A Task-Specific Analysis of the Benefit of Haptic Shared Control During Telemanipulation

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Abstract: Telemanipulation allows human to perform operations in a remote environment, but performance and required time of tasks is negatively influenced when (haptic) feedback is limited. Improvement of transparency (reflected forces) is an important focus in literature, but despite significant progress, it is still imperfect, with many unresolved issues. An alternative approach to improve teleoperated tasks is presented in this study: Offering haptic shared control in which the operator is assisted by guiding forces applied at the master device. It is hypothesized that continuous intuitive interaction between operator and support system will improve required time and accuracy with less control effort, even for imperfect transparency. An experimental study was performed in a hard-contact task environment. The subjects were aided by the designed shared control to perform a simple bolt-spanner task using a planar three degree of freedom (DOF) teleoperator. Haptic shared control was compared to normal operation for three levels of transparency. The experimental results showed that haptic shared control improves task performance, control effort and operator cognitive workload for the overall bolt-spanner task, for all three transparency levels. Analyses per subtask showed that free air movement (FAM) benefits most from shared control in terms of time performance, and also shows improved accuracy.

Index Terms: Teleoperation, haptic guidance, haptic shared control, transparency, task performance, human factors experiment

1 Introduction

Certain tasks need to be performed in environments where direct manipulation by human is not possible, due to for example the hostile nature of the environment (e.g., deep sea and nuclear or toxic environments), or due to dimension constraints (e.g., micro assembly or minimal invasive surgery). A human-in-the-loop approach using telemanipulation robots is commonly used when tasks have an unpredictable nature [1], [2]. Especially because this unpredictability, combined with issues like safety, responsibility [3], and costs, often restrict the usability of full robotic automation. Fig. 1 shows a schematic representation of the total system of human operator, telemanipulator, and environment, which is defined as the connected telemanipulation system (CTS) [4]. Task performance achieved using such systems is limited and needs to be improved [5]. The conventional approach focuses on the telemanipulator itself, aiming at increasing task performance by improving the naturally available visual/haptic feedback to the operator. In an ideal situation the human should have the sensation of actually being present at the remote location performing the task (telepresence [6]). Accurate visual and auditory representation of (interaction with) the remote environment is important for a good telepresence, but also a precise representation of physical interaction is required. Especially this last issue, also called transparency, remains one of the main challenges of the field. Perfect transparency, defined as perfect tracking of both forces and positions [7] or as a ratio of one between transmitted and environmental impedance [8], is still far from achieved in most practical applications. Previous research showed that improvement of transparency by providing force feedback (FF) from the environment to the human is beneficial and improves task performance [9], [10] and reduces cognitive workload [11]. However, technical issues limit the quality level of the provided FF. Although great efforts have been made over the past decades to improve transparency, and substantial progress has been made (e.g., [4], [8], [12], [13], [5]), optimal transparency is not yet realized.

Instead of focusing on the telemanipulator and the achieved transparency to improve task performance, another option is to assist the task execution. This approach was first used by Rosenberg [14], presenting additional passive guiding forces—called virtual fixtures—to assist the operator during a teleoperated peg-in-hole task. The artificial forces worked like a virtual ruler and resulted in a large improvement of task performance. This research laid foundation for further research in virtual guiding forces, which can be seen as a way of combining automation and manual control. In literature, all kinds of definitions and names can be found for this type of shared control (e.g., virtual fixtures, haptic guiding, and virtual guiding

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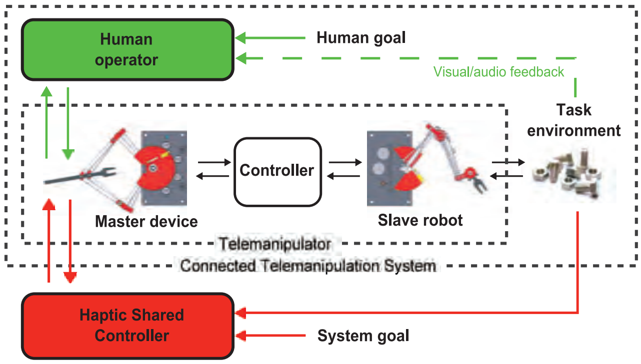

Fig. 1. The five components of the connected telemanipulation system (upper part), adapted from Christiansson [4]. The lower part shows the haptic shared control approach to assist the human operator with the task. Arrows indicate information flow. Both human and shared control systems get feedback from the task performance and have a goal input.

forces), in this paper, we will use from now on the term *haptic shared control*. Haptic shared control is defined as an approach in which an assisting system continuous communicates a calculated ideal control input to the human operator by forces (in a passive or active way). The operator and the shared control system share control by applying forces on the same input device (see Fig. 1).

One of the main applications of haptic shared control that is found in literature is in operational assistance: guiding to a certain reference position (e.g., [14], [15], [16], [17]), protecting areas (e.g., [18], [19]), and vehicle control (e.g., car following [20] and curve negotiation [21], [22]). The results of these studies are positive although most of this research is limited to one or two degrees of freedom and/or focuses on motions in free air. A closely related field of research is the use of haptic shared control for training of manual tasks (e.g., [23], [24]).

In literature, different examples and implementations of haptic shared control were found, but how should control be shared in a comfortable and intuitive way? An interesting metaphor is horseback riding [25]. The rider is in control and guides the horse. The horse can act autonomously and find a way by itself in case the rider loosens his or her control for a moment. Through the forces on the reins, control authority is switched smoothly back and forth between horse and rider.

As described above, haptic shared control seems a promising candidate to assist full scale telemanipulation. This paper proposes an extension of the found haptic shared control in literature to telemanipulation in more degrees of freedom, using the continuous haptic shared control based on the principle used by Abbink et al. [26]. Based on additional information like virtual models and sensor information (e.g., about the human, task, and environment), the haptic shared control system calculates the ideal control action. This ideal control action is presented as a force on the master device, making the operator continuously aware of the optimal control action. The system assists the operator in execution of the optimal action, but the operator is in control and can always resist the shared control forces if he does not agree with the system. A general scheme of the proposed haptic shared control is illustrated in Fig. 1.

