Shared-Control Paradigms in Multi-Operator-Single-Robot Teleoperation

Daniela Feth, Binh An Tran, Raphaela Groten, Angelika Peer and Martin Buss

Abstract Extending classical bilateral teleoperation systems to multi-user scenarios allows to broaden their capabilities and extend their applicability to more complex manipulation tasks. In this paper a classical Single-Operator-Single-Robot (SOSR) system is extended to a Multi-Operator-Single-Robot (MOSR) architecture. Two shared-control paradigms which enable visual only or visual and haptic coupling of the two human operators are introduced. A pointing task experiment was conducted to evaluate the two control paradigms and to compare them to a classical SOSR system. Results reveal that operators benefit from the collaborative task execution only if haptic interaction between them is enabled.

1 Introduction

This paper extends classical bilateral teleoperation architectures to multi-user scenarios with the aim of broadening their capabilities and extending their applicability to more complex manipulation tasks. The focus of this work is on a Multi-Operator-Single-Robot (MOSR) architecture which enables two humans (H), both operating a human-system interface (HSI) to control collaboratively one teleoperator (TOP) in a shared-control mode.

In literature, MOSR-like shared-control architectures are known from student-teacher scenarios, whereby a trainee is supported by a trainer in performing manipulation tasks. Chebbi et al. [1] introduced three different types of haptic interaction modes suitable for such an scenario: no, unilateral, or bilateral haptic signal exchange. An example for an unilateral information exchange is implemented in [2], whereby a trainee receives position and force feedback about the trainer's actions. In [3] control architectures that allow a bilateral haptic signal exchange in a virtual bone drilling scenario are presented. Finally, in [4, 5] a dominance factor α is introduced to assign clear roles of dominance to the interacting partners according to their skill level.

Further applications for MOSR systems can be found in the field of semi-autonomous teleoperation. The high physical and cognitive requirements when operating a classical bilateral teleoperation system desire often for a technical assistant

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which helps the human operator in executing a task [6]. This results in a semi-autonomous teleoperation system that enables the interaction between a human operator and an assistance function and, thus, forms a MOSR system.

Finally, a quite different motivation for MOSR architectures is given by studies of haptic human-human interaction in joint object manipulation tasks. It is shown that task performance of two humans solving a haptic task collaboratively [7] is higher than of a single operator performing the same task. Hence, we expect that adding an additional human operator to a classical bilateral teleoperation scheme has a positive effect on task performance.

Not only single and partner conditions are compared but also the influence of the presence of haptic feedback in technically mediated systems is analyzed. In [8] the performance of a vision-only and vision-haptic condition in a ring-on-wire task is contrasted. They conclude that the interacting partners benefit from the additional haptic feedback. Sallnäss [9] reports the same positive effect of haptic feedback on task performance in a collaborative cube lifting task.

In this paper, we propose a general framework for a MOSR teleoperation system that enables haptic interaction with the remote environment and with the interacting partner. Based on this, we introduce two shared-control paradigms which realize different types of interaction. Unlike teacher-student scenarios, we assume equally skilled human operators and focus on the interaction between them. Furthermore, we consider only tasks which can be performed successfully by a single operator, too. The two paradigms are implemented on a 6 DOF teleoperation system and compared to each other with respect to task performance. Additionally, they are compared to a Single-Operator-Single-Robot teleoperation condition which allows to make statements on the differences between multi-user and single-user teleoperation.

2 Overall MOSR Control Architecture

A classical force-position (F-P) architecture [10] has been extended to form a MOSR system.

The realization of a haptic MOSR system requires to face three main challenges: i) realizing simultaneous control of the remotely located teleoperator, ii) providing feedback from the remote environment, and iii) from the interacting partner.

To approach these challenges, we define three different components: *signal fusion*, *feedback distribution*, and *partner interaction*. Their location within the global

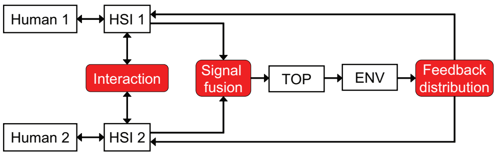


Fig. 1: Multi-Operator-Single-Robot architecture

teleoperation control scheme is illustrated in Fig. 1. Depending on the selected shared-control paradigm different implementations of these components have to be realized.

3 MOSR Shared-Control Paradigms

Two shared-control paradigms enabling different couplings between the human operators and the environment are introduced in this section. They lead to different haptic interaction forms, manifested in different implementations of the above mentioned components *signal fusion*, *partner interaction*, and *feedback distribution*.

