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Co-operation and Haptic Assistance for Tele-manipulated Control over Two Asymmetric Slaves

Proefschrift

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door

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All of this has happened before,
and all of it will happen again

James Matthew Barrie | Peter Pan

Contents

Summary

Co-operation and Haptic Assistance for Tele-manipulated Control over Two Asymmetric Slaves

The success of future fusion power plants as a sustainable energy source greatly depends on their uptime. This uptime relies on the plant's maintenance, which must be performed via tele-manipulation. Tele-manipulated maintenance is challenging, as exemplified by strictly selected and highly trained operators who still require more time to work tele-manipulated, than they do for working hands-on. Many future maintenance tasks involve delicate components that require accurate placement with a dexterous tele-operated slave. Some components are very heavy and need simultaneous hoisting support from a crane, thereby confronting operators with two asymmetric subtasks that have an interactive nature. Literature indicates that having two asymmetric subtasks complicates task execution even more than the already challenging tele-manipulation with one slave system, presumably due to problems in the coordination of the subtasks. Such tele-manipulation with asymmetric slaves must be improved to ensure high plant uptime for future fusion plants. The standard industrial approach to coordinate the control of two asymmetric subtasks prescribes two co-operating operators. However, a single individual could perform the task as well with a bi-manual or hybrid uni-manual control interface. The impact of such differences in control interface design for asymmetric slaves is still a matter of scientific debate. Regardless, the tele-manipulated task will be challenging, and even highly trained operators might benefit from a system that supports them in the task. Although haptic assistance generally improves operator task performance, the main underlying assumption is the availability of perfect knowledge of the task and environment. Handling heavy loads causes manipulator links to deflect statically or dynamically due to their compliance, which cannot be measured or model in sufficient detail. This results in static or dynamic mismatch (inaccuracy) between the real and modelled world that will manifest in the haptic assistive cues, which could negatively affect operator control behaviour.

The goal of this thesis is to quantify the impact of interface design choices and haptic assistance to facilitate action coordination between the asymmetric subtasks. Specifically, the interface design choices for single and dual operators will be evaluated with and without haptic assistance, under realistic conditions that incorporate potential inaccuracies in the assistance arising from mismatches between the real and modelled world.

Firstly, a literature review was conducted to investigate published studies that compare a co-operated interface with an individual interface, to control two asymmetric slaves. Studies that compare task performance between dual- and single operators did not indicate a favourable interface design. An experimental human-factors study was performed to quantify task performance, control activity and acceptance during control over two asymmetric slaves, comparing the co-operated approach (8 pairs of operators) to both a bi-manual approach (8 individuals) and a uni-manual approach (8 individuals). The study concludes that two co-operating operators can better control two asymmetric subtasks than a single uni-manual or bi-manual operator.

Secondly, a novel haptic assistance system was proposed to support operators during the challenging task of tele-manipulated coordination of two asymmetric slaves. Its novelty consists of a haptic link between asymmetric subtasks through the joint task space. As proof of principle, a human-factors study demonstrates that both co-operators (15 pairs) and uni-manual operators (15 individuals) benefit from this haptic assistance with respect to unassisted tele-manipulation. Notably, haptic assistance allows a single operator to perform asymmetric interactive subtasks as well as co-operators.

Thirdly, this thesis assessed the impact of static inaccurate assistive cues on task performance during a single-operator (14 individuals) single-slave peg-in-hole type task. Performance degraded during the insertion of the peg, which has the potential for jamming, comparing inaccurate to accurate assistive cues. However, performance for the major part of the task revealed limited to no effect from the addition of inaccuracies to the assistance cues. In conclusion the benefits of assistance are hardly affected by static inaccuracies.

Finally, the effects of dynamic inaccurate assistive cues were studied during a co-operated (12 pairs) heavy load mounting task with and without haptic assistance. The dexterous slave could be rigid or compliant. Co-operators induced the inaccuracies in the assistance themselves via the compliant slave. Although slave compliance in itself degrades task performance, it does not change the performance benefits of haptic assistance.

In conclusion, the interface with two co-operating operator is favourable over the bi- and uni-manual single operator interface to coordinate two asymmetric subtasks that have an interactive nature. The newly designed haptic assistance system improves both co-operated and uni-manual task performance. Interestingly, the observed favour for the co-operated interface with respect to the uni-manual interface is not found when both are haptically assisted. Moreover, haptic assistance still provides benefits when the support cues become statically or dynamically inaccurate due to heavy load handling.

Samenvatting

Coöperatie en Haptische Ondersteuning voor de Besturing van Twee Asymmetrische Tele-robots

Het succes van toekomstige fusie-centrales als duurzame energiebron, hangt grotendeels af van de operationele tijd van die centrales. Een bepalende factor hierin is het onderhoud van die centrales, dat via tele-manipulatie moet worden uitgevoerd. Dit onderhoud is complex, zoals blijkt uit strikte selectie en intensieve training van tele-operators. Zelfs zij doen een taak langzamer via een tele-manipulator dan wanneer ze handmatig werken. In veel toekomstige onderhoudstaken werken operators met kwetsbare componenten, die zij nauwkeurig moeten plaatsen via de tele-robot. Sommige componenten zijn erg zwaar en vereisen gelijktijdige hijsondersteuning van een kraan. De kraan en tele-robot vormen twee asymmetrische sub-taken die operators op een interactieve manier moeten besturen. De literatuur stelt dat het besturen van twee asymmetrische sub-taken nog moeilijker is dan de al complexe besturing van één tele-robot. Vermoedelijk komt dit door problemen in de coördinatie van de sub-taken. Dit soort asymmetrische tele-manipulatietaken moeten verbeterd worden om een hoge operationele tijd van een fusie-centrale te garanderen. De standaard industriële interface voor twee asymmetrische sub-taken vereist twee coöpererende operators. Dit terwijl één individuele operator de taak ook zou kunnen uitvoeren via een bi-manuele of een hybride uni-manuele interface. De impact van dergelijk verschillen in interfaceontwerp voor asymmetrische tele-robots is nog steeds onbekend. Los daarvan zijn tele-manipulatietaken moeilijk en hebben zelfs ervaren operators mogelijk nog voordeel van systemen die hen ondersteunen in de taak. Zo verbetert haptische ondersteuning over het algemeen de taakprestatie. Daarbij wordt wel aangenomen dat de beschikbare kennis van de taak en omgeving perfect is. Echter, het verplaatsen van zware componenten zorgt voor een statisch of dynamische doorbuiging van de tele-robot door zijn elasticiteit. Dergelijke doorbuigingen kunnen niet nauwkeurig gemeten of gemodelleerd worden. Dit resulteert in statische of dynamische onnauwkeurigheden tussen de werkelijkheid en het theoretische model. Deze onnauwkeurigheden werken door in de haptische ondersteuning en beïnvloeden de operatorprestatie mogelijk negatief.

Het doel van deze thesis is het kwantificeren van de impact van interface ontwerpkeuzes en haptische ondersteuning om de coördinatie tussen de twee asymmetrische sub-taken te verbeteren. In het bijzonder worden de ontwerpkeuzes van de interface voor één en twee operators geëvalueerd met en zonder haptische ondersteuning. Dit onder realistische omstandigheden met potentiele onnauwkeu-

righeden in de ondersteuning die voortkomen uit verschillen tussen de werkelijkheid en het theoretische model.

Allereerst werd de literatuur onderzocht op vergelijkingsstudies over coöperator en individuele interface om twee asymmetrische tele-robots te besturen. Studies die taakprestaties vergelijken tussen één en twee operators gaven geen indicatie welk interfaceontwerp de voorkeur heeft. Een onderzoek naar menselijke factoren werd uitgevoerd om de taakprestatie, control activiteit en acceptatie te kwantificeren tijdens het besturen van twee asymmetrische tele-robots. Hierbij werd de coöperator interface (8 paren) vergeleken met zowel de bi-manuele (8 individuen) als uni-manuele interface (8 individuen). De studie concludeert dat twee coöpererende operators twee asymmetrische sub-taken beter besturen dan één individuele uni-manuele of bi-manuele operator.

Als tweede werd een nieuw haptisch ondersteuningssysteem voorgesteld om operators te ondersteunen in de coördinatie over twee asymmetrische tele-robots. De vernieuwing hiervan bestaat uit een haptische link tussen de asymmetrische subtaken via de gezamenlijke taakruimte. De succesvolle werking hiervan blijkt uit een onderzoek naar menselijke factoren dat laat zien dat zowel coöperators (15 paren) als uni-manuele operators (15 individuen) baat hebben van deze haptische ondersteuning ten opzichte van tele-manipulatie zonder ondersteuning. Opmerkelijk is dat de haptische ondersteuning één operator in staat stelt om de asymmetrische interactieve sub-taken net zo goed uit te voeren als de twee coöperator.

Ten derde onderzoekt deze thesis de impact van statische onnauwkeurigheden die doorwerken in de haptische ondersteuning. Het effect van onnauwkeurige ondersteuningskrachten op de taakprestatie werd onderzocht voor een 'pen-in-gat'-taak met één operator (14 individuen) die één tele-robot bestuurde. Tijdens het inbrengen van de pen in het gat werd de taakprestatie slechter door de onnauwkeurige krachten van de ondersteuning, die de hier mogelijkheden tot schranken verergerde. Maar de taakprestatie van het grootste deel van de taak werd niet beïnvloed door onnauwkeurige krachten. De conclusie luidt dat operators voordelen ondervinden van haptische ondersteuning ondanks statische onnauwkeurigheden.

Als laatste werden de effecten van dynamische onnauwkeurige ondersteuningskrachten bestudeerd. Coöperatoren (12 paren) monteerde een zwaar component met en zonder haptische ondersteuning. De tele-robot kon rigide of flexibel zijn. Coöperatoren creëerde de onnauwkeurigheden in de ondersteuning zelf via de flexibele tele-robot. Hoewel de flexibiliteit van de tele-robot de taakprestatie verslechterde, het verandert niet de voordelen van haptische ondersteuning.

Concluderend, twee coöpererende operators besturen twee asymmetrische subtaken met een interactief karakter beter dan een individuele bi-manuele of uni-manuele operator. De nieuw ontworpen haptische ondersteuning verbeterd de taakprestatie van zowel coöperators als uni-manuele operators. Opmerkelijk genoeg blijft het voordeel dat niet ondersteunde coöperators hadden ten opzichte van uni-manuele operators verdwijnt wanneer beide haptische ondersteund worden. Bovendien zijn de voordelen van haptische ondersteuning bestand tegen statisch en dynamisch onnauwkeurige ondersteuningskrachten.

1

Introduction

The way to get started is to
quit talking and begin doing

Walt Disney

Sustaining our modern life requires environmentally friendly solutions to replace fossil fuels as the world's primary energy source. One of the sustainable options relies on nuclear fusion [1, 2]. The ITER and DEMO devices (and several other initiatives) signify the next steps towards fusion energy [3]. ITER consists of about one million components distributed over an enormous vacuum vessel, many sensor systems and advanced control systems. These components will wear under the extreme conditions of the fusion process and thus require regular maintenance. Notably, ITER has to demonstrate that fusion plants can be maintained by attaining an uptime of 70% [4]. DEMO must demonstrate the economic viability of fusion by producing energy for at least 75% of the time [5].

Two aspects make fusion plant maintenance particularly challenging. First of all, maintenance has an unpredictable and complex nature in an environment that contains high levels of radiation and toxic dust. Therefore, maintenance relies on master-slave tele-manipulation (remote handling), which connects the human operator to the task via robots, also called the connected tele-manipulator systems, as illustrated in Fig. 1.1 [6]. These systems have proven to work successfully in, for example, nuclear maintenance [7, 8] and deep-sea operations [9]. However, tele-manipulation has certain disadvantages, such as performance degradation with respect to direct hands-on manipulation and limited tele-presence [10] which demands strict operator selection and extensive training [8]. Studies show that these trained experts still require 3.5-8 times longer to complete the task tele-manipulated compared to manual handling [11–13]. Here, the task performance of the connected tele-manipulator relates to time, but performance could relate to other measures as well (e.g. number of errors, accuracy, movement smoothness).

The second aspect considers the weight of the components, which can be as much as 45 tonnes in the ITER device. Typically, master-slave tele-manipulators have a limited lifting capacity of 15-25 kg [14, 15]. Components that weight more than the robot's lifting capacity require a crane to support the load. Such loads include fragile and expensive components, such as tools [16], mirror modules [17–19] and shielding tiles/modules [7, 14, 20]. These loads may still require support from a dexterous master-slave system for precise manoeuvring [7], meaning the use of two dissimilar, or asymmetric, slaves. Controlling the two asymmetric slaves takes expert operators 23 times longer to complete a tele-manipulated task with

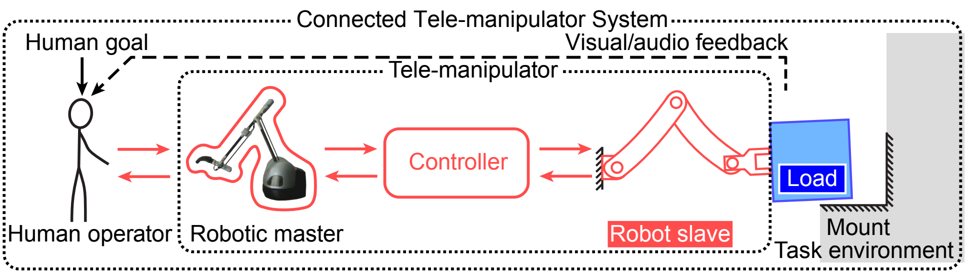

Fig. 1.1: A connected tele-manipulator system [6], which connects a human operator with a tele-manipulator to accomplish a task.

respect to manual handling [13]. This urgently requires a solution to ensure efficient maintenance and high plant uptime for future fusion plants [21, 22]. Note that a solution is not only required in the fusion domain, but also in, for example, maintenance of deep-sea installations [9], neutron spallation sources [23] and nuclear research facilities [24], as shown in Fig. 1.2. Therefore, this thesis focuses on examining and improving operator control behaviour of tele-manipulated maintenance with two asymmetric slaves by assessing the impact of single and dual operator interface designs and haptic assistance.

