Haptic Shared Control in Tele-Manipulation: Effects of Inaccuracies in Guidance on Task Execution

Jeroen van Oosterhout, Jeroen G. W. Wildenbeest, Henri Boessenkool, Cock J. M. Heemskerk, Marco R. de Baar, Frans C. T. van der Helm, and David A. Abbink

Abstract

Haptic shared control is a promising approach to improve tele-manipulated task execution, by making safe and effective control actions tangible through guidance forces. In current research, these guidance forces are most often generated based on pre-generated, errorless models of the remote environment. Hence such guidance forces are exempt from the inaccuracies that can be expected in practical implementations. The goal of this research is to quantify the extent to which task execution is degraded by inaccuracies in the model on which haptic guidance forces are based. In a human-in-the-loop experiment, subjects (n = 14) performed a realistic tele-manipulated assembly task in a virtual environment. Operators were provided with various levels of haptic guidance, namely no haptic guidance (conventional tele-manipulation), haptic guidance without inaccuracies, and haptic guidance with translational inaccuracies (one large inaccuracy, in the order of magnitude of the task, and a second smaller inaccuracy). The quality of natural haptic feedback (i.e., haptic transparency) was varied between high and low to identify the operator's ability to detect and cope with inaccuracies in haptic guidance. The results indicate that haptic guidance is beneficial for task execution when no inaccuracies are present in the guidance. When inaccuracies are present, this may degrade task execution, depending on the magnitude and the direction of the inaccuracy. The effect of inaccuracies on overall task performance is dominated by effects found for the Constrained Translational Movement, due to its potential for jamming. No evidence was found that a higher quality of haptic transparency helps operators to detect and cope with inaccuracies in the haptic guidance.

Index Terms

Tele-manipulation, remote handling, haptics, haptic shared control

1 Introduction

Tele-manipultion allows for remote operations in environments where human presence is unfeasible, unsafe or impractical. The tele-manipulator serves as a tool to transfer movements from a human operator on a local station (the master) to a remote station (the slave), through a controller. The human operator receives visual information and information about position and force of the remote robot (haptic information) from the remote environment.

- *J. van Oosterhout and M. R. de Baar are with the FOM Institute DIFFER (Dutch Institute for Fundamental Energy Research), Association EURATOM-FOM, Partner in the Trilateral Euregio Cluster, PO Box 1207, 3430 BE Nieuwegein, The Netherlands.*
- *J. G. W. Wildenbeest is with the Delft Haptics lab, Department of BioMechanical Engineering, Delft University of Technology, Mekelweg 2, 2628 CD Delft, The Netherlands and with the Heemskerk Innovative Technology B.V., Jonckerweg 12, 2201 DZ Noordwijk, The Netherlands.*
- *F. C. T. van der Helm and D. A. Abbink are with the Delft Haptics lab, Department of BioMechanical Engineering, Delft University of Technology, Mekelweg 2, 2628 CD Delft, The Netherlands.*
- *H. Boessenkool is with FOM Institute DIFFER (Dutch Institute for Fundamental Energy Research), Association EURATOM-FOM, Partner in the Trilateral Euregio Cluster, PO Box 1207, 3430 BE Nieuwegein, The Netherlands, and with the Delft Haptics lab, Department of BioMechanical Engineering, Delft University of Technology, Mekelweg 2, 2628 CD Delft, The Netherlands.*
- *C. J. M. Heemskerk is with the Heemskerk Innovative Technology B.V., Jonckerweg 12, 2201 DZ Noordwijk, The Netherlands.*

The bilateral information flow of haptic information allows humans to make use of their unique problem solving and manipulative skills in remote environments [1], [2]. Fig. 1 shows a schematic representation of a tele-manipulator, a human operator and the remote environment. This is referred to as the Connected Tele-manipulator System [3].

A tele-manipulator is typically not able to represent the full spectrum of natural haptic feedback from the environment as it filters and degrades the position and force information that passes through [4]. The quality of the feedback is often referred to as the transparency of the tele-manipulator and can be indicated by e.g. the transmitted impedance of the remote environment that is felt by the operator [5]. The transparency of tele-manipulators is still imperfect and has many unresolved issues. Research shows that limited transparency already improves task performance substantially compared to no transparency [4], [6], [7]. Further system oriented improvements in transparency by better haptic control architectures (e.g. [3], [5], [8]) and better hardware configurations (e.g. [3], [9]) tend to have limited additional benefit on the overall task performance [3], [7].

A promising approach to improve tele-manipulated task performance is to haptically guide the operator with forces. Haptic guidance has many experimental implementations, with various definitions, including haptic guidance to a reference position or trajectory (e.g. [10], [11], [12], [13], [14], [15]) and shielding areas from entering (i.e., virtual fixtures, e.g. [16], [17]).

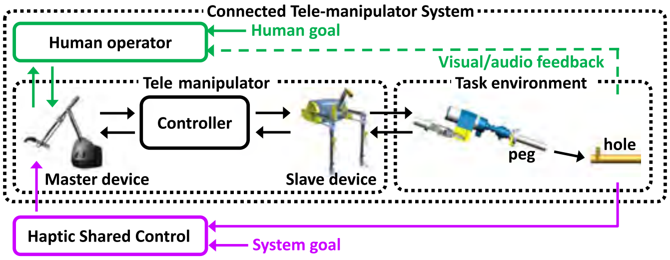

Fig. 1. Elements of the connected tele-manipulator system combined with haptic shared control. The task has the representation of a peg-in-hole task.

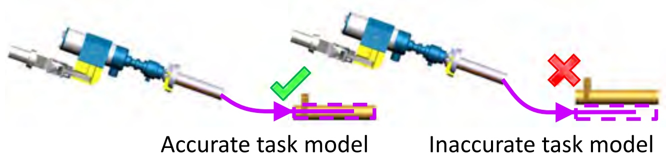

Fig. 2. Side view of the peg-in-hole task, showing haptic guidance (arrows) based on an accurate and inaccurate task models (dashed lines).

The current research adopts the definition of *haptic shared control*, which "allows both the human and the [guidance] system to exert forces on a control interface, of which its output (its position) remains the direct input to the controlled system [18]." Guidance forces are based on a task model, which contains information about both the remote environment and the systems goal. (see Fig. 1).

In general, studies report positively on the effect of haptic guidance on task performance [10], [11], [12], [13], [14], [15], [16], [17], [19], [20], [21]. Research shows that, haptic guidance assists operators to work almost on a similar performance level as in manual manipulation, while control effort is improved [14]. However, all these studies assumed that haptic guidance forces are based on pre-generated, errorless models of the task and remote environment.

Yet in practical implementations of a haptic guidance system, the system might not have perfect knowledge of the environment. Typically the environments, tasks and components are complex, unstructured, unpredictable and, moreover, dynamic [9], [22]. This will introduce *inaccuracies* in the model on which the guidance forces are based, due to, for example, unexpected objects, elastic and/or plastic structural deformations or sensory inaccuracies. Hence, resulting in mismatches between the model and the real world. A real world example is the replacement task of the ITER Divertor (ITER [23] is an experimental nuclear fusion reactor currently under construction, the Divertor is its subsystem that ensures the exhaust of heat and particles), in which a nine ton segment must be removed remotely. Due to deformations, the handling system can deflect 80 mm from its kinematic model. Real time models can still have a mismatch of about 5 mm [24]. In case the inaccurate models are used as a basis for the haptic guidance system, the operator will be guided incorrectly as indicated in Fig. 2.

