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Haptic Assistance Improves Tele-manipulation With Two Asymmetric Slaves.

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***Abstract*—Tele-manipulation of heavy loads typically requires the simultaneous use of two asymmetric slaves: a crane for vertical weight support and a robot for accurate lateral positioning. The industrial standard prescribes a pair of operators for such tasks (one operator to control each slave), although in principle one operator might control both slaves with a single, hybrid interface. Accurate and safe co-operative handling of the expensive and fragile heavy components is difficult, presumably due to problems in the coordination of the subtasks and the lack of mutual awareness between the two operators. This study proposes a novel haptic assistance system to improve subtask coordination and task performance. Its novelty consists of haptically linking operators/interfaces through the joint task environment. The system's efficacy is evaluated with fifteen pairs of co-operators and fifteen individual uni-manual operators who manoeuvred a heavy load through a bounded path in Virtual Reality. Haptic assistance improves task completion time for both groups. It also reduces control activity and self-reported workload without affecting a number of critical errors made by the operators. Moreover, without haptic assistance, uni-manual operators perform worse than co-operators, but this difference between the interfaces was not found with haptic assistance.**

***Index Terms*—Collaboration, Co-operation, Dyads, Haptics, Remote handling, Tele-manipulation, Haptic assistance, Haptic shared control.**

I. Introduction

In construction and industrial maintenance, heavy objects are commonly manipulated by using two asymmetric systems: for example, a crane to hoist the load and a helping hand to position the load. In hazardous environments, the heavy load handling has to be done remotely, such as in deep-sea repair actions (e.g., the Deepwater Horizon oil rig [1]). Typically, such tasks are performed by two operators using the standard industrial approach: one human operator performs the hoisting subtask via a joystick in rate control [2] and another operator performs the lateral positioning subtask via a master device in position control.

Similarly, maintenance in future fusion power plants will be done remotely, due to high radiation levels, and will involve accurate manipulation that requires the use of two asymmetric systems [3]. The envisioned system for remote maintenance, a dexterous slave, is typically limited to carrying 15-25 kg [4], [5]. Many loads surpass this limit, such a fragile and

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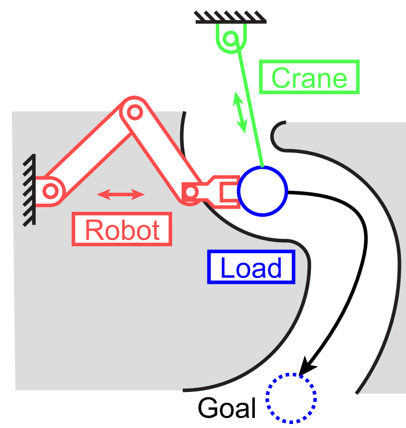

Fig. 1. An illustration of two asymmetric slaves with interactive subtasks. The crane (green) hoists the load (blue) vertically, and the dexterous robotic arm (red) accurately manipulates the load horizontally along a curved bounded path.

expensive components, like: tools [6], mirror modules [7]–[9] and shielding modules [4], [10], [11]. To guide and align such loads with millimetre precision to its mount, a crane will perform the hoisting task, while the dexterous slave performs the accurate horizontal manoeuvring, as illustrated in Fig. 1.

These tasks, with asymmetric slaves, cannot be controlled by autonomous systems. Autonomous robots perform repetitive tasks in standardized environments very well, but their capabilities are limited especially when they need to physically interact in complex varying environments [12]. To deal with the unpredictable nature of maintenance and repairs, a human-in-the-loop approach is crucial [13], [14].

Tele-manipulation is not as easy as direct hands-on manipulation. Well-known disadvantages of tele-manipulation are limited performance, accuracy and situation awareness [15], [16]. Even an experienced tele-operator controlling one dexterous slave system needs 3.5 to 8 times longer to complete the task than an operator working hands-on [17]–[19]. When a crane uses 10 to 20% of the task time, this same operator would need 13 to 23 times longer to complete a tele-manipulated task than an operator working hands-on [19]. This time cost conflicts with uptime requirements of future fusion power plants, such as ITER (the International Thermonuclear Experimental Reactor) and DEMO (a DEMOnstration power station). While one of ITERs goals is to demonstrate the feasibility of fusion plant maintenance, DEMO aims to prove the economic viability of fusion energy by maintaining uptime above 75% [20]. To meet these goals, DEMO's maintenance facility is currently estimated at a unique scale of 737000 m^3 and includes many parallel work cells [21]. Improving tele-manipulation working speed and reliability can reduce the number of parallel work cells, and thus hot cell volume and cost, while meeting plant uptime demands. Therefore, this study aims to contribute to improving time-efficiency and safe handling for remote maintenance tasks that require two asymmetric slaves.

For pairs of operators work together efficiently, they must account for task constraints in the remote environment as well as the specific relative behaviour of each slave. Operator behaviour and task constraints form the basis of Jarrassé's framework to classify two-operator tasks [22]. This framework, combined with suggestions from [23], comprises four classes:

- Asymmetric divisible [23]: Operators have different (sub)tasks that they can complete individually;
- Symmetric divisible (co-active [22]): Operators have identical tasks that they can complete individually;
- Symmetric interactive (collaborative [22]): Operators have identical tasks that they must coordinate precisely together; and
- Asymmetric interactive (co-operative [22]): Operator have different (sub)tasks that they must coordinate precisely together.

The remote maintenance task considered in this study has an asymmetric interactive nature because the actions in the two asymmetric subtasks must be coordinated closely together to perform the overall task, as illustrated in Fig. 1. Presumably, close coordination of actions between the asymmetric subtasks is one of the most challenging aspects for co-operators, because they have to integrate one's own control activity with those of the other, while their capabilities are dissimilar. To increase time-efficiency and safe handling, we explore two design options: 1) to provide haptic assistance to the operators, or 2) to provide an interface by which the two asymmetric slaves can be controlled by a single operator.

The first design option aims to improve coordination between two operators by haptically linking their control actions through a joint task environment, via an assistive controller that guides the heavy load towards a pre-determined ideal trajectory. To this end, the assistance translates the control actions between the asymmetric subtasks via the joint task, such that each operator perceives haptic cues in their own task space to match, or even correct for, the other's actions. Meanwhile, the assistance also facilitates supportive forces to perform the joint task. Literature provides ample examples of haptic assistance for a single task (i.e., without subtasks) performed by one operator, which can be divided in two categories: repulsive assistance and attractive assistance [24]. Repulsive assistance includes virtual fixtures [25], and similar approaches that prevent movement into restricted areas, but do not influence movement elsewhere (e.g., [26], [27]). This type of assistance acts like a barrier, similar to a guardrail preventing cars from driving off a cliff. Attractive assistance, supports operators towards a reference trajectory (e.g., [18], [27]–[34]). While both approaches improve task performance, this study focuses on attractive haptic assistance.

