Haptic shared control for enhanced user comfort in robotic telemanipulation

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Haptic shared control for enhanced user comfort in robotic telemanipulation

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I. INTRODUCTION

Shared control methods have been used in many applications related to robotic teleoperation, making it possible to *share* the degrees of freedom of the system between the human operator and the autonomous controller. Examples include mobile robotics [1], robot-assisted surgery [2], and assistive robotics [3]. Haptic shared control is one such method, which utilizes haptic active constraints to share the control of the system between the user and the autonomous controller [4]. Haptic shared control has been successfully used to perform different tasks, e.g., to guide the operator toward a reference position [5], to avoid certain areas of the environment [6], to apply virtual nonholonomic constraints [7] and for learning manual tasks [8].

However, researchers have rarely focused on designing methods accounting for the user's comfort during robotic telemanipulation. While a few examples are available in the field of human robot interaction (HRI), e.g. [9], [10], haptic shared control has never been, to the best of our knowledge, designed for this specific purpose. This is nonetheless a very important issue for operators in many high-impact applications, using robotic teleoperation systems for long periods of time.

This paper introduces a haptic shared control technique minimizing the user's workload during robotic teleoperation. Using an inverse kinematic model of the human arm and an online implementation of the Rapid Upper Limb Assessment (RULA) tool [11], the proposed approach starts by estimating the current user's discomfort at runtime. Then, this metric is combined with some knowledge of the target task and system (e.g., direction to follow, target position to reach, effort demanded to the robot) to generate dynamic active constraints guiding the user towards a successful completion of the task along directions that require a reduced workload.

II. SYSTEM DETAILS

In this work, we consider a bilateral teleoperation system composed of a 6-DoF master interface and a velocity controlled 7-DoF slave robot, as shown in Fig. 1.

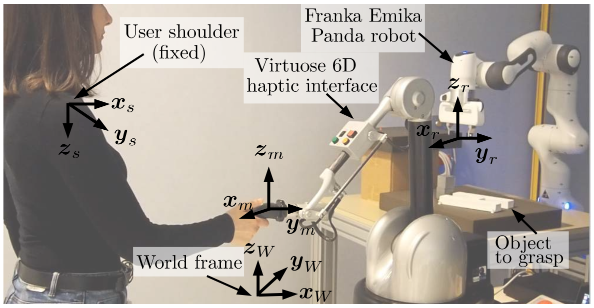

Fig. 1. The experimental setup for the pick and place task. On the master side, a Haption Virtuose 6-DoF haptic device, on the slave side a 7-DoF Franka Emika Panda robot. The user shoulder is assumed to be fixed.

As a first step, we devise an innovative approach to estimate the user's muscular comfort during the task, using an inverse kinematic model of the human arm and the popular RULA tool. We model the human arm as a 7-DoF robotic arm, with a spherical joint for representing the shoulder and the wrist, and a revolute joint for the elbow. Using the pose of the hand registered by the grounded haptic interface, and without the need of any additional sensor, we calculate, at each time step, $\boldsymbol{q}_s$ the shoulder angles, q_e the elbow angle, and $\boldsymbol{q}_w$ the wrist angles. More details on the inverse kinematics algorithm and solving the redundancy of the arm are presented in [12].

The workload $\mathcal{W}$ is then defined as the sum of the squared differences between the angles and their rest positions ($\pi/2$ for the elbow angle, and 0 for the others).

$$\mathcal{W} = \boldsymbol{q}_s^T \boldsymbol{q}_s + (q_e - \pi/2)^2 + \boldsymbol{q}_w^T \boldsymbol{q}_w. \qquad (1)$$

Although rather simple and fast to compute, this estimation has shown a good correlation and prediction capability with respect to the NASA TLX [13] results compiled by the users at the end of the task, proving its effectiveness and viability in this scenario.

In a second step, we combine this workload measure with a cost function related to the task at hand or the status of the robotic system. As an example, in our experiments, we considered a cost function $\mathcal{H}_r = [\boldsymbol{p}_{r,g} - \boldsymbol{p}_r, {}^r(\theta\boldsymbol{u})_{r,g}][\boldsymbol{p}_{r,g} - \boldsymbol{p}_r, {}^r(\theta\boldsymbol{u})_{r,g}]^T$, indicating the distance between the current pose of the robot $\{r\}$ and its goal position $\{r,g\}$. However, the proposed framework supports *any* other task-related cost function (e.g., trajectory minimizing the energy consumed, displacement, risks of encountering singularities). From the combination of the two cost functions $\mathcal{H}_\mathcal{W} = \mathcal{W}$ and $\mathcal{H}_r$, we then generate a dynamic active constraint guiding the user towards a successful completion of the task along directions maximizing the user comfort.

R. Rahal and G. Matarese are with Univ Rennes, Inria, CNRS, IRISA, Rennes, France, {rahaf.rahal, giulia.matarese}@irisa.fr. These two authors contributed equally to the manuscript.

M. Gabiccini and A. Artoni are with the Dip. Ingegneria Civile e Industriale, Univ. Pisa, Pisa, Italy, {m.gabiccini,a.artoni}@ing.unipi.it. M. Gabiccini is also with the Centro di Ricerca "E. Piaggio", Univ. Pisa, Pisa, Italy.