The effect of inaccuracies in the haptic guidance on task performance and control effort in tele-manipulation has received limited attention in literature. In one case research describes the introduction of an inaccuracy due to varying grasping locations on a cassette, but mentions that the accuracy required to install it in a rack accommodates for this [15]. Another research shows that if the guidance system is not aware of obstacles, control effort is increased due to human-guidance disagreement [25]. Also, intentionally introduced inaccuracies in the haptic guidance by not avoiding obstacles during car driving, reduced task performance compared to manual control [26]. Our previous study investigated the effect of a 7.5 mm translational inaccuracy during a 30 mm diameter peg-in-hole type task [27]. We showed that haptic guidance with small inaccuracies still improves overall task performance compared to conventional tele-manipulation.

The goal of the current research is twofold. The first goal is to quantify the effects of haptic guidance when it suffers from inaccuracies (with different magnitudes and direction) on operators task performance and control effort. We will consider effects on the overall task, as well as on certain generalizable *task primitives*: Free Space Movement, Contact Transition, Constrained Translational Movement and Constrained Rotational Movement [7]. The task primitives are defined and explained in Section 2.3.

The second goal is to quantify the effect of the quality of haptic feedback (i.e., transparency) on the operator's ability to detect and cope with inaccuracies in haptic shared control.

This means that, compared to our previous study [27], this research will gain more insight in task execution as, besides task performance, we also investigate control effort. Further the assessment is detailed with the analysis of the task primitives. The effect of the quality of haptic feedback was entirely not investigated in our previous research. Finally, an additional inaccuracy level was evaluated.

For this research three hypotheses are defined. The first hypothesis is that haptic guidance *without* inaccuracies improves overall task execution compared to conventional tele-manipulation, as was found in previous research (e.g. [10], [13]). Additionally, the quality of natural haptic feedback (i.e., haptic transparency) will only have a limited effect on task execution [14].

Second, we hypothesize that haptic guidance *with* inaccuracies will degrade overall task execution in comparison with haptic guidance *without* inaccuracies. Specifically, these degradations are expected to manifest mainly during contact tasks, where accurate manoeuvring will be complicated by the guidance inaccuracies, especially when these inaccuracies are large and require active compensation by the operator. However, during free space tasks, without a clear reference, any haptic guidance inaccuracy will not be relevant.

Third, we expect that during contact tasks high-quality feedback of natural interaction force (i.e., haptic transparency) helps operators to detect and cope with inaccuracies in the haptic guidance.

These hypotheses are depicted in Table 1.

2 Methods

2.1 Subjects

Fourteen right handed subjects, aged of 18 to 40 (mean age: 27.1 years, standard deviation: 5.9 years) participated in the experiment. The experiment was approved by Delft University of Technology Human Research Ethics Committee.

TABLE 1
The Hypotheses (H1, H2 and H3) Depicted in a Table

		Transparency	
		High	Low
(H1) Task execution in free space/contact tasks	Conventional*	0	0
	Without inaccuracies	+	+
(H2, H3) Task execution in free space tasks	Without inaccuracies*	0	0
	With small inaccuracies	0	0
	With large inaccuracies	0	0
(H2, H3) Task execution in contact tasks	With small inaccuracies*	0	0
	With small inaccuracies	0	-
	With large inaccuracies	-	- - -

*Here 0, - and + mean respectively similar, degraded and improved task execution compared to the respective baseline (indicated by *).*

2.2 Experimental Setup

The tele-manipulated task is performed in a Virtual Reality environment. The simulation is done by the Interactive Task Simulator [28] where the slave device and task are modelled with NVIDIA PhysX that simulates real-time rigid body dynamics and contact interaction at 1 kHz. Fig. 3 shows an impression of the environment and slave.

The master device is a Haption Virtuose 6D35-45 as shown in Fig. 4. This haptic device has a cubic workspace of 450 mm and a rotational workspace of 145-115-148 degree. It can generate feedback forces and torques up to 35 N and 3.1 Nm (respectively 10 N and 1 Nm continuous). These forces are transmitted with a maximum controller stiffness of 2,000 N/m (translational) and 30 Nm/rad (rotational). The apparent inertia is 1 kg. The controller runs on a real-time Linux system and updates at 1 kHz.

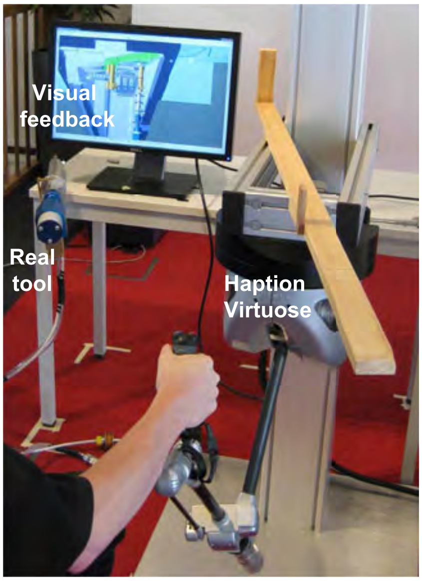

Fig. 4. Impression of the experimental set-up with the Haption Virtuose 6D35-45. Also shown is a wooden bar used to define the start position of the master device. Adapted from Oosterhout et al. [27].

The Virtuose 6D35-45 connects to the (virtual) slave with a two-channel position error controller (also known as PERR-control). This controller calculates forces and torques to apply on the master and slave device based on their position/orientation differences and their velocity. Table 2 specifies the controller parameters in more detail.

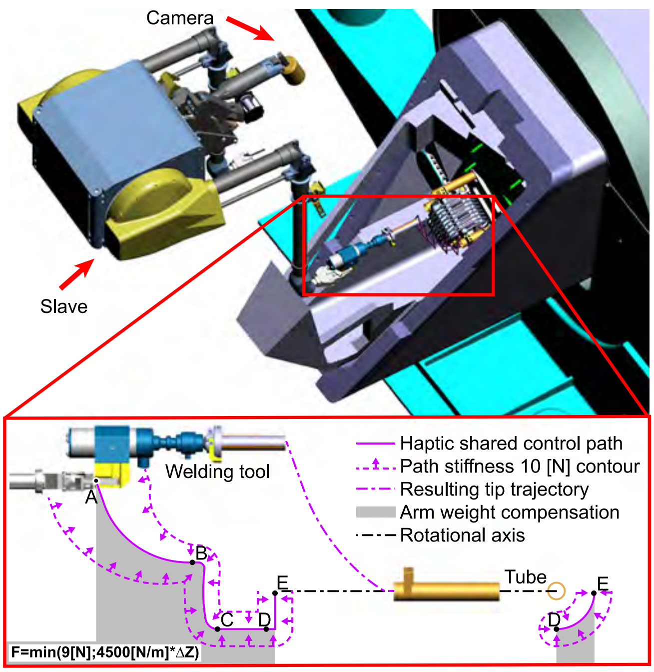

Fig. 3. The top part shows the (virtual) slave in the (virtual) environment. The red bordered part shows a side- and front-view of the welding tool placement task. The procedure is to follow the purple path which comprises four subsequent task primitives (as explained in Section 2.3): Free Space Movement (A-B), Contact Transition (B-C), Constrained Translational Movement (C-D) and Constrained Rotational Movement (D-E). The front-view in the lower right shows the out of plane rotation (D-E). Adapted from [27].