A preliminary study showed beneficial effects of haptic shared control on time performance, showing an improved time-to-complete of 20 to 32 percent for the teleoperated bolt-and-spanner task [27]. The current study aims to provide further insight in two directions. First, besides time performance, effects on other factors like control effort and cognitive workload of the operator are considered [21]. Second, it is interesting which part of the task benefits most from the applied shared control. Interesting task-specific performance metrics are execution time (for each subtask), positional accuracy (movement in free air), and applied forces to the environment (in contact situations) [28].

For different types of motions, human beings apply different control strategies (e.g., they adjust their response to visual and haptic feedback). When designing and analyzing a haptic shared control system, it is important to consider these different types of motion. Wildenbeest [29] defined four fundamental types of motion for a hard contact task environment, based on an analytical task span presented by Aliaga [13]. For each of these fundamental motion types, a different haptic shared control strategy was proposed:

1. *Free air movement (FAM)*. The slave robot has no interaction with the environment. Proposed guiding strategy for haptic shared control: guiding of tool position and orientation to an *ideal* path (as considered by the automatic controller). This type of guiding is also used in vehicle control [26].
2. *Contact transition (CT)*. The slave robot moves close to a surface and makes contact. Haptic guiding should prevent hard collision by an artificial damping.
3. *Constrained translational movement (CTM)*. One or more degrees of freedom of the slave robot are constrained (e.g., moving over a surface, coaxial sliding of pipes, peg-in-hole task). Proposed guiding strategy for haptic shared control: guiding of tool position and orientation.
4. *Constrained rotational movement (CRM)*. A movement around a rotation point, containing a constrained circular trajectory (e.g., moving a door handle). Proposed guiding strategy for haptic shared control: haptic guiding introduces a virtual rotation/compliance centre at the bolt origin.

The main objective of this research was to provide evidence that appropriately designed haptic shared control can result in larger improvements in human-in-the-loop (task) performance than improving transparency, and that this applies not only for task completion time [27] but also for control effort and operator cognitive workload. Second, this research wanted to answer the question which of the subtasks benefits most. To test and quantify this, an experiment was designed using a simple bolt-and-spanner task [29], containing the four fundamental motion types. To prevent the results to be valid for only one arbitrary controller, the subjects had to execute the task for three different levels of transparency: direct control (DC) (almost perfect transparency), telemanipulation with FF, and telemanipulation without FF (no transparency). These conditions were tested with and without haptic shared control.

It was hypothesized that, for the total task, reducing transparency will degrade (task) performance, while

TABLE 1
Hypotheses About the Effect of Shared Control on Task Performance and Operator Cognitive Workload for Different Levels of Transparency

Transparency:	Ideal <—	Medium	—> No
F1:	*Direct Control*	*Teleoperation - Force Feedback*	*Teleoperation - No Force Feedback*
F2:			
Total task (time, control effort, operator workload)			
No Shared Control	0	-	- -
Shared Control	+	+	+
Subtask: Free Air Movement (time, accuracy)			
No Shared Control	0	0	0
Shared Control	+	+	+
Subtasks: Movement with contact (time, force on environment)			
No Shared Control	0	-	- -
Shared Control	+	+	+

DC is taken as baseline (denoted as "0").

appropriate haptic shared control will increase task performance with respect to DC, independent of the level of transparency (see Table 1). Moreover, it is expected that the hypotheses for the total task will be reflected in the individual three "no FAM" subtasks. Note that the level of transparency is expected to have no influence on time performance and accuracy during FAM, since FAM is mainly a visual task. Since all subtasks contain movement, the use of haptic shared control is expected to improve time performance for all subtasks. Because DC is the "gold standard" in transparency-oriented research, it is defined here as a baseline condition.

2 Methods

The methods are described in more detail in [27].

2.1 Subjects

The proposed shared control was tested on a group of 9 male subjects. The mean age of the subjects was 26.1 year, with a standard deviation of 1.1 year. All subjects were right-handed and no one had experience with teleoperation.

2.2 Task Description

The subjects were asked to take place in front of the master device and hold the interface of the master device like a normal spanner. Subsequently, the following task had to be executed (see green arrows in Fig. 2): Begin 2 cm below P1, move to points P1, P2, and P3, make contact with the bolt (moving from P3 to P4), slide the spanner over the bolt at P4, and finally rotate the bolt to the visible reference angle. The subjects were asked to perform this task as fast as possible. The locations of the target points were, respectively, $(\mathrm{x}, \mathrm{y}, \theta) = (0\ \mathrm{m}, 0\ \mathrm{m}, 0^\circ)$, $(0\ \mathrm{m}, 0.02\ \mathrm{m}, 0^\circ)$, $(-0.06\ \mathrm{m}, 0.07\ \mathrm{m}, 0^\circ)$, $(0.06\ \mathrm{m}, 0.08\ \mathrm{m}, 65^\circ)$, and the bolt position $(\mathrm{x}, \mathrm{y}) = (0\ \mathrm{m}, 0.12\ \mathrm{m})$.

These instructions were handed out to the subjects and were verbally explained in addition by the experiment leader before the start of the experiment.

2.3 Experimental Setup

The haptic shared control experiment was performed using a 3-DOF planar telemanipulation system. The system consisted of a parallel force-redundant master device and a serial slave device. A schematic drawing (topview) of the

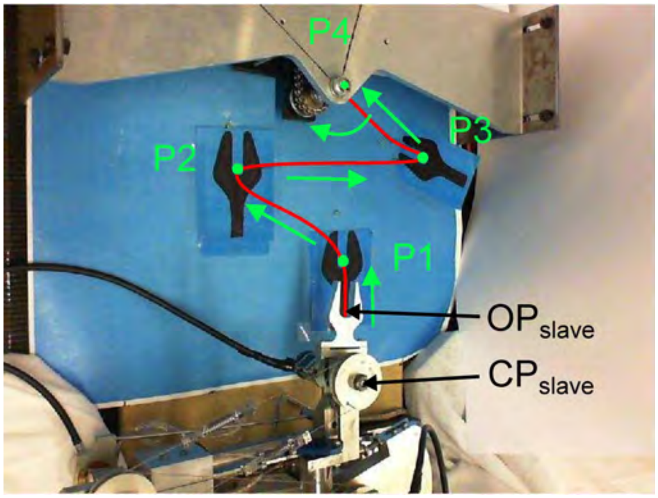

Fig. 2. Visual feedback to the subjects; a tilted camera view from the task environment. The experimental task is indicated in the picture by the green arrows; move OP_{slave} to the bolt (P4) following the red path (via P1, P2, and P3) and rotate the bolt until the visible reference. OP_{slave} and CP_{slave} is operational/centerpoint slave, respectively (modified from Boessenkool [27]).

master and slave is shown in Fig. 1, note the spanner on the master device required for the "DC" condition.

