Human-subject Evaluation of Shared-Control Approaches for Robotic Telemanipulation
Firas Abi-Farraj, Claudio Pacchierotti, Paolo Robuffo Giordano

To cite this version:
Firas Abi-Farraj, Claudio Pacchierotti, Paolo Robuffo Giordano. Human-subject Evaluation of Shared-Control Approaches for Robotic Telemanipulation. 2017 IEEE/RSJ IROS Workshop Human in-the-loop robotic manipulation: on the influence of the human role, Sep 2017, Vancouver, Canada. hal-01691114

HAL Id: hal-01691114
https://inria.hal.science/hal-01691114
Submitted on 23 Jan 2018

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I. INTRODUCTION

Remote telemanipulation has shown significant advancements over the last years and promising results have been achieved in several robotic tasks [1], [2]. Handling radioactive waste in nuclear decommissioning sites is an important example of such a task where telemanipulation systems are already heavily used. However, currently-employed systems are still extremely primitive, making the handling of these materials prohibitively slow and ineffective. As the estimated cost for the decommissioning and clean-up of nuclear sites keeps rising, it is clear that one would need faster and more effective approaches.

Towards this goal, several recent works have been presented in the context of the European H2020 Robotic Manipulation for Nuclear Sort and Segregation (RoMaNS) project [3], [4]. We present, in this context, the evaluation of a haptic-enabled shared-control architecture for telemanipulation. It was inspired by the work of Abi-Farraj et al. [5], who presented the algorithmic design of the shared-control architecture, but without providing any user evaluation. The experimental setup is shown in Fig. 1. The master system is composed of the Haption Virtuose 6D haptic device, a high performance force feedback device with three active translational DoF and three active rotational DoF. The slave system is composed of a 6-DoF Viper S850 robotic arm carrying a pneumatic parallel gripper. A wooden object is placed on a table in front of the robotic manipulator. An autonomous algorithm is in charge of regulating a subset of the manipulator DoF to help the human operator in grasping the object. At the same time, the human operator steers the robotic end-effector along the remaining null-space directions with respect to the main task using the Virtuose haptic interface.

II. SHARED CONTROL ARCHITECTURE

In our implementation, the autonomous algorithm controls 2 DoF of the robotic manipulator, keeping the gripper always oriented toward the object to grasp. The gripper is therefore constrained to move on the surface of a virtual sphere centered on the object. The human operator is then able to move the gripper across the surface of the sphere and toward/away from the object (i.e., changing the radius of the sphere), controlling the remaining 4 DoF of the robot.

To this end, let \( s \) be the variable designating the direction from the gripper to the object \( s = \frac{G P_o}{||G P_o||} \in \mathbb{S}^2 \). The autonomous algorithm drives \( s \) to be aligned with the \( z \)-axis of the gripper in order to keep the gripper oriented towards the object as described before. The control law governing the motion of the gripper will then be

\[
V_G = \begin{bmatrix} v_G \\ \omega_G \end{bmatrix} = k_G L_s^\dagger (Z_G - s) + \sum_{i=1}^{n} \lambda_i n_i, \quad k_G > 0, \tag{1}
\]

where \( k_G \) is a control gain, \( L_s^\dagger \) represents the Moore-Penrose pseudo-inverse of the interaction matrix \( L_s \) associated with \( s \) (\( s = L_s V_G \)), \( Z_G \) is the axis associated with the gripper (Fig. 1), \( \Lambda = [\ldots \lambda_i \ldots] \in \mathbb{R}^4 \) indicates the pseudo-velocity commands of the human operator and \( N_B = [\ldots n_i \ldots] \in \mathbb{R}^{6 \times 4} \) is a basis spanning the null space of \( L_s \).

On the master side, the force feedback received by the operator mainly aims at keeping the user away from pre-defined constraints (singularities and joint limits in our scenario), which are described by a cost function \( H \). The corresponding force cues are then defined by

\[
\tau = -B_M \dot{x}_M - \left( \frac{\partial H(q)}{\partial q} \right)^T J_G^{-1}(q)n_i, \tag{2}
\]

i.e., by projecting the joint motion caused by the \( i \)-th null-space direction \( n_i \) onto the negative gradient of \( H(q) \). Matrix \( J_G(q) \in \mathbb{R}^{6 \times 6} \) is the geometric Jacobian of the manipulator. \( B_M \in \mathbb{R}^{4 \times 4} \) is a positive definite matrix indicating the damping factor and \( x_M \) represents the master device's configuration vector.

III. EXPERIMENTAL EVALUATION

A. Experimental conditions, task, and participants

Participants were required to control the motion of the robotic manipulator and gripper to grasp the wooden piece and lift it from the ground.

We considered two different ways of commanding the motion of the robot through the haptic interface

1) Position-Velocity (PV): positions of the haptic device are mapped into velocities of the manipulator
2) Velocity-Velocity (VV): velocities of the haptic device are mapped into velocities of the manipulator.
Figure 2b shows the average linear motion covered by the robotic gripper during the task. The two-way ANOVA test revealed a statistically significant change in the trajectory length for both the human involvement in the control (F(1, 9) = 30.968, p < 0.001) and the motion control type (velocity vs. position, F(1, 9) = 9.035, p = 0.015) variables. The one-way ANOVA test revealed a statistically significant change in the trajectory length across the conditions (F(1.929, 17.360) = 14.072, p < 0.001). Post hoc analysis with Bonferroni adjustments revealed a statistically significant difference between S+V vs. S+P (p = 0.049), S+V vs. T+V (p = 0.043), S+V vs. T+P (p = 0.002), and S+P vs. T+P (p = 0.012).

Figure 2c shows the average angular motion covered by the robotic gripper during the task. The two-way ANOVA test revealed a statistically significant change in the angular motion for both the human involvement in the control (F(1, 9) = 39.350, p < 0.001) and the motion control type (position-velocity vs. velocity-velocity, F(1, 9) = 8.202, p = 0.015) variables. The one-way ANOVA test revealed a statistically significant change in the trajectory length across the conditions (F(3, 27) = 12.994, p < 0.001). Post hoc analysis with Bonferroni adjustments revealed a statistically significant difference between S+V vs. S+P (p = 0.025), S+V vs. T+V (p = 0.007), S+V vs. T+P (p = 0.001), S+P vs. T+V (p = 0.034), and S+P vs. T+P (p = 0.005).

Figure 2d shows the perceived effectiveness for the four experimental conditions, asked using bipolar Likert-type nine-point scales. A Friedman test showed a statistically significant difference between the means of the four feedback conditions (χ²(3) = 26.753, p < 0.001, α = 0.05). The Friedman test is the non-parametric equivalent of the more popular repeated-measures ANOVA. The latter is not appropriate here since the dependent variable was measured at the ordinal level. Post hoc analysis with Bonferroni adjustments revealed a statistically significant difference between S+V vs. S+P (p < 0.001), S+V vs. T+P (p = 0.026), S+P vs. T+V (p < 0.001), and S+P vs. T+P (p = 0.044).

IV. CONCLUSIONS

Results showed that, in all the considered metrics, the shared-control approach significantly outperformed the more classic teleoperation architecture. Moreover, all the subjects preferred the shared-control architecture with respect to teleoperation. This proves our hypothesis that shared-control can be a viable and very effective approach to improve currently-available teleoperation systems in remote manipulation tasks.

REFERENCES