Note that a haptic link between operators can substantially improve task performance without such haptic assistance (e.g. [35]–[40]). Haptic links between operators have also been proposed with haptic assistance (e.g., [40]–[43]). These studies linked the positions and/or velocities between operators for the object carried or oriented, which improved their task execution. However, these studies did not assist operators during the overall task, like manoeuvring from point A to B. Moreover, these studies (including those on haptic links without assistance) considered only symmetrical interactive subtasks, in which the operators ideally perform identical control actions, and thus have well-defined clear interactions between the control tasks of the operators. In contrast, asymmetric subtasks have no straightforward relationship between the control tasks of the operators. An example is given in Fig. 1 where the movement on a curve implies that position and/or velocity must continuously change for each subtask. Since literature does not provide details on how to design haptic assistance in these cases, we will explore the design and evaluation of a novel haptic assistance system that haptically links two operators through the joint task environment via asymmetric subtasks.

The second design option considers a single hybrid control interface for one-handed (uni-manual) operation. This hybrid interface allows to control both subtasks as described in [23], and theoretically merely requires a different control scheme as proposed in, for example, [43]–[45]. In a previous study [23], this uni-manual approach had worse performance than the co-operated approach. The study explains that human performance deteriorates when controlling more axes that have different (complex) dynamics, as identified by McRuer and Schmidt [46]. We will also determine the efficacy of the haptic assistance for uni-manual controlled tasks. Literature shows that haptic assistance allows individual novice operators to perform complex dynamic tasks better than without assistance [27]. Individual novice operators also learn new movement strategies for complex tasks better with than without haptic assistance [33]. To the best of our knowledge, haptic assistance has never been applied to an individual controlling two interactive asymmetric subtasks.

We hypothesise that assistance with a haptic link between subtasks improves task performance, requires less control activity and subjective workload, and increases acceptance and safety for both co-operated and uni-manual tasks. Furthermore, for uni-manual operators, we hypothesise that haptic assistance improves task performance up to, or even beyond, the performance of the co-operators.

II. Haptic assistance design

The design of a haptic assistance system for two asymmetric slaves poses several challenges, even when assuming it has a sufficiently accurate model of the task environment. First, the system must have knowledge of the 'ideal' task that links each interface at each moment in time. Secondly, the system must direct the desired slave control actions between the interfaces, even while the linked actions are inherently

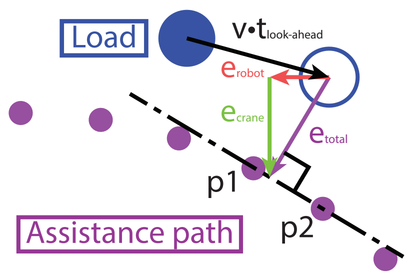

Fig. 2. The basis of the haptic link between subtask through the joint task space. The assistance algorithm estimates the future state of the load (blue) using a look-ahead time (black arrow). Then it finds the closest support path points (p1 and p1) and calculates the closest distance (orthogonal) towards the line between these points. This is the load's desired heading (purple e_{total}). The assistance algorithm splits this heading into the horizontal (red e_{robot}) and vertical (green e_{crane}) components.

different. Finally, the system must intuitively communicate the desired actions towards each of the asymmetric interfaces. In essence, this requires a solution that is usable and intuitive for both operators simultaneously, because a failure in effectively assisting one operator would impact the other as well.

Addressing these design challenges can be simplified by considering the joint task in the remote environment, rather than the separate subtasks. For the joint task, there is only one task description in six degrees of freedom, independent of the number of slaves or interactive subtasks. For example, there is only one joint task definition in Fig. 1: the load must move to its goal while staying between the bounds. The assistance system should primarily satisfy the joint task constraints, specific subtask and interface designs can be handled later on. For the joint task in this study, the assistance has a predefined support path consisting of discrete points (spaced at 2 mm resolution), located at the centre line of a bounded path. The assistance system calculates the distance towards the support path as a measure of the load's desired heading, as illustrated in Fig. 2.

This kinematic approach does not include the load dynamics, which are substantial for heavy load movement. A look-ahead controller was used to account for load dynamics, using the load's heading to predict its future state [28], [29]. From this prediction the total error with respect to the assistance path is derived, the desired heading, as illustrated in Fig. 2. Note that for this study, the look-ahead time was manually tuned to 0.4 s.

The load's desired heading in task space contains information for both subtasks. For this study, we split the total error in vertical and horizontal components for the crane and dexterous slave interfaces, respectively, as illustrated in Fig. 2. To exemplify this, consider that only the crane moves vertically along a curved support path. This inherently increases the vertical distance, but also the lateral distance. The distance components of each direction increase at different rates, depending on the local slope of the curved support path. Thus, the assistance system directs not only the overall task, but also haptically links the subtasks along the curve.

Finally, the assistance system must translate the system's desired control inputs to guiding forces on the interfaces, which we based on the design principles for haptic shared control [47]. Here, both the human and the assistance system exert forces on the control interface. The output of this interface is the direct input to the controlled system. Practically, for the crane interface, the assistance shifts the neutral position of the joystick interface by the vertical component of the desired heading. Similar implementations are used for cars [48], [49], other non-holonomic devices [24] and unmanned aerial vehicles [50]. For the dexterous slave interface, the assistance multiplies the lateral distance towards the support path by a stiffness (600 N/m) to produce a corrective force, as is commonly done in tele-manipulation (e.g., [18], [27]–[29], [31]–[34]). This approach accounts for the separate system dynamics and interface designs. The basis of the haptic assistance algorithm was adapted from Boessenkool et al. [29], which was further extended and tested in [32], [34].

III. Methods

A. Participants

We recruited 45 right-handed participants for this experiment: 15 uni-manual operators (3 women and 12 men) and 30 co-operators (15 pairs: 3 consisting of women; 12 men). None of the participants were familiar with the task prior to the experiment. For co-operation, all pairs were strangers to each other. All participants were between the age of 21 and 39 years (mean 28.4, std 5.2) and gave their informed consent. The Human Research Ethics Committee of Delft University of Technology approved the experiment.