A position-error control was implemented and the controller ran on a Mathworks xPC Target real-time operating system at 1 kHz. The positional accuracy was 0.03 mm and the minimal time delay between master and slave was estimated at 1.5 ms (1 ms measurement interval and 0.5 ms due to the zero-order hold of the analog output [30]). The design of this telemanipulator is discussed in detail by Christiansson [4].

The device performance and stability was evaluated by Wildenbeest [29] using the two-port network modeling framework [31]. The device characteristics for the different transparency conditions are listed in [27].

The setup was equipped to perform a bolt and spanner task. Both master and slave were equipped with a spanner interface. The interaction forces at the slave side could be estimated using the series-elastic principle.

The (remote) environment consisted of a construction with an M6 bolt (Fig. 2). This construction could be placed at the slave or the master side. The torque required to rotate the bolt was artificially created by a friction force induced by a spring. The tightening torques to overcome static and dynamic friction were estimated to be respectively 35.7 Nmm (standard deviation: 2.0) and 31.6 Nmm (standard deviation: 6.0). The bolt rotation was measured with an angle sensor.

2.4 Haptic Shared Control Design

The haptic shared control design could be based on two fundamentally different types of guiding: *attractive* guiding [15], [22], creating guiding forces toward an ideal path, and *repulsive* guiding [14], [19], preventing users to enter forbidden regions by presenting repulsive forces. Attractive motion guiding can be done in a *passive* or in an *active* way: Passive guiding only applies forces orthogonal to the path and will not initiate a motion along the path by itself. Active guidance actively pushes the master to the (sub)goal and

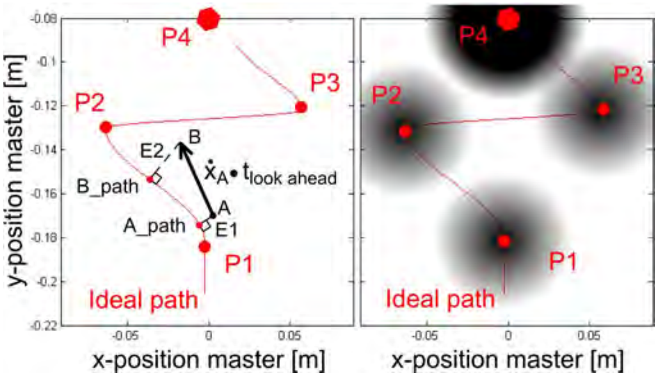

Fig. 3. Shared control design. Left: The position guiding force is based on the path error *E2* at "look-ahead position" B (look-ahead time is 0.1 s). This force is applied at the current position A, orthogonal to the path (in direction of *E1*), adapted from Mulder [22]. Right: The rotational guiding force increased linear within the reported radia of the target points (visualised by the black circles).

will induce a motion along the path when the operator releases the master.

A small pilot experiment with two subjects was used to get an indication of which type of haptic shared control design is most promising for this type of task. A variety of shared control designs, partly based on the literature that was discussed above, was implemented: A protective layer protecting the environment, a passive/active guiding tunnel, passive/active guiding on an ideal path with and without look-ahead guiding. The different types of shared control were judged on required time to complete the task and the subjective measure how intuitive the guiding was. Passive look-ahead guiding based on an ideal path showed the best performance and was chosen for the experiment. This chosen guiding is not necessarily the optimal guiding and neither totally optimized, though suitable for a proof of principle.

Fig. 1 shows that both human and the haptic shared control system have a *goal* input. Ideally, the haptic shared control system should be able to figure out the human goal (intention and strategy) and adapt to this goal. The shared control system used in the current study is simplified at this point: The shared control system determines the goal (e.g., the ideal path), and shows this visually to the human. This *"ideal"* path is chosen and is not optimized to human motions (for this study).

The haptic shared control design used for the experiments is described below per subtask (see also Fig. 3):

1. *FAM*. A smooth path between the target points was chosen as ideal path (see red line in Fig. 2). The guiding forces were based on the "look ahead" path error (E2 in Fig. 3) [22], which is defined as the path error at an estimated position in future (B) based on the current velocity vector ($\dot{x}$) and a look ahead time of 0.1 s. The resulting guiding force was applied orthogonal to the path (in a passive manner, i.e., when the operator does not touch the master, the device does not move by itself).

$$F_{shared-control} = -\overrightarrow{E_2} * k_2. \qquad (1)$$

TABLE 2
The Six Experimental Conditions

Transparency:	Ideal <—	Medium	—> No
F1:	*Direct Control*	*Teleoperation - Force Feedback*	*Teleoperation - No Force Feedback*
F2:			
No Shared Control	DC	FF	NoFF
Shared Control	DC-SC	FF-SC	NoFF-SC

The shared control stiffness was $k_2 = 120[N/m]$. Within a radius of 0.04 m of the target points 1 to 3, guiding of the tool orientation was linear increased to a stiffness of 0.5 [Nm/rad].

2. *CT*. Between a radius of 0.05 and 0.04 m of the bolt, the tool orientation guiding was linearly increased to a stiffness of 0.5 [Nm/rad]. A linearly increasing artificial damping of 15 [Ns/m] prevented hard collision.
3. *CTM*. The spanner was guided to the right orientation with a stiffness of 0.5 [Nm/rad]. Within 0.5 cm from the bolt, an attractive force of 1.5 N was activated, pulling the spanner to the bolt.
4. *CRM*. The presented guiding force was only perpendicular to the movement. The attractive force of 1.5 N was active to ensure that the spanner stayed on the bolt head. In the *no force feedback* (NoFF) condition, the shared control system introduced a virtual rotation/compliance centre at the bolt origin with a stiffness of 150 [N/m].