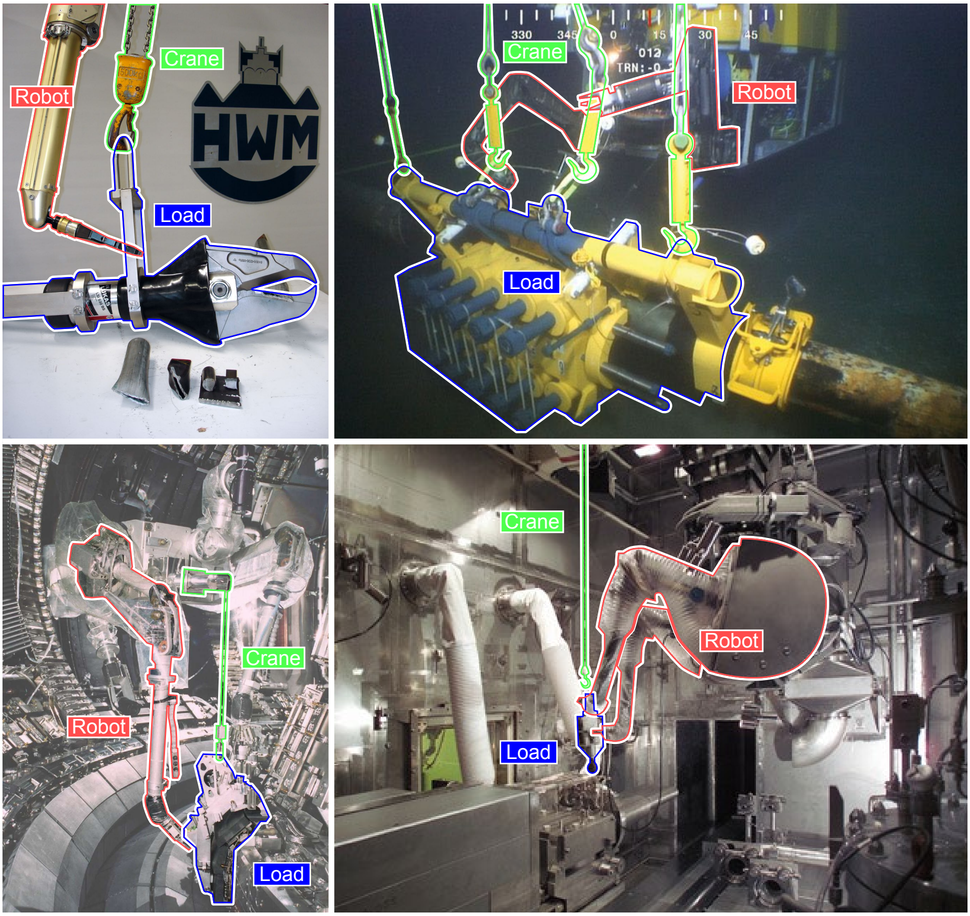

Fig. 1.2: Examples of heavy load maintenance with asymmetric slaves in hazardous environments. The load, tele-robot and crane are highlighted in blue, red and green, respectively. Top left: cutting nuclear waste material after maintenance or at plant decommissioning (photo credit: Wälischmiller Engineering GmbH [25]). Top right: repairing deep-sea pipelines (photo credit: Oceaneering International Inc. [26]). Bottom left: placing tile during a major overhaul of the nuclear fusion vessel at JET [7] (photo credit: EUROfusion [27]). Bottom right: handling nuclear material in the hot cell of the Spallation Neutron Source at ORNL (photo credit: Merrick & Company [28]).

1.1. Heavy load handling with two asymmetric slaves

Many heavy load maintenance tasks require two asymmetric slaves, as shown in Fig. 1.2. In practice, two co-operating operators control these asymmetric slaves, as schematically illustrated in Fig. 1.3. One operator controls the crane in rate control, via a joystick, to perform the lifting subtask. Typically the joystick provides a self-centring force to the operator. This force points towards a zero velocity control signal. The second operator controls the dexterous slave-manipulator to perform the sideways manoeuvring subtask. Usually, for maintenances on nuclear facilities, the operator controls the slave via a robotic master in position control, while receiving force-feedback from the remote environment [7, 29, 30].

The two asymmetric slaves and their control contain several asymmetrical properties such as the direction of motion, the relation between in- and output, and the haptic feedback from the environment to the operator. On one hand, findings in literature suggest that the asymmetry in the direction of motion is beneficial [31, 32]. On the other hand, haptic feedback from the environment improves task performance [12, 33, 34]. Meanwhile, the task requires accurate temporal coordination between the operators, while communication between operators is limited to visual action observation in the remote environment and spoken instruction. Several studies suggest that multi-modal communication between the operators greatly improves task performance [35–43]. Despite all these efforts, physical interaction between two humans is still a topic of scientific debate, providing numerous experimental studies [35, 37, 38, 44–55] and theoretical frameworks [56–58] describing different categories of human-human interaction. This knowledge is not easily transferred to human-human interaction while controlling two asymmetric slaves.

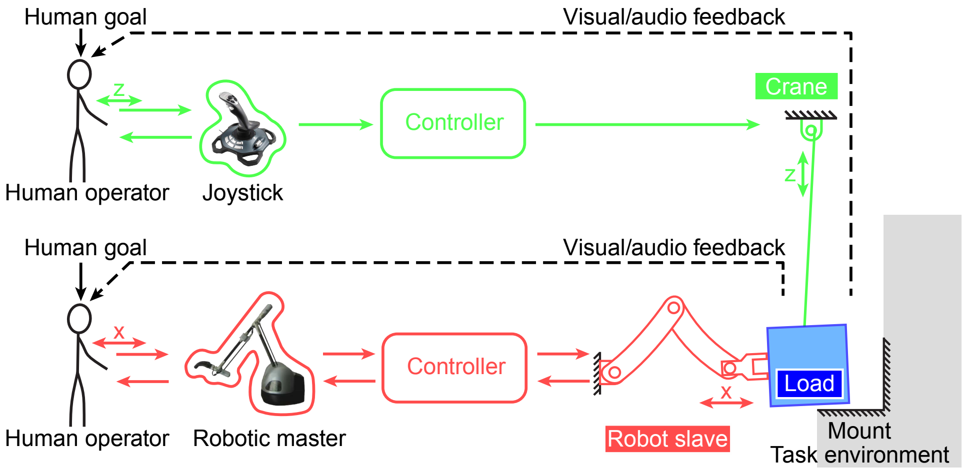

Fig. 1.3: Example of two operators controlling two asymmetric slaves that must act simultaneously to complete a tele-manipulated maintenance task. The slaves consist of a robot (red), which can move the load (blue) sideways, and a crane (green), which can move the load vertically. Note that a single human could bi-manually control both interfaces.

Do we truly need two co-operating operators to control two asymmetric slaves? On one hand, each slave has its own distinct classical interface. On the other hand, a single individual could control both interfaces bi-manually. Moreover, several studies show that, with modern control technology, two robotic systems can act as one [59]. Specifically, in tele-manipulation, several frameworks exist that describe how to merge or distribute the control over a multi-master, multi-slave system [54, 60, 61]. This means that a single human could control both asymmetric subtasks via one hybrid interface. These three examples of control interfaces (i.e. co-operated, bi-manual and uni-manual) are illustrated in Fig. 1.4.

It is not evident whether a dual- or single-operator interface is preferred, despite several comparative studies. These studies show cases where two operators perform the task best [37, 38, 44–46, 62], while in other cases one operator outperforms two [35, 47, 48, 52–55]. Some researchers [37] have suggested that this difference arises due to other dynamic characteristics of the task (periodic force [37] versus constant force [35, 47] production). Other researchers [55] have suggested that it arises from task-related feedback (visual only [50] versus visual plus haptics and proprioception [55]). In essence, the (dis)advantages of single-operator systems with respect to dual-operator systems is still under debate.

1.2. Haptic assistance for two asymmetric subtasks

Regardless of knowing the preferable interface design, tele-manipulated tasks are challenging and the operators and task performance might benefit from a system that supports the task. A growing number of researchers aim to provide such support by considering the human, task and tele-manipulator as a whole system (i.e. the connected tele-manipulator system [6]). Instead of improving individual components, they intend to compensate for the weaknesses of one system with the strengths of the other. Humans have, for example, limited situational awareness, limited haptic fidelity and poor depth perception via the tele-manipulator [10]. In compensation, the tele-manipulators can be connected to intelligent controllers with constantly attentive sensors or enhanced (haptic) feedback. Automated controllers have their limitations in unexpected events [63], but the idea is that human resourcefulness can cover this. This is captured in the concept of sharing control between a human and an automated system [64]. The system assists the operator haptically, in other words: haptic assistance.

The effectiveness of haptic assistance has been demonstrated in many fields. Besides tele-manipulation [65–69], it has applications in, for example, car driving

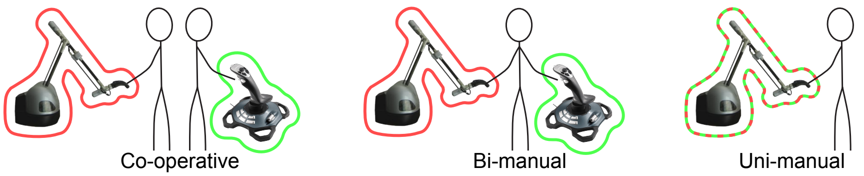

Fig. 1.4: Three examples of control interfaces that allow operators to control two asymmetric subtasks.

[64], aviation [70] and surgery [71, 72]. Most of these implementations roughly belong to one of the following two paradigms: Virtual Fixtures [65, 71, 72] and continuous assistance [64, 66–69]. Virtual Fixtures prevent operators from moving into restricted areas, but they are allowed to move elsewhere. This type of assistance acts as a guardrail preventing cars from driving off a cliff. Continuous assistance provides attractive force towards an ideal and safe trajectory. This type of assistance acts similarly to a teacher guiding the hand of a student to hit a tennis ball. This thesis focuses on this continuous type of haptic assistance.

Assistance for heavy load maintenance has to support two asymmetric subtasks with an interactive nature. Potentially, there are two operators, one for each subtask. Each operator, or subtask, could get its own specialised intelligent haptic assistance controller, as illustrated in Fig. 1.5. A distinct controller could isolate the operators in their own subtask, which does not contribute to co-operation. Assuming that communication is essential, a solution could be a single intelligent assistance controller that overlooks the entire task. Several studies have proposed such assistance for two operators with identical (or symmetric) interfaces [43, 54, 73]. They tested cues that matched the positions and velocities of the operators, which resulted in better performance [54, 73] or improved accuracy and safety [43]. However, these studies considered symmetrical subtasks, with well-defined, clear interactions between the subtasks where operators have to match each other's control actions, while asymmetric subtasks hold no straightforward relationship. Therefore, it is presently unclear how to intuitively assist (two) operators of asymmetric subtasks.

1.3. Impact of model and sensory inaccuracies

In controlled laboratory environment, the benefits of haptic assistance has been shown, often assuming perfect sensory information about the environment. Researchers remove all potential confounding variables and create an ideal task environment and assistance. In such flawless environments, the assistance could, when tuned for it, autonomously perform the task and do that better than with the operator being involved. However, in real life, no such ideal environments exist, meaning that task models and sensory data will contain inaccuracies. These inaccuracies will present themselves to the human operator, through the haptic assistance, as inaccurate assistive cues. The impact of inaccurate assistive cues on operator control behaviour is still unclear. Inaccuracies could be detrimental to the task performance, the operator effort or even the safety of the operation when operators blindly follow the support. Inaccurate assistance could also trigger some well known issues of human-automation interaction, such as reduced trust and even disuse of the system [74]. Therefore, this thesis also takes into account the potential effect of assistive cues that arise due to heavy load handling.

Heavy loads, as well as their manipulators, have a fundamental problem: they cannot be made rigid enough to ignore deflections in the mechanical structures [75]. Mechanical structures deflect due to a weight put on them [29, 75–82]. Deflections cannot be measured directly, because these movements bypass the

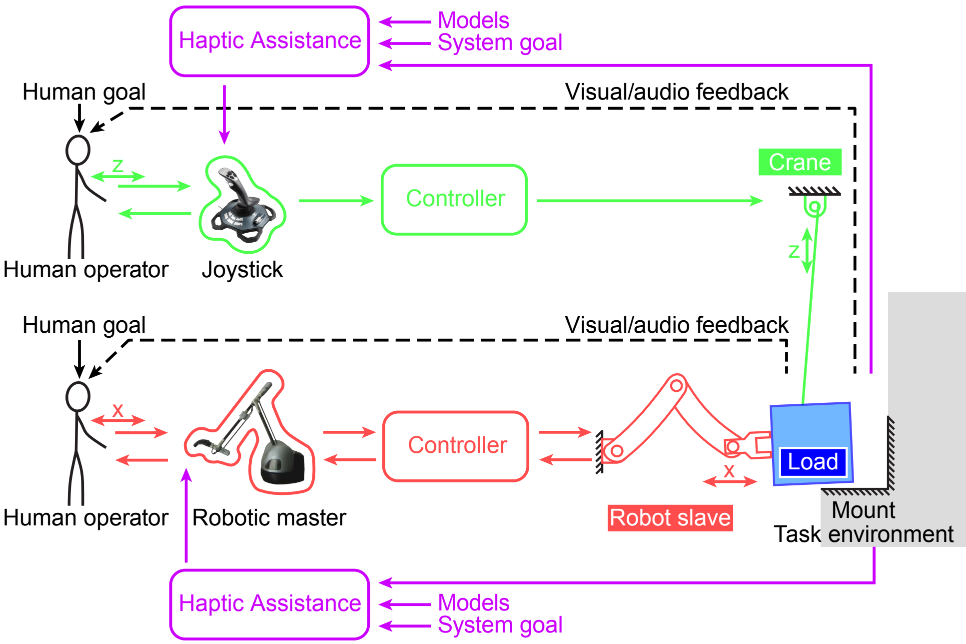

Fig. 1.5: Example of two operators, each controlling one of the asymmetric slaves. Each operator receives support from its own independent haptic assistance systems. Would this be a workable approach?

(tele-manipulator's) sensory system [82, 83]. Fig. 1.6 illustrates this issue by presenting both the actual and measured robot position. These deflections could result in inaccuracies that are either static or dynamic in nature.

1.3.1. Static inaccuracies

At a first glance, static inaccuracies appear to be a minor issue. Under specific circumstances, these inaccuracies can be accommodated for by the task design. This occurs when for example, a peg is griped inaccurately, but the hole is much wider than the inaccuracy [84]. However, fusion maintenance requires the accurate placement, with millimetre precision, of fragile components [7]. It appears that humans can re-weight sensory information between two inaccurate cues (a visual and haptic assistance) during an abstract repetitive free-space reaching task [69]. However, fusion maintenance involves complex tasks with contact transitions and in-contact movements. A theoretical study by Smisek et al. [85] shows that static offsets in tele-manipulation assistance results in higher contact forces on the slave side. Meanwhile, on the master side, the assistance cancels the contact forces, practically occluding the inaccuracies. Currently, the impact of static inaccuracies in haptic assistance on operator control behaviour remains unknown.

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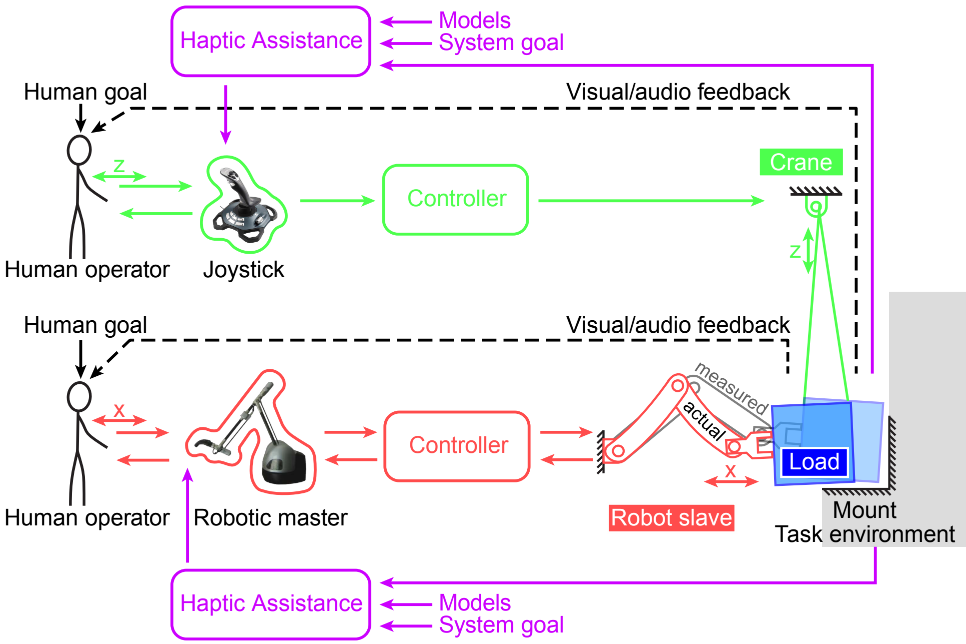

Fig. 1.6: Example of two operators controlling each one of the asymmetric slaves. The robotic slave is not rigid enough to ignore deflections in the mechanical structures due to the heavy load (blue). Therefore, the actual robot (red) is deformed. In this case, the sensors only measure at the joint encoder positions, and thus register a different end effector position.