B. Experimental set-up

The slaves and the remote task environment were simulated in the Interactive Task Simulator [51], modelled as rigid bodies in NVIDIA PhysX^{TM} (1 kHz update rate). A Unity 3D programme visualised the task environment at 60 Hz as a camera view: a close-up of the dexterous slave holding the load with about one metre of space above and below. The camera moved up and down with the crane and was presented to subjects on a 43-inch tv screen.

The asymmetric slave devices are depicted in Fig. 3. The crane consisted of a 20 m cable (constant length) and was modelled to include hoisting dynamics (1 Hz second order low-pass Butterworth filter). The robotic slave was modelled as a planar device with three degrees of freedom device. The robot's base displaced vertically with the crane. The tool-centre-point of the robotic slave was already connect to the centre of the heavy load, as was the hoisting crane.

The haptic master devices used for this study were two Haption Virtuose 6D devices [52], as shown in Fig. 4. The Virtuose devices were chosen for their ability to present both the natural haptic feedback and a realistic workspace without scaling them. For co-operation, each Virtuose was connected to a single slave. One Virtuose was connected to the robotic slave with a 2-channel position-error control architecture. The sideways control stiffness and damping were 2000 N/m and 10 Ns/m, with a maximum force of 30 N. For the in-plane rotational, stiffness and damping were 20 Nm/rad and 0.05 Nms/rad, with a maximum torque of 3 Nm. The second

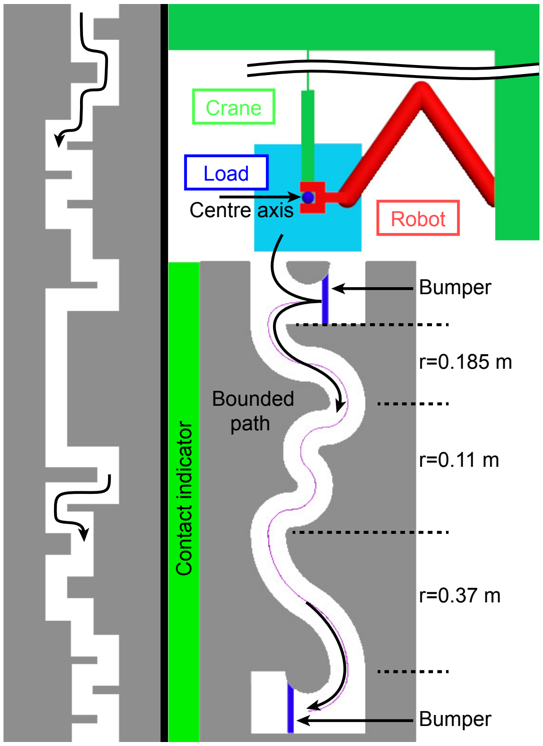

Fig. 3. Illustration of the familiarisation and experimental task. The left side shows the familiarisation part with arrows indicating the direction of movement. The right side shows one experiment path. Here the dark blue centre axis of the load had to be manoeuvred through the bounded path following the arrow. Participants hit the bumper to initiate a timer. At the end of the path, they hit another bumper to stop the clock. The purple centre line represents the support path.

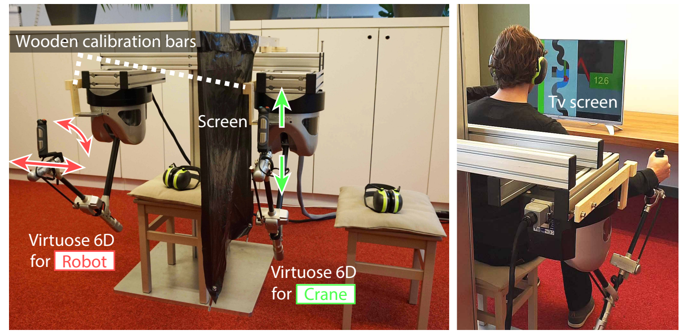

Fig. 4. Impression of the experimental set-up. Left shows the two Haption Virtuose 6D devices with the directions of motions for the co-operated conditions. Uni-manual operators controlled one device with the joint control capabilities. The wooden calibration bars could be shifted to define the starting position of the devices. The screen and ear caps served to prevent co-operators from seeing or hearing each other's actions. Right shows how the operators observed the tv screen.

Virtuose connected to the crane in rate-control. The set-point velocity for the crane was the vertical Virtuose offset times two. The Virtuose itself fed back a force to a zero vertical offset with a 50 N/m spring and 0.01 Ns/m damping. An additional 700 N/m spring and 0.1 Ns/m damping, till max 3 N, made the centre tangible, similar to a real joystick. For the uni-manual mode, one Virtuose had the combined control capabilities.

Unused translational degrees of freedom on both Virtuose devices presented forces towards the workspace centre with the same settings as the crane interface. Unused rotational degrees of freedom gave a torque towards the workspace centre with a 5 Nm/rad spring and 0.1 Nms/rad damping.

The set-up was made for right-handed use only. A screen between co-operators prevented them from seeing each other's movements, as shown in Fig 4. This eliminated visual action observation as a potential confounding factor. Co-operators also had to wear ear caps to exclude auditory signals (e.g., mechanical or spoken) as a potential confounding factor. They were further instructed not to communicate in any form on task-related matters.

C. Task description

The experimental task consisted of manoeuvring a 0.03 m radius circle through a bounded path, as shown in Fig. 3. To give the load a realistic body, the 0.03 m circle was the centre axis of a 0.5 m square box that represents a JET shielding tile [10]. Although the rotational degree of freedom for this task was not necessary, the load could rotate freely around its centre axis to make the task more realistic.

The bounded path consisted of three sections with different curvatures. The radii were either 0.37, 0.185 or 0.11 m. Each curvature occurred once in each path. The curves dictated that the velocities of each slave must change continually, but remain linked along the path. The paths were planar to exclude complications from suboptimal 3D views, and to simplify data analysis. The paths had a constant width of 0.16 m and a maximum left-to-right movement of 0.37 m. Fig. 3 shows one such path. The different paths were assumed to be equally difficult as they all contained the same number and type of sections.

Participants worked through a set of six paths. Each path was different based on the variation in a Williams design. For example: slm, lms, msl, sml, mls and lsm. Where s, m and l stand for the small, medium and large radii sections. In this way six unique sets of six paths were composed. These were provided in a balanced order, such that no more than two sequential sets started with the same radii. Paths were different to prevent participants from optimising their control strategy (e.g., feed-forward) to a single path.