2.5 Experiment Design

2.5.1 Experimental Conditions

The two main factors of the experiment were two different types of haptic information: (F1) the "level of transparency," and (F2) "with/without haptic shared control." These factors were combined into six experimental condition (see Table 2).

Transparency was defined as how transparent the interaction forces were transmitted to the operator. The two extremes of these factors were DC, which gives almost perfect transparency, and NoFF, which gives no transparency. A third condition in between was FF using a classical position-error controller. The FF and the NoFF conditions were tested in telemanipulation configuration. The NoFF condition was tested by setting the position-error slave-to-master PD-gains to zero. For the DC condition, the environment was placed at the master side and the task was executed hands on using the spanner mounted at the master.

The experiment contained eight repetitions of each of the six conditions per subject. Every subject started with the FF condition, to have a reference for the subjective measures. The remaining conditions were presented randomly to minimize the influence of learning effects during the experiment. All trials were analyzed for the total task, but also for the four fundamental subtasks; FAM, CT, CTM, and CRM.

All subjects did have training sessions for each new condition in advance of the actual experiment.

2.5.2 Controlled Variables

Visual feedback. Visual feedback from the remote environment is very important during telemanipulation tasks and is usually achieved by camera views. Yet in many cases the often hazardous environments limit the quality and available depth information, which increase the difficulty of the task for the human operator.

For all conditions of the experiment, the subjects were dependent on visual feedback from the (remote) environment by a camera view (see Fig. 2). This camera view had a limited resolution (960×544 pixels) and was displayed on a 14-inch laptop screen next to the setup. The camera was placed under an angle of 45 degrees with respect to the horizontal and could be placed at the slave or master side. This tilt of the camera was done to make the task more difficult (and realistic) by introducing depth effects.

Task instruction. Upon executing a task humans always have a (subconscious) preference for certain control strategies. In most cases, this control strategy has to do with a tradeoff between energy consumption, accuracy and/or time. During the training trials preceding the experiments the subjects got an explicit instruction to perform the task with one of the two following control strategies:

1. *Accurate*. Perform the task as accurate as possible. This would lead to optimization of strategy toward positional accuracy and low exerted forces.
2. *Fast*. Perform the task as fast as possible. This would lead to optimisation of strategy toward time duration.

During the pilot study, it appeared that testing both strategies on each subject resulted in a high burden on the subjects. Hence, during the actual experiments, the subjects were instructed to perform the task *as fast as possible* for all conditions.

2.6 Measured Variables and Metrics

To analyze the effect of shared control on teleoperated task performance, a vast amount of variables were recorded during the measurements, all sampled at 1 kHz. Based on the recorded data, a number of metrics were calculated to determine the performance. These metrics can be separated into two categories and are explained below:

Task performance metrics:

- *Time-to-complete (ttc).* The time it takes for a subject to complete the (sub)task.
- *Integrated path error* (err_{int}). Integration of the error with the ideal path.
- *Average contact force* ($F_{c,av}$). Average of the measured interaction force with the environment.

Control effort metric:

- *Reversal rate* (n_{rev}). Number of steering corrections done by the human operator, which can be seen as a measure for control effort of the subject to control the system. The reversal rate was defined as the amount of times the movement changes direction (amount of sign changes of the velocity). The raw position data was first filtered with a 15-Hz lowpass filter to reduce the "not human induced" measurement noise (human manipulation frequencies go up to around 10 Hz). The derivative of this filtered vector was checked for sign changes. This paper only presents the reversal rate for the x-direction, but same trends were found in y- and rotational directions.

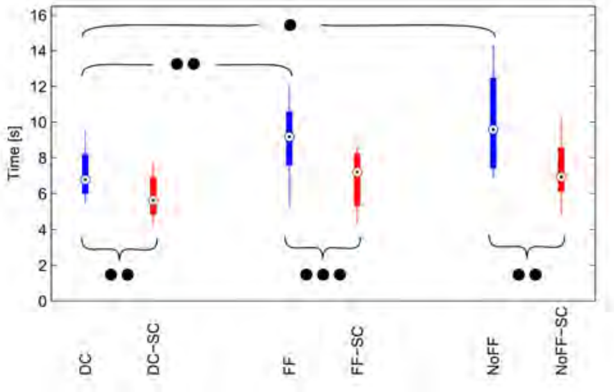

Fig. 4. Time-to-complete for the entire bolt-and-spanner task (nine subjects, eight repetitions), shown for six conditions. The boxplot shows: median, 25th and 75th percentiles, and whiskers untill the most extreme data point within 1.5 times interquartile range. The marks (●●●), (●●), (●) denote a significance of $p \leq 0.001$, $p \leq 0.01$, and $p \leq 0.05$, respectively, from Boessenkool et al. [27]

Furthermore, the following subjective measures were tracked for all six conditions:

- Self-reported cognitive workload using the NASA task load index (NASA-TLX) [32]. A scale from 0 to 100 represents the amount of workload.
- The subjects were asked to grade their own performance with respect to accuracy and with respect to time performance. A 14-point scale from 1 to 8 was used; 1 represented "very bad" and 8 represented "very good."
- The subjects were asked to rate the helpfulness of the shared control. A 16-point scale from -4 to 4 was used; -4 represented "totally opposing" and 4 represented "very helpful."

2.7 Data Analysis

A repeated measurement design was used; all nine subjects performed the task under all conditions in random order. The eight repetitions per subject were averaged, for each of the six conditions. A paired t-test was used to evaluate the differences between the conditions, corresponding the defined hypotheses. First, the differences between the three *transparency* conditions (F1) without shared control were analysed. Second, the effect of shared control was compared to the "baseline" condition DC. Furthermore, the effect of shared control (F2) separately for the three *transparency* conditions was analysed. Normality assumption was checked for the difference between variables ($p = 0.05$) to ensure the applicability of the statistical tests.

Besides the effect size (difference in mean), the 95 percent confidence interval and the p-value is shown. Results were regarded as statistical significant when $p \leq 0.05$. The boxplots in Figs. 4, 5, 6, and 9 show the median, the 25th and 75th percentiles. The whiskers extend to the most extreme data point within 1.5 times interquartile range. The marks (●●●), (●●), (●) denote the significance of $p \leq 0.001$, $p \leq 0.01$, and $p \leq 0.05$, respectively, and (−) denotes no significance.

