# Evaluation of a Coordinating Controller for Improved Task Performance in Multi-User Teleoperation

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**Abstract** In virtual reality as well as teleoperation the interaction between multiple users is impaired by the mediated signal exchange between partners. To answer challenges of such scenarios assistance functions taking the interaction into account need to be developed. In this work, a coordinating controller implementing a virtual coupling between the participants is evaluated. Goal of the controller is to improve movement synchronization between partners leading to higher overall performance. As the coupling may cost additional effort, the evaluation considers an efficiency measure which relates performance to effort. An experiment is conducted with 20 participants. Contrasting the presented approach to relevant control conditions shows that the proposed virtual coupling results in a significantly higher efficiency: the relative growth in performance exceeds the increase in effort. Hence, the coordinating controller can be concluded to be a beneficial assistance for haptic collaboration.

**Keywords:** teleoperation, telepresence, collaboration, multi-user, coordinating controller, evaluation, performance, effort, efficiency

## 1 Introduction

Manipulating objects over a teleoperation system or within a virtual environment is per se challenging. Joint manipulation of an object in a shared remote environment poses an additional challenge: interacting partners must coordinate their actions although the signal exchange between them may be impaired by the technical system. Thus, perception of the partner and environment, and joint action of the partners may not be as realistic as in everyday life. This is especially problematic when the task involves precise movements, or the object is valuable or sensitive. Adding a coordinating controller can help to overcome these difficulties and significantly improve coordination and thus, facilitate joint manipulation.

A known approach in this direction based on an adaptive controller was published in [1]. In their work stable interaction with the object is achieved by using

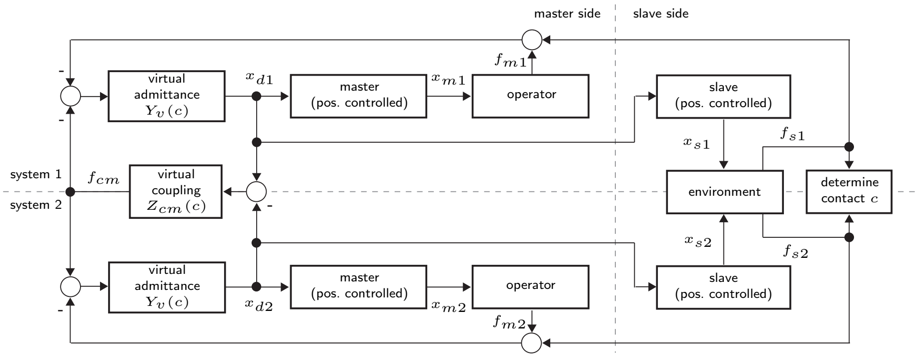

**Figure 1.** Control structure of coordinating controller.

an internal force controller. The object dynamics in the remote environment is canceled and replaced by a virtual object. This results in several drawbacks: Dynamic properties of the object are not observable any more by the operators, and forces applied to the object are predefined by the desired internal force. Furthermore, the effect of these issues on human performance, coordination ability, and feeling of presence was not studied since no evaluation was performed.

In [2] two new algorithms were presented for haptic interaction in virtual environments: a) a virtual spring is pulling both users towards the object and b) a virtual damping is guiding the partners towards equivalent speed of the individual movements. However, the results do not indicate that the newly developed algorithms lead to higher user-performance than approaches providing classical force feedback resulting from the interaction with the virtual environment only.

In [3] we introduced a new coordinating controller: it adds a virtual coupling between the two interacting partners, which consists of a damper acting on the relative speed of the two systems. The goal of this paper is to investigate the potential of this controller to improve task performance in multi-user setups.

### 1.1 Coordinating Controller

Fig. 1 depicts the coordinating control structure developed in [3]: Two single-user teleoperation systems (system 1/2) are connected using a *virtual coupling* $\boldsymbol{Z}_{cm}(c)$ which generates a force $f_{cm}$ proportional to the relative desired motion $x_{d1} - x_{d2}$ of the single systems. The virtual coupling is only active in contact. Contact phases ($c = 1$) are distinguished from non-contact phases ($c = 0$) by a force threshold: if the two teleoperator arms push against each other with a force of 1 N or above this is determined as contact, if the force is below this threshold this is determined as non-contact[1]. As virtual coupling we consider the impedance

$$\boldsymbol{Z}_{cm} = c\, b_{cm} s. \tag{1}$$

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[1] The threshold of 1 N was determined as suitable with pre-studies.