2.3 Task Description

The experimental task is the placement of a welding tool in a tube as shown in Fig. 3. The welding tool has the dimensions of $440 \times 70 \times 125$ mm (L × W × H), a tip diameter of 30 mm and a mass of 1.8 kg. The tool should be inserted for 140 mm in a 30 mm diameter tube with a clearance of 0.1 mm. The tool is actuated by the master via the slave gripper on point "A" as indicated in Fig. 3. The welding tool placement task comprises four subsequent task primitives:

1) Free Space Movement A-B. In general, this task primitive involves unconstrained transportation of the slave to a specific location, without contact forces being involved. Specifically for the current task, it involves simultaneously movement and turning

TABLE 2
Properties of the Tele-Manipulator with High and Low Transparency

Property	High quality	Low quality
K_{trans} N/m	2,000	300
B_{trans} Ns/m	14	10.5
K_{rot} Nm/rad	16.88	3
B_{rot} Nms/rad	0.12	0.105
Slave mass kg	0.3	1.2
Slave inertia kgm^2	675	2,700
Max force N	35	12
Max torque Nm	3.3	1.2

(20 degree) of the welding tool to the tube. This task primitive ends when the tool is 30 mm away from the tube, seen from above.

2) Contact Transition B-C. In general, this task primitive is a stage between free space and environmental interaction, often characterized by a slower, more specific movement. Specifically for the current task, it involves the final movement (30 mm) and subsequent alignment of the tool to the tube. It ends when contact is made, and the tool is horizontally aligned.
3) Constrained Translational Movement C-D. In general, this task primitive involves movement along a single direction, with stiff mechanical constraints in other directions (often characterized by problems with jamming). In this study, the task comprises full insertion of the tool into the tube, until the end stop is reached.
4) Constrained Rotational Movement D-E. In general, this task primitive involves rotation around a fixed point (e.g. opening a door or bolting with a spanner). Specifically for this task: to rotate the tool 90 degree counter clockwise.

The instructed strategy, using the tilted approach, allows the round shapes of the tube and tool to act like a funnel and gradually constrain the degrees of freedom. This approach has proven to be successful in peg-in-hole insertions [29], [30].

2.4 Haptic Shared Control Design

This research adapted and modified the proposed haptic shared control design from Boessenkool et al. [14]. The haptic guidance consists of three path segments along which the operator is assisted during the four task primitives (see Fig. 3). The segments consist of 23 to 43 discrete points with a defined orientation. The guidance forces and torques can build up to 10 N and 1 Nm. The motion is critically damped for each degree of freedom. In more detail:

A-B: Free Space Movement with a translational stiffness increasing linearly from 100 to 300 N/m and a rotational stiffness increasing linearly from 2 to 8 Nm/rad as the tool moves along the path.

B-D: Contact Transition and Constrained Translational Movement with a translational and rotational stiffness of 300 N/m and 8 Nm/rad respectively.

D-E: Constrained Rotational Movement with only a translational stiffness of 300 N/m. The path is circular around the tubes centreline and facilitates a snapping force of 1.2 N.

Several modifications to the shared control design by [14] where made. First a pilot study showed that artificial damping near contact rather decreased the ability to detect potential inaccuracies than reduced the harm of contact. Therefore it was chosen to omit artificial damping near contact.

The look-ahead controller—to guide operators based on a state they would obtain considering their heading—showed no merit in a pilot study, while it had the potential to destabilize the controller in low transparency. Therefore we omitted it and based the haptic guidance on the operator's present state.

TABLE 3
The Four Experimental Conditions Composed from Transparency and Operation Mode

Operation mode	Transparency High	Transparency Low
Conventional tele-manipulation	CT_HT	CT_LT
Haptic Shared Control (Accurate and -/+ inaccurate)	SC_HT_-17.5 SC_HT_-7.5 SC_HT_0.0 SC_HT_7.5 SC_HT_17.5	SC_LT_-17.5 SC_LT_-7.5 SC_LT_0.0 SC_LT_7.5 SC_LT_17.5

New features were added to the shared control design by [14]. Haptic shared control is supplemented with gravity compensation for the weight of the welding tool and the operator arm. These weights interfere with the translational inaccuracy in the task model by shifting the zero force reference level. Ideally this level is the path as haptic shared control is designed as a spring perpendicular to the path. But the tool and human arm weight stretch this spring by their weight without the operator noticing it.

This might be unexpected for the operator arm weight, as humans should carry their own weight. Nevertheless a pilot study revealed that several operators moved the tool at a constant line below the haptic guidance path, which therefore carried about half the arm weight. In other words: operators rest their arm on the guidance forces.

To remove the interfering translational inaccuracy, the arm weight is compensated—when the tool sinks below the path—with a stiffness of 4,500 N/m (max 9 N upward). Further the tool weight is fully compensated; a feature which is also applied in practice, e.g. at JET [31].

2.5 Experimental Design

2.5.1 Experimental Conditions

The experiment consists of four condition being composed of two *operation modes* with two transparency levels as shown in Table 3. Transparency levels are set to a relative *high* and *low quality*. The high quality is defined as the best performance that our tele-manipulator can handle. Low transparency represents an—manually tuned—inferior device in the sense of controller stiffness, controller damping, device inertia and maximum force/torque representation. Table 2 lists these device properties for both transparencies. The transparency is further quantified as the slave to master force bandwidth in translational direction. These bandwidths are 19 and 3.7 Hz for high and low transparency, respectively (obtained via the HapticAnalysis package [3]).

The operation modes are conventional tele-manipulation and haptic shared control. The haptic shared control paths were provided with five accuracy levels. Fig. 5 shows the used inaccuracies. The magnitudes are set to 7.5 (from the previous experiment [27]) and 17.5 mm (between the 15 mm inner and 20 mm outer radius of the tube in an attempt to parameterize it to the order of size of the task). The inaccuracies were applied randomly and in a plus (SC_7.5; SC_17.5) and minus (SC_-17.5; SC_-7.5) direction—together with haptic guidance without inaccuracies (SC_0.0)—in the haptic shared control condition. This

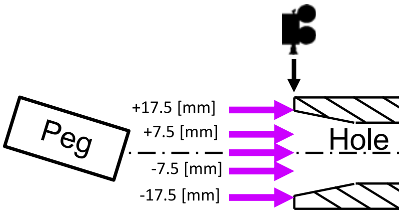

Fig. 5. Magnitude of the translational inaccuracy and the relation to the provided visual feedback.

randomization is done to prevent operators from predicting the size of the inaccuracy. In addition a practical implementation would also hold random positive and negative inaccuracies.

The experiment contains seven repetitions for the conventional tele-manipulation mode and 35 repetitions for the haptic shared control mode (five accuracy levels with each seven repetitions) in two transparency conditions. The order with which the four conditions were presented to the subjects was randomized to minimize the influence of order effects.

2.5.2 Controlled Variable-Task Instruction and Training

Before the experiment instructions were handed out and verbally explained to each participant. They were instructed to:

- Place the tool as specified in Section 2.3.
- Train to obtain a minimum performance level (15 s target time during training), but work as accurate as possible due to the delicate welding tool.