D. Experimental design

1) Experimental conditions: The experiment consisted of two factors, assistance and interface design, each of which had two conditions. The interface designs were uni-manual and co-operated. Each participant/pair performed the experiment for only one interface design (between subject design). The assistance condition was labelled as either 'on' (with haptic assistance, HA) or 'off' (conventional tele-manipulation, noHA). Each assistance condition was performed by all participants (within-subject design) according to a Latin square design per interface design to mitigate order bias.

2) Experimental procedure: The experiment contained three main phases: familiarisation, training and the experimental conditions. Familiarisation lasted two minutes per interface and the corresponding subtask separately. Participants manoeuvred through a bounded path with pure horizontal (dexterous slave) and vertical (crane) parts, as presented in the left of Fig. 3, which uncouple the interactive nature between the subtasks. As such, each co-operator could practice two minutes with each interface, giving them an equal amount of time per subtask as that given to uni-manual operators. Operators could not fail the familiarisation and they were instructed to focus on controlling the individual subtasks. After the familiarization, co-operators were assigned randomly to their permanent roles.

Subsequently, participants started training for 24 paths in the conventional tele-manipulation condition. They received written and spoken task instructions to manoeuvre the small dark blue centre axis of the load as fast as possible through the bounded path, while not hitting the bounds. Hitting the bounds meant that they had made a critical error (and worked unsafe). In such an event, the screen blanked and the task froze for 6 seconds. To boost training, participants learned after the first six paths that they could approximately achieve 50% reduction in the average task-completion time per six paths by the end of the training (based on pilot and previous experiment [23]).

Finally, participants had 24 paths in conventional tele-manipulation and 24 paths with haptic assistance. They were motivated to freely test each condition in the very first two paths as training. The assistance condition was introduced as an intelligent controller that would help the participants in their task. Additionally, the assistance had a visual representation, as shown in Fig. 3, for training purposes during the first two paths. After six paths, participants had a one minute break. Co-operators were not allowed to discuss the experiment.

To quantify the success of moving fast without making critical errors, participants received standardized feedback visually per path: elapsed time and the contact indicator colour (bar on the left). The indicator started green, as shown in Fig. 3, and turned red upon a critical error. The indicator could also turn orange during training to notify a near critical error when the centre axis came closer than 0.01 m to the bounds. Participants also obtained their average task-completing time and number of critical errors per six paths.

Participants were further motivated to move fast, while upholding safety, by a competition. The pair and individual with the fastest average task-completion time (excluding training) would win €10. Note that each critical error added a 6 seconds penalty time for that path. Disqualification followed when they had less than three paths per set of six without critical errors (including during training). This competition encouraged a speed-accuracy trade-off resembling real tele-manipulation demands. Here, operators must minimise task-completion time while upholding safety and reliability that otherwise might result in expensive downtime [10].

E. Data acquisition & metrics

Measured data included force, position and velocity signals for the masters, slaves and load at 1 kHz and was later on down sampled to 100 Hz. The data was used to evaluate task execution within the curved section (i.e., between the upper and lower dashed lines in Fig. 3). Task execution was expressed in terms of task performance, control activity and safety with the following metrics:

- tct: Task-completion time [s], the performance measured in seconds to complete one path.
- sal: Spectral arc length [-], the performance quantified in movement smoothness, as introduced by [53] and related to expert vs. novice performance by [54]. It measures the arc length along amplitude and frequency-normalised Fourier magnitude spectrum of the lateral (robot, sal_L) or vertical (crane, sal_v) speed profile.
- tim: Total input movement [m], the operator control activity measured by the total path length he/she made with the Virtuose in either the lateral (robot, tim_L) or vertical (crane, tim_v) direction.
- ttc: Shortest time to contact [s], the task safety expressed as the time left before the load would hit the bounds considering the load's heading at each instance, while mitigating extremes by taking the fifth percentile.
- dtc: Shortest distance to contact [m], the task safety expressed as the proximity of the load to the bounds in the direction of the load's heading at each instance, while mitigating extremes by taking the fifth percentile.
- ce: Critical errors [-], the task safety quantified by the total number of critical errors the last six paths.

Additionally, each participant completed the NASA-TLX weighting and questionnaire [55] to evaluate the subjectively perceived workload on a 0 to 100 scale. A higher score presented a higher subjective workload. Further, participants filled-out a van der Laan usefulness and satisfaction acceptance scale [56] to evaluate perceived acceptance of the interface on a 5-point Likert scale. A higher score represented a better acceptance.

F. Data analysis

The calculated metrics were averaged over the last four repetitions (ignoring repetitions with a critical error) of each condition per subject. To analyse the effect of interface design and assistance, a mixed-design ANOVA was used for the metrics on task performance and control activity. Significant interaction effects were followed by a simple effects post-hoc analysis with Bonferroni correction. Observed differences were considered statistically significant at p-values of 0.05 or less.

The workload, acceptance and safety metrics are represented by median and percentiles as they were measured on an ordinal scale. The metric were analysed using non-parametric tests in R statistics [57]. There exist a couple of non-parametric mixed-design tests from which two methods were selected, as explained in the discussion. The first is a permutation test called ezPerm (with perms = 1e3) from the ez package [58]. Permutation tests perform statistics on data sets constructed from the original data that was randomly shuffled between conditions. The second test comprises a set of functions, called sppba, sppbb and sppbi from the WRS2 package [59], based on Huber's M-estimator bootstrap. Bootstrap methods artificially extend the original data per condition by randomly sampling data points from that original data. Significance was judged

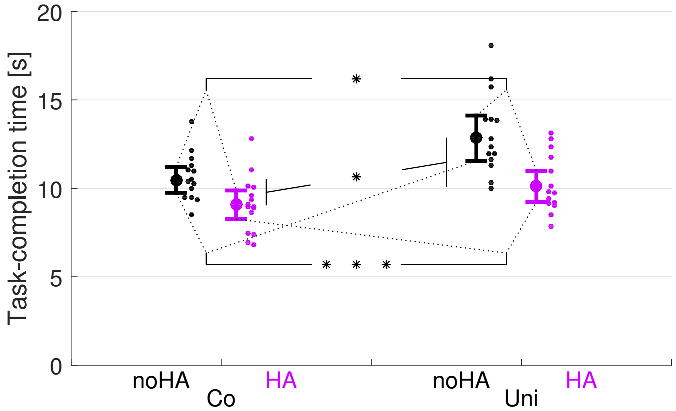

Fig. 5. Task-completion time to manoeuvre down the path. The dots represent the means per dyad/individual, while they performed the task conventionally (noHA, black) or haptically assisted (HA, purple) with the co-operated (co) or uni-manual (uni) interface design.

based on the methods with the most conservative outcome: the highest p-value.