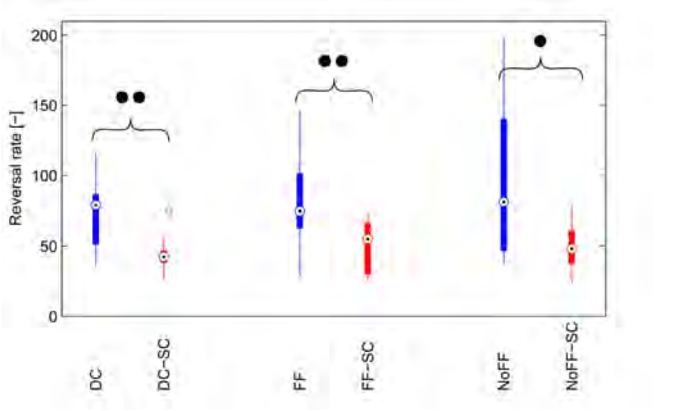

Fig. 5. Reversal rate entire bolt-and-spanner task (nine subjects, eight repetitions), shown for six conditions (see also Table 3). The marks (•••), (••), (•) denote a significance of $p \leq 0.001$, $p \leq 0.01$, and $p \leq 0.05$, respectively.

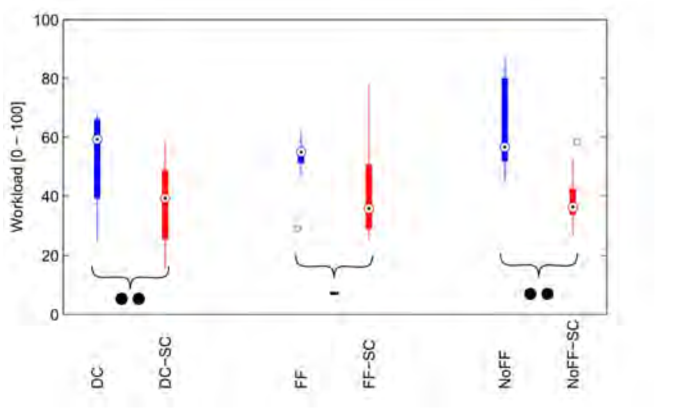

Fig. 6. Self-reported cognitive workload; NASA TLX test (nine subjects). The marks (•••), (••), (•) denote a significance of $p \leq 0.001$, $p \leq 0.01$, and $p \leq 0.05$, respectively.

Although multiple comparisons were made, the authors chose to not apply a multiple comparison correction, because a limited amount of specific hypotheses were tested and it is easier to compare H0 and H1 rejections. The drawback is a higher chance on type 1 errors (false rejection of H0).

3 Results

The measured metrics as defined in Section 2.6 are presented in the upcoming two paragraphs. The first paragraph presents the general results for the entire task, and the second paragraph presents the results per subtask.

3.1 Effect of Transparency and Haptic Shared Control on Entire Task

3.1.1 Task Performance and Control Effort

The descriptive results for completion time and the reversal rate (control effort) are listed in Table 4. Fig. 4 shows the time-to-complete for the entire task [27]. With respect to transparency, it shows that the baseline (DC/ almost perfect transparency) yields the shortest time to complete. Compared to DC, the FF and NoFF conditions showed an increased time-to-complete of 1.71 s ($p = 0.001$) and 3.5 s ($p = 0.010$). Haptic shared control resulted in an improved time-to-complete of 1.43 s ($p = 0.006$), 2.17 ($p = 0.0002$), and 3.43 ($p = 0.008$) for respectively the DC, FF, and NoFF condition. There was no significant difference in time performance between perfect transparency (DC) and shared control without transparency (NoFF_SC), $p = 0.692$ and between perfect transparency (DC) and shared control with Force Feedback (FF_SC), $p = 0.107$. See Table 3 for the summarized analyses.

Reversal rates for the entire bolt-and-spanner task are shown in Fig. 5 as control effort measure. Presented are the reversal rates in x-direction, but the same trends were found in y-direction and rotational direction. No significant differences between the transparency conditions were found. Shared control resulted for all transparency conditions in a significant decrease of the reversal rate (see Table 3).

3.1.2 Subjective Measures

The TLX-scores for each of the six conditions were compared (Fig. 6). On average the cognitive workload for DC, FF, and NoFF was rated at 52, 52, and 64, respectively. Haptic shared control resulted in a decreased workload of 28 percent ($p = 0.005$), 18 percent ($p = 0.138$), and 39 percent ($p = 0.002$) for DC, FF, and NoFF, respectively. Seven out of nine subjects reported a decreased cognitive workload for all transparency conditions when shared control was added. Two subjects reported a slightly higher workload for the FF-SC condition.

Eight out of nine subjects rated the helpfulness of haptic shared control positive for all conditions, with an average grade of 2.4, 2.5, and 2.5 (range -4 to 4) for DC, FF, and NoFF, respectively. The only negative rating was a -0.3 for DC_SC. The mean of self-reported time performance (how fast do you think you performed the task?) were 5.9, 5.6, and 4.5 (range 0 to 8) for DC, FF, and NoFF, respectively. The

TABLE 3
Analyzed Differences between Conditions, for the Metrics: Time to Complete, Reversal Rate, Integrated Path Error and Average Contact Force

The table shows the difference in mean, the 95 percent confidence interval and the significance (p-value).