3.1 Visual Coupling of Operators

The first shared-control paradigm enables operators to move their haptic interfaces independently. This is achieved by providing only visual, but no haptic feedback about the partner's action and distributing the feedback from the remote environment such that the operator receives only forces caused by her/his own action. In terms of assistance functions, this would correspond to a function that supports the task execution on the remote side and the human operator receives only visual, but no haptic feedback about this support. In order to realize this paradigm the components *signal fusion, partner interaction* and *feedback distribution* are as follows:

Signal fusion: Shared control of the common teleoperator is realized by a weighted sum of the positions of the single haptic interfaces

$$x_m = \alpha x_{m1} + (1-\alpha) x_{m2}. \tag{1}$$

The dominance factor α has been first introduced in [4, 5] to account for different dominance distributions in teacher-student scenarios. We assume both interaction partners to be equally skilled as dominance distributions are not the focus of this work, hence, $\alpha = 0.5$ is chosen.

Partner Interaction: There are no haptic signals exchanged between the haptic interfaces of the interacting operators.

Feedback Distribution: Feedback forces from the remote environment have to be mapped to both of the operators' haptic interfaces. Inspired by [11] we decided for a paradigm where each human operator receives only haptic feedback about her/his own action. Thus, the operator receives force feedback only if she/he really contributes to the interaction force f_{env} with the environment, which means that f_{env} points to the opposite direction of f_h, the force applied by the respective operator. Force feedback is divided as follows: If the partner does not apply a force against f_{env}, the operator receives full force feedback from the environment $f_{env1} = f_{env}$. However, if both partners apply a force against f_{env}, force feedback is distributed as follows:

$$f_{env1} = \beta f_{env}, \qquad f_{env2} = (1-\beta) f_{env}, \qquad \text{with} \quad \beta = \frac{f_{h1}}{f_{h1} + f_{h2}}. \tag{2}$$

This kind of shared-control paradigm can not be realized in real physical scenarios, but in teleoperation or in virtual reality. It enables free-space motion of the operators without any interference by the partner as they act independently. But, the human operators can infer on their partner's action only by the visual motion of the teleoperator. Haptic and visual feedback are inconsistent.

3.2 Visual and Haptic Coupling of Operators

The second shared-control paradigm realizes a visual and haptic coupling of the operators, see Fig. 2. Imagine two human operators holding the ends of a rigid object, e.g. a rod, and interacting with the environment via this rod. In our teleoperation scenario, the rod is represented by the teleoperator and the required coupling of the operators is realized by a virtual rigid connection between the two haptic interfaces. Again, the components to achieve such a coupling are discussed in the following paragraphs.

Signal Fusion: The stiff coupling of the operators causes $x_{m1} = x_{m2} = x_m$. Hence, only the position of one haptic interface has to be sent to the remotely located teleoperator.

Partner Interaction & Feedback Distribution: Due to the rigid connection of the operators they receive full haptic feedback from their partner as well as from the remote environment. Hence, the desired forces f_{m1d} and f_{m2d} to be displayed by the haptic interfaces are calculated by

$$f_{m1d} = f_{m2d} = f_{h1} + f_{env} + f_{h2} \qquad \text{where} \qquad f_{env} = f_{env1} = f_{env2}. \tag{3}$$

In this shared-control paradigm visual and haptic feedback are congruent without any inconsistencies. Operators receive full information about the task execution and the partner's behavior. However, the operators' actions are not independent as they strongly depend on the partner's behavior what results in a restricted operating range.

4 Teleoperation System

Both shared-control algorithms are implemented on a real teleoperation system with visual and haptic feedback devices. As shown in Fig. 3a the operator side consists of two admittance-type haptic input devices with 6 DOF. The kinematics and technical specifications of the teleoperator (Fig. 3b) are the same as the ones of the haptic input devices. A 6 DOF force/torque-sensors (JR3) is mounted at the tip of the manip-

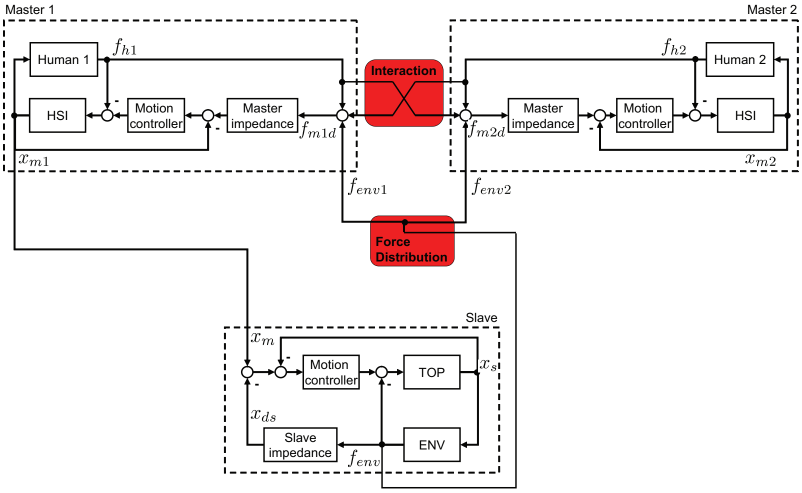
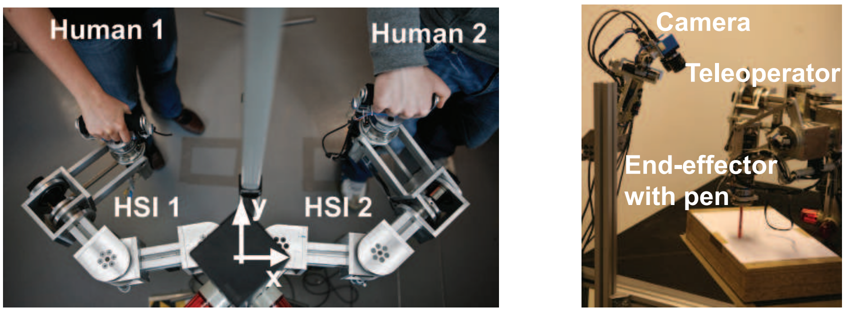