1.3.2. Dynamic inaccuracies

A special issue with a heavy load tele-manipulation, is that the load, connected to a robot, acts like a mass-spring system. As such the mechanical system can start oscillating at a frequency eigenmode, as described in several studies [29, 76, 78, 79]. Meanwhile, the sensory system would report the assistance that all is (nearly) steady. Oscillations start as soon as external factors (i.e., operator input or contact events) perturb the mechanical system. These oscillations can remain dominant for a long period of time. For astronauts, these oscillations can cause a delay of up to one-third of the task time [78, 79]. Although reports on the extensive JET remote handling experience shows that such oscillations are no problem during tele-manipulation [29], their impact on operator control behaviour during haptically assisted tele-manipulation has yet to be investigated.

1.4. Motivation and goal

In short, several tele-manipulated tasks require human-in-the-loop control over two asymmetric slaves. A typical example includes a crane to lift a heavy load, and a dexterous manipulator to accurately place it. Controlling these two asymmetric slaves remains difficult when using existing interface designs. Therefore, the main research question addressed in this thesis is:

How to design a control interface to facilitate the operator's action co-ordination between two asymmetric subtasks?

More specifically this thesis investigates to what extent operators can benefit from haptic assistance during heavy load handling task, under realistic conditions. A potential complication during the assistance of such a task is that the tele-manipulator deflects due to the load it handles. Such deflections (e.g., static or dynamic) are generally not observed by sensors and cannot be fully captured in models to the exact location of task relevant properties. This means that the operator receives inaccurate assistive cues through the assistance system. The impact of these inaccuracies (static or dynamic) on operator control behaviour, are still unknown.

Therefore, this thesis aims to quantify the impact of interface design and haptic assistance to facilitate action coordination between the asymmetric subtasks under realistic conditions that may incorporate inaccuracies due to heavy load handling.

This aim will be achieved by carrying out following four tasks:

- Identify the favourable interface design for tele-manipulation tasks with asymmetric slaves;
- Design a haptic assistance system to support the operator(s) of two asymmetric slaves and evaluate its effect on operator control behaviour;
- Investigate to what extent static inaccurate cues from haptic assistance impact operator control behaviour; and
- Investigate to what extent dynamic inaccurate cues from haptic assistance impact operator control behaviour.

1.5. Thesis outline

A summary of this thesis' outline is schematically represented in Fig. 1.7. Chapter 2 aims to identify the favourable human-machine interface design for the asymmetric slaves. A human factors study compares a co-operation approach against one individual controlling both industrial interfaces (i.e., bi-manual), but also against one individual controlling both slaves with one hand (i.e., uni-manually). This reveals whether or not these changes in interface design can improve operator control behaviour.

Chapter 3 focuses on providing a proof of principle to haptically assist human operators in their coordination of asymmetric slaves. This assistance supports not only the co-operated interface design, but also the uni-manual approach. Via a study on human factors, this chapter identifies the effect of this haptic assistance on operator control behaviour.

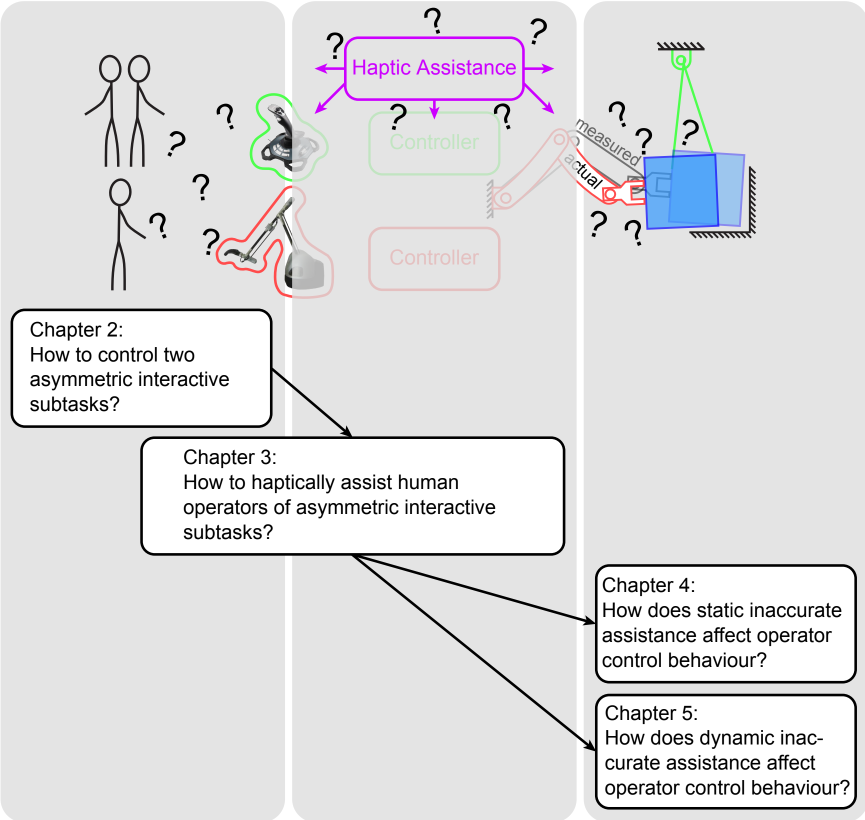

Fig. 1.7: Schematic overview of the chapters of this thesis. Each chapter explores the effects of a change or addition to a part of the connected tele-manipulator system, which is visualised by each of the three columns shown here.

Chapters 4 and 5 address the question to what extent static inaccuracies in assistive cues impact operator control behaviour. Causes and effects of mechanical compliance are analysed and implemented in two human factors experiments. Each experiment is presented in a separate chapter, using the same assistance design principles from chapter 3. Chapter 4 exposes haptic assistance to static inaccuracies during a single-operator, single-slave task. Chapter 5 examines the effects of dynamic inaccuracies on haptic assistance during a dual-operator task with asymmetric slaves.

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2

Tele-manipulation With Two Asymmetric Slaves: Two Operators Perform Better Than One

Thought is an idea in transit, which when once released, never can be lured back, nor the spoken word recalled

Pythagoras

Although we regularly use two asymmetric slaves (e.g. a crane and a tele-manipulator) to perform heavy load handling tasks, it is still unclear how to best design human-machine interface. Would that be the standard two-operator interface or a single operator approach? This chapter presents a literature survey on studies that compared human-human interaction to individual operation tasks, which provided valuable insights, but no directions towards the favourable interface design. Then it compares co-operated behaviour to both a bi-manual and an uni-manual control approach. Participants (36 divided in 8 pairs and two time 8 individuals) manoeuvred and mounted a heavy load using a vertical crane and a horizontal tele-robotic arm. It was hypothesised that the bi-manual approach had worse operator control behaviour, while the uni-manual operators would do better. The results show that a co-operating pair of co-operators work better than both bi-manual and the uni-manual operators, who worked individually.

This chapter is based on a publication in the IEEE Transactions on Haptics (2017) [1].

2.1. Introduction

In special tele-manipulation cases, two operators mutually depend on each other's actions in a shared task environment while each operates a separate slave system with asymmetric properties. Such tasks occurred during the repairs of the Deepwater Horizon oil rig, when a crane and remotely operated vehicles were required to work together, for example during placement of the Macondo capping on 12 July 2010 [2]. Similar multi-slave tele-manipulation tasks arise during maintenance of fusion plants [3], as shown in Fig. 2.1.

In fusion reactor maintenance, tele-manipulation is required to replace and revise components [5]. Components are typically heavy, and include tools [6], mirror modules [7–9] and shielding tiles/modules [3, 10, 11]. These components require accurate manoeuvring by a dexterous manipulator, but the limited lifting capacity of these dexterous manipulators (typically 15-25 kg [10, 12]) require simultaneous use of a crane. Fig. 2.1 illustrates a joint manipulation task for a 35 kg shielding tile. The tile manipulation requires 6 DOF translations and rotations by the (relatively weak) robot manipulator and hoisting by the crane [3]. Conventionally, one operator controls the robot manipulator in position control and another operator controls the lifting subtask via a joystick in rate control [5]. The tele-manipulation

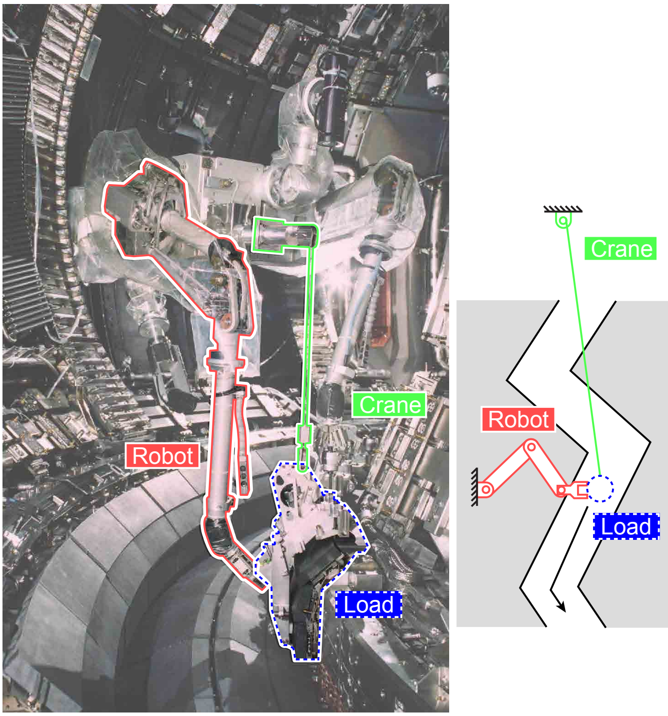


Fig. 2.1: The left shows a dexterous manipulator (red robot) and a chest mounted winch (green crane), both required to accurately position a heavy tile (dotted blue load) in a major overhaul of JET [3]. The photo is adapted from EUROfusion [4]. The right panel shows a planar abstraction of this task.

paradigm potentially allows alternative interface solutions, like bi-manual control over two slaves, or single operator control using a 6 DOF master device. The goal of this chapter is to quantify differences in control behaviour between single or two-operator interface solutions, and determine which is more favourable for asymmetric tele-manipulated maintenance tasks.

In this chapter we will use the term co-operators to describe the two operators jointly performing the task as depicted in Fig. 2.1, in lieu of other definitions from literature like dyads, collaborators, co-actors, co-workers, partners, or agents. Previous work on studies comparing performance between pairs and individuals provide inconclusive evidence as to which paradigm to choose: some show that task performance improves with two operators over that of a single operator (e.g. [13–23]), whereas others show no improvement (e.g. [24–29]) or even worse performance (e.g. [25, 26, 30–34]). Therefore, at first glance the above literature provides no guidelines for designing the most favourable control interface for the co-operative tele-manipulation task (Fig. 2.1). This chapter aims to identify this favourable control interface among three alternatives.

In section 2.2 we will put the chosen experimental task in context with related literature, in order to generate meaningful hypotheses. Section 2.3 explains the methods used to empirically evaluate task performance for two alternative single operator interface designs against the conventional approach of two-operator control. Section 2.4 shows the experimental results and section 2.5 discusses them. Finally, section 2.6 presents the conclusions.

2.2. Technical background

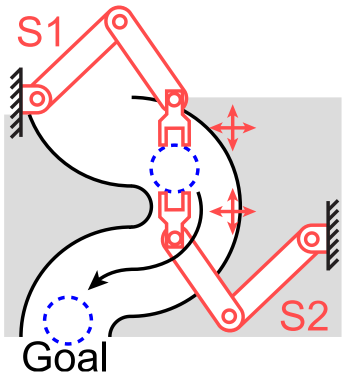
2.2.1. Two operator task characteristics

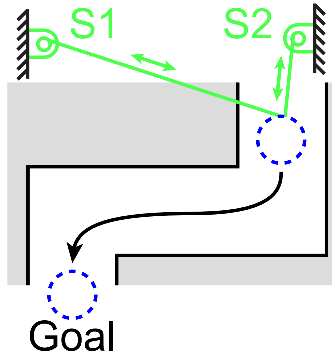
What determines whether one or two operators would be better at performing a task? Several studies compare performance between one and two operators against other research. For example, Masumoto and Inui [21] found that two operators performed better than single operators, and compare their results to contradictory findings of Knoblich and Jordan [31] and Bosga and Meulenbroek [25], who report that single operators performed better. They state that the difference could be due to other dynamic characteristics of the task (periodic force [21] versus constant force [25, 31] production). Likely, the favourable control allocation (one or two operators) highly depends on the task characteristics.

An overview paper of Jarrassé et al. characterised dual-agent tasks in terms of the task constraints and the possible behaviour of each of the two agents [35] (91 references). They propose a high-level framework based on Game Theory. Here, each agent (i.e. operator) minimises his/her own cost function while performing the task. The cost function incorporates the effort to perform the task and the error with respect to the target. They divide two operator interaction into groups based on the *task constraints* and the *agents' behaviour* (i.e. their *role*).

2

	Divisible	Interactive
Symmetric	Symmetric divisible defined as co-active in [35] Operators: can act **individually**; have **equal** roles. Symmetric divisible ≥ Individual [13–22, 24, 27, 29] Asymmetric divisible = Individual > Symmetric interactive [25, 26] Asymmetric divisible ≥ Symmetric divisible [36, 37] For example: Move the load through the path and do not hit the bounds. Subtasks S1 and S2 state move horizontal and vertical to move the load. Following a path/target [38–41]	Symmetric interactive defined as collaborative in [35] Operators: are **dependent**; have **equal** roles. Individual > Symmetric interactive [30–34] Asymmetric divisible = Individual > Symmetric interactive [25, 26] Symmetric interactive = Asymmetric interactive [33] For example: Move the load through the path and do not hit the bounds. Subtasks S1 and S2 state pull/lowers the cable to move the load. Manipulating objects from opposite sides like a: plank [42], table [43–45], car windshield [46], couch [47], pan [48], brick [33, 49–51], ring on a wire [52], shape through a hole [53] or concave shape over pillars [54].