	ttc [s]		$n_{rev} - x$ [-]		err_{int} [cm^2]		$F_{e,av}$ [N]	
Cond.	Diff. mean (95% CI)	p diff.	Diff. mean (95% CI)	p diff.	Diff. mean (95% CI)	p diff.	Diff. mean (95% CI)	p diff.
DC-FF	-1.71 (-2.53; -0.89)	0.001	-8.5 (-28.6; 11.6)	0.358	-2.58 (-6.86; 1.70)	0.202	-	-
DC-NoFF	-3.50 (-5.92; -1.08)	0.010	-27.2 (-60.6; 6.3)	0.098	0.19 (-2.66; 3.03)	0.883	-	-
DC-DC_SC	1.43 (0.55; 2.30)	0.006	27.9 (9.2; 46.7)	0.009	4.92 (1.64; 8.21)	0.009	-	-
DC-FF_SC	0.46 (-0.12; 1.04)	0.107	22.7 (8.6; 30.8)	0.006	6.07 (3.84; 8.28)	<0.001	-	-
DC-NoFF_SC	-0.07 (-0.47; 0.33)	0.692	24.0 (13.0; 34.9)	0.001	6.64 (4.04; 9.25)	<0.001	-	-
FF-FF_SC	2.17 (1.41; 2.94)	<0.001	31.2 (11.1; -51.2)	0.007	8.65 (4.34; 12.95)	0.002	-0.55 (-1.43; 0.32)	0.184
NoFF-NoFF_SC	3.43 (1.20; 5.66)	0.008	51.1 (13.4; 88.8)	0.014	6.46 (2.51; 10.40)	0.005	0.30 (-0.86; 1.47)	0.565

TABLE 4
Experimental Results; Four Metrics Measured for the Six Different Conditions (Nine Subjects, Eight Repetitions)

Metrics	DC	DC_SC	FF	FF_SC	NoFF	NoFF_SC
	Experimental results; mean (SE)					
ttc [s]	7.26	5.83	8.97	6.80	10.76	7.33
	(0.49)	(0.42)	(0.72)	(0.56)	(1.47)	(0.58)
n_{rev}	72.8	44.9	81.3	50.1	100.0	48.9
[-]	(8.64)	(4.50)	(11.64)	(6.67)	(20.17)	(5.72)
err_{int}	13.21	8.28	15.79	7.14	13.02	6.56
$[cm^2]$	(1.11)	(0.59)	(1.88)	(0.59)	(1.42)	(0.62)
$F_{e,av}$	-	-	5.35	5.90	6.22	5.91
[N]	-	-	(0.33)	(0.36)	(0.49)	(0.45)

The table shows the mean and the standard error of the mean (SE).

means for self-reported accuracy were 3.9, 4.9, and 3.3 (range 0 to 8). Eight out of nine subjects rated their time performance higher when haptic shared control was added, for self-reported accuracy this was seven out of nine subjects.

3.2 Effect of Transparency and Haptic Shared Control on Fundamental Subtasks

The results above showed the effects of transparency and haptic shared control for the entire bolt-and-spanner task. Question remains how these effects are related to the four fundamental subtasks. Fig. 7 shows a bar chart of the time-to-complete, per fundamental subtask (see Table 5 for descriptive results). The general trends found for the total task are reflected in the subtasks. Compared to DC, the time to complete increased with decreasing transparency for each subtask. Table 6 shows the effects of haptic shared control on time-to-complete per subtask. The subtasks FAM and CTM showed significant improvement in time performance for all transparency conditions. The CT showed significant improvements for DC and FF, but not for NoFF ($p = 0.143$). CRM showed only significant improvement for DC and not for FF ($p = 0.132$) and NoFF ($p = 0.062$).

Although slightly improved completion time was measured, the average force exerted on the environment during CT and CTM showed no significant difference between transparency and/or shared control conditions (see Table 3). Note that the average contact force ($F_{e,av}$) was only measured and analysed for the teleoperated conditions (FF and NoFF).

The effect of haptic shared control on positional accuracy is shown in Fig. 8. This figure shows the master motion trajectories of a typical subject during the DC condition. Compared to normal control, shared control showed less deviation and a lower nominal path error. Trajectory plots for FF and NoFF showed comparable results, indicating that transparency does not influence positional accuracy. Results for the metric integrated path error are shown in Fig. 9. Transparency had no significant effect on path error, providing haptic shared control improved path error with 38 to 56 percent (see Table 3).

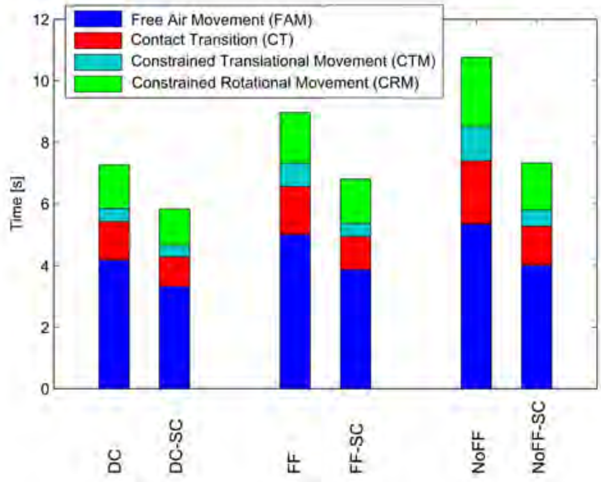

Fig. 7. Time-to-complete for the entire bolt-and-spanner task (nine subjects, eight repetitions), separated for the four fundamental subtasks (see Table 6)

TABLE 5
Experimental Results; Time to Complete per Subtask, Measured for the Six Different Conditions (Nine Subjects, Eight Repetitions)

Subtasks	DC	DC_SC	FF	FF_SC	NoFF	NoFF_SC
	Time to complete per subtask [s]; mean (std)					
FAM	4.19	3.33	5.00	3.87	5.34	4.02
	(0.27)	(0.32)	(0.44)	(0.44)	(0.54)	(0.41)
CT	1.23	0.97	1.56	1.05	2.05	1.25
	(0.14)	(0.10)	(0.16)	(0.11)	(0.53)	(0.18)
CTM	0.43	0.35	0.76	0.44	1.10	0.53
	(0.05)	(0.05)	(0.16)	(0.07)	(0.26)	(0.07)
CRM	1.41	1.18	1.65	1.44	2.27	1.53
	(0.12)	(0.06)	(0.19)	(0.15)	(0.39)	(0.12)

The table shows the mean and the standard error of the mean (SE).

4 Discussion

The experimental results showed that this telemanipulated bolt-and-spanner task benefits from haptic shared control, for all three levels of transparency. Essentially, the presence of haptic shared control allowed for a worse transparency while the level of performance was maintained (required time) or even improved (control effort, cognitive workload, and accuracy) compared to the DC condition (almost perfect transparency).