Fig. 2: Teleoperation architecture with local position-based admittance controllers applied for visual and haptic coupling of operators

ulators to measure interaction forces with the human operator and the environment. For details on the teleoperation system please refer to [12, 13].

The control of the telemanipulation system, see Fig. 2, was implemented in Matlab/Simulink. Real-time capable code is generated by using the Matlab Real-Time Workshop and executed on two computers with the Linux Real-Time Application Interface (RTAI). Communication between the two computers is realized by an UDP connection in a local area network, thus time delay can be neglected.

Visual feedback was provided by two computer monitors displaying the image of a CCD firewire camera that captures the remote environment and teleoperator. Thus, both operators had the same fixed view point and, hence, the same information about the remote environment.



(a) Haptic input devices on operator side

(b) Teleoperator side

Fig. 3: 6 DOF teleoperation system

5 Experimental Evaluation

An experiment was conducted to evaluate the implemented MOSR shared-control paradigms with respect to task performance. We compared the two implemented control strategies of operator coupling to a classical bilateral teleoperation system where one human operates one teleoperator. As an exemplary task a pointing task was chosen, requiring fast as well as accurate behavior of the operators.

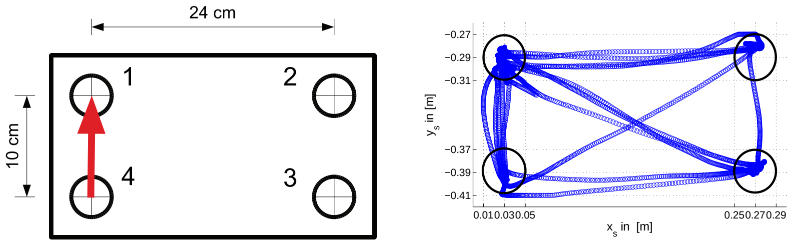
Task: Participants carried out a pointing task by controlling their haptic input devices such that the teleoperator's end-effector moved from one desired position to the next. These target positions were visualized as 4 circles with a radius of 2 cm on a sheet of paper which was placed underneath the end-effector of the teleoperator, see Fig. 3b and Fig. 4a.

Participants were instructed to move the tip of a pen mounted on the teleoperator's end-effector as fast and as accurate as possible from a starting position to the center of one of the circles. By touching the surface of the paper with the pen a dot was drawn on the paper to provide visual feedback to the operators. A target was achieved successfully as soon as the surface was contacted by the pen within the desired circle (if $F_z > 1$ N). After the first target was achieved a new circle was assigned as next target. Information about the current target circle was provided by a second monitor placed next to the camera image. The current step was always marked with an arrow as indicated in Fig. 4a.

The order of the targets was a random combination of four pre-defined paths each containing four different circles (e.g. $1 \rightarrow 2 \rightarrow 3 \rightarrow 4$). The length of the resulting overall paths was kept constant.

Experimental Design & Procedure: Three experimental conditions were analyzed. The already introduced shared-control paradigms were contrasted to a single condition, whereby the meaning of each experimental condition can be summarized as follows:

- Single (S): each participant performed the task alone
- Visual coupling (V): operators were only visually coupled
- Visual and haptic coupling (VH): operators were visually and haptically coupled



(a) Target positions indicated by circles; the arrow indicates the next target

(b) x-y position of one trial (VH conditon)

Fig. 4: Pointing task

Table 1: Experimental results: Means and std. deviations of performance measures

	$\overline{\varepsilon}$ in [m]	σ_ε	$\overline{tct}$ in [s]	σ_{tct}
S	0.0069	0.0017	72.64	24.99
V	0.0076	0.0014	54.11	16.43
VH	0.0078	0.0023	41.16	9.51

In the experiment, 26 participants (13 female/ 13 male, age $= 25.04 \pm 2.79$ years) took part. They were assigned pseudorandomly to 13 independent couples of 1 male and 1 female. Each participant performed the task once in each of the three randomized conditions.