IV. Results

The figures 5-8 and Table I provide the means and 95% confidence intervals based on 15 participants/dyads. Figures present jitter plots and visually denote significant ANOVA results with '$*\,*\,*$', '$**$' and '$*$' for p<0.001, p<0.01 and p<0.05, respectively. Significance bridges above, between and below the data present significance for the between-subject factor, the interaction, and the within-subjects factor, respectively.

A. Task performance

The task-completion time results show a significant main effect for both assistance and interface design (Fig. 5 and Table II). Furthermore, there is a significant interaction effect of assistance on interface design. Table I presents the Bonferroni corrected simple effects analysis, showing that the observed differences in time for assistance are significant (p<0.001) for both the co-operated and uni-manual interface. This means that assistance enables co-operating and uni-manual operators to move 1.4 and 2.7 s faster, respectively. The mean difference between the conventionally operated interfaces, showing that uni-manual operators require 2.4 s more time than co-operators, is also significant (p=0.016). The differences between interfaces with assistance is not significant (p=0.406).

The spectral arc length has a significant interaction effect between the assistance and interface design for the lateral movements (Fig. 6 and Table II). The simple effects analysis with Bonferroni corrected shows that the observed difference in interface design are not significant (p>0.200, Table I). Furthermore, assistance creates no significant difference in movement smoothness for co-operators (p=0.062); however, assistance causes a significant difference (p<0.001) for uni-manual operators, which move 0.28 units smoother with assistance. Assistance significantly changes movement smoothness for the crane interface (0.13 units lower for the assisted than

TABLE I

Mean and 95% confidence interval (CI) results based on 15 participants/dyads. The signs ↔ and ↕ in the centre column indicate a significant main effect for interface design and assistance respectively. Similarly, ⤧ denotes a significant interaction. In that case, ↔ or ↕ in-between data present significant results from the simple effects Post Hoc analysis.

	Co mean [95% CI]		Uni mean [95% CI]
	Task-completion time [s]		
	Co mean [95% CI]		Uni mean [95% CI]
noHA	10.48 [9.75;11.21]	↔	12.84 [11.56;14.12]
	↕	✥ ⤧	↕
HA	9.07 [8.26;9.88]		10.10 [9.22;10.98]
	Spectral arc length lateral [-]		
	Co mean [95% CI]		Uni mean [95% CI]
noHA	4.07 [3.94;4.21]		4.11 [3.97;4.24]
		↕ ⤧	↕
HA	3.95 [3.86;4.04]		3.82 [3.74;3.90]
	Spectral arc length vertical [-]		
	Co mean [95% CI]		Uni mean [95% CI]
noHA	4.65 [4.60;4.70]		4.77 [4.71;4.83]
		✥	
HA	4.54 [4.49;4.59]		4.61 [4.55;4.67]
	Total input movement lateral [m]		
	Co mean [95% CI]		Uni mean [95% CI]
noHA	1.16 [1.14;1.19]		1.12 [1.11;1.14]
		✥	
HA	1.11 [1.09;1.14]		1.08 [1.06;1.10]
	Total input movement vertical [m]		
	Co mean [95% CI]		Uni mean [95% CI]
noHA	0.45 [0.36;0.54]		0.57 [0.51;0.63]
		↔	
HA	0.47 [0.36;0.57]		0.59 [0.51;0.68]
	Distance to contact [m]		
	Co mean [95% CI]		Uni mean [95% CI]
noHA	0.089 [0.085;0.093]		0.089 [0.086;0.093]
		↕	
HA	0.101 [0.097;0.105]		0.101 [0.096;0.107]
	Time to contact [s]		
	Co mean [95% CI]		Uni mean [95% CI]
noHA	0.45 [0.42;0.47]		0.54 [0.48;0.59]
		↔	
HA	0.44 [0.40;0.48]		0.52 [0.47;0.56]

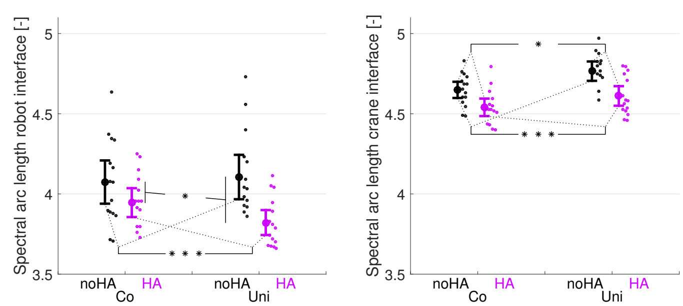

Fig. 6. Spectral arc length for the lateral master velocity to control the robot (left) and the vertical master velocity to control the crane (right). The dots represent the means per subtask, while operators performed the task conventionally (noHA, black) or haptically assisted (HA, purple) with the co-operated (co) or uni-manual (uni) interface design.

the unassisted operators). Additionally, movement smoothness differs significantly between co-operators and uni-manual operators, such that co-operators move vertically 0.10 units smoother.

B. Control activity

For control activity, Fig. 7 and Table II show the total movement made by the master devices. Both the total lateral

TABLE II

ANOVA AND NON-PARAMETRIC TEST RESULTS FOR ALL METRIC. SIGNIFICANT P-VALUES ARE PRESENTED IN BOLDFACE.