TABLE 6
Differences in "Time to Complete" between Conditions, for the Four Subtasks
The table shows the difference in mean, the 95 percent confidence interval and the significance (p-value).

Cond.	*ttc FAM [s]* Diff. mean (95% CI)	p diff.	*ttc CT [s]* Diff. mean (95% CI)	p diff.	*ttc CTM [s]* Diff. mean (95% CI)	p diff.	*ttc CRM [s]* Diff. mean (95% CI)	p diff.
DC-FF	-0.81 (-1.27; -0.35)	0.004	-0.33 (-0.61; -0.05)	0.026	-0.33 (-0.61; -0.05)	0.027	-0.24 (-0.58; 0.10)	0.148
DC-NoFF	-1.15 (-1.84; -0.47)	0.005	-0.83 (-1.84; 0.19)	0.096	-0.66 (-1.17; -0.16)	0.016	-0.86 (-1.56; -0.15)	0.024
DC-DC_SC	0.86 (0.16; 1.56)	0.022	0.26 (0.02; 0.50)	0.038	0.077 (0.04; 0.12)	0.003	0.23 (0.07; 0.40)	0.012
DC-FF_SC	0.31 (-0.30; 0.93)	0.273	0.18 (-0.09; 0.45)	0.167	-0.01 (-0.14; 0.13)	0.916	-0.03 (-0.17; 0.12)	0.680
DC-NoFF_SC	0.17 (-0.27; 0.61)	0.405	-0.019 (-0.43; 0.40)	0.919	-0.10 (-0.25; 0.05)	0.172	-0.12 (-0.31; 0.07)	0.178
FF-FF_SC	1.12 (0.66; 1.59)	0.001	0.51 (0.13; 0.89)	0.015	0.33 (0.04; 0.61)	0.030	0.21 (-0.08; 0.50)	0.132
NoFF-NoFF_SC	1.32 (0.79; 1.85)	<0.001	0.81 (-0.34; 1.95)	0.143	0.57 (0.10; 1.03)	0.023	0.73 (-0.05; 1.52)	0.062

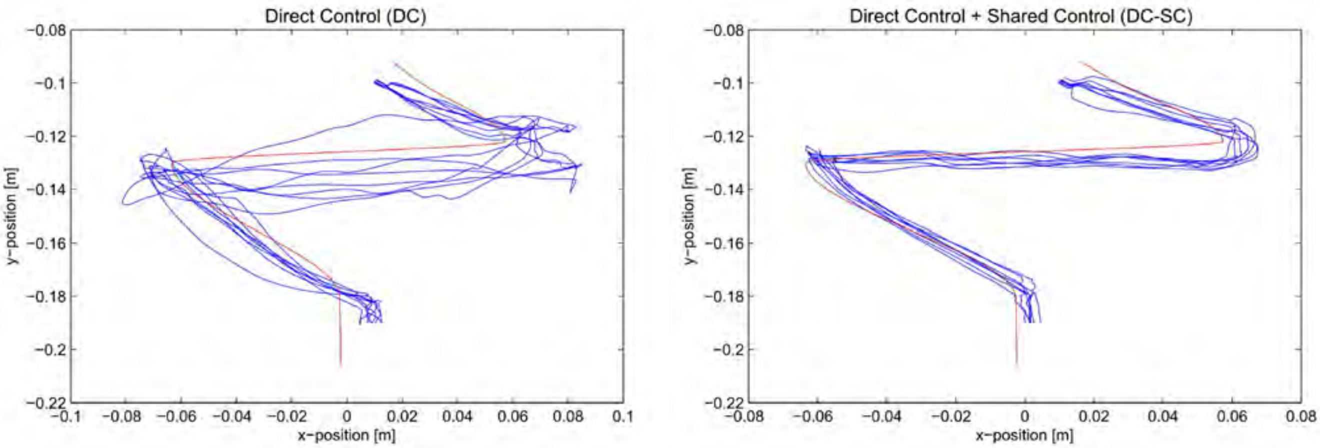

Fig. 8. Comparison of the Free Air master trajectories of the center point from a typical subject (eight repetitions each), obtained during the DC condition (almost perfect transparency), without (left) and with (right) haptic shared control.

The experimental results for the entire task, are quite close to the defined hypotheses. The time-to-complete only deviates from the hypothesis for the FF_SC and the NoFF_SC conditions; it was not expected that lower transparency levels would result in decreased time performance when applying shared control. The result indicates that when applying haptic shared control, improvement of transparency may result in extra decrease of time-to-complete for at least a part of the task. The time-to-complete results are discussed in more detail by Boessenkool et al. [27]. Subjective measures show that the subjects perceived shared control to be beneficial for improving accuracy and speed.

It was expected that less transparency would result in a higher control effort of the human operator, since less FF was expected to make the task more difficult. The found differences in reversal rate were not significant; however, the increased variation between subjects for the FF and NoFF conditions indicates a higher control effort for at least a part of the subjects. Shared control resulted in a decreased control effort for all transparency conditions. Comparable results were found for self-reported cognitive workload. This result corresponds with findings of Griffiths and Gillespie [21], reporting a lower workload during car steering with haptic shared control. The decreased cognitive workload found during haptic shared control is important to notice, since it has been shown that workload directly influences the human's ability to perform tasks [11]. Optimization of cognitive workload could reduce human error, improve system safety, increase productivity, and increase operator satisfaction [33].

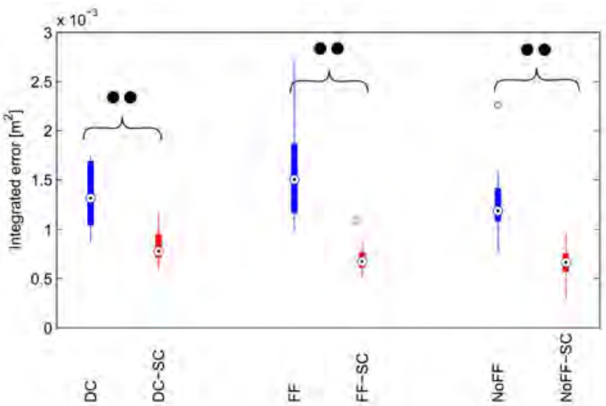

Fig. 9. Integrated error subtask FAM (nine subjects, eight repetitions), shown for six conditions (see Table 6). The marks (●●●), (●●), (●) denote a significance of $p \leq 0.001$, $p \leq 0.01$, and $p \leq 0.05$, respectively.