D. Prattichizzo is with the Dip. Ingegneria dell'Informazione e Scienze Matematiche, Univ. Siena, Siena, Italy and with the Dept. Advanced Robotics, Istituto Italiano di Tecnologia, Genova, Italy, prattichizzo@diism.unisi.it.

P. Robuffo Giordano, and C. Pacchierotti are with CNRS, Univ Rennes, Inria, IRISA, Rennes, France, {prg, claudio.pacchierotti}@irisa.fr.

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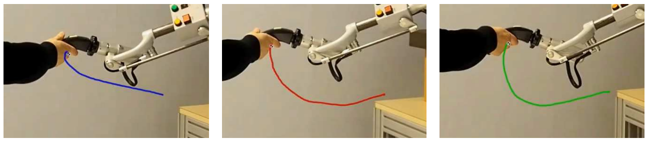


(a) A0 (b) A20 (c) A40

Fig. 2. User trajectory for a reaching movement for the three weightings A0 (blue), A20 (red), and A40 (green). In A0, only $\mathcal{H}_r$ is considered, and the user trajectory is therefore almost horizontal. As the contribution of $\mathcal{H}_\mathcal{W}$ to the haptic feedback increases, the trajectory tries to minimize the user discomfort by moving the arm to a downward (more comfortable) position.

We design the haptic feedback to guide the user during teleoperation, such that both task- and human-comfort-inspired cost functions are minimized. We thus divide our haptic feedback force into two components: a human-related component, $\boldsymbol{f}_\mathcal{W}$, and a robot/task-related one, $\boldsymbol{f}_r$. The forces applied at the master end effector are defined as

$$\boldsymbol{f}_m = \alpha \boldsymbol{f}_\mathcal{W} + \beta \boldsymbol{f}_r, \tag{2}$$

where $\boldsymbol{f}_\mathcal{W}$ is the force vector instantaneously guiding the user towards the position with the highest comfort (minimizing $\mathcal{H}_\mathcal{W}$), and vector $\boldsymbol{f}_r$ is the force minimizing the task cost function $\mathcal{H}_r$, which in our case is related to the distance from the target release position. α and β are weights to be tuned depending on the importance to be given to each cost function. More details on the system architecture and the haptic feedback implementation are given in [12] and in the video at `https://youtu.be/DodGI4wMRFA`.

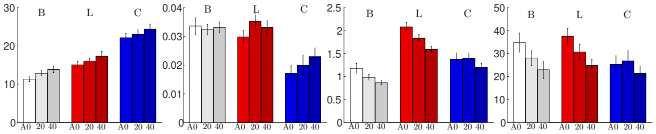
Fig. 2 shows the effect of the weighting schemes in a simple reaching movement between two fixed points.

III. EXPERIMENTS AND RESULTS

To evaluate the effectiveness of our method, we designed a user study with 15 participants. The task consisted of pick and place trials on three different objects: a box (B), 2 cubes (C), and a wooden letter (H). We consider three weighting schemes for the contribution of each force component in eq. (2): $\alpha = 0, \beta = 1$ (A0, the human-centered metric is disregarded), $\alpha = 0.2, \beta = 0.8$ (A20, weak human-centered guidance), and $\alpha = 0.4, \beta = 0.6$ (A40, strong human-centered guidance).

To evaluate the effectiveness of the proposed human-centered shared control approach, we recorded *(i)* the completion time, *(ii)* the error in placing the objects at the target, *(iii)* the maximum $\mathcal{H}_\mathcal{W}$ registered, and *(iv)* the NASA Task Load Index (NASA-TLX). Results of the statistical analysis performed are summarized in Fig. 3.

Completion time showed a significant degradation when adding our human-centered guidance (A20, A40) vs. standard task-centered guided teleoperation (A0). However, this (small) performance degradation is compensated by a significant reduction of the estimated muscular discomfort ($\mathcal{H}_\mathcal{W}$) and measured workload (NASA TLX). In fact, while the completion time and placing error degrade by 14% and 10%, respectively, the NASA TLX value is improved by 30%.



(a) Completion time (s). (b) Error placing the objects (m). (c) Maximum $\mathcal{H}_\mathcal{W}$ value (rad^2). (d) NASA TLX load index.

Fig. 3. Human subjects experiment. Mean and standard error of the mean of (a) completion time, (b) error in placing the objects, (c) maximum $\mathcal{H}_\mathcal{W}$, and (d) NASA TLX load index for the three control conditions (A0, A20, A40) and the three target objects (B, L, C).

IV. CONCLUSION

In this paper, we presented a haptic shared control for robotic teleoperation that combines human-centered and task-centered cost functions. We propose a metric to estimate the user discomfort at runtime, and combine it with some knowledge of the target task to generate active constraints guiding the user towards a successful completion of the task along directions that require a reduced workload. Studies with human subjects show the effectiveness of the proposed approach, yielding a 30% perceived reduction of effort with respect to standard guided human-in-the-loop teleoperation.

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