Therefore, the two systems are coupled via a virtual damping $b_{cm}$. The force $f_{cm}$ generated by the virtual coupling is fed into the virtual admittance $\boldsymbol{Y}_v$ of each system together with the respective measured forces $f_{m1}$ / $f_{m2}$ from master side and $f_{s1}$ / $f_{s2}$ from slave side. For the virtual admittance $\boldsymbol{Y}_v$ a mass-damper system

$$\boldsymbol{Y}_v = \frac{1}{m_d s^2 + c\, b_{dc} s + (1-c)\, b_{df} s} \tag{2}$$

is used in which $m_d$ is the desired mass and damping can be switched depending on the contact situation, i.e. the damping is $b_{df}$ during free-space motion and $b_{dc}$ in contact. The desired positions $x_{d1}$ / $x_{d2}$ generated by the two admittance models are used as input for position-controlled haptic interfaces on master side and teleoperator arms on slave side[2].

### 1.2 Research Questions

The research questions raised in the experimental evaluation consider the efficiency (relation between performance and physical effort) of haptic interaction. This is motivated by the fact that we want to relate performance benefit to the increased physical effort which may accompany higher damping parameters.

**Virtual coupling:** If the two partners, who jointly perform the haptic interaction task are coupled via a damper, asynchronous movements of the two partners are prevented. This should avoid mistakes like dropping the object. Furthermore, we assume that the coupling does not provoke additional physical effort (forces) during task completion, as long as the two partners move in synchrony. Hence, we expect a higher performance if virtual coupling is provided ($b_{cm} > 0$). In addition, we will examine the effect of virtual coupling on physical effort and efficiency.

**Damping:** We want to determine whether an increase in task performance and efficiency is caused by higher damping in general or specifically by the virtual coupling between the two partners. Therefore, we vary damping $b_{df}$ and $b_{dc}$ of the separate systems to access this effect. Higher damping is expected to increase the effort necessary to perform movements. However, additional damping can also be seen as a low pass filter for movements which may lead to a more stable interaction, i.e. the partner's movements become more predictable which might lead to better performance.

**Repetition:** A well-trained dyad could benefit less than unfamiliar partners from the coordinating controller. As a preliminary investigation, we analyze repetitions of the same task to check for learning effects.

## 2 Experiment

Two partners manipulated a 4 degrees of freedom (DOF) haptic interface each, which allowed them to control two teleoperator arms with 4 DOF (see Fig. 2).

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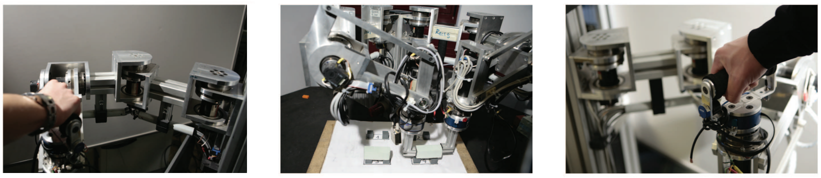
[2] Computed-torque controllers with gravity compensation are used in the inner control loop, where PD-controllers compensate remaining modelling errors.



master 1 slaves 1 & 2 master 2

**Figure 2.** *Experimental Setup:* One partner controlled the left teleoperator arm (slave 1) by using the haptic interface depicted on the left (master 1) while the other partner controlled the right teleoperator arm (slave 2) by using master 2.