After the instruction, participants were trained with the task and conventional tele-manipulation (in high transparency) until they performed the task in about 15 s. To indicate inaccurate (reckless) operations, a threshold was set on the impact energy to trigger a buzzer and stop the simulation. In a second training session participants were acquainted with haptic shared control (in high transparency) until they were confident with the provided guidance forces. In addition, subjects practiced at least three times before the start of each condition, where—in case of haptic shared control—they were told that the system could have some sort of inaccuracies.

2.5.3 Controlled Variable-Visual Feedback and Direction of the Inaccuracy

During the training participants could rely on a top, rear and side view of the task. In the actual experiment only the top view was presented. This top view was positioned above the tube's entrance and placed in line with the translational guidance inaccuracy (see Fig. 5). This visually occluded the inaccuracy to control this potential confounding variable.

2.6 Data Acquisition & Metrics

For both master and slave the time, forces, positions and velocities were recorded at 1 kHz. The gathered data serves to evaluate task execution in terms of both task performance and control effort. The task performance is evaluated as:

- tct: Task-completion time [s], the time in seconds required to complete the task. Note that even though the task instruction was to perform the task as accurately as possible (and not as fast as possible), task-completion time as a metric is highly insightful because participants inherently make speed-accuracy trade-offs while coping with inaccuracies in guidance.

Control effort is evaluated in terms of:

- csa: Cumulative steering angle [degree] in Free Space Movement, Contact Transition and Constrained Translational Movement, the total amount of rotation that the operator made with his hand, which is a measure of effort to steer the tool accurately. It is measured by summing the differences between all subsequent orientations of the master device.
- err_{int}: Integrated path error [cm^2] in Constrained Rotational Movement, the area between the master position and the ideal path. This is treated as a measure of effort to steer around a rotational axis. Note that this metric closely relates to task performance: an integrated path error in directions constrained by the remote environment leads to undesirable increased contact forces.

2.7 Data Analysis

The calculated metrics were averaged over the seven repetitions per subject, for each of the 12 conditions. To analyse the effect of haptic guidance *without* inaccuracies and transparency (first hypothesis), a two-way repeated-measures ANOVA was done with factors F_{a1} operation mode (guided and conventional tele-manipulation) and F_{a2} transparency (high and low quality). To analyse the effect of haptic guidance *with* inaccuracies and transparency (second and third hypothesis) a two-way repeated-measures ANOVA was done with independent variables F_{b1} inaccuracy level (-17.5; -7.5; 0; 7.5; 17.5) and F_{b2} transparency (high and low quality). The ANOVAs were performed on the "tct" metric for the entire task and all four task primitives. The ANOVAs were also performed on the "err_{int}" metric for the Constrained Translational Movement and on the "csa" metric for the other three task primitives. The assumption of sphericity—equality of variances of the differences between levels—was tested with Mauchlys test. When sphericity assumption was violated, results were corrected with the Greenhouse-Geisser method. When inaccuracies had an effect on haptic guidance (the second hypothesis), specific hypothesis where tested using a contrast analysis. For this analysis no multiple comparison correction was applied to make, in view of our findings, a more conservative approach: a correction increases the chance of Type II errors. p-values of 0.05 or below are considered significant ($\alpha \leq 0.05$).

3 Results

Figures and tables in this section show the mean and 95 percent confidence interval (CI) based on 14 subjects, which each performed seven repetitions. Significant results are

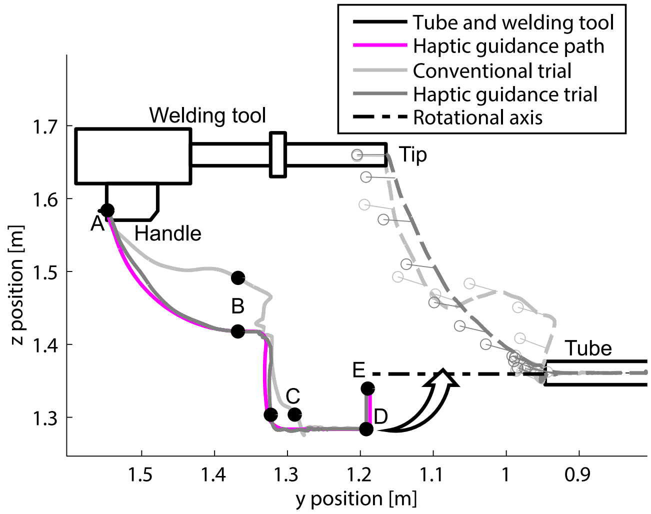

Fig. 6. Typical generated trajectories of the handle and tip for the peg-in-hole task, during conventional tele-manipulation (light grey) and haptic guidance without inaccuracies (dark grey) with high transparency. The trajectories for the handle (solid) comprises the four task primitives (as explained in Section 2.3): Free Space Movement (A-B), Contact Transition (B-C), Constrained Translational Movement (C-D) and Constrained Rotational Movement (D-E, highlighted by an arrow). The trajectories for the tip (dashed) have pins indicating the tool orientation.

denoted with '• • •', '••' and '•' for respectively $p < 0.001$, $p < 0.01$ and $p < 0.05$ (in figures) and in boldface (in tables).

Fig. 6 illustrates two trials performed by a typical subject, shown in a side view perspective. The trials were performed with conventional tele-manipulation (light grey) and haptic guidance *without* inaccuracies (dark grey). Subjectively seen the results suggest that the haptic guidance trial has improved task performance. Fig. 7, presenting the task-completion time of the entire task, shows that haptic guidance *without* inaccuracies indeed improves task performance ($F(1,13) = 62.73$, $p < 0.001$). It also shows that transparency improves task performance ($F(1,13) = 5.85$, $p = 0.031$). Further Fig. 7 shows that haptic guidance *with* inaccuracies decreases task performance ($F(1.86,24.18) = 20.3$, $p < 0.001$, Greenhouse-Geisser corrected). The contrast analysis shows that, except for SC_7.5, inaccuracies degrade task

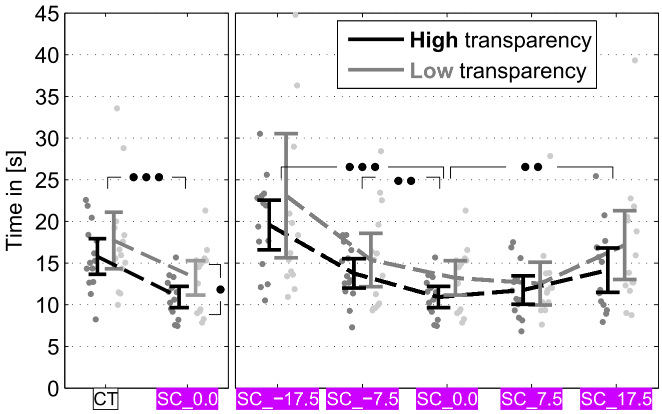

Fig. 7. Task-completion time for the entire task showing left Conventional Tele-manipulation (CT) and haptic guidance without inaccuracies (SC_0.0) for both transparencies. Both haptic guidance and transparency improve task performance. Right shows the effect of inaccuracy levels (-17.5; -7.5; 0; 7.5; 17.5) which is that inaccuracies degrade task performance.

