also demonstrated in reproduction of remembered distances [32]. These leaded us to explore whether the effect of delay that was revealed by declarative responces is similar to the effect that can be measured by evaluation of motor performance in interaction with delayed environment. We explored motor representation of the stiffness of delayed elastic SLF by investigating adaptation to virtual environment [9]. We asked subjects to reach a target inside virtual force field, and observed adaptation and its after-effects in catch trials. Interestingly, we have found that declarative and motor-related estimations of stiffness are inconsistent. The mismatch between the expected stiffness as

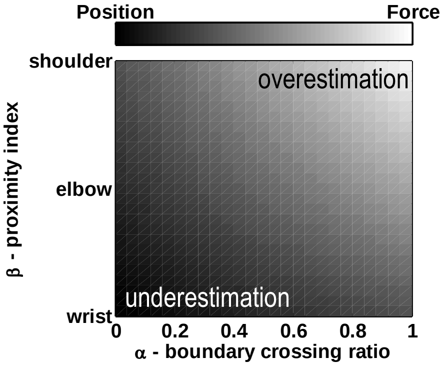

Figure 4: According to our hypothesis the human motor control system combines force and position control according to the environmental demands (boundary crossing ratio) and the proximity index, and therefore subjects overestimate and underestimate the stiffness of delayed SLF respectively.

measured by the motor behavior and the reported stiffness may indicate two parallel processes. From a more practical perspective this finding further emphasizes that the influence of teleoperation channel should be evaluated when action as well as perception are taken into account, and the gap between the two can be exploited for achieving transparency for imperfect channels.

IV. MULTIDIMENTINAL TRANSPARENCY MEASURE

Transparency in bilateral teleoperation

Teleoperation systems are typically described as two-port networks that are represented by a hybrid parameters model [27, 33-36]. Transparency is a measure of teleoperation system fidelity and various definitions and conditions for transparency have been presented. Some authors define ideal transparency according to network functions, such as impedance or admittance [27, 35, 37]. Others define transparency by correspondence of position and force signals [38, 39]. Generally, ideal transparency conditions are unattainable [40], particularly in the presence of transmission delays [26]. Moreover, the design goals of stability and transparency are in mutual conflict, and as such, there is a stability-transparency, or stability-performance tradeoff [27, 40-42]. In the presence of delay, achieving transparency essentially requires prediction [35], which is not practical for real-time applications such as teleoperation in space.

The common feature of traditional definitions of transparency is that they define transparency according to the properties of local and remote controllers and teleoperation channel, mainly according to linear transfer functions. However, our findings about the effect of pure delay on human perception and action in virtual teleoperation suggest that such approaches do not capture the full picture, and that the human operator must be taken into account when transparency of teleoperation systems is defined.

In some studies, the human operator was taken into account by considering force perception thresholds [43]. These studies used a just noticeable difference (JND) paradigm for mechanical properties and time delay [36, 40], or frequency dependent weighted relative change in environment impedance [36, 44]. However, these studies only addressed the effect of teleoperation on the ability of the operator to discriminate between two levels of environment impedance, and not its effect on the perception of continuous levels of mechanical properties. Other approaches consider various coordinate transformations between the human hand and the remote robot, e.g. the hidden robot concept [45]. More abstract transformations involving gesture recognition were recently proposed [46]. However, these do not address force feedback.

The importance of the human operator for teleoperation in space application was stressed in previous works [6]. Moreover, evaluation of success of teleoperation in space in terms of EVA equivalency yielded strongly antromorphic arrangements of teleoperators [2, 16]. Our findings about the effect of pure delay in teleoperation on human perception and action motivate our approach, which is based on the adaptive properties of the human operator, and suggest a multidimensional measure for transparency that addresses both the perceptual and the motor aspects of bilateral teleoperation [15].

Perceptuomotor transparency

Consider a remote procedure that requires drilling a hole in a relatively soft material while avoiding damage to stiffer parts. In this scenario there are two actions (probing and drilling) and two perceptions (soft and stiff material). The operator acts in a local virtual environment in the ground control center but the actual procedure is done at a geosynchronous orbit. Three potential problems can arise due to an imperfect channel: (i) the operator can misperceive soft material as rigid; (ii) the operator can virtually damage the local model of the part when she wishes to probe it; (iii) the operator can actually damage the real remote part when she intends to probe it. These three problems correspond to the three aspects of transparency that we suggested [15] and review in the remainder of the section.