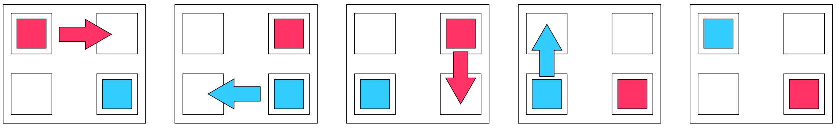


**Figure 3.** *Instructions for one trial of the experiment:* The five images above were shown from left to right during one trial of the experiment. The two colored squares mark the positions of the objects at the beginning of the current manipulation, the arrows show the desired movement of the objects. Participants had to perform 4 moving operations, thereby swapping the position of the two objects.

The devices provide all three translational DOF and rotations around the vertical axis. As rotation was not necessary to perform the task the devices were controlled to always have the same orientation of the end-effectors. The task was to move two objects (7.5 cm × 3.0 cm × 2.5 cm blocks made of polystyrene) sequentially in an instructed order to four different positions marking the corners of a rectangle (compare Fig. 3). The objects had to be placed on top of pedestals (two cubes with an edge length of 2.0 cm, see Fig. 2) accurately enough so they did not fall down (an accuracy of approx. 1 cm was necessary). The teleoperator arms did not provide any grippers, which increased the difficulty of the task. Thus, it was essential that the two partners found a shared strategy to maneuver the object by pressing the end-effectors against each other. In addition to haptic feedback, visual mono feedback was provided over a camera image displayed on a monitor[3]. The participants were shown the task they had to execute by a presentation (see Fig. 3) which was shown on a second monitor. Haptic interfaces and teleoperator arms were located in the same room, leading to negligible time-delay. To increase the internal validity of the experiment participants wore headphones to prevent oral communication and a wall was placed between them.

We were interested in the effect of virtual coupling and "general" damping on performance and related effort. Therefore, we examined the two factors **damping** and **virtual coupling**. See Table 1 for the different conditions and related

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[3] The camera covered the area in which the task was performed from a $45^o$ degree viewing angle (relative to the horizontal plane) from the front.

**Table 1.** Experimental conditions based on two factors (see section 1.1 for details).

| Condition No. | Damping | | | Virtual coupling | |
|---|---|---|---|---|---|
| | | $b_{df}$[Nsm$^{-1}$] | $b_{dc}$[Nsm$^{-1}$] | | $b_{cm}$[Nsm$^{-1}$] |
| 1 | **low** | 10 | 10 | **off** | 0 |
| 2 | **mixed** | 10 | 100 | | |
| 3 | **high** | 100 | 100 | | |
| 4 | **low** | 10 | 10 | **on** | 100 |
| 5 | **mixed** | 10 | 100 | | |
| 6 | **high** | 100 | 100 | | |

parameters (determined by pre-studies) [4]. As shown in [3] these values result in a robustly stable system. Although switching (when coming into contact and loosing contact with the partner via the object) was not considered in the stability analysis, no instabilities were observed during the experiments. In addition, a **repetition** factor (repetition number 1, 2, 3) is investigated to check for a possible interaction with the assistance functions. This results in a three (damping) × two (coupling) × three (repetition) completely crossed experimental plan which was realized with a repeated measurement design. The experimental conditions where executed in three repetition blocks within which the other two factors where presented counterbalanced. The experiment was performed voluntarily by 20 participants[5]. All had normal or corrected-to-normal vision and were right-handed. Partners did not know each other. The participants were instructed to perform the task as fast as possible.

The data is analyzed on the dyadic level. The performance of each trial is measured as the time from the beginning of the first contact phase until the end of the last contact phase (task completion time, $TCT$). This measure not only takes the speed into account but also penalizes dropping of objects by the time it takes to pick them up. The necessary precision to accomplish the task is constant over all experimental conditions. In addition, we investigate the physical effort with the mean absolute force ($MAF$), which is computed as mean of the Euclidean norm of the force vector over a complete trial. To understand the relation between performance and effort an efficiency measure is used which is introduced for haptic interaction in [4,5]. The (across the whole sample) z-standardized values (standard deviation = 1, mean = 0) of effort and performance can be utilized to examine the *relative* efficiency of conditions compared *within* the sample.