TABLE 4
Contrast Analysis for the Entire Task for Factor F_{b1} Inaccuracy Level

	tct Entire task [s]		
SC to	Mean diff. (95% CI)	F(1,13)	p diff.
SC_-17.5	-9.25 (-13.06;-5.45)	27.61	**0.000**
SC_-7.5	-2.50 (-3.89;-1.10)	14.86	**0.002**
SC_7.5	-0.07 (-1.26;1.11)	0.02	0.894
SC_17.5	-3.58 (-5.62;-1.54)	14.39	**0.002**

performance ($p \leq 0.002$, see Table 4). For the effect of transparency on inaccuracy no evidence has been found ($F(1.70,22.05) = 0.57$, $p = 0.544$, Greenhouse-Geisser corrected). The figure does not show which task primitives contribute to the improvements/decrease of task performance due to haptic guidance. Therefore this section further describes the results per task primitive.

3.1 Effects of Haptic Guidance and Transparency

Table 5 summarizes the results for haptic guidance *without* inaccuracies and conventional tele-manipulation for both transparency levels. In Free Space Movement, task performance is not affected by haptic guidance or transparency ($F(1,13) \leq 4.423$, $p \geq 0.056$), while control effort is reduced by both haptic guidance and transparency ($F(1,13) \geq 17.23$, $p \leq 0.001$).

In Contact Transition, both haptic guidance and transparency improve task execution ($F(1,13) \geq 25.37$, $p < 0.001$).

In the Constrained Translational Movement, haptic guidance improves task execution ($F(1,13) \geq 6.18$, $p \leq 0.027$). Transparency does not affect control effort ($F(1,13) = 3.62$, $p = 0.08$), while it affects task performance ($F(1,13) = 8.16$, $p = 0.013$).

In the Constrained Rotational Movement, haptic guidance does not improve task execution ($F(1,13) \leq 0.26$, $p \geq 0.618$). Transparency does not affect task performance ($F(1,13) = 0.55$, $p = 0.470$), but it affects control effort ($F(1,13) = 84.51$, $p < 0.001$).

3.2 Effects of Inaccuracies and Transparency

Table 5 summarizes the results for haptic guidance *with* inaccuracies for both transparency levels. Table 6 summarizes the ANOVA results for the effect of haptic guidance *with* inaccuracies and transparency. For task performance during **Free Space Movement**, the results show that inaccuracies do not affect task performance ($p = 0.263$, Greenhouse-Geisser corrected). Inaccuracies do affect control effort ($p = 0.003$). The contrast analysis shows that only SC versus SC_-17.5 increases effort with 2.65 degree ($p = 0.014$, see Table 7). The results show that there is no interaction between transparency and inaccuracies for task execution ($p \geq 0.271$).

For **Contact Transition**, the results show that inaccuracies do not affect task performance and control effort ($p \geq 0.14$, Greenhouse-Geisser corrected), even though some participants clearly had more trouble with SC_-17.5 provided low transparency, as indicated by the large confidence interval which clearly shows in Fig. 8. The results show that there is no interaction between transparency and

TABLE 5
The Mean (1.96 × SD Describing +/-95% CI) for Task Performance and Control Effort Metrics for Each of the Four Task Primitives

	Free Space Movement		Contact Transition		Constrained Translation Movement		Constrained Rotational Movement	
Metric	*tct* [s]	*csa* [°]	*tct* [s]	*csa* [°]	*tct* [s]	*csa* [°]	*tct* [s]	err_{int} [cm^2]
CT_HT	4.25 (0.92)	39.50 (0.92)	5.81 (0.83)	66.69 (0.83)	5.06 (1.36)	93.89 (1.36)	0.66 (0.08)	0.87 (0.08)
SC_HT_-17.5	4.08 (0.45)	27.00 (0.45)	4.50 (1.09)	43.74 (1.09)	10.22 (2.39)	184.82 (2.39)	0.77 (0.15)	1.16 (0.15)
SC_HT_-7.5	4.06 (0.60)	25.96 (0.61)	3.45 (0.94)	33.47 (0.94)	5.59 (1.01)	92.98 (1.01)	0.66 (0.08)	0.82 (0.08)
SC_HT_0.0	3.73 (0.37)	25.41 (0.37)	3.58 (0.90)	37.07 (0.90)	3.00 (0.55)	51.91 (0.55)	0.62 (0.09)	0.75 (0.08)
SC_HT_7.5	3.80 (0.49)	26.29 (0.49)	3.40 (0.78)	35.95 (0.77)	3.97 (1.02)	57.38 (1.02)	0.61 (0.08)	1.41 (0.08)
SC_HT_17.5	3.94 (0.72)	26.20 (0.72)	4.10 (0.87)	40.65 (0.87)	5.52 (1.47)	81.04 (1.48)	0.60 (0.07)	1.99 (0.07)
CT_LT	4.23 (0.71)	43.66 (0.71)	9.74 (2.72)	125.39 (2.72)	3.14 (0.76)	64.50 (0.75)	0.60 (0.07)	9.04 (0.07)
SC_LT_-17.5	4.22 (0.54)	36.50 (0.53)	7.77 (4.39)	92.48 (4.39)	10.33 (4.21)	198.03 (4.21)	0.76 (0.11)	7.89 (0.11)
SC_LT_-7.5	3.99 (0.52)	32.96 (0.52)	5.43 (2.18)	62.85 (2.19)	5.27 (1.72)	106.05 (1.72)	0.69 (0.10)	7.18 (0.11)
SC_LT_0.0	3.92 (0.43)	32.79 (0.43)	5.64 (1.27)	64.85 (1.26)	3.01 (0.95)	45.25 (0.95)	0.65 (0.08)	8.46 (0.07)
SC_LT_7.5	4.14 (0.59)	32.62 (0.58)	5.12 (1.59)	57.36 (1.59)	2.63 (0.87)	34.88 (0.87)	0.64 (0.10)	11.84 (0.09)
SC_LT_17.5	4.40 (0.77)	34.44 (0.77)	5.41 (1.09)	61.16 (1.09)	6.66 (3.03)	131.01 (3.03)	0.70 (0.10)	14.32 (0.09)

The grey coloured data are excluded from the analysis as will be explained in the discussion.

inaccuracies for both task performance and control effort ($p \geq 0.407$, Greenhouse-Geisser corrected).

During **Constrained Translational Movement**, the inaccuracies affect task execution ($p < 0.001$, Greenhouse-Geisser corrected). The contrast analysis shows that, except for SC_7.5, inaccuracies result in decreased task execution by at least 2.43 s and 50.93 degree ($p \leq 0.048$) as shown in Table 7. The results give the impression of a (asymmetric) parabola as shown for task performance in Fig. 9. The results show that there is no interaction between transparency and inaccuracies for task performance and control effort ($p \geq 0.199$, Greenhouse-Geisser corrected).

For **Constrained Rotational Movement**, the results show that inaccuracies affect task performance ($p < 0.001$, Greenhouse-Geisser corrected) but not control effort ($p = 0.394$, Greenhouse-Geisser corrected) as shown in Figs. 10 and 11 respectively. Note that for control effort (shown in Fig. 11) the SC_7.5 and SC_17.5 results are excluded from the analysis as will be explained in the discussion. The contrast analysis for task performance shows that SC_-17.5 requires on average 0.13 s more time than haptic guidance without inaccuracies (p=0.002) as shown in Fig. 10 and Table 7. The results show that there is no interaction between transparency and inaccuracies for task performance and control effort ($p \geq 0.321$, Greenhouse-Geisser corrected).