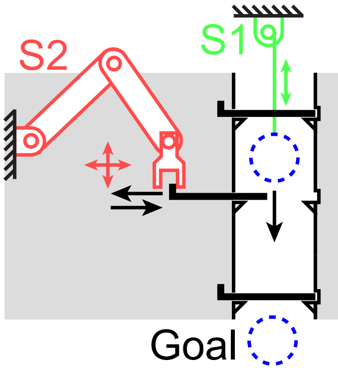
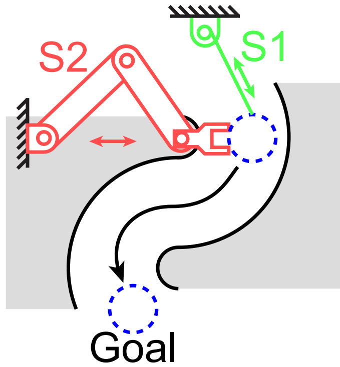
	Asymmetric divisible (undefined in [35])	Asymmetric interactive defined as co-operative in [35]
Asymmetric	Operators: can act **individually**; have **unique** roles. Asymmetric divisible ≥ Symmetric divisible [36, 37] For example: move the load passed the gates. Subtasks S1 state to wait for gates to open and pass them. Subtasks S2 state to open gates in front of the load and close them after passing. Controlling separate dof like: x or y in a square maze [55]; x or y and z in a 3D peg-in-hole task [56]; or a mobile base or its arm [33] 	Operators: are **dependent**; have **unique** roles. Symmetric interactive = Asymmetric interactive [33] **Focus of this chapter** For example: Move the load through the path and do not hit the bounds. Subtasks S1 state lowers the load. Subtasks S2 state move the load sideways (it is to heavy to lift). Controlling x and y or the rotation in a curved maze [33]. 

Table 2.1: Two operator tasks classification, adopted from the agonistic tasks of Jarrassé's framework. Each class shows the results of existing comparative studies. Here >, ≥ or = mean that task performance is respectively better, better or equal, or equal to. Each also class gives a crane/manipulator teamwork example and a selection of representative studies. This chapter focuses on interactive asymmetric class, because of the tele-manipulation task, as highlighted with black text, while the others are gray.

2

They proposed a decision tree to help in task characterisation. The first step determines whether subtasks can be done alone, which results in the following task constraints [35]:

- Divisible: *"... composed of compatible subtasks that can be completed by each agent independently."*
- Interactive: *"... (at least) one agent needs a partner to carry out its (sub)task ..."*

Because our selected remote handling task consists of two asymmetric subtasks requiring simultaneous input, they have an interactive nature. This interactive nature reflects the fact that either two operators could control the standard industrial interfaces (joystick and manipulator), but that in principle also a single operator could control both subtasks. To understand what the divisible/interactive division means with respect to existing research, we re-framed Jarrassé's framework according to an illustrated table (Table 2.1). The aim of this table is to illustrate similarities and differences in published and future tasks that could be performed by individuals or duos. The top row of Table 2.1 juxtaposes existing research according to the first step. The table shows that, in divisible tasks, duos perform better than or equal to individuals [13–22, 24–29]. Opposed to this, individuals outperform duos in controlling interactive subtasks [25, 26, 30–34].

Literature shows several explanations why operators in divisible tasks perform better than individuals, such as specialisation in subtasks and dyadic co-contraction [17]. Furthermore, in divisible tasks dual operators seem to alternatively give and take dominance over the task [39]. Finally, dual operators seem to minimise the total error only and not their own error, which agrees with the optimal feedback control theory [21].

Many studies on two interactive operators found that they had poor timing and synchronisation [25, 26, 30, 31, 34]. Additionally, Newman-Norlund et al. showed that interactive operators displayed more brain activity than divisible operators [26].

The second step in the tree asks whether interactive partners can harm each other, opting two task constraints [35]:

- Antagonistic: *"... performance improvement in (at least) one agent is detrimental to the partner ..."* .
- Agonistic: *"... improvement in one agent's subtask contributes to the improvement in the common task."*

Antagonistic tasks will be ignored in the remainder of this chapter.

Thirdly, the decision tree separates the roles of the interactive partners. The agents' behaviour can be either of the following [35]:

- Symmetric: *"... cost function's structure does not change under the permutation [agent$_1$↔agent$_2$ meaning that] agents work on an even basis ..."*

- Asymmetric: *"... agents work towards the same end and need each other to complete the task, but are not equal."*

When strictly considering the *structure* of the cost function, our operators would have symmetric roles. Each of our operators try to minimise the effort and error for both, which forms a symmetric structure according to Jarrassé's framework. However, the *cost functions* themselves, in particular the effort, are unequal as the asymmetric subtasks have different control interfaces, which gives operators unequal roles. Table 2.1 juxtaposes these roles in the right column. Here, most existing studies considered tasks with symmetric roles as operators have identical control capabilities [25, 26, 28, 30, 31, 33, 34]. Malysz and Sirouspour investigated the effect of different control interfaces (i.e. roles) in a maze task and found that operators with symmetric and asymmetric roles perform similarly [33].

Jarrassé et al. divide the interactive asymmetric class further in assistance and education. These will be ignored in the remainder of this chapter.

Jarrassé's framework does not further categorise divisible tasks in symmetric or asymmetric divisible tasks. But, consider for example both Pinho et al. [36] and Gromov et al. [37], who gave operators partial control over the task (e.g. operators controlled either the x or z direction) with which each operator could perform subtasks independently. These studies compared this approach to both operators having full (symmetric) control over the divisible task and found that performance with asymmetric roles is better. Therefore in our Table 2.1 we extend Jarrassé's framework and juxtapose asymmetric and symmetric divisible tasks (left column).

In summary, several studies compared task performance within or between single and dual operators, mainly for symmetric subtasks. In general, they suggest the following:

- A pair of operators performs better or equal to individual operators on a symmetrical divisible task.
- A pair of operators performs worse than individual operators on a symmetric interactive subtask.

Literature on asymmetric subtasks is scarce with, at most, two studies per class. This means that, to the best of our knowledge, existing research does not directly compare performance of asymmetric interactive operators with individual operators.

2.2.2. Asymmetric interactive subtasks: dual vs. single operators

What difference in performance could we expect between dual and single operators when controlling two asymmetric subtasks? Newman-Norlund et al. investigated *joint task demand*, which they defined as follows:

> *"... the degree to which one's own actions depend on and needed to be temporally coordinated with the actions of another individual in order to successfully achieve a shared goal." [26]*

They found that, brain activity in the right hemisphere is higher for two operators of symmetric interactive subtask than for symmetric divisible tasks. They hypothesised that this is due to higher demands on action understanding in the brain by the *human mirror system* [26]. The mirror system activates not only when executing one's own actions but also when observing actions from others, suggesting it may facilitate understanding actions performed by others [26, 57–59].

For asymmetric interactive subtasks, with the standard co-operator interface, the joint task demand is probably higher than for symmetric interactive subtasks. Although the interactive nature of the subtasks is similar, the asymmetry in control is not. The dissimilarities in each interface could hamper co-operators in temporally coordinating their actions. As such, it is likely that, co-operators perform worse than, or at best equal to, symmetrically interactive operators, as suggested by results from Malysz and Sirouspour [33]. This implies that individuals would perform better than, or equal to, co-operators.

To test whether individual operators outperform co-operators in our tele-manipulated task, it is crucial to allocate the asymmetric subtasks in some way to the individual. An individual operator could bi-manually operate both standard industrial interfaces. This commonly occurs in comparative studies between individuals and two operators who control symmetric interactive subtasks. However, task performance of bi-manual handling greatly depends on spatial and temporal constraints, like relative rhythm, amplitude or direction, of the task [60]. Literature shows that bi-manual coordination is accurate and stable when spatial and temporal constraints act in coalition, i.e. symmetric, but that performance deteriorates when constraints are in conflict, i.e. asymmetric, [60–63].

For tasks in literature within the symmetric interactive class, the constraints act in coalition. For our asymmetric bi-manual task, however, we expect several bi-manual constraints to conflict. Consider, for example, the difference of velocity and position control for the crane and robot, respectively. This will likely trigger differences in rhythm, amplitude and direction of interface control. As such, we hypothesised that a bi-manual control interface will not yield better task execution than the co-operated interface in terms of performance, control activity, workload and interface acceptance.

Alternatively, controlling the degrees of freedom of the object manipulated by the two asymmetric slaves could be translated to the effective manipulation of a 'virtual' single slave device that is both powerful and accurate enough to control the entire task. This means that an uni-manual control interface could suffice. Such interface theoretically merely requires a different control scheme for the two asymmetric slaves (or robots) to act as one, like in e.g. [33, 64, 65]. The uni-manual interface also fits in the single master/multiple slave framework as described in [66]. Practically this means, in this case, implementing the joystick function in the vertical axis of the robotic master as this motion is the redundant one.

Note that the uni-manual condition imposes two changes compared to the co-operative condition: both the number of operators as well as the control interface for the vertical movements (joystick vs. Virtuose). We took great care in matching the interface behaviour (see section 2.3.3) in terms of movement and gains between the input and the commanded velocity. Therefore, we believe that the confounding factor of having a different control interface, is minimal. As such, we hypothesised that, given their respective interfaces, uni-manual operators outperform co-operators with reduced control activity and workload, and a higher interface acceptance.

2.3. Methods

2.3.1. Experimental setup

The tele-manipulated task was performed in a Virtual Reality simulation with the Interactive Task Simulator [67]. Here, the slave devices and the task were modelled as rigid bodies in NVIDIA PhysX^{TM} 2.8.4. The simulator calculated rigid body dynamics and contact interaction at 1 kHz. Body poses were visualised with Unity 3D, as shown in Fig. 2.2.

The slave devices were a crane and a robotic slave, as shown in Fig. 2.3. The crane was modelled as a cable with a constant length of 20 m that could raise or lower the load. The crane's hoisting dynamics were modelled by a second order low-pass Butterworth filter with a 1 Hz cut-off frequency. The robotic slave arm was implemented as a planar device with 3 degrees of freedom. Its base displaced vertically with the crane position. Throughout the experiment, the robotic slave was controlled as if its tool-centre-point was the centre of rotation of the load.

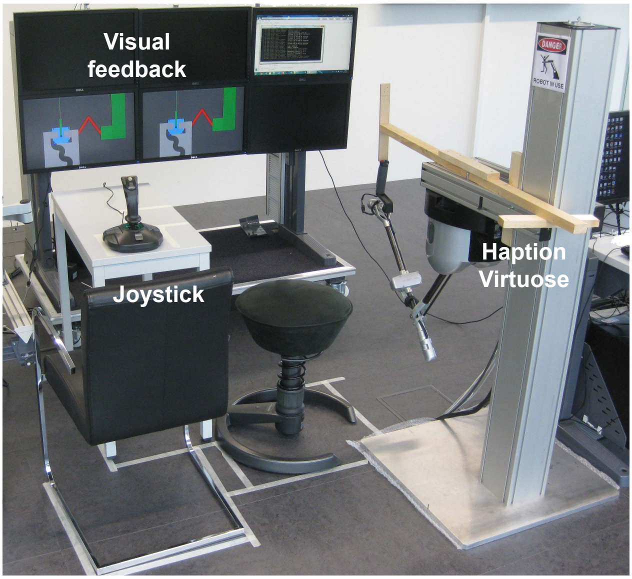


Fig. 2.2: The experimental set-up with the Haption Virtuose 6D, the joystick and the Virtual Reality environment presented on the monitor. The wooden bar defined the start position of the Virtuose and the tape on the floor indicated the position of equipment in the different conditions.

2

The two master devices used were a Haption Virtuose 6D [68] and a consumer-grade USB joystick (Thrustmaster T.16000M), as shown in Fig. 2.2. Lateral motion of the slave manipulator was controlled by the Virtuose for all three conditions. It rendered force feedback to the operator via a position-error controller at 1 kHz. Its lateral stiffness and damping were 2000 N/m and 10 Ns/m respectively, with a maximum of 30 N. The in-plane rotational stiffness and damping were 20 Nm/rad and 0.05 Nms/rad with a maximum of 3 Nm. Unused DOF's had a 100 N/m or 5 Nm/rad spring.

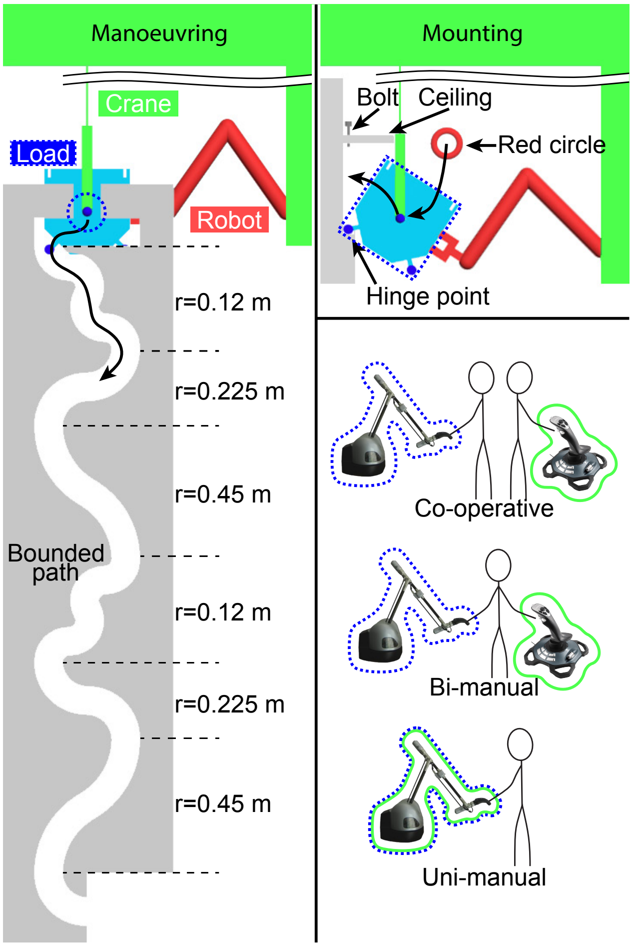


Fig. 2.3: Illustration of the experimental task and conditions. The task consists of manoeuvring the blue centre axis of the load through the bounded path (left). At the bottom of the path, subjects encounter the mounting task (top right) where participants should place one of the lower axes in the hinge point while the load is tilted until it is upright and locked with a bolt. The three methods to perform the experimental task are illustrated in the lower right.

The vertical motion of the load was controlled by rate-control, where velocity commands were limited to 0.4 m/s. The rate-control commands were generated differently for the experimental conditions. Co-operators and bi-manual operators used the joystick to control the set-point velocity for the crane. The joystick updated at 100 Hz and was modified to fit left and right hands similarly.

Uni-manual operators controlled the vertical motion of the Virtuose (within a 20 cm workspace) to provide the set-point velocity for the crane. The Virtuose fed back a force to a zero vertical offset with a 100 N/m spring and a 0.01 Ns/m damper. This stiffness centre was made better tangible by an additional stiffness (1000 N/m) and damping (0.1 Ns/m) within 0.005 m around that centre. Forces were limited to 10 N, whereas the maximum velocity set-point (0.4 m/s) was made tangible by an additional 1000 N/m spring beyond 20 cm. This was done to resemble the forces from the joystick.

All participants obtained the same camera view: a close-up of the manipulator holding the load with about one meter of space above and below, as shown in Fig. 2.2, that moved with the crane. The left monitor was used for co-operators only.