	Task-completion time [s]			Spectral arc length robot interface [-]			Spectral arc length crane interface [-]			Lateral master movement [m]			Vertical master movement [m]		
Factor	$F(1,28)$	p	r	$F(1,28)$	p	r	$F(1,28)$	p	r	$F(1,28)$	p	r	$F(1,28)$	p	
F_b	7.11	**.013**	.45	.40	.534	.12	6.12	**.020**	.42	8.20	**.008**	.48	5.01	**.033**	.39
F_w	66.34	**<.001**	.84	33.47	**<.001**	.74	73.57	**<.001**	.85	34.27	**<.001**	.74	.44	.513	.12
$F_b * F_w$	6.79	**.015**	.44	4.79	**.037**	.38	2.23	.147	.27	.01	.943	.01	.01	.916	.02
	Distance to contact [m]			Time to contact [s]				Critical errors [-]		NASA TLX		Acceptance scale Usefulness		Acceptance scale satisfaction	
Factor	$F(1,28)$	p	r	$F(1,28)$	p	r		p_{ez}	p_{wrs2}	p_{ez}	p_{wrs2}	p_{ez}	p_{wrs2}	p_{ez}	p_{wrs2}
F_b	.01	.936	.02	8.85	**.006**	.49		.108	.434	.506	.818	.510	.982	.611	.918
F_w	35.83	**<.001**	.75	1.17	.289	.20		**.005**	.194	**<.001**	**<.001**	**.001**	**<.001**	**.001**	**<.001**
$F_b * F_w$	.02	.884	.03	.34	.563	.11		.171[1]	.298	.757[1]	.806	.900[1]	.848	.560[1]	.794

[1]For package 'ez' Version 4.4-0, only main effects, thus not the interaction, may be trusted [58].

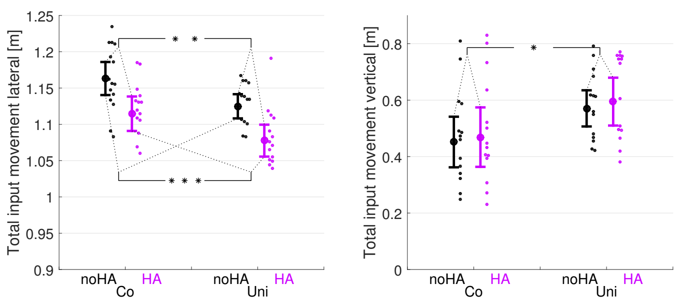

Fig. 7. Total master device movement for manoeuvring down the path. The left figure shows the lateral master movement to control the dexterous slave. The right figure shows the vertical master movement to control the crane. The dots represent the means per subtask, while operators performed the task conventionally (noHA, black) or haptically assisted (HA, purple) with the co-operated (co) or uni-manual (uni) interface design.

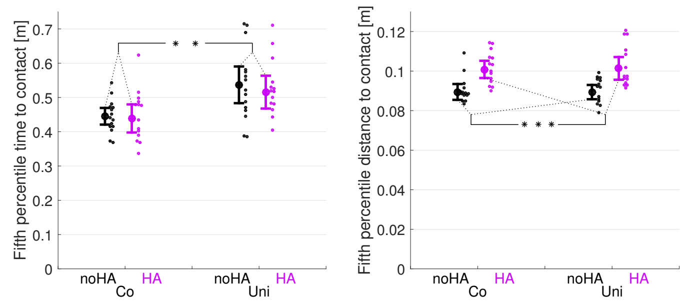

Fig. 8. Safety in terms of the fifth percentile shortest time (left) and distance (right) to contact. The dots represent the means per dyad/individual, while they performed the task conventionally (noHA, black) or haptically assisted (HA, purple) with the co-operated (co) or uni-manual (uni) interface design.

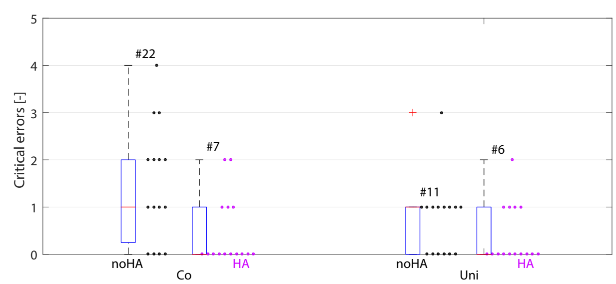

Fig. 9. Safety in terms of the total number of critical errors made during the last six paths in each condition. The dots represent the number of critical errors dyads/individuals made, while they performed the task conventionally (noHA, black) or haptically assisted (HA, purple) with the rigid and compliant slave. The numbers above the conditions present the sum of all errors per condition.

(robot) movement and the total vertical (crane) movement reveal a significant main effect of interface design. Uni-manual operators move 0.04 m less in the lateral direction, but 0.12 m more in the vertical direction. Additionally, assistance significantly changes the required lateral activity for both the uni-manual and co-operated interface, such that assisted operators move 0.05 m less then unassisted operators.

C. Safety

The fifth percentile shortest time to contact shows a significant main effect for interface design. Uni-manual operators have, at critical moments, 0.08 s more time towards the bounds (Fig. 8 and Table II). The fifth percentile closest distance to contact only has a significant difference for assistance, where assistance facilitated a 0.01 m larger distance to the bounds than having no assistance.

The number of critical errors made in the last six paths are presented in Fig. 9 and Table III. Although 33 critical errors occurred during conventional tele-manipulation, compared to 13 during assisted control, this is not significantly different, as the most conservative *p*-value, from the sppbb, was well above 0.05 (Table II).

D. Subjective workload and acceptance

The subjectively rated workload and acceptance, as presented in Fig. 10 and Table III, has significant differences for assistance (Table II). Haptic assistance reduces workload and improves interface acceptance compared to conventional tele-manipulation.

V. DISCUSSION

A. Main effects of interface design

This study proposed a novel haptic assistance systems to support operators with two asymmetric subtasks, which efficacy was evaluated for a co-operated and uni-manual interface. The findings are that task performance of uni-manual operators was 23% slower than that of co-operators. This finding is consistent with the 20% difference found in our previous studies [23]. The lateral spectral arc length (i.e., human input to control the dexterous slave) showed no significant difference between the interface designs. However, the vertical

TABLE III
MEDIAN, 25TH AND 75TH PERCENTILE RESULTS BASED ON 15 PARTICIPANTS/DYADS FOR THE NON-PARAMETRIC METRIC.