Motor Transparency Error

The following definitions refer to both local and remote transparencies. Consider the mixed configuration/force vector $q(t)$ which consists of the position, orientation, force, and angular torque:

$$q(t)=\left(\begin{pmatrix} x \\ y \\ z \end{pmatrix}^T \begin{pmatrix} \theta_x \\ \theta_y \\ \theta_z \end{pmatrix}^T \begin{pmatrix} f_x \\ f_y \\ f_z \end{pmatrix}^T \begin{pmatrix} \tau_x \\ \tau_y \\ \tau_z \end{pmatrix}^T \right)(t). \tag{3}$$

For a specific temporal window and sampling rate we observe the following mixed configuration/force matrix:

$$\underline{q}=\left(q(t_1)^T \quad q(t_2)^T \quad \cdots \quad q(t_N)^T\right)^T, \tag{4}$$

and define the motor transparency error based on the distance between the target reference trajectory $\underline{q}_{ref}$ and the actual (local or remote) trajectories using the teleoperation channel $\underline{q}_T$. Since noise always exists we compare the difference between the reference and actual trajectory $\underline{q}$ to the difference between reference and ideal trajectory – the trajectory through the ideal channel $\underline{q}_I$ – and propose the following measure for the Motor Transparency Error:

$$MTE=\frac{\left\|\underline{q}_T-\underline{q}_{ref}\right\|_W-\left\|\underline{q}_I-\underline{q}_{ref}\right\|_W}{C}, \tag{5}$$

where $\left\|\underline{q}\right\|_W$ is a norm with weighting matrix W that takes care of units conversion, physical quantities conversion, etc., such as the weighted quadratic norm $\underline{q}^T W \underline{q}$, or Mahalanobis distance, and C is a complexity measure of the task, such as the length or duration of the movement.

Perceptual Transparency Error

We concentrate on the perception of stiffness as an example of mechanical property of the environment. Since human perception of mechanical properties follows Weber's law [47, 48], we use a relative measure for perceptual transparency, and define the Perceptual Transparency Error as:

$$PTE=\left|\frac{\hat{K}_T-\hat{K}_I}{\hat{K}_I}\right|, \tag{6}$$

where $\hat{K}_I$ and $\hat{K}_T$ are the estimation of the perceived stiffness through the ideal and the transmission channels respectively.

Optimization of transparency

We formulated the goal to minimize the perceptual and remote motor transparency error as follows:

$$H = \underset{\substack{\text{teleoperation}\\ \text{channel}\\ \text{parameters}}}{\arg\min} \left\{ w_P PTE + w_{MR} MTE_R \right\}, \tag{7}$$

where the $_R$ subscript refers to remote, and where w_P and w_{MR} are the weights for perceptual and motor remote transparency errors respectively. This optimization should be performed such that human factor constraints are met at the local side.

A detailed derivation of analytical conditions for perfect transparency as well as simulation of transparentizing of non-ideal virtual teleoperation scenario can be found in [15].

V. DISCUSSION

There are numerous applications for teleoperation in space exploration including assembly, maintenance, and repair of satellites and space stations. These become even more prominent with the increasing use of satellites for communication, weather, and military applications, as well as with the progress in the exploration further into deep space, such as Mars exploration. In this paper we reviewed our human operator centered approach to teleoperation. We explored the effect of delay on perception and action of mechanical properties of the environment, and found that this effect is complicated and highly nonlinear. The perceptual distortion due to delay is modulated by the joint that is dominant in probing and by the relative frequency of contact with the boundary of elastic spring like force field. We also found inconsistency between the effect of delay on declarative and motor related estimations of mechanical stiffness. Based on these findings we suggested that the transparency of bilateral teleoperation systems should be assessed using a multidimensional measure which takes into account perceptual, remote motor, and local motor components. We suggest that it is important to achieve perceptual and remote motor transparency, and it can be achieved with non-ideal teleoperation channel by exploiting the adaptive properties of human motor control system, and the possible gap between perception and action.

One should note that there is an important difference between the environments that we explored in our studies and typical environments in today's space applications. In our studies we explored the effect of delay on perception of compliant objects with low to moderate levels of stiffness. However, in space applications up to date the tasks typically involve interaction with rigid parts. Future studies are required to reveal the effects of delay on human interaction with rigid objects. For example, the transition between movement in free space and contact with rigid object is of particular interest since it imposes instability on the system [49].

Nevertheless, interaction with compliant objects will become important in future applications of space teleoperation. In the recent years there has been extensive development of telesurgery techniques and devices [50-57]. With increasing number of personnel and time spent onboard of the international space station as well as the development of "space tourism" telesurgery will be the solution for the need in surgical intervention in case of medical emergency of crew members or passengers. In ground-space telesurgery the perception of mechanical properties of tissues becomes of great interest and importance. In addition, exploration of the surfaces of planets, e.g. Mars can be performed via teleoperation. While the delays are too large for the perception of mechanical properties of objects through teleoperation from Earth it is not the case for teleoperated exploration from orbit based space station.

Achieving transparency of a teleoperation system is a daunting challenge which is yet to be solved. We strongly believe that understanding the human motor control is essential in order to develop a useful system, and hope that the definitions and tools provided in this study would be useful in future development of teleoperation systems for space applications as well as for terrestrial applications such as telesurgery, telerehabilitation, and future applications of telepresence.

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