2.3.2. Task description

The experimental task consisted of manoeuvring a 50 kg load along a bounded path and subsequently mounting the load, as shown in Fig. 2.3. We chose to analyse these two tasks separately, to better understand behaviour in free-air and in physical contact. To start the mounting tasks equally between trials, the load's centre axis had to be positioned upright in the red circle (see Fig. 2.3) until the circle turned green.

The load is a 0.5 m square (similar to JET shielding tiles [3]), which can rotate freely around its centre of mass by means of a dedicated hoisting tool (similar to hoisting tools proposed in [8, 11]). The load contains a dark blue axis, with a 0.03 m radius, which must be manoeuvred through the bounded path. Each path has six curved sections with radii of either 0.45, 0.225 or 0.12 m. Each curvature occurs once moving from left to right and once in the reversed order. Curved paths are more difficult to navigate along than straight paths [69]. They dictate that the velocities of each of the slaves are coupled and must vary with the curve. Further, the paths have the following properties:

- Planar, to exclude complications from (suboptimal) 3D views and to simplify data analysis.
- Constant path width (0.16 m), with a maximum left to right movement of 0.45 m (compatible with the Virtuose workspace)
- Straight lead-in section to reduce position variability at the start.
- Lead-out section, that is half a 0.225 m radii section, to facilitate analysis near the end of the path (e.g. calculating distance to the wall).

To avoid participants from adopting open-loop strategies they were presented with 12 different paths. These 12 path variations were assumed to be equally difficult as they all contain the same number and type of segments, although the sections were arranged semi-randomly. Each path started with a sequence of three unique radii section (3!=6 variation), which were repeated, but mirrored, in the second half, as shown in Fig. 2.3. The overall paths were mirrored which provided a total of 12 balanced variations.

The six paths that started right were combined with mounting the load on the right; for the paths that started left, the mounting was on the left. These 12 sets were provided to the participant in a balanced order, such that no more than two sequential trials started on the same side.

The mounting task was inspired by fusion plant maintenance tasks that use a sideways mounting via a hinge point [11]. The load had to approach the mount tilted about $30°$, see the top right of Fig. 2.3. Once the lower hinge axes (dark blue) was placed in the hinge point, the load could be moved up and turned straight again. Finally, operators could lock the load by pressing a button.

2.3.3. Experimental design

The experimental tasks were performed by three groups of subjects: pairs of operators for the standard industrial co-operated condition, and single operators for bi-manual and uni-manual control modes (see section 2.2.2). In the co-operated condition, one operator controlled the sideways position and rotation of the load, via the Virtuose, with his right hand. The other operator controlled the vertical motion of the load via the joystick in rate control with his right hand.

In the bi-manual condition, a single operator used his left hand to rate control the hoisting velocity via the joystick, and his right hand for horizontal position control of the load, via the Virtuose. We chose this division of labour between hands based on Guiard's theory for bi-manual control [70]. This theory suggests that the non-dominant hand should lead the dominant hand, set the spatial reference frame for the dominant hand and perform course movements. Practically, the crane set/changed the course movements of the load and, with it, the reference frame for the robotic interface. A different choice of dividing the subtasks between hand might produce different results, as suggested by Sainburg [71].

In uni-manual control, the operator held the Virtuose with his right hand. He controlled the motion of the load in position control in the sideways and rotational direction.

2.3.4. Procedure

Before the experiment participants received the following task instructions textually and verbally:

- Manoeuvre the small dark blue centre axis of the load through the bounded path without hitting the bounds.
- Mount the load gently via the hinge point without hitting the ceiling. Gently means an impact energy below 0.7 J.

After each trial, participants received feedback on their performance by visually and orally presenting relevant metrics: elapsed time for manoeuvring down the path;

elapsed time for mounting; and maximum impact energy during mounting. When participants hit the bounds or the ceiling, or had a too high impact energy, an alarm indicated a critical error. In this case, participants still had to complete the trial.

Participants were further motivated to avoid critical errors by means of a competition: the participant with the least number of trials with a critical error would win €10. In case of a tie, the participant with the best time would win. This competition encouraged a speed-accuracy trade-off resembling real-world demands, where operators must minimise task-completion time while upholding safety and reliability that otherwise might result in expensive downtime [3]. Note that co-operators were allowed to discuss their performance and strategy between trials to match a realistic scenario, in which communication would also be allowed or even mandatory.

After receiving the task instructions participants first had a familiarisation period before receiving twenty training trials. Uni- and bi-manual operators received five familiarisation trials. Co-operators familiarised themselves not only for five trials with the joystick (and the corresponding hoisting subtask) but also for five trials with the Virtuose (and the positioning subtask). Afterwards, their permanent roles were assigned randomly. This means that, although training time was identical to uni- and bi-manual operation, co-operators had five more familiarisation trials than the other two groups (though the extra familiarisation was with a different interface). In all three groups, the learning curves were flattened before the onset of the actual experiment. The actual experiment consisted of seven trials. If critical errors were made participants were allowed to redo the trial, although they were told they would be excluded from the competition if more than three critical errors were made: no one had more than three. Both during training and the actual experiment there was a one minute break between each set of five trials.

2.3.5. Participants

Thirty-six right handed males volunteered in this experiment: nine in the uni-manual condition, nine in the bi-manual condition and eighteen (nine pairs) in the co-operated condition. The participants could enrol in an online agenda not knowing which condition they would be assigned to. None of the participants were familiar with the task prior to the experiment or participated in a similar (pilot) study. For co-operation, all pairs were composed of strangers. All participants were in the age range of 18 to 42 years. The experiment was approved by Delft University of Technology Human Research Ethics Committee and all participants gave their informed consent.

2.3.6. Data acquisition & metrics

Force, position and velocity data were recorded for the master, slave and load at 1 kHz. Joystick data was scaled to make it comparable between the uni-manual (Virtuose as joystick), bi-manual and co-operation (real joystick). The Virtuose data was scaled up by a factor of 2 (a 0.2 m offset makes 0.4 m/s crane input). The joystick data was scaled by a factor of 0.4 (0.4 m/s). No other data treatments or transformations were applied. The data was used to evaluate task execution in terms of task performance and control activity. Task performance was evaluated in the following:

- tct: Task-completion time [s], the time in seconds to complete the task.
- dtc: Shortest distance to contact [s], the distance to the bounds considering the heading of the load at each instance. For car driving, this metric (when accounting for the velocity) is better known as time-to-lane crossing or TLC [72].
- sal: Spectral arc length [-], the movement smoothness measured by the arc length along the amplitude and frequency-normalised Fourier magnitude spectrum of a speed profile, as introduced by Balasubramanian et al. [73]. Smooth vs. un-smooth movements have been related to expert vs. novice performance in [74].

Control activity was evaluated in terms of the following:

- L: Trajectory length [-] and [m], the total distance of (scaled) movements that operators made to control either the crane or the load, measured by summing the differences between all subsequent position set-points of the master device(s).

Additionally, a NASA-TLX questionnaire [75] was completed to evaluate the subjectively perceived workload on a 0 to 100 scale. A lower score represents a lower workload. Further, a van der Laan usefulness and satisfaction acceptance scale [76] was completed to evaluate the perceived usefulness of, and satisfaction on, the interface on a 5-point Likert scale.

2.3.7. Data Analysis

The calculated metrics were averaged over the seven last repetitions without critical errors per participant. To analyse the effect of control mode, a one-way ANOVA was performed for the subtasks (manoeuvring and mounting) and for the metrics (tct, dtc, sal, L). If the Levene's test was significant (unequal variances between groups), the Welch test was performed and reported instead. When the ANOVA revealed that control mode had an effect on a metric, a Bonferroni (or Dunnett's T3 in case of unequal variances) corrected Post Hoc analysis was performed. For the subjective metric, Kruskal-Wallis tests were performed. p-values of 0.05 or below were considered significant ($\alpha \leq 0.05$).

Furthermore, the learning curve was examined on being flattened in terms of task-completion time. The average of the last three successful training trials per participant were compared to the average of the last three successful final trials in a paired t-test. These tests should support that the differences are not significant. Therefore no multiple comparison correction was applied to minimise chances of Type II errors.

To gain insight into the speed-accuracy trade-off, we derived the trade-off from the results by calculating the percentage of successes per manoeuvring velocity. To this end, all final trials were sliced into the six path sections. In successful trials, each section provided an average velocity. In trials with critical errors, only the section of the first contact provided a velocity. Variations in velocities per curvature - due to the difference in path difficulty [69] - were compensated for by shifting the data per curvature per participant to the participant's mean velocity, according to equation 2.1. Here, v is the velocity, p is the participant, c is the curvature and t is the trial.

$$v(p,c,t) = v(p,c,t) - \frac{\sum_{t=1}^{n} v(p,c,t)}{n} + \frac{\sum_{c=1}^{3}\sum_{t=1}^{n} v(p,c,t)}{3 \times n} \tag{2.1}$$

The shifted velocities were grouped in 10 bins of similar velocities per condition to calculate a histogram and the percentages of successful trials as function of velocity.

2.4. Results

Figures and tables show the mean and 95% confidence interval (CI) based on nine participants/teams. Figures denote significant results with '• • •', '••' and '•' for $p<0.001$, $p<0.01$ and $p<0.05$, respectively; tables present significant results in boldface.

2.4.1. Speed-Accuracy trade-off

The learning curve shows no significant difference in task-completion time for manoeuvring ($-1.04 \leq t_8 \leq 0.66$, $p \geq 0.327$) and mounting ($-0.11 \leq t_8 \leq 1.27$, $p \geq 0.240$) for all conditions. The average number of critical errors during the final trials was 1.4, 1.4 and 1.3 for co-, bi-manual and uni-manual operation, respectively. This indicates that, between conditions, participants made similar numbers of critical errors.

Fig. 2.4 shows a histogram of the velocities used and number of critical errors per bin (thickness of the horizontal lines). The percentages of successful trials per bin, is shown in the right of Fig. 2.4. It illustrates that most critical errors were on the high velocity side of the distribution.

2.4.2. Manoeuvring

The left of Table 2.2 summarises the results for the manoeuvring task. For **task performance** it shows that task-completion time differs significantly (see left of Fig. 2.5). Table 2.2 shows a mean difference in time with respect to co-operation of bi-manual (12.54 s longer than co-operation) and of uni-manual (5.64 s longer). The Dunnett's T3 Post Hoc test revealed that these mean difference were significant.

The spectral arc length differs significantly for the joystick input (see right of Fig. 2.5) but not for the Virtuose input. Table 2.2 shows a mean difference in joystick input with respect to co-operation of bi-manual (1.68 units less smooth) and of uni-manual (1.12 units less smooth). The Dunnett's T3 Post Hoc test revealed that these mean difference were significant.

Table 2.2: Experimental results for all metrics during the manoeuvring and mounting task. These include the ANOVA results, the first p-value below each metric, and the Post Hoc results, the p-values behind bi(-manual) and uni(-manual) for the respective comparison to co(-operation).

	Manoeuvring		Mounting	
Task-completion time [s]				
	$F_{2,14.4} = 11.56$, $p =$ **0.001**[1]		$F_{2,14.13} = 21.9$, $p = <$**0.001**[1]	
	Mean (95% CI)	p diff.	Mean (95% CI)	p diff.
co	28.21 (26.24;30.18)		9.78 (8.87;10.69)	
bi	40.75 (35.35;46.16)	**0.005**[2]	17.03 (14.96;19.10)	<**0.001**[2]
uni	33.85 (31.05;36.65)	**0.017**[2]	13.40 (11.71;15.09)	**0.009**[2]
Spectral arc length Joystick [-]				
	$F_{2,14.6} = 18.51$, $p = <$**0.001**[1]		$F_{2,14.3} = 3.13$, $p = 0.075$[1]	
	Mean (95% CI)	p diff.	Mean (95% CI)	p diff.
co	4.67 (4.41;4.92)		3.42 (3.15;3.69)	
bi	6.35 (5.67;7.04)	**0.003**[2]	4.25 (3.58;4.93)	-
uni	5.79 (5.45;6.14)	<**0.001**[2]	3.34 (3.14;3.54)	-
Spectral arc length Virtuose [-]				
	$F_{2,24} = 0.31$, $p = 0.733$		$F_{2,24} = 2.99$, $p = 0.070$	
	Mean (95% CI)	p diff.	Mean (95% CI)	p diff.
co	5.42 (5.17;5.66)		4.02 (3.62;4.41)	
bi	5.52 (5.17;5.87)	-	4.79 (4.25;5.34)	-
uni	5.56 (5.27;5.86)	-	4.53 (4.15;4.91)	-
Shortest distance to contact [m]				
	$F_{2,24} = 12.28$, $p = <$**0.001**			
	Mean (95% CI)	p diff.		
co	.064 (.057;.072)			
bi	.042 (.037;.048)	<**0.001**		
uni	.052 (.046;.058)	**0.028**		
Trajectory length joystick [-]				
	$F_{2,24} = 5.70$, $p =$ **0.009**		$F_{2,24} = 0.54$, $p = 0.591$	
	Mean (95% CI)	p diff.	Mean (95% CI)	p diff.
co	1.42 (0.93;1.91)		0.80 (0.53;1.07)	
bi	2.04 (1.46;2.63)	0.211	0.85 (0.28;1.42)	-
uni	2.53 (2.33;2.72)	**0.008**	0.59 (0.49;0.69)	-
Trajectory length Virtuose [m]				
	$F_{2,24} = 5.24$, $p =$ **0.013**		$F_{2,24} = 0.16$, $p = 0.855$	
	Mean (95% CI)	p diff.	Mean (95% CI)	p diff.
co	2.63 (2.59;2.68)		0.80 (0.53;1.07)	
bi	2.55 (2.50;2.59)	**0.020**	0.85 (0.28;1.42)	-
uni	2.56 (2.51;2.61)	**0.046**	0.59 (0.49;0.69)	-

[1]Welch's F statistics.

[2]Dunnett's T3 corrected Post Hoc.

The shortest distance to contact has a significant difference for control interface. Table 2.2 shows a mean difference in distance to contact with respect to co-operation of bi-manual (0.022 m less) and of uni-manual (0.012 m less). The Bonferroni corrected Post Hoc test revealed that these mean difference were significant.

For **control activity**, both the trajectory length of the joystick and the Virtuose show significant differences (see Fig. 2.6 and Table 2.2). Table 2.2 shows a mean difference in both the joystick and Virtuose trajectory length with respect to co-operation of uni-manual (1.11 units longer and 0.07 m shorter). The Bonferroni corrected Post Hoc test revealed that these mean difference were significant. Fur-

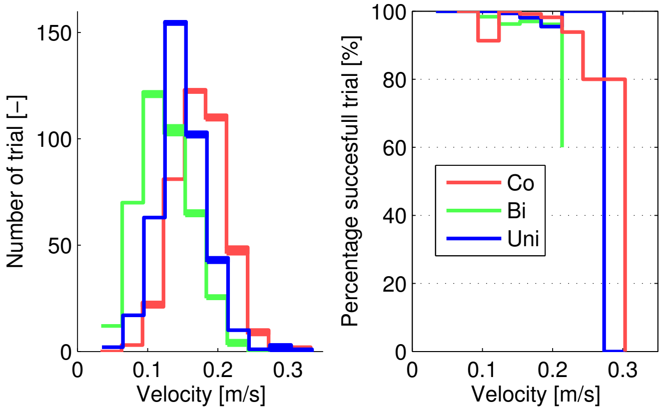


Fig. 2.4: Left: A 10 bin histograms of average manoeuvring velocities achieved in the path for all trials over all participants per condition. The thickness of the horizontal lines indicates the number of critical errors per bin. Right: Speed-Accuracy trade-off obtained by calculating the percentage of successful trials per bin. Note that bi-manual operators could attain 60% successful trials in the last bin, but that they did not reach higher velocities.