When examining the four different subtasks in detail, all subtasks showed a decreased time performance during worse transparency conditions. This decrease in time performance was not expected to be found for the FAM subtask, since FAM is mainly a visual task, not requiring force reflection. It is possible that the addition of extra slave dynamics in the FF and NoFF condition resulted in the decreased time performance.

For positional accuracy during FAM no difference was found under different transparency conditions. Most likely this is because FAM is mainly a visual task as no contact is involved.

The largest improvement of haptic shared control in time-to-complete can be found during FAM (from P1 to P3) and CTM (sliding over the bolt head). This is not surprising since the execution of these two subtasks highly depend on the right position and orientation of the spanner, both guided by shared control.

The addition of shared control substantially improved the positional accuracy during FAM for all three transparency conditions (as shown in Fig. 8).

The average force exerted on the environment during the CT and the CTM was not measured to be significantly higher with shared control, although an improved time performance was found. The artificial damping and orientation guiding added by the shared control system allows for higher speeds without compromising exerted forces during the CT and the CTM.

It is remarkable that haptic shared control during CRM does not show a significant improvement for the NoFF condition. Several subjects mentioned the difficulty of these subtask without shared control, as they had to rotate around a "virtual" point. These subjects mentioned a beneficial effect of shared control, and this effect is slightly represented in the measured time-to-complete, but the effect is not significant. The beneficial effects are probably better represented in other metrics like lower contact forces and a lower operator cognitive workload, but this could not be verified with the available measurement data.

One of the main areas of improvement is the choice for the "ideal" path used for the haptic shared control in free air. Currently, an arbitrary path was chosen that was smooth but not optimized for minimum jerk [34]. In real telemanipulation situations an optimized path, completely matching with the human intention, is often not available (or hard to derive). Of course, a path that is far from intuitive for humans would give strange results.

Haptic shared control is a special way of assisting, since it does not directly control the output (e.g., the slave robot), but indirectly influences the output by applying forces at the input device (e.g., master device). This approach is focused on the human-in-the-loop, allowing the operator to be fully aware of the guiding and the system status.

To provide the proposed haptic shared control, information is required about the environment, task, and human intention, since the control system needs to define an ideal path. These conditions limit the general use of haptic shared control, because a large part of telemanipulation tasks is typically performed in unknown and unstructured environments, and information about the environment and task is not always available. Environmental information could be obtained and derived from sensor data (in real time). In more structured and known environments (e.g., maintenance of nuclear plants) virtual (CAD) models could be used, in combination with real-time calibration based on sensor data. Obtaining specific task information is in most cases even more challenging. Except for specific maintenance applications, most telemanipulation situations do not have closely monitored task sequences available. The level/amount of haptic shared control which can be applied depends on the detail of achievable information from the environment and the task. Operator intention and operator motion planning also play an important part. The experimental results showed the importance of including human intention and motion planning into a haptic shared control design: In 9 to 14 percent of the executed trials, counteracting control behavior between the human and the shared control system was observed. A mismatch of intentions between human and the shared control system (aiming for a different part of the trajectory; P1-P2/P2-P3) caused the struggles. Although the subjects could detect and solve these conflicts with guiding forces quite fast, these mismatch problems should be solved. Note that despite these imperfect trials, shared control still resulted in an overall improved performance.

As described above, haptic shared control requires information about the task and the environment. If this information is available, why apply haptic shared control and not automation? First of all, automation requires exact and complete information and also a high accuracy and reproducibility of the robot system, which is often not available or hard to achieve in teleoperated situations. Since shared control includes the human intelligence in the task control, the quality requirements for the input information and system accuracy are less strict and therefore earlier achieved. Furthermore the human-in-the-loop approach of haptic shared control keeps the operator involved and trained, which is expected to avoid common automation problems of losing skills and attention [26]. On the other hand several potential pitfalls might occur with haptic shared control: For example, confusion about authority and dependency on shared control [34]. It is important to include these topics in future research.

4.1 Future Work

Shifting from a three degree of freedom (DOF) planar telemanipulator to a six DOF device will make the task considerably harder, mainly due to two extra rotations and the need for visual depth cues. Because the haptic channel is inherent 3D, the improvements of haptic shared control in 3D are expected to be even higher than in 2D.

As discussed above, human intention recognition (i.e., goal) is an important factor which is an important research direction. Closely related is the question how to deal with conflicts between human goals and controller goals and how to address changes in control authority. Our group has previously proposed to relate such changes to adaptations in the stiffness of the shared controller [26], [35]. In the ideal case this gain shifts automatically depending on human intention, shared controller and the task and environment. This requires in-depth knowledge of human motion control [36] and about the physical behavior of the human limb [37].

Haptic shared control is best viewed as a human-machine interface for automation, that can smoothly shift authority between full automation and manual control. This research shows that haptic shared control exhibits some of the short-term benefits of automation (e.g., improved time and accuracy, reduced cognitive workload), but does not address the long term (negative) issues of human-automation interaction (trust, overreliance, dependency on the system, and retention of skills).

Haptic shared control is a challenging approach: It not only requires the design of an automation system, but it also requires information about complex human behavior. However by including that information, it is possible to optimize the entire human-machine interaction system, allowing us to bridge the gap between full automation and manual control.

5 Conclusion

Assistance of operators by haptic shared control was investigated for execution of a teleoperated task in a hard contact environment. The designed shared control system has been evaluated using an experimental bolt-spanner task, executed for three different levels of teleoperator transparency. For all three levels of transparency, shared control allowed subjects to significant and substantially improve their time performance and accuracy without needing to exert more force. Control effort and cognitive workload decreased with shared control and subjective measures showed that shared control was perceived as helpful and beneficial. Analyses per subtask showed that the level of transparency has limited influence on task performance in FAM, while haptic shared control is most effective in that subtask. The presented results indicate that teleoperated tasks, especially tasks dominated by movement, may benefit more from focusing on haptic shared control than focusing on improvement of transparency.

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