	Critical errors [-]		
	Co median (25;75%)	Uni median (25;75%)	
noHA	1 (0.25;2)	1 (0;1)	
HA	0 (0;1)	0 (0;1)	
	NASA TLX [-]		
	Co robot median (25;75%)	Co crane median (25;75%)	uni median (25;75%)
noHA	65.1 (57.0;73.8)	64.7 (53.2;74.2)	60.7 (55.7;71.3)
HA	50.0 (48.1;62.9)	54.7 (41.7;63.1)	52.4 (44.1;56.4)
	Acceptance scale (usefulness) [-]		
	Co robot median (25;75%)	Co crane median (25;75%)	uni median (25;75%)
noHA	0.80 (0.05;1.80)	0.80 (0.40;1.00)	0.60 (0.40;1.35)
HA	1.00 (0.80;1.75)	1.00 (0.60;1.35)	1.20 (1.00;1.35)
	Acceptance scale (satisfaction) [-]		
	Co robot median (25;75%)	Co crane median (25;75%)	uni median (25;75%)
noHA	0.25 (-0.75;1.25)	0.50 (-0.13;0.94)	0.50 (-0.38;1.19)
HA	1.00 (0.56;1.44)	1.00 (0.75;1.19)	1.00 (0.81;1.50)

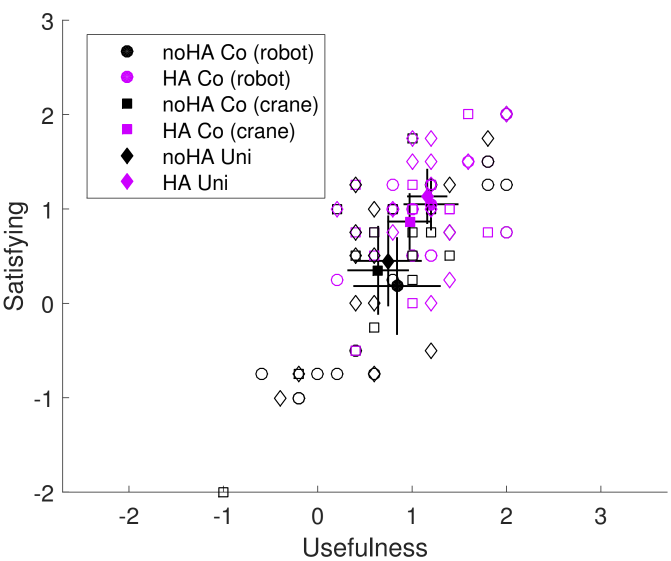

Fig. 10. Van der Laan usefulness and satisfaction acceptance scale. The open symbols represent the acceptance of the individuals while they performed the task conventionally (noHA, black) and haptically assisted (HA, purple).

component (i.e., human input to control the crane) showed 2% less smooth movements for uni-manual operators. Although 2% on itself is not substantial, it constitutes to the notion that co-operators performance better, and not equal or worse, than uni-manual operators. Both of the spectral arc length results resemble the outcomes in [23], even though the previous study showed a greater difference (25%) for crane input. This difference could be caused by the change in crane interface (from a real joystick to a Virtuose). Additionally, the changes in control activity for both interfaces corresponded to that found in the previous study: uni-manual operators moved 3% less laterally and moved 27% more vertically compared to co-operators (compared to 3% and 73% previously, which could be due to the different crane interface). Finally, no differences were observed in the interface design in the subjectively rated workload or the acceptance, similar to previous results in [23]. Essentially, the present results underline the conclusions from our previous study [23].

B. *Effects of assistance*

In terms of **performance**, haptic assistance improved the task-completion time by 13% and 21% for co-operators and uni-manual operators, respectively. This is consistent with previous research on haptic assistance for operators of symmetrical interactive subtasks [41]–[43]. Their results also showed that operators benefit from haptically linking their motion. The present results also showed that haptic assistance improved performance more for the uni-manual operators than for co-operators. Haptic assistance also improved movement smoothness (spectral arc length) by 3% for the vertical movement. An interaction effect for the lateral movement revealed that only uni-manual operators moved 7% smoother. Altogether, this substantiates the hypotheses that haptic assistance supports operators during their task. Moreover, uni-manual benefit more from assistance than co-operators.

For **control activity**, the total master device motion decreased, as hypothesised, by 4% for the lateral input due to the haptic assistance. In contrast to the hypothesis, the crane interface was not found to move less. Other studies reported that assistance reduced control effort for single-operator single-slave (tele-)manipulation studies [18], [29], [31]. However, this holds not for all cases, as Passenberg et al. found increased effort for single-operator [60]. More relevant, Schauß et al. [42] found increased physical effort when haptically linking two operators of symmetric interactive subtasks. They suggested effort could have increased under assistance due to the result of the reduced task-completion time, which requires higher speeds, and thus, more effort.

The **safety** metric showed that assisted operators had 13% more distance to the bounds at the fifth percentile closest encounters. Although the absolute distance seems only 0.01 m, it should be seen with respect to the 0.06 m diameter centre axis (17%) and the 0.16 m path width (6%). On one hand, the increased distance implies that the haptic assistance increased safety, as hypothesised. On the other hand, time to contact did not change significantly. We theorise that the participants may have exploited the extra safety margin from the assistance to increase their speed to a time criticality comparable with the conventional condition. This is consistent with the number of critical errors made, which constituted no significant change for assistance.

The **subjectively** measured workload results show that operators found the haptic assistance less demanding than the conventional approach. This corresponds with finding of reduced workload by assistance in other studies [24], [29], [34], [50], [61]. As such, haptic assistance can contribute in the optimisation of mental workload, which in turn could reduce human error, improve system safety, increase productivity and increase operator satisfaction [62]. Additionally, operators found the interface with assistance more acceptable (both in terms of usefulness and satisfaction) than the conventional interface.

C. Limitations and future work

This experiment used a Latin square design, meaning that ideally an equal number of participants start in one of the two assistance conditions. However, one pair of operators could not be recorded before the return date of the second borrowed Virtuose device. Thus, there are 15 measurements for each interface design. By coincidence, uni-manual operators were split into a fast- and slow-learning group, making it impossible to tell whether or not the order of receiving the assistance conditions had an effect.

The experimental design enforced us to use a mixed-design statistical analysis for the non-parametric data. These analysis seem to be rarely used, but they exist, as indicated by Field and Miles [63] and tested by Feys [64]. Currently, literature lacks evidence for selecting the best analysis. Therefore, we selected one promising permutation and one promising bootstrap analysis. We chose to follow the most conservative p-value to counter false-positives as much as possible.

The support path design could have influenced the effect of the haptic assistance. The present study used one predefined fixed support path (the centre line of the bounded path) for all participants. In real life a path has to be created based on sensory and CAD data. Such information could be inaccurate due to e.g. elastic deformations in the mechanical structures and thus provide inaccurate haptic assistance [32]. Additionally, this 'one-size-fits-all approach' has been shown to work in general, but also may have small conflicts in trajectories. This can lead to annoyance [30], and increased force, discomfort or even reduced performance [65]. Adapting the assistance to the individual would probably improve acceptance and performance of operators [66]. Future research should explore how to adapt the support path towards two co-operating operators.