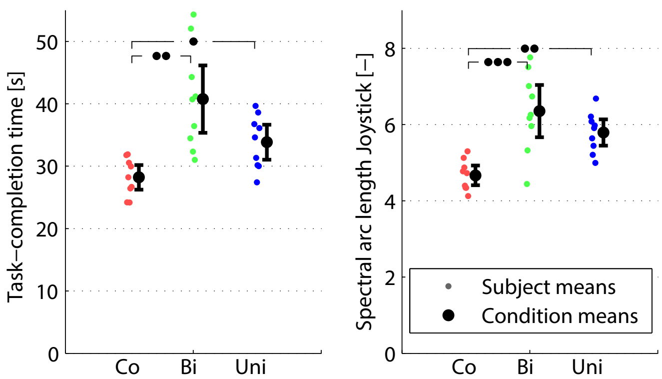


Fig. 2.5: Task-completion time (left) and Spectral arc length of the velocity of the joystick (right). Both measured for manoeuvring down the path.

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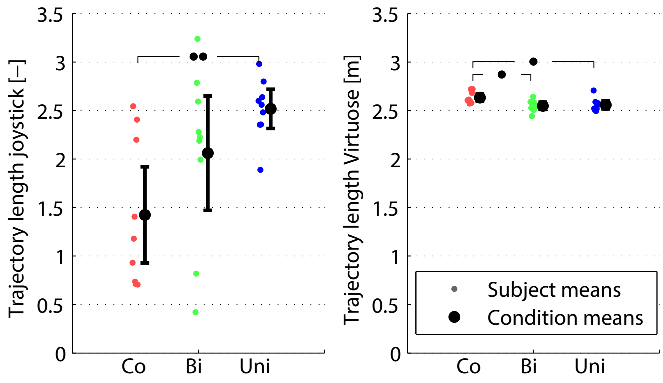

Fig. 2.6: Trajectory length for the joystick (left) and the Virtuose (right). Both measured for manoeuvring down the path.

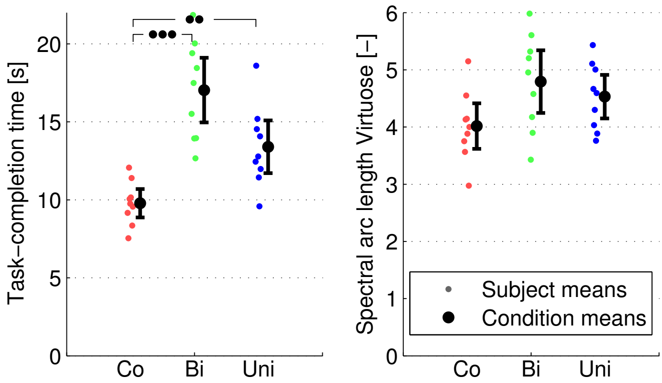

Fig. 2.7: Task-completion time (left) and Spectral arc length of the velocity of the joystick (right). Both measured for mounting the load.

thermore, the observed difference for the Virtuose trajectory length with respect to co-operation of bi-manual (0.08 m shorter) was significant.

2.4.3. Mounting

The right of Table 2.2 summarises the results for the mounting task. For **task performance**, the task-completion time, results have a significant difference (see left of Fig. 2.7). Table 2.2 shows a mean difference in time with respect to co-operation of bi-manual (7.25 s longer than co-operation) and of uni-manual (3.62 s longer). The Dunnett's T3 Post Hoc test revealed that these mean difference were significant. The spectral arc length had no significant difference for either interface (right of Fig. 2.7).

For **control activity**, the trajectory length of both the joystick and the Virtuose show no significant differences.

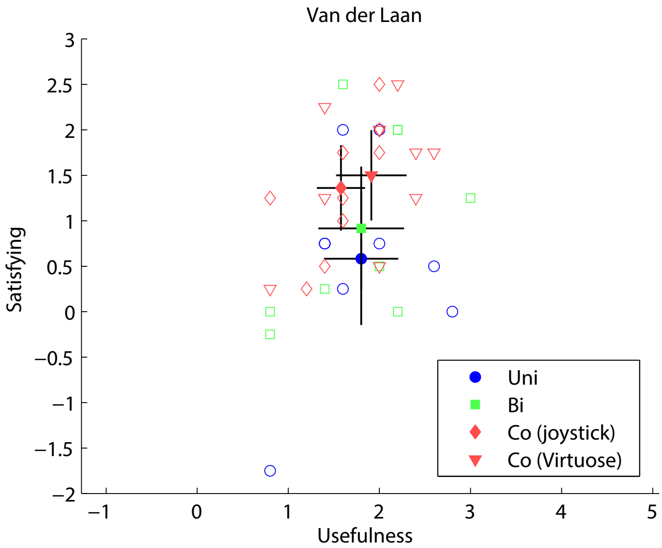

Fig. 2.8: Van der Laan usefulness and satisfaction acceptance scale.

2.4.4. Subjective metric

The NASA-TLX scores show no significant difference (H_3 = 1.30, p=0.729). The median scores (and Inter-quartiles) were as follows: Virtuose co-operators 59.9 (48.5; 70.9); joystick co-operators 60.7 (53.6; 66.5); bi-manual operators 66.0 (52.7; 70.8); and uni-manual operators 59.5 (52.8; 64.8).

For the van der Laan acceptance scale, the Cronbach's α stays well above 0.65 ((α=0.74), meaning that the results are reliable [76]. The results show no significant difference for both usefulness (H_3=1.93, p=0.588) and satisfaction (H_3=4.14, p=0.247), see Fig. 2.8.

2.5. Discussion

2.5.1. Speed-accuracy trade-off

The training phase aimed, among other things, to allow participants to settle for a specific speed-accuracy trade-off [77, 78]. Fig. 2.4 illustrates that participants chose different speeds between conditions. The speed-accuracy trade-off shows that, at higher velocities, participants moved too fast to act decisively, which increased chances of critical errors. This corresponds to speed-accuracy trade-off observed for a discrimination task [77].

2.5.2. Effects of bi-manual control vs. co-operation

In terms of **performance**, bi-manual operators had more trouble completing the task than co-operators, as shown by the increased overall task-completion time (44%-74%). During the manoeuvring task they showed reduced distance to the bounds (34%) and reduced smoothness of joystick movements (35%) compared to co-operators. Interestingly, this finding corresponds to results from studies on bi-manual control over asymmetric subtasks [60–63], but contrasts with studies with symmetrical interactive subtasks, where bi-manual operators outperform pairs of operators [25, 26, 30, 31, 33, 34].

Contrary to our hypothesis, the **subjective metrics** show no difference in the reported workload and interface acceptance. Additionally, the **control activity** metric indicates that the control activity of the Virtuose was merely 3% less for bi-manual operators compared to co-operators during manoeuvring, and no differences for mounting. Apparently, bi-manual operators performed worse, but did not rate their task as worse than co-operators. Possibly, they were forced to decrease both performance and activity to cope with their constraints.

2.5.3. Effects of uni-manual control vs. co-operation

For **performance**, uni-manual operators had more difficulty completing the task than co-operators, as shown by the increased task-completion time (20%-36%) and -during the manoeuvring task- less smooth joystick movements (25%) and reduced distance to the bounds (19%). These metrics do not support our hypotheses for uni-manual operators. The **subjective metrics** on reported workload and acceptance did not differ significantly between these conditions.

Interestingly, the **control activity** metric indicates that uni-manual operators moved 73% more with the joystick and 3% less with the Virtuose than co-operators during manoeuvring. Literature suggests two potential mechanisms that may explain these contradictory results, related to the high degree of asymmetry in the subtasks.

First, there is the asymmetric system dynamics on two control axes (position versus rate control). McRuer's human-in-the-loop models for multi-axis systems suggest that as operators control more axes, which have different (complex) dynamics, the crossover frequency drops while the remnant, closed-loop system performance (error) and phase margin increases [79–81].

Second, there is the asymmetry in required force (pushing a relatively compliant static spring joystick versus a dynamic 50 kg load), which could conflict with the accuracy of the neuromuscular systems. Research shows that the variability in force linearly relates to the magnitude of the force applied [82]. For our task, this might have forced individual operators to 'optimise' this multi-axis control system to their abilities, i.e. allowing more joystick input and reducing sideways work.

The above could also explain why the results in [33] suggest similar performances for individuals and co-operators. In their maze task, each co-operator controlled either the translation or rotation. In a similar, but separate experiment, individuals controlled both subtasks via one interface. In both experiments the interface to the translation and rotation worked in position control with force feedback. The degree of asymmetry was thus much lower, which reduced the task complexity for the individual operator.

The co-operators did not receive haptic or auditory feedback from each other's control actions, but could only see their combined effect on the virtual load. Literature shows that task performance of two operators increases as partners receive more feedback (i.e. haptic or auditory) as shown for symmetric divisible [18, 21, 39], asymmetric divisible [41] and symmetric interactive [31, 49, 52, 54] tasks. Most likely co-operators in our asymmetric divisible task would benefit from additional feedback well, although the high degree of asymmetry in the control interface might hamper them.

2.5.4. Limitations and future work

This chapter aimed at comparing a co-operating pair of operators (each controlling one asymmetric subtask) to two approaches that would allow a single operator to control both asymmetric subtasks: bi-manual or uni-manual control. Our experimental design was not aimed to specifically test the difference between these two single-operator approaches. Note that a potentially confounding factor between the uni-manual and co-operation condition may be the accompanying change in crane interface (from Virtuose to joystick). However, given the very similar tuning of the interfaces, this is not expected to constitute a substantial influence.

Potentially, other metrics than we used might capture other elements of the control behaviour. For example several studies for symmetric tasks proposed human-human interaction metrics to describe the operator behaviour or the (relative) performance during the task like: correlation coefficients [21, 27]; dominance [83]; contribution [17]; or sharing pattern drift [28]. Unfortunately, for asymmetric tasks these existing measures have limited value as they do not capture the relationship between each input and the overall spatio-temporal constraints in the task. An interesting perspective on this appears by considering the impact of crane velocity. A constant (vertical) crane velocity implies a forced pacing of the overall task, requiring the (lateral) robot operator to handle all critical situations, which intensify with higher crane velocities. Our results (not further illustrated here) indicate that in general co-operators used a more constant crane velocity profile compared to the other two conditions. Single operators seemed to provide themselves more space or time for lateral movements, while they increased their vertical speed elsewhere.

The limited sample size (n=9) of this study could raise concerns on its statistical power, although the reported effects are both significant and substantial. Note that we applied strict Bonferroni corrections (as if a comparison between bi-manual and uni-manual was made) providing an extra margin on type I error for the limited sample size. On the other hand, we made several experimental design choices to reduce variability between participants: we recruited solely right-handed young males and trained for a specific speed-accuracy trade-off.

This study used naïve participants, which complicates extrapolation of the results to the selected and highly trained operators from industry practice. Moreover, the co-operator teams were formed impromptu. In reality, teams will probably not only improve skills with their own subtask, but will also learn to co-operate better. Therefore, only a longitudinal study could reveal which interface is truly preferable.

Because of the simulated physical environment and the planar abstraction of the experimental task, the results might not transfer directly to a real world system. Considering the simulated environment, we showed that the experimental outcome resembles existing work [84]. Considering the planar abstraction of the task, we expect that 3D tasks are harder for all conditions for both manoeuvring and mounting. It remains to be investigated how such changes impact the observed results for the current experiment.

An interesting area to extend the current work is towards human-robot co-operation. Research in other domains shows that this can be as effective as human-human operation [22, 85]. Our initial efforts in haptic shared control [86] for tele-manipulation tasks [84, 87] might be extended to provide an alternative strategy to increase single operator performance of asymmetric tasks towards that of co-operators. Other literature indicates that such haptic assistance systems can also improve task performance for dual operator tasks [33, 51, 54].

In future work, we will extend our experiments and analyses towards a deeper understanding of the underlying benefits in control behaviour of pairs of co- operators. The resulting knowledge is expected to help in determining when to use single or multiple operators, and to guide the design of haptic assistance.

2.6. Conclusion

We investigated a remote handling task that involves controlling a single heavy object via two asymmetric slaves: a crane for hoisting controlled by a joystick, and a dexterous robot arm for fine manipulation controlled by a haptic master device. In industry practice, each slave is controlled by a dedicated operator, which - based on a taxonomy extended from literature - constitutes co-operation, characterised by an interactive asymmetric task. Potentially, a single operator might control both slaves bi-manually, or even uni-manually through one haptic master device that controls both slaves.

In a human factors experiment, operators manoeuvred and mounted a simulated heavy load comparing a pair of co-operators to both uni- and bi-manual operation. For the experimental conditions studied, bi-manual operators performed these tasks on average 59% slower than co-operators. Contrary to the hypothesis, uni-manual operators were 20% slower in the manoeuvring subtask and 36% slower in the mounting subtask than co-operators. Interestingly, during the manoeuvring subtask, the hypothesised control activity benefit for uni-manual operators was not clearly found: they exerted 73% more crane input, but gave 3% less input on the robot arm. In conclusion, co-operators performed the investigated manoeuvring and mounting task best. Apparently controlling a single load with two slaves benefits from dividing the required control actions over a pair of operators.

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3

Haptic Assistance Improves Tele-manipulation With Two Asymmetric Slaves

Divide each difficulty into as many parts as is feasible and necessary to resolve it

René Descartes | Discourse on Method

In chapter 2, two co-operating operators attained better performance than a single uni-manual operator in a tele-manipulated heavy load handling task with two asymmetric slaves (i.e., a crane and tele-robot). Although inter-personal coordination between co-operated was presumed extremely difficult, individuals had their own challenges in controlling such multi-axis system with different dynamics. This chapter 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.

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3.1. Introduction

We frequently use two asymmetric systems to accurately manipulate heavy objects: a crane to hoist the load and a helping hand to position the load. For example, during the final positioning of pre-manufactured components on construction sites or 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 controls a lifting subtask via a joystick in rate control [2] and another operator controls the sideways subtask in position control.

Similarly, tele-manipulated maintenance for future fusion power plants often requires two asymmetric systems. The dexterous slave are typically limited to carrying 15-25 kg [3, 4], but loads frequently surpass this limit. To handle these loads, a crane completes the vertical weight lifting task, while the dexterous slave performs the accurate horizontal manoeuvring, as illustrated in Fig. 3.1. Occasionally, the subtasks of the crane and dexterous slave must guide and align the load with millimetre precision to its mount [5]. Such loads include fragile and expensive components, like: tools [6], mirror modules [7–9] and shielding modules [3, 5, 10].