4 Discussion

The results for the entire task show that haptic guidance *without* inaccuracies improves task-completion time compared to conventional tele-manipulation, as also found by most studies on haptic guidance [10], [11], [12], [13], [14], [15], [16], [17], [19], [20], [21]. The results also show that improved transparency decreased task-completion time in, while [3], [7] found no effect. For haptic guidance *with* inaccuracies, the benefits of guidance decrease especially for the large inaccuracies. Interestingly, the direction of inaccuracies seems to influence the effect: task performance decrease is larger for SC_-17.5 and SC_-7.5 compared to the SC_17.5 and SC_7.5. Further the results provide no evidence for the hypothesis that the quality of haptic transparency helps operators to detect and cope with inaccuracies in the guidance. To better understand what task elements contribute to the overall task effects described above, and to be able to generalize and compare with other studies, we subdivided the task in four task primitives [7], and the effects of the experimental conditions on each task primitive will be discussed in the next section.

4.1 Effects of Haptic Guidance and Transparency

The effect of haptic guidance *without* inaccuracies and transparency on task performance and control effort shows up

TABLE 6
ANOVA Results, Per Task Primitive and Metric, for the Effect of Inaccuracy Level (F_{b1}) and the Interaction of Inaccuracies with Transparency (F_{b1}*F_{b2})

	Free Space Movement		Contact Transition		Constrained Translation Movement		Constrained Rotation Movement	
Performance	*tct* [s]		*tct* [s]		*tct* [s]		*tct* [s]	
F_{b1} (Inac.)	F(2.2,28.1) = 1.40	p = 0.263[1]	F(1.7,21.7) = 2.22	p = 0.140[1]	F(1.8,23.8) = 18.14	p = **0.000**[1]	F(2.0,25.9) = 10.85	p = **0.000**[1]
F_{b1}*F_{b2}	F(4,52) = 1.26	p = 0.297	F(1.6,20.4) = 0.65	p = 0.498[1]	F(2.3,29.8) = 0.85	p = 0.452[1]	F(1.7,21.5) = 0.82	p = 0.434[1]
Control effort	*csa* [°]		*csa* [°]		*csa* [°]		err_{int} [cm^2]	
F_{b1} (Inac.)	F(4,52) = 4.65	p = **0.003**	F(1.7,21.8) = 1.83	p = 0.188[1]	F(1.9,25.2) = 11.27	p = **0.000**[1]	F(1.3,16.5) = 0.86	p = 0.394[1,2]
F_{b1}*F_{b2}	F(4,52) = 1.33	p = 0.271	F(1.6,20.1) = 0.87	p = 0.407[1]	F(1.9,25.0) = 1.72	p = 0.199[1]	F(1.4,18.6) = 1.14	p = 0.321[1,2]

The contrast analysis, for ANOVA results with a significant main effect, can be found in Table 7.
[1]*Corrected with the Greenhouse-Geisser method as the sphericity assumption has been violated.*
[2]*Data for the 17.5 and 7.5 mm inaccuracy is excluded from the analysis as explained in the discussion.*

TABLE 7
Contrast Analysis for F_{b1} Inaccuracy Level for the Task Primitives That Had a Significant Main Effect

	csa Free space [°]		
SC to	Mean diff. (95% CI)	F(1,13)	p diff.
SC_-17.5	−2.65 (−4.66;-0.65)	8.16	**0.014**
SC_-7.5	−0.36 (−1.66;0.938)	0.36	0.560
SC_7.5	−0.36 (−1.44;0.73)	0.50	0.494
SC_17.5	−1.22 (−2.49;0.5)	4.30	0.058
	tct Constrained translation [s]		
SC to	Mean diff. (95% CI)	F(1,13)	p diff.
SC_-17.5	−7.27 (−10.05;−4.50)	31.90	**0.000**
SC_-7.5	−2.43 (−3.45;−1.40)	26.24	**0.000**
SC_7.5	−0.30 (−0.97;0.37)	0.91	0.357
SC_17.5	−3.08 (-4.80;−1.37)	15.08	**0.002**
	csa Constrained translation [°]		
SC to	Mean diff. (95% CI)	F(1,13)	p diff.
SC_-17.5	−142.84 (−209.84;−75.85)	21.22	**0.000**
SC_-7.5	−50.93 (−79.81;−22.05)	14.51	**0.002**
SC_7.5	2.45 (−13.61;18.52)	0.11	0.747
SC_17.5	−57.44 (−114.16;−0.73)	4.79	**0.048**
	tct Constrained rotation [s]		
SC to	Mean diff. (95% CI)	F(1,13)	p diff.
SC_-17.5	−0.13 (−0.20;−0.06)	14.62	**0.002**
SC_-7.5	−0.04 (−0.08;0.01)	3.60	0.080
SC_7.5	0.01 (−0.01;0.04)	1.28	0.279
SC_17.5	−0.01 (−0.04;0.02)	0.62	0.446

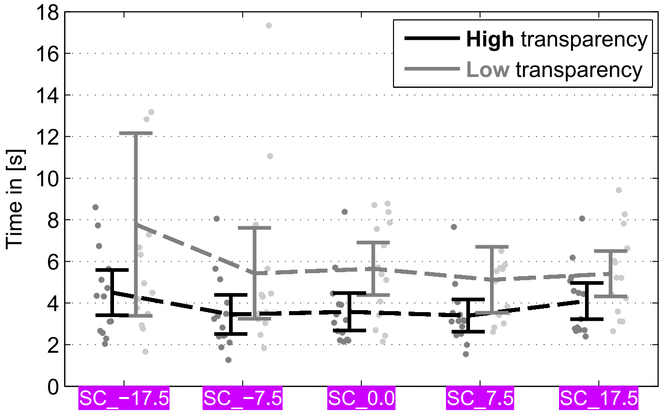

Fig. 8. Task-completion time for the Contact Transition showing the effect of inaccuracy levels. There is no significant difference between haptic guidance with and without inaccuracies. A higher quality transparency does not support operators to detect and cope with inaccuracies.

differently among the four task primitives. Haptic guidance improves task execution (combined task performance and control effort) during Contact Transition and Constrained Translational Movement tasks. For Free Space Movement, haptic guidance reduces control effort. Providing high-quality natural haptic feedback on the other hand, improves Contact Transition and Constrained Rotational Movement, while reducing task performance for Constrained Translational Movement.

While we expected haptic guidance to improve task execution for **Free Space Movement**, guidance only improved control effort (20-30 percent compared to conventional telemanipulation). For a similar task in a maze, [25] found a

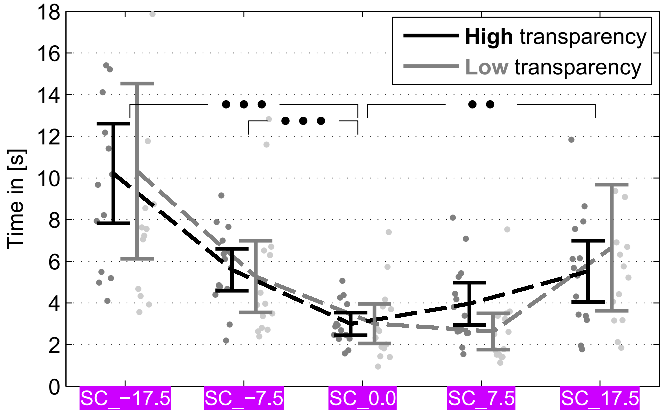

Fig. 9. Task-completion time for Constrained Translational Movement showing the effect of inaccuracy levels. Task performance decrees for SC_-17.5, SC_7.5 and SC_17.5. A higher quality transparency does not support operators to detect and cope with inaccuracies.