Additionally, this study used heuristically tuned parameters for look-ahead time, stiffness, damping, force feedback and stiffness feedback. A different tuning could affect the results, for example the purpose of the look-ahead time is making the assistance more meaningful by account for systems dynamics. It is less effective when it looks ahead too near or even providing wrong assistance when looking too far ahead. Therefore, tuning occurred at a velocity that most participants would presumably work at. Parameters selection occurred based on the tangibility of the assistance force (stiffness, damping, force feedback and stiffness feedback), usefulness of predicted assistance cues (look-ahead time) and stability of the controller over a wide range of velocities (all parameters).

A powerful aspect of the presented haptic assistance is its ability to present two haptic cues (task related assistance and the haptic link between subtasks/participants) as one meaningful and intuitive force. Still, this assistance is presented simultaneous with natural/centring force feedback on one interface to the operator. Such merging of forces could be confusing and difficult to interpret for the operator, as found by Powell and O'Malley [67]. They classified this assistance type as Gross Assistance and formulated several alternative paradigms. Future studies should identify which paradigms is more beneficial for asymmetric subtasks.

The anthropometrics of participants was not accounted for, meaning that e.g. smaller or taller participants could have had more difficulty in controlling the task. Non-verbal communication (e.g. head movements and facial expressions) was in principle possible during the task, though participants were instructed not to communicate in any form on task-related matter, and were reminded of this in questionable situations.

The van de Laan acceptance scale was originally designed and validated for driver acceptance of new (supportive) technologies. Because the van der Laan acceptance questions itself are generic, the authors expect it to be an insightful method for new supportive technology in other domains like tele-manipulation. Notably, the results are in line with the expectation.

The 6 seconds penalty time for each critical error represents a substantial fraction of the task-completion time. This potentially shifted the speed-accuracy trade-off of some participants/dyads towards the accurate site. As a result the variability between participants/dyads could have increased. To counter this potential variability, participants/dyads received standardized feedback (reminding them on the speed/competition and accuracy goals) and extensive training to funnel them to a specific speed-accuracy trade-off.

The present experiment expressed task execution in terms of task performance, control activity, safety, acceptance and workload. However, operators should also be able to detect and respond to anomalies during the task like broken tools, missing components or unexpected obstacles. This means that the operator(s) must be aware of the situation of the (remote) task to prevent critical errors. Additionally, co-operators should have a shared situational awareness [68]. For robot assisted Urban Search and Rescue, teams with a good shared awareness are nine times more likely to find victims [69]. We recommend that future studies identify the level of situation awareness and analyse the effect of interface design and haptic assistance on it.

To gain better insights into operator control behaviour of asymmetric interactive subtasks, future studies should include tasks with real slave hardware. Realistic tasks in 6 degrees of freedom may result in additional difficulties when controlling two asymmetric slaves: orienting objects with sub-optimal viewing angles severely complicates task execution. Additionally, the crane could be controlled in 3 degrees of freedom instead of one (by adding the two horizontal translations). Especially for haptic assistance this would be interesting as it could direct large-scale and/or slowest dynamic movements to the crane while it directs fine and/or faster movements to the robotic slave. For practical applications, however, it is expected that a crane first roughly aligns the load horizontally to its position. Once positioned, the crane acts only vertical and the robot performs the final horizontal manoeuvring and positioning.

Currently, a method for measuring the quality of haptic assistance does not exist. For example, assisted uni-manual operators increased performance by 21% with respect to the conventional condition, but it is unclear whether this is the best an assistance system can do. For car driving, a known well working haptic assistance can be described by the horse metaphor [70]. This metaphor expresses that the horse (both assistance and car) is highly autonomous, but always keeps the human in the loop and even warns the human operator through a multi-modal interface in case of confusion or danger. Such autonomous systems do not yet exist, but in a 'Wizard of Oz' study a human confederate can take the role of the autonomous systems [71]–[73]. Essentially, the confederate is a second operator who co-acts with the driver in a symmetric divisible nature [22]. Thus, human-human performance of a symmetric divisible task is an important quality milestone, lets say 100%. Any well designed haptic assistance systems, anthropomorphic or not, should ideally attain, or even surpass, this quality level.

A few studies have presented performance levels of human-human and human-automation interaction tasks [74]–[76]. However, notably, these studies aimed to understand human-human interaction by first modelling a human operator, and then building an effective assistance system. Still, they can exemplify that the assistance quality can be negative [74], [75], between 0 and 100% [75] or reach $\approx$ 100% [76]. Although the present results do not include a symmetrical divisible task distribution, the assisted uni-manual operators performed better than the unassisted co-operators (116%). Remarkably, as discussed before, the assistance system was not optimised for the task or human behaviour. This suggests that our team of the uni-manual operator and haptic assistance attained a super human performance level with the potential to increase performance even further.

VI. Conclusion

This study proposed and tested a novel haptic assistance system for tasks with two asymmetric tele-manipulator slaves: a crane and a dexterous slave robot. The novelty of this system constitutes a haptic link between the control actions of two co-operating operators through a joint task environment. This haptic assistance can also be mapped onto a hybrid interface for a single operator who controls both the crane and dexterous slave. We designed the haptic assistance for a virtual remote handling manoeuvring task with a 50kg load, and evaluated its efficacy in a human factors experiment (n=15) with and without haptic assistance. This gave the following results regarding conventional tele-manipulation vs. haptic assistance:

- Assistance improved the task-completion time by 13% for co-operators and 21% for uni-manual operators;
- Assistance reduced the required lateral control activity by 4%;
- Assistance reduced the subjective workload and increased the interface acceptance.

For co-operators vs. uni-manual operators, the results showed the following:

- The uni-manual interface, without assistance, increased task-completion time by 23% with respect to co-operation, but this difference was not found with haptic assistance;
- The uni-manual interface reduced lateral control activity by 3% with respect to co-operation, but it increased crane control activity by 27%;
- Neither interface design constituted a significant change in subjective workload or interface acceptance.

In conclusion, haptic assistance improves task execution for co-operators and uni-manual operators. Moreover, haptic assistance allows a single operator to control asymmetric interactive subtasks as good as co-operators.

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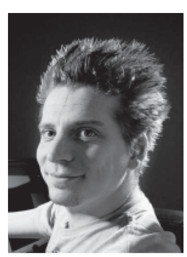

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