## 3 Results & Discussion

Descriptive results of the evaluation are depicted in the following: We show the performance measured in task completion time ($TCT$), the physical effort it

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[4] As mixed condition we consider the case with high damping in contact ($b_{dc}$) and low damping in free-space ($b_{df}$) only, as this could improve handling of the object while not introducing additional effort in free-space.

[5] Mean age: 23.9 years, age range: 19 to 32 years; 3 female, 3 male, and 4 mixed dyads.

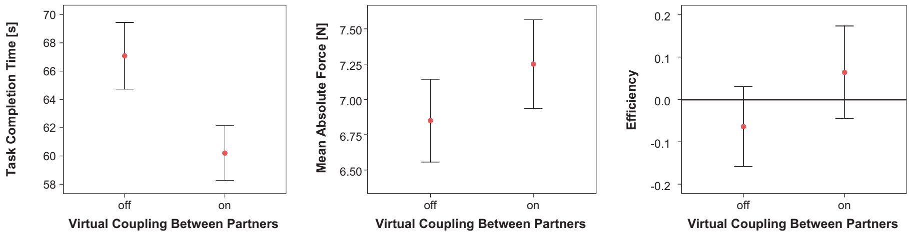

**Figure 4.** Comparison between the two levels of the **virtual coupling** factor on the three measures TCT, MAF, and efficiency. Mean and standard error are depicted.

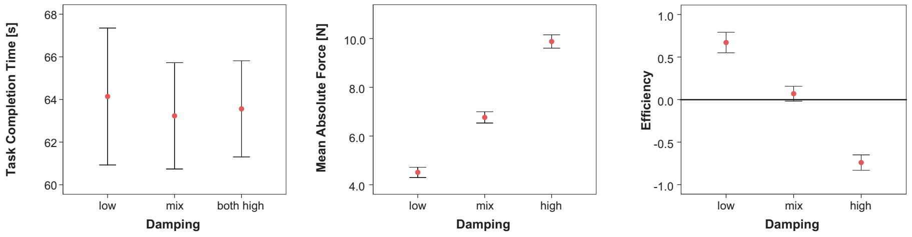

**Figure 5.** Comparison between the three levels of the **damping** factor on the three measures TCT, MAF, and efficiency. Mean and standard error are depicted.

took to complete the task (measured as the mean absolute force across each trial, $MAF$), and the resulting efficiency [4]. This is done for the three experimental factors: virtual coupling (Fig. 4), damping (Fig. 5), and repetition (Fig. 6).

We executed a 3-factorial repeated measurement ANOVA (analysis of variance, see e.g. [6]) separately for each of the three measures. As $TCT$ was not normally distributed it was logarithmized before running the statistic test which is common practice [6].

Allocation of **virtual coupling** significantly (tested on a 5% significance level) increases performance compared to conditions where this feature is not provided ($F(1,9)=16$; $p<0.01$; partial $\eta^2=0.63$). It can be assumed that the coupling simplifies the task execution by preventing dropping of the object and avoiding asynchronous motion between the two partners. This leads to a lower task completion time. The fact that virtual coupling leads to higher mean effort ($F(1,9)=21$; $p<0.01$; partial $\eta^2=0.70$) shows that this assistance is actually active during the given task (partners moved in asynchrony). However, some of the additional effort may be caused by the shorter task execution time, which results in higher speeds and therefore a larger force. The time saving is such a big advantage compared to the risen effort that the efficiency is significantly higher with virtual coupling ($F(1,9)=6.0$; $p=0.04$; partial $\eta^2=0.40$).

**Damping** does not significantly influence task performance. However, with higher damping the applied effort increases as well ($F(2,18)=256$; $p<0.01$; partial $\eta^2=0.97$). The difference in effort reaches significance between all three levels

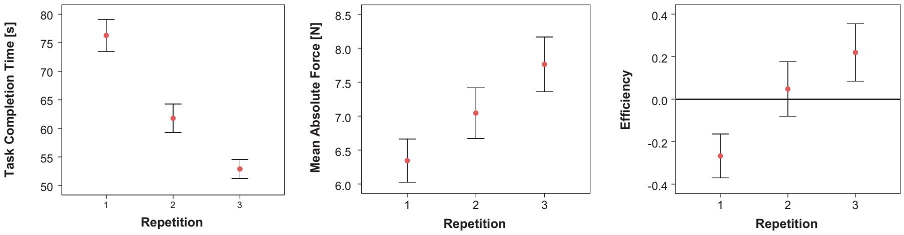

**Figure 6.** Comparison between the three levels of the **repetition** factor on the three measures TCT, MAF, and efficiency. Mean and standard error are depicted.