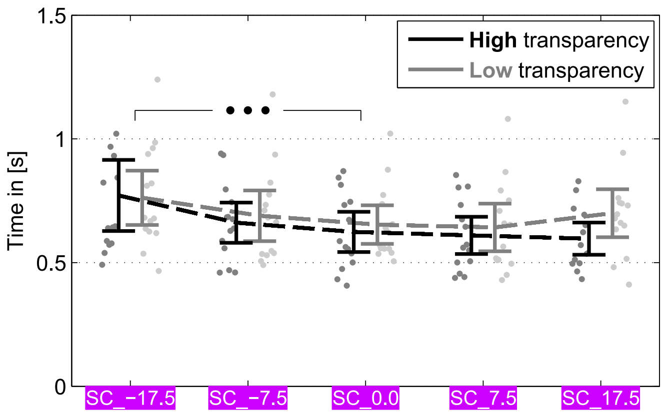

Fig. 10. Task-completion time for Constrained Rotational Movement showing the effect of inaccuracy levels. SC_-17.5 requires more time to complete the task. A higher quality transparency does not support operators to detect and cope with inaccuracies.

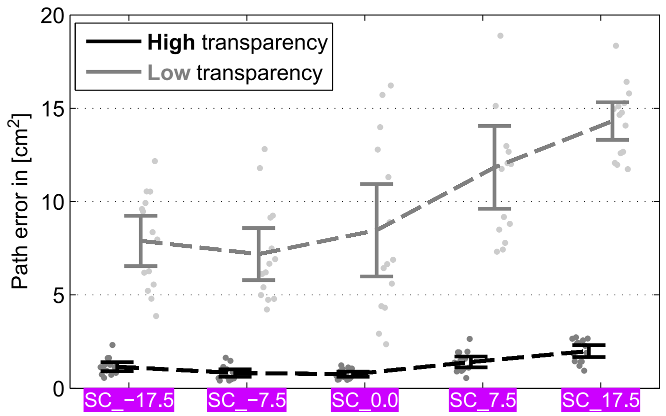

Fig. 11. Integrated path error for Constrained Rotational Movement showing the effect of inaccuracy levels. SC_17.5 and SC_7.5 are excluded from the analysis. The other inaccuracies do not affect control effort. A higher quality transparency does not support operators to detect and cope with inaccuracies.

task performance improvement of 30 percent, while control effort remained unaffected. Boessenkool et al. [14] found a 20-25 percent reduction in time and a 38-56 percent reduction in control effort due to haptic guidance in their bolt-and-spanner task.

An explanation for this difference with [14], [25] could be that operators chose a different path during conventional tele-manipulation than the guided trajectory, since the current task execution was not judged on how accurate operators followed the prescribed path. By moving straight from point A to B (see Fig. 3) this could reduce task-completion time by roughly 7 percent as the path is that shorter. However such direct motions were hardly possible, and not observed, because of the limited perception on their position in the vertical plane due to the camera view from above.

An alternative explanation could be the difference in task instruction, which may lead to different performance-effort trade-offs. In [14], [25] participants were instructed to move as fast as possible, while our participants were instructed to be as accurate as possible. Our instructions might have caused operators to exploit the haptic guidance for accuracy instead of for speed, which may explain the improved control effort without effects on task performance.

Interestingly, a higher transparency reduces control effort during Free Space Movement. Possibly a higher quality transparency helps operators to control the dynamics of the—relatively heavy—tool, as was for example found in [32].

For the task primitive **Contact Transition** task execution improves by 20-50 percent due to haptic guidance compared to conventional tele-manipulation. The reduction in task-completion time (20-40 percent) agrees with the approximate 32 percent reduction in earlier research [14]. However, it should be noted that the reduction found in our research could be a result of operators ending the preceding task primitive (Free Space Movement) too high or low during unguided trials. Therefore they might require extra time and effort during the Contact Transition to reach the tube. Nevertheless, if such effects occurred, they are the result of limited depth perception, which is a realistic and frequent occurring phenomenon in tele-manipulation.

A higher level of transparency substantially improves task performance (36-40 percent) and control effort (43-47 percent) during Contact Transition, against our expectations. Previous work in our group [3], [7] suggests that there are certain minimum requirements to the content of feedback information. Apparently, for this task primitive, the low transparency condition failed to provide sufficient information.

For **Constrained Translational Movement** haptic guidance without inaccuracies improves task performance up to 40 percent and control effort up to 44 percent compared to conventional tele-manipulation. This is in agreement with previous research which found reduced contact forces at the remote site [15] and a 42-52 percent improved task-completion time [14].

Interestingly, low transparency improves task performance with 38 percent compared to high transparency for Conventional Tele-manipulation. This finding corresponds to the notion that some tasks might benefit from a certain amount of compliancy, which may occur anywhere in the master-slave chain [3]. This can be mechanical compliancy in the slave or, as in our case, the reduced controller stiffness in the low transparency condition.

During **Constrained Rotational Movement** haptic guidance without inaccuracies does not improve task execution. This is in agreement with previous work [14]. We did however hypothesize improvements as the guidance was expected to allow operators to follow the ideal path at least more accurately, due to our task instructions having a focus on accuracy. What we observed is that operators adapt their behaviour by approximating a tangential force, while acting compliant in axial and radial directions, as also observed by [7]. By adapting this strategy, in general, task constraints ensure accurate path following, but only if these task constraints are made sufficiently tangible, by either the haptic transparency or the haptic guidance. Apparently, in this experiment the task constraints were only sufficiently tangible for the high transparency condition; for these conditions the integrated path error is substantially lower (90 percent), compared to the low transparency conditions. This suggests that, in this task primitive, operators benefit more from any transparency than from haptic guidance, as guidance did not improve control effort in the low transparency condition.

4.2 Effects of Inaccuracies

The effect of haptic guidance *with* inaccuracies on overall task execution (performance and control effort) is dominated by the effects seen during Constrained Translational Movement. For Constrained Rotational Movement, inaccuracies increases task performance. Control effort during Free Space Movement is marginally affected. Contact Transition is not affected at all by the presence (or magnitude) of inaccuracies in the haptic guidance.

During **Free Space Movement** haptic guidance with inaccuracies degrades control effort by 6-11 percent for SC_-17.5, while not expected. The cause of this difference is unclear as there were no means to obstruct task execution during this task primitive. Furthermore the inaccuracies in the haptic guidance condition were randomized to prevent operators from predicting the size of the inaccuracy.

Haptic guidance with inaccuracies during **Contact Transition** does not affect task execution, which is in contrast to the hypotheses. Yet the large confidence interval of SC_-17.5 under low transparency suggests that this condition was more troublesome. For this SC_-17.5 condition it was observed that operators could not always discriminate whether they placed the tool in or underneath the tube. Low transparency, limited visual feedback and the presence of haptic guidance forces by itself may lead to difficulties in detecting erroneous placement of the tool.