Tele-manipulation is not as easy as direct hands-on manipulation. Well-known disadvantages of tele-manipulation are limited performance, accuracy and situation awareness [11, 12]. Even an experienced tele-operator who controls one dexterous slave system would need 3.5 to 8 times longer to complete the task than an operator working hands-on [13–15]. When a crane uses 10 to 20% of the task time, this

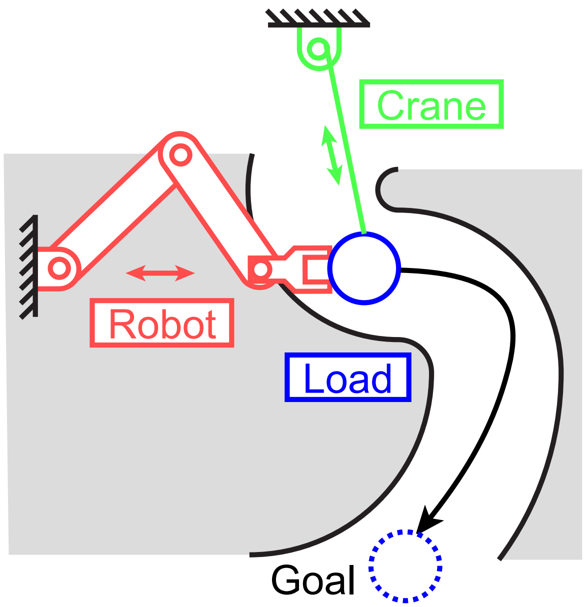

Fig. 3.1: An illustration of two asymmetric slaves with interactive subtasks. The crane (green) hoists the load (blue) vertically, and the dexterous robotic arm (red) accurately manipulates the load horizontally along a curved bounded path.

same operators would need 13 to 23 times longer to complete a tele-manipulated task than an operator working hands-on [15]. This time cost conflicts with the needs of future fusion power plants, such as ITER and DEMO. While one of ITER's 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% [16]. 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 [17]. 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 chapter aims to improve tele-manipulated tasks that require two asymmetric slaves.

When pairs of operators work together, they must account for specific relative behaviours and task constraints. Operator behaviour and task constraints form the basis of Jarrassé's framework to classify two operator tasks [18]. This framework, combined with suggestions from chapter 2 and [19], comprises four classes:

- Asymmetric divisible [19]: Operators have different (sub)tasks that they can complete individually;
- Symmetric divisible (co-active [18]): Operators have identical tasks that they can complete individually;
- Symmetric interactive (collaborative [18]): Operators have identical tasks that they must coordinate precisely together; and
- Asymmetric interactive (co-operative [18]): Operator have different (sub)tasks that they must coordinate precisely together.

The task considered in this chapter 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. 3.1.

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 moves with those of the other while their capabilities are dissimilar. To improve the coordination between operators, we propose to haptically link their control actions through a joint task environment, via an assistive controller that guides the heavy load towards an 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.

Support on one task (i.e., without subtasks) already exists as haptic assistance for one operator. This type of haptic assistance has roughly two approaches. The first, virtual fixtures, prevents operators from moving into restricted areas, but allows movement elsewhere (e.g., [20–22]). This type of assistance acts like a barrier, similar to a guardrail preventing cars from driving off a cliff. The second, continuous assistance, supports operators towards a reference trajectory (e.g., [14, 22–29]). This type of assistance acts similar to a teacher guiding the racket of a student to hit a tennis ball. While both approaches improve task performance, this chapter focuses on continuous assistance.

Some studies already described a haptic link between operators (e.g., [30–33]). These studies linked the positions and/or velocities between operators for the object carried or oriented. This haptic link 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 considered only symmetrical interactive subtasks, in which the operators ideally make identical control action, 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. 3.1 where the movement on a curve implies that position and/or velocity must continuously change for each subtask. Thus, literature does not provide details how to design a haptic assistance system in such case. Therefore, this chapter describes a novel haptic assistance system that haptically links two operators through the joint task environment via asymmetric subtasks. Furthermore, this chapter evaluates the efficacy of this novel haptic assistance system in terms of task performance, control activity and safety.

The efficacy of the haptic assistance is evaluated not only in co-operated tasks, but also in uni-manual controlled tasks. Uni-manual operators can control both subtasks via a hybrid control interface as described in chapter 2 and [19]. In a previous study (chapter 2, [19]), 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 dynamics, as identified by McRuer and Schmidt [34]. Literature shows that haptic assistance allows individual novice operators to perform complex dynamic tasks better than without assistance [22]. Individual novice operators also learn new movement strategies for complex tasks better with than without haptic assistance [28]. Consequently, uni-manual operators may benefit greatly from the assistive forces and haptic link between the asymmetric control axes.

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

3.2. Haptic assistance design

An assistance system that constitutes a haptic link, poses several challenges. First, it must have knowledge of the 'ideal' task that links each interface at each moment in time. Secondly, the system must direct the desired control actions between the interfaces, even while the linked actions are inherently different. Finally, it 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 at the same time, because a failure to serve one hits the other as well.

These challenges are impossible to solve by considering the subtasks and interfaces separately. Divide-and-conquer fails here. By looking at the joint task, rather

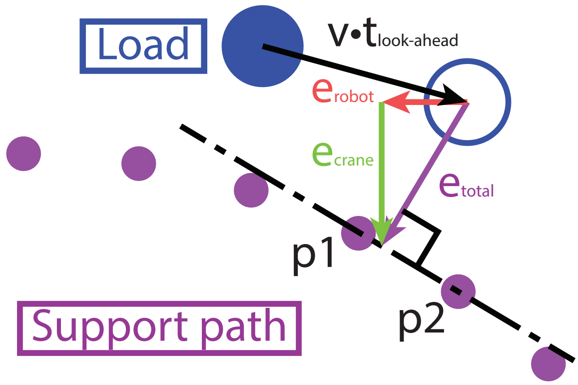

Fig. 3.2: The basis of the haptic link between subtask through the joint task space. The assistance algorithm estimates the future state of the load (blue) using a look-ahead time (black arrow). Then it finds the closest support path points (p1 and p1) and calculates the closest distance (orthogonal) 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.

than the separate subtasks, the design challenges are simplified. 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. 3.1: the load must move to its goal while staying between the bounds. The assistance system should, at first, only reason on the overall task and disregard the subtasks and interfaces. Practically for this study, the assistance has a predefined support path consisting of discrete points spaced 0.002 m apart 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. 3.2.

The presented method for deriving the desired heading makes a fair first estimate. Nevertheless, it could result in suboptimal support, because it does not include the load's dynamics. A look-ahead controller can account for system dynamics, using the load's heading to predict its future state [23, 24]. There it derives the desired heading, as illustrated in Fig. 3.2. For this study, the look-ahead time was manually tuned at 0.4 s.

The load's desired heading in task space contains information for both subtasks. The assistance system must cleverly direct the right information to the right subtask. Therefore, it splits the error in vertical and horizontal components for the crane and dexterous slave interfaces, respectively, as illustrated in Fig. 3.2. 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 present intuitive haptic cues to the interface of each subtask for which it uses the haptic shared control principles [35]. 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 [36, 37], other non-holonomic devices [38] and unmanned aerial vehicles [39]. 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., [14, 22–24, 26–29]). This approach accounts for the separate system dynamics and interface designs. The basis of the haptic assistance algorithm was adapted from Boessenkool et al. [24], which was further extended and tested in [27, 29].

3.3. Methods

3.3.1. Participants

We recruited 45 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 and gave their informed consent. The Human Research Ethics Committee of Delft University of Technology approved the experiment.

3.3.2. Experimental set-up

The asymmetric slave devices were a crane to hoist and a robotic slave to horizontally position and orient the load, as shown in Fig. 3.3. The crane consisted of a 20 m cable (constant length) and modelled hoisting dynamics (1 Hz second order low-pass Butterworth filter). The robotic slave was modelled as a planar, three degrees of freedom, device. The robot's base displaced vertically with the crane. The tool-centre-point of the robotic slave held the centre of the load.

The tele-manipulation task was simulated in the Interactive Task Simulator [40]. The slave devices and the tasks were modelled as rigid bodies in NVIDIA PhysX^{TM}, which updated at 1 kHz. A Unity 3D programme visualised the body poses 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 on a 43-inch tv screen.

The masters were two Haption Virtuose 6D devices [41], as shown in Fig. 3.4. The first Virtuose 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 Virtuose connected to the crane in rate-control. The set-point velocity for the crane was the 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.

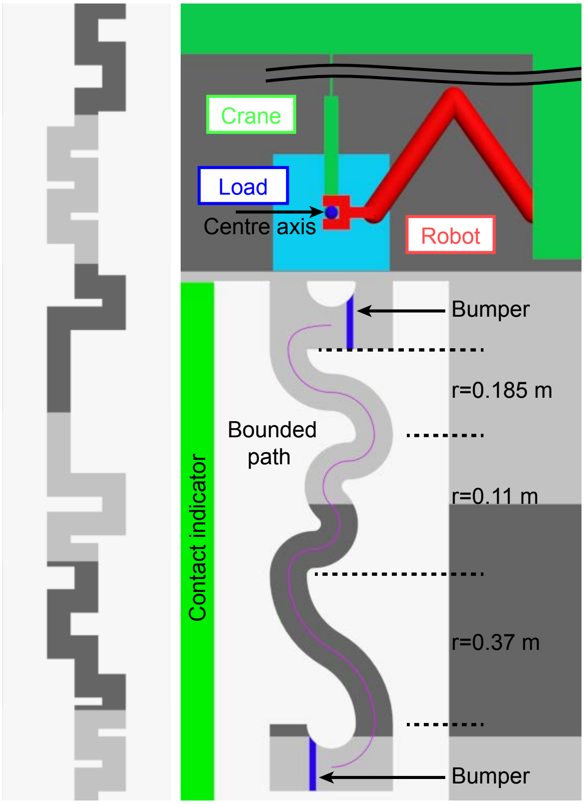

Fig. 3.3: Illustration of the experimental task. The left side shows the familiarisation part. The right side shows one experimental path. Here the small dark blue centre axis of the load had to be manoeuvred through the bounded path. Participants hit the bumper to initiate the path and its timer. At the end of the path, they hit another bumper to stop the clock. The purple centre line represents the support path, which was not visible during the experiment.

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.

A screen between co-operators prevented them from seeing each other movements, as shown in Fig 3.4. 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.

3.3.3. Task description

The experimental task consisted of manoeuvring a 0.03 m radius circle through a bounded path, as shown in Fig. 3.3. 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 [5]. Although the rotational degree of freedom for this task was not necessary, the

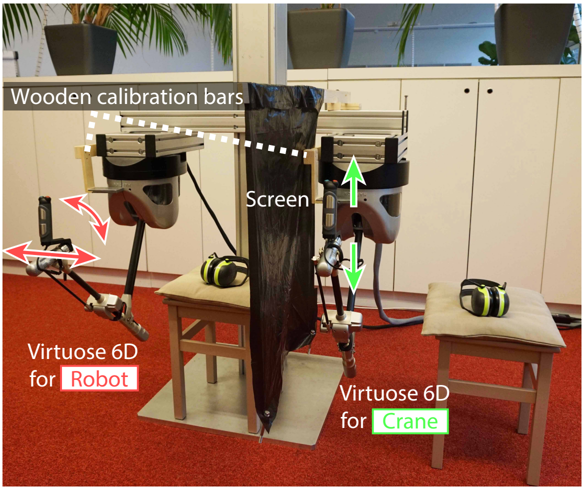

Fig. 3.4: The experimental set-up with two Haption Virtuose 6D devices. The wooden calibration bars could be shifted to define the starting position of the devices. The screen and ear caps served to prevent co-operators from seeing or hearing each other's actions. Uni-manual operators controlled one device with the joint control capabilities.

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. 3.3 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 six paths in one row, called a block. Each path in a block was different based on the variation in a Williams design. For example, one block contained paths in the order: 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 blocks were composed. These blocks were provided in a balanced order, such that no more than two sequential blocks started with the same radii. Paths and blocks were different to prevent participants from optimising their control strategy (e.g., feed-forward) to a single path.

3.3.4. Experimental design

Experimental conditions

The experiment consisted of two factors, assistance level 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 level was labelled as either 'on' (with haptic assistance) or 'off' (conventional tele-manipulation). Each assistance level was performed by all participants (within-subject design) according to a Latin square design per interface design to mitigate order bias.

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. 3.3, 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 (four blocks) 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. In such an event, the screen blanked and the task froze for 6 seconds. To boost training, participants learned after the first block that they could approximately achieve 50% reduction in the average task-completion time per block by the end of the training (based on pilot and previous experiment in chapter 2 and [19]).

Finally, participants had 24 paths, four blocks, in conventional tele-manipulation and 24 paths with haptic assistance. They were motivated to freely test each condition in the first two paths of the first block 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. 3.3, for training purposes during the first two paths. After each block, 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 feedback visually per path: elapsed time and the contact indicator colour (bar on the left). The indicator started green, as shown in Fig. 3.3, and turned red upon a critical error. The indicator could also turn orange during training blocks 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 block.

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 blocks) 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 block without critical errors (including training blocks). 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 [5].

3.3.5. 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. 3.3). 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 [42] and related to expert vs. novice performance by [43]. 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 shortest time to contact.
- 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 shortest distance to contact.
- ce: Critical errors [-], the task safety quantified by the total number of critical errors the last block (six paths).

Additionally, each participant completed a NASA-TLX questionnaire [44] 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 [45] to evaluate perceived acceptance of the interface on a 5-point Likert scale. A higher score represented a better acceptance.

3.3.6. 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 level, a mixed-design ANOVA was used for the metrics (tct, sal_L, sal_V, tim_L, tim_V, dtc). 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 subjective metric and the number of critical errors were analysed using non-parametric tests in R statistics [46]. 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 [47]. 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 [48], 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 based on the methods with the most conservative outcome: the highest p-value.

3.4. Results

The figures and Table 3.1 provide the means and 95% confidence intervals based on 15 participants/teams. Figures 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.

3.4.1. Task performance

The task-completion time results show a significant main effect for both the assistance level and interface design (Fig. 3.5 and Table 3.2). Furthermore, there is a significant interaction effect of assistance level on interface design. Table 3.1 presents the Bonferroni corrected simple effects analysis, showing that the observed differences in time for assistance level 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.

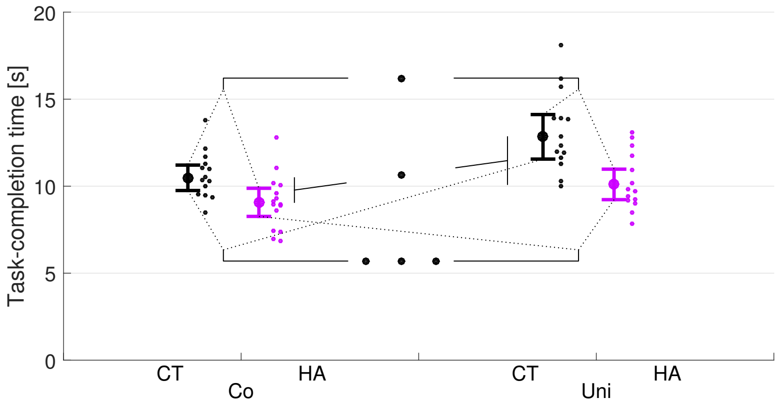

Fig. 3.5: Task-completion time to manoeuvre down the path. The dots represent the means per team/individual, while they performed the task conventionally (CT, black) or haptically assisted (HA, purple) with the co-operated (co) or uni-manual (uni) interface design.

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).