($p$-values of Bonferroni adjusted pairwise comparisons: low vs. mixed: <0.01; low vs. high: <0.01; mixed vs. high: <0.01). High damping can principally have two different effects: a) either participants perform slower movements or b) participants increase their effort to execute the given task: obviously participants tend to increase the effort to keep the performance on an equal level. Due to the effort differences, the resulting efficiency measure is significantly influenced by damping ($F(2,18)=98$; $p<0.01$ ; partial $\eta^2=0.92$) where all three levels are significantly different from each other ($p$-values of Bonferroni adjusted pairwise comparisons tests: low vs. mixed: <0.01; low vs. high: <0.01; mixed vs. high: <0.01): the higher the damping the lower the efficiency in the given task.

**Repetition** positively affects performance, i.e. with each repetition performance increases ($F(2,18)=39$; $p<0.01$; partial $\eta^2=0.81$). This effect reaches significance between all three repetitions ($p$-values of Bonferroni adjusted pairwise comparisons: 1vs.2: <0.01; 1vs.3: <0.01; 2vs.3: <0.01). In the effort measure significant differences between the first and third repetition are found, i.e. growing effort with training ($F(2,18)=10$; $p<0.01$; partial $\eta^2=0.54$; $p$-values of Bonferroni adjusted pairwise comparisons: 1vs.2: 0.11; 1vs.3: 0.01; 2vs.3: 0.15). We explain the higher effort by two effects: on the one hand participants learned that pushing their end-effectors together more strongly was a valuable strategy to prevent the object from falling down, on the other hand participants executed the task more quickly, thereby making a higher effort necessary to overcome the damping. Based on the performance and effort measures, there is a significant effect of repetition on efficiency ($F(2,18)=7.6$; $p<0.01$; partial $\eta^2=0.46$), where an increasing trend can be found with the number of repetitions. Only the first and third repetition are significantly different ($p$-values of Bonferroni adjusted pairwise comparisons: 1vs.2: 0.11; 1vs.3: 0.03; 2vs.3: 0.23).

There is a significant **interaction** between the damping and the repetition factors for the effort measure ($F(4,36)=3.6$; $p=0.02$; $\eta^2=0.29$): the differences between the three damping levels increase with more training. This finds an explanation in physics: as the task completion time decreases with the number of repetitions (thus velocity increases) the relation between the damping factor and the amount of force, which is necessary to overcome it, becomes more evident.

## 4 Conclusion

The evaluation of haptic collaboration in the multi-user teleoperation system shows that in the given task a coordinating controller, here virtual coupling, between partners increases performance. However, the costs in physical effort increase as well: whenever the virtual coupling generates a force facilitating coordination, this leads to higher forces, and thus to an overall higher effort. Relating both measures results in an increased efficiency for virtual coupling relative to task execution without that feature. Contrasting the new controller to other damping-based controllers shows that higher damping leads to more applied forces (effort) whereas performance remains at a constant level. Hence, the increase in efficiency when applying virtual coupling is indeed caused by the coordinating controller and not only by adding more damping to the overall system. Performance also increases with training, and as this only causes relatively small additional effort, efficiency increases as well. This can have several explanations e.g. participants adapt to their partner and develop shared strategies or they adapt to the teleoperation system and task.

Virtual coupling was identified as promising coordinating controller for multi-user teleoperation systems. Future studies will focus on generalizing these results to other setups, tasks (e.g. for training or rehabilitation) and coupling parameters (e.g. spring-damper coupling). Furthermore, we are considering the possibility of functions which take the adaptation between partners into account. Finally the effects of additional oral communication could be investigated.

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