Data Analysis: We analyzed task performance by evaluating the task error (accuracy) and task completion time (speed).
The *task error* ε of each trial is defined by the mean Euclidian distance of the dot's position $(x_{dot}|y_{dot})$ (drawn by the participants) from the center of the respective target circle $(x_c|y_c)$

$$\varepsilon = \frac{1}{M}\sum_{i=1}^{M}\sqrt{(x_c - x_{dot})^2 + (y_c - y_{dot})^2} \tag{4}$$

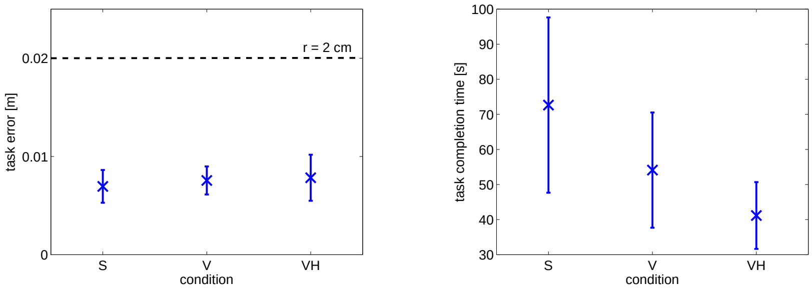
with $M = 16$ the total number of target circles in each trial. If multiple points were drawn, the first point inside the circle was taken.
The *task completion time* tct is defined as the time required to perform the task sucessfully.

Results: We analyzed the experimental data with respect to the above introduced performance measures for each of the three experimental conditions. The x-y teleoperator position for an exemplary VH trial is shown in Fig. 4b. Table 1 as well as Fig. 5a and 5b show the means and standard deviations.

As can be observed there is no difference in task performance with respect to the *mean task error* for each of the three conditions (one-factorial repeated measurement ANOVA, Greenhouse-Geisser corrected, $F(1.3, 15.60) = 0.994$, $p = 0.357$).

Task completion time is smallest in the VH condition. A one-factorial repeated measurement ANOVA (Greenhouse-Geisser corrected, $F(1.16, 13.93) = 14.86$, $p = 0.001$, partial $\eta^2 = 0.553$) reveals a significant effect of the shared-control conditions on task completion time. Post-hoc Bonferroni adjusted pairwise comparisons show a significantly better task completion time in the VH condition compared to the S as well as the V condition. There is no significant difference between S and V.

Discussion: For interpretation of the achieved results our special task design has to be considered: Participants could move to the next target only if they placed the pen inside the current target circle which automatically causes the task error to be upper bounded by 2 cm. This explains why the task completion time varies between the conditions, but the task error remains approximately constant.



(a) Task error (mean and standard deviation); $r = 2$ cm is the radius of the target circles

(b) Task completion time (mean and standard deviation)

Fig. 5: Task performance in the three experimental conditions

In the here presented teleoperation scenario task performance is better if haptic feedback is provided compared to the V and S condition. This is consistent with results reported by related work out of the field of haptic human-human interaction [8, 9, 7].

However, our results reveal no significant difference of task performance in S and V condition. This is contradictory to the results we presented on a 1 DOF pursuit tracking task in [14]. We assume this is due to the fact that the multi-DOF pointing task is more complex and requires higher motion coordination of the operators than the 1 DOF tracking task. In fact, during the experiment we observed that participants had difficulties to synchronize their actions in the V condition.

6 Conclusion

In a Multi-Operator-Single-Teleoperator scenario appropriate shared-control laws have to be defined to enable i) *fusion of the signals sent to the teleoperator*, ii) *distribution of the feedback received from the remote environment*, and iii) *haptic interaction between the human operators*. We introduced two different Multi-Operator-Single-Teleoperator (MOSR) shared-control paradigms that are characterized by a visual coupling only and visual and haptic coupling of the operators. According to the desired behavior of the MOSR teleoperation system the three parts i)-iii) were defined and have been realized on a 6 DOF teleoperation system. The achievable task performance using these couplings was evaluated by an experiment comparing them to a classical SOSR teleoperation system. Results showed that adding a second human operator had only a positive effect on task performance if haptic feedback of the partner was provided. The results cannot be compared to findings obtained in student-teacher scenarios [4, 5] due to their different dominance distributions. Furthermore, the observed benefit might be task-dependent. Hence, further studies are needed for generalization.

Future research will focus on defining further MOSR shared-control architectures to improve task performance in haptic interaction tasks as well as the stability analysis of the proposed architectures.

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