Table 3.1: Mean and 95% confidence interval (CI) results based on 15 participants/teams. The signs ↔ and ↕ in the centre column indicate a significant main effect for interface design and support level respectively. Similarly, ⤧ denotes a significant interaction. In that case, ↔ or ↕ in-between data present significant results from the simple effects Post Hoc analysis.

	Task-completion time [s]		
	Co mean (95% CI)		Uni mean (95% CI)
CT	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)
CT	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)
CT	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)
CT	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)
CT	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)
CT	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)
CT	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)

Table 3.2: ANOVA and non-parametric test results for all metric. Significant p-values are presented in boldface.

Factor	Task-completion time [s] F(1,28)	Task-completion time [s] p	Spectral arc length robot interface [-] F(1,28)	Spectral arc length robot interface [-] p	Spectral arc length crane interface [-] F(1,28)	Spectral arc length crane interface [-] p	Lateral master movement [m] F(1,28)	Lateral master movement [m] p	Vertical master movement [m] F(1,28)	Vertical master movement [m] p
F_b	7.11	**0.013**	0.40	0.534	6.12	**0.020**	8.20	**0.008**	5.01	**0.033**
F_w	66.34	<**0.001**	33.47	<**0.001**	73.57	<**0.001**	34.27	<**0.001**	0.44	0.513
$F_b * F_w$	6.79	**0.015**	4.79	**0.037**	2.23	0.147	0.01	0.943	0.01	0.916

Factor	Distance to contact [m] F(1,28)	Distance to contact [m] p	Time to contact [s] F(1,28)	Time to contact [s] p	Critical errors [-] p_{ez}	Critical errors [-] p_{wrs2}	NASA TLX p_{ez}	NASA TLX p_{wrs2}	Van der Laan usefulness scale p_{ez}	Van der Laan usefulness scale p_{wrs2}	Van der Laan satisfaction scale p_{ez}	Van der Laan satisfaction scale p_{wrs2}
F_b	0.01	0.936	8.85	**0.006**	0.108	0.434	0.506	0.818	0.510	0.982	0.611	0.918
F_w	35.83	<**0.001**	1.17	0.289	**0.005**	0.194	<**0.001**	<**0.001**	**0.001**	<**0.001**	**0.001**	<**0.001**
$F_b * F_w$	0.02	0.884	0.34	0.563	0.171[1]	0.298	0.757[1]	0.806	0.900[1]	0.848	0.560[1]	0.794

[1] For package 'ez' Version 4.4-0, only main effects, thus not the interaction, may be trusted [47].

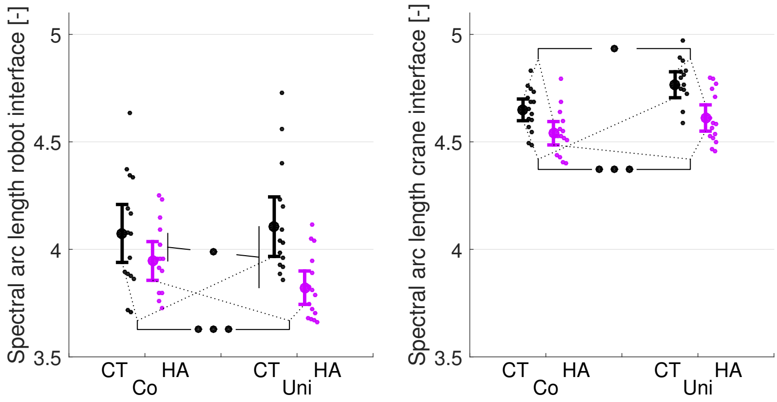

Fig. 3.6: Spectral arc length for the lateral master velocity to control the robot (left) and the vertical master velocity to control the crane (right). The dots represent the means per subtask, while operators performed the task conventionally (CT, black) or haptically assisted (HA, purple) with the co-operated (co) or uni-manual (uni) interface design.

The spectral arc length has an significant interaction effect between the assistance level and interface design for the lateral movements (Fig. 3.6 and Table 3.2). The simple effects analysis with Bonferroni corrected shows that the observed difference in interface design are not significant (p>0.200, Table 3.1). Furthermore, assistance creates no significant difference in movement smoothness for co-operators (p=0.062); however, assistance level 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 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.

3.4.2. Control activity

For control activity, Fig. 3.7 and Table 3.2 show the total movement made by the master devices. Both the total lateral (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 level 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.

3.4.3. 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. 3.8 and Table 3.2). The fifth percentile closest distance to contact only has a significant difference for the assistance level, where assistance facilitated a 0.01 m larger distance to the bounds than having no assistance.

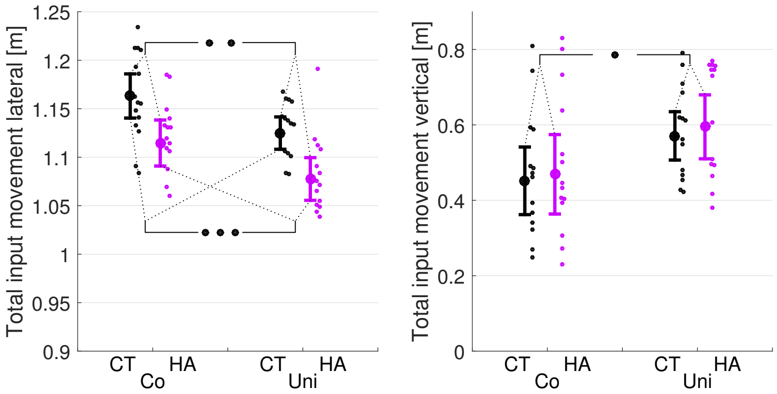

Fig. 3.7: Total master device movement for manoeuvring down the path. The left figure shows the lateral master movement to control the dexterous slave. The right figure shows the vertical master movement to control the crane. The dots represent the means per subtask, while operators performed the task conventionally (CT, black) or haptically assisted (HA, purple) with the co-operated (co) or uni-manual (uni) interface design.

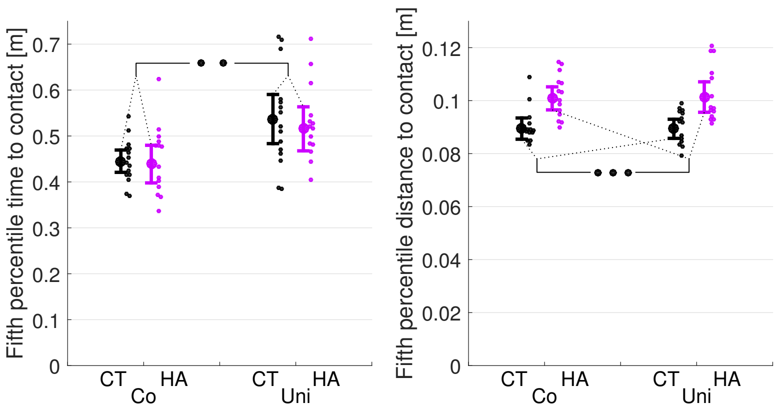

Fig. 3.8: Safety in terms of the fifth percentile shortest time (left) and distance (right) to contact. The dots represent the means per team/individual, while they performed the task conventionally (CT, black) or haptically assisted (HA, purple) with the co-operated (co) or uni-manual (uni) interface design.

The number of critical errors made in the last six paths are presented in Fig. 3.9 and Table 3.3. Although 33 critical errors occurred during conventional tele-manipulation, compared to 13 during assisted control, this is not significantly different, as the most conservative test, the sppbb, was well above 0.05 (Table 3.2).

3.4.4. Subjective workload and acceptance

The subjectively rated workload and acceptance, as presented in Fig. 3.10 and Table 3.3, has significant differences for assistance level (Table 3.2). Haptic assistance reduces workload and improves interface acceptance compared to conventional tele-manipulation.

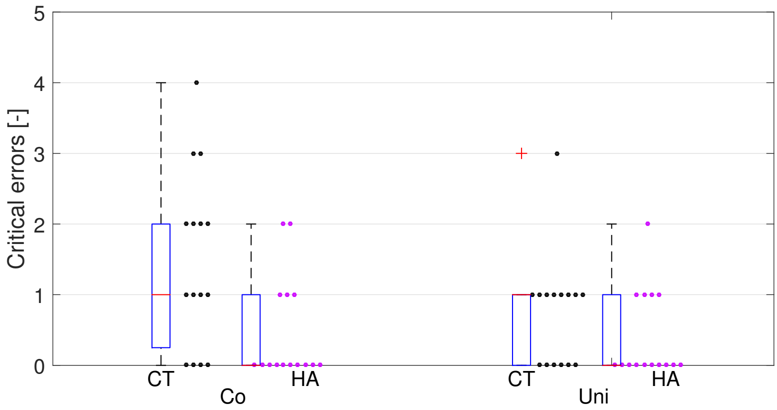

Fig. 3.9: Safety in terms of the total number of critical errors made during the last six paths in each condition. The dots represent the number of critical errors teams/individuals made, while they performed the task conventionally (CT, black) or haptically assisted (HA, purple) with the rigid and compliant slave.

Table 3.3: Median, 25th and 75th percentile results based on 15 participants/teams for the non-parametric metric.

	Critical errors [-]		
	Co median (25;75%)	Uni median (25;75%)	
CT	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%)
CT	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)
	Van der Laan usefulness scale [-]		
	Co robot median (25;75%)	Co crane median (25;75%)	uni median (25;75%)
CT	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)
	Van der Laan acceptance scale [-]		
	Co robot median (25;75%)	Co crane median (25;75%)	uni median (25;75%)
CT	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)

3.5. Discussion

3.5.1. Main effects of interface design

This chapter proposed a novel haptic assistance systems to support operators with two asymmetric subtasks, which efficacy was evaluated for a co-operated and uni-

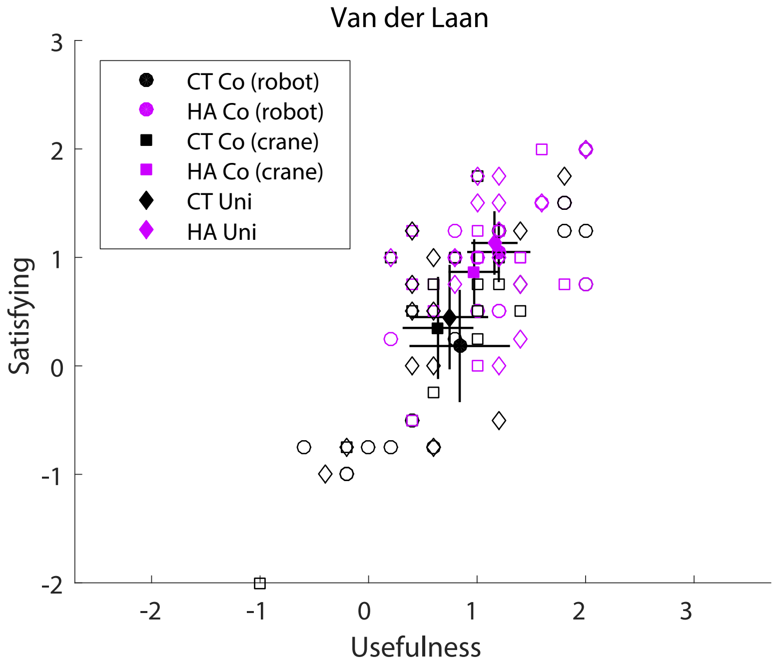

Fig. 3.10: Van der Laan usefulness and satisfaction acceptance scale. The open symbols represent the acceptance of the individuals while they performed the task conventionally (CT, black) and haptically assisted (HA, purple).

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 (chapter 2, [19]). 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 component (i.e., human input to control the crane) showed 2% less smooth movements for uni-manual operators. Both of these results resemble the outcomes in chapter 2 and [19], even though the previous study showed a greater difference (25%) for crane input. 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). Finally, no differences were observed in the interface design in the subjectively rated NASA TLX or the van de Laan acceptance scale, similar to previous results in chapter 2 and [19]. Essentially, the present results underline the conclusions from our previous study (chapter 2, [19]).

3.5.2. Effects of assistance level

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 [30, 31, 33]. 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 [14, 24, 26]. However, this holds not for all cases, as Passenberg et al. found increased effort for single-operator [49]. More relevant, Schauß et al. [31] found increased physical effort when haptically linking two operators of symmetric interactive subtasks. They suggested this may be 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. On one hand, this 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 the assistance levels.

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, 38, 39, 50]. 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 [51]. Additionally, operators found the interface with assistance more useful and satisfying than the conventional interface.

3.5.3. 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 levels. 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 levels 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 [52] and tested by Feys [53]. 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 fixed support path (the centre line of the bounded path) for all participants. 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 [25], and increased force, discomfort or even reduced performance [54]. Adapting the assistance to the individual would probably improve acceptance and performance of operators [55]. Future research should explore how to adapt the support path towards two co-operating operators.

The present experiment expressed task execution in terms of task performance, control activity and interface acceptance. 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 [56]. For robot assisted Urban Search and Rescue, teams with a good shared awareness are nine times more likely to find victims [57]. We recommend that future studies identify the level of situation awareness and analyse the effect of interface design and haptic assistance on it.

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 could do. For car driving, a very well working haptic assistance can be described by the horse metaphor [58]. 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 [59–61]. Essentially, the confederate is a second operator who co-acts with the driver in a symmetric divisible nature [18]. 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 [62–64]. 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 [62, 63], between 0 and 100% [63] or reach $\approx$ 100% [64]. 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.

3.6. Conclusion

This chapter 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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4

The Effects of Static Inaccurate Haptic Assistance Cues and Feedback Quality on Tele-manipulated Tasks

The beginning is the most important part of the work

Plato

Support forces from haptic assistance are based on measured or model data from the real world, which can be inaccurate and thus cause inaccurate assistive cues. The effect of such inaccurate cues on task performance is presently unknown and assessed in this chapter during a single-operator single-slave peg-in-hole type task in Virtual Reality. Participants (14 individuals) worked with three levels of haptic assistance, namely no assistance, accurate assistance, and inaccurate assistance. Furthermore the quality of natural haptic feedback (i.e. haptic transparency) was varied between a relative low and high quality to identify the participant's ability to detect and cope with inaccurate haptic cues. The inaccurate haptic cues were not handled differently between the haptic transparency levels. Inaccurate assistive cues deteriorated task performance during the insertion of the peg, due to its potential for jamming, but had a limited effect on the major part of the task.

This chapter is based on the publication: "Haptic Shared Control in Tele-manipulation: Effects of Inaccuracies in Guidance on Task Execution" in the IEEE Transactions on Haptics (2015) [1].

4.1. Introduction

Tele-manipulation 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. The bilateral information flow of haptic information allows humans to make use of their unique problem solving and manipulative skills in remote environments [2, 3]. Fig. 4.1 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 [4].

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 [5]. 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 [6]. 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 [5, 7, 8]. Further system oriented improvements in transparency by better haptic control architectures (e.g. [4, 6, 9]) and better hardware configurations (e.g. [4, 10]) tend to have limited additional benefit on the overall task performance [4, 8].

A promising approach to improve tele-manipulated task performance is to haptically assist the operator with forces. Haptic assistance has many experimental implementations, with various definitions, including haptic assistance to a reference position or trajectory (e.g. [11–16]) and shielding areas from entering (i.e. virtual fixtures, e.g. [17, 18]).