During **Constrained Translational Movement** task execution decreases more as the inaccuracy in haptic guidance gets larger. This originates from the tasks potential to jam, which is makes it especially vulnerable to forces tangential to the insertion direction, as the forces due to inaccuracies in the guidance do. Interestingly, though, the effect seems to be larger for the SC_-17.5 and SC_-7.5 compared to the SC_17.5 and SC_7.5, as found for the entire task. Task execution degrades similarly for SC_-7.5, SC_17.5 with 75-134 percent, while tasks execution for SC_-17.5 degrades with 340-438 percent. A cause for this unexpected difference between the inaccuracies could be due to the task kinematics; the tool is held such (point A in Fig. 3) that jamming is enhanced with negative inaccuracies, and reduced with positive inaccuracies. This suggests that task execution should have increased with positive inaccuracies. We do however think that, during this task primitive, operators made use of the task constraint, providing mainly a force in the direction of the desired movement. Therefore they did not rely on the arm weight compensation force (max 9 N). As such, the compensation force could drive the tool to jam as well.

For **Constrained Rotational Movement**, haptic guidance with inaccuracies increases task-completion time with 16-24 percent for SC_-17.5, while SC_17.5 is not affected. This might be explained by the fact that during SC_-17.5 the haptic guidance applies a downward force on the operator hand, therefore counteracting the rotation and decreasing task performance. For SC_17.5 the inverse is observed; the guidance force acts in the direction of movement.

4.3 Effects of Transparency

The results indicate that haptic transparency does not affect the operators ability to detect and respond to inaccuracies in the haptic guidance. This could be caused by the simultaneous presentation of guidance and contact forces to the operator. According to Powell and O'Malley [33] our haptic guidance implementation can be classified as "Gross Assistance" for which they found that forces were confusing and difficult to interpret. As such it may be difficult to distinguish between natural haptic feedback and guidance forces. In particular, in case of jamming during the Constrained Translational Movement, operators seemed to get confused about the state of the task and perhaps lose situation awareness.

4.4 Limitations and Future Work

A point of discussion is the effect of the arm weight compensation force on the results. The compensation force provides an upward force (max 9 N with a 4,500 N/m stiffness) when the tool sinks below the path as shown in Fig. 3. This compensation force has affected the control effort results for the Constrained Rotational Movement. For this task primitive we found extreme values for the integrated path error for SC_17.5 and SC_7.5, while not for the SC_-17.5 and SC_-7.5. By analyzing the raw data, we found that, with low transparency, the compensation force pushed the master position upward to roughly the haptic guidance path. This is also the equilibrium in path and tele-manipulator stiffness (4,500 + 300 N/m and 300 N/m respectively). This suggests that the results are dominated by the arm weight compensation force instead of inaccuracies in the haptic guidance itself. Therefore we excluded them from the analysis.

The compensation force—of the arm weight—might as well have affected the Free Space Movement and the Contact Transition. Though this was not observed.

The effect of model inaccuracies might be substantially affected by the stiffness of the haptic shared control system (also referred to as the level of haptic authority [18], [21]). Using a low stiffness haptic shared control lessens the effect of an inaccuracy (operators can easily overrule the guidance forces) but also provides less clear guidance forces. Increasing the stiffness makes haptic shared control act more like automation in which case small inaccuracies/obstacles will cause increased execution time [11], [25] and increased control effort [25]. Literature suggests to adapt control authority depending on the task, the operator's intention or the criticality of the task [21], [25]. Additionally one can adjust the authority based on accuracy of the shared controllers task and environmental model.

The effect of inaccuracies will strongly relate to the order of magnitude (e.g. tube radius) and the criticality of the task. Consider for example the insertion of an injection needle in a slightly larger tube, which requires careful handling and high accuracy. On the other hand the insertion of a 4 inch drain-pipe in a fitting allows rough handling and less accuracy. When considering a relative inaccuracy (e.g. a magnitude of one radius) for these examples, we expect to find similar effects for Free Space Movement and Contact Transition as in our research. For constrained tasks the effect will likely depend on the maximum guidance force as that will enhance jamming. Based on the above reasons, the effect of the absolute size of inaccuracies depend greatly on the task. How this relates could be the topic of future research.

This research considered translational inaccuracies, while [27] also defined rotational inaccuracies, spatial distortions (e.g. pincushion effect) and missing objects. Many of these inaccuracies will locally behave like a translational inaccuracy and therefore generate similar effects. For other situations new research should reveal their effects.

By definition a Virtual Reality model, as used in our experiment, is a simplified representation of the real world. Therefore it cannot be *validated* or *verified* to a real system as the model is not *truly* the same as reality [34]. This means that our results might not transfer one-on-one to a real system. To gain confidence in the fidelity of the model and results, several tests are done on e.g. the dynamics in a mass spring system and friction. Here we found that the simulated dynamics and friction closely resemble real world behaviour [28] and that jamming effects appear realistic [35]. Furthermore our results on haptic guidance *without* inaccuracies and transparency closely resemble those of previous research (like e.g. [13], [14], [25]) or can be explained by research (like e.g. benefits of a low or high transparency [3], [32]). As such, the main effects of our experiment—inaccuracies mainly affect Constrained Translational Movement and a higher transparency does not help operators to detect and cope with inaccuracies—are expected to be the same in hardware setups that have a similar experimental design.

This research demonstrates that an intuitive and reliable haptic shared control system is possible despite small errors in the model on which the guidance forces are based. Haptic shared control is especially robust against inaccuracies during Free Space Movement and Contact Transition, which could be classified as task primitives without much constraints. Moreover, the effect of inaccuracies in haptic shared control does not depend on transparency. However, the effect of transparency itself should not be neglected as tasks with mainly Free Space Movements and Contact Transitions and Constraint Rotational Movements will benefit from high transparency.

5 Conclusion

This human factors study investigated how inaccuracies in the model on which haptic shared control guidance forces are based, affects execution of a realistic virtual tele-manipulated assembly task. Operators performed a peg-in-hole type task, where we manipulated the magnitude of inaccuracy of the haptic guidance trajectory and quality of the natural haptic feedback (i.e., transparency). For the experimental conditions studied, we conclude that: Task-completion time is substantially improved compared to conventional tele-manipulation, both by offering haptic guidance *without* inaccuracies as well as by increasing haptic transparency.

- Specifically, the overall benefit of haptic guidance is the result of improvements in task performance and control effort during Contact Transition and Constrained Translational Movement, and in control effort during Free Space Movement.
- The overall benefit of a higher quality of haptic transparency is the result from improved task performance and control effort during Contact Transition and control effort during Free Space and Constrained Rotational Movement. Interestingly, during Constrained Translational Movement this effect is opposite: this task primitive actually benefits from a reduced transparency and the resulting compliancy in the tele-manipulation system.

Inaccuracies in haptic guidance can degrade task performance, depending on the magnitude and the direction of the inaccuracies. The benefits of haptic guidance are relatively robust against small inaccuracies—only for one direction a significant but small (20 percent) degradation in task performance was found, compared to guidance without inaccuracies—whereas large inaccuracies substantially degrade task performance (29-77 percent).

- The effect of inaccuracies on overall task performance is dominated by effects found for the Constrained Translational Movement, due to its potential for jamming. Here, inaccuracies that increase the potential for jamming, lead to a larger degradation in task performance and control effort than inaccuracies that do not.

No evidence was found that a higher quality of haptic transparency helps operators to detect and cope with inaccuracies in the haptic guidance, neither during the entire task nor during any of the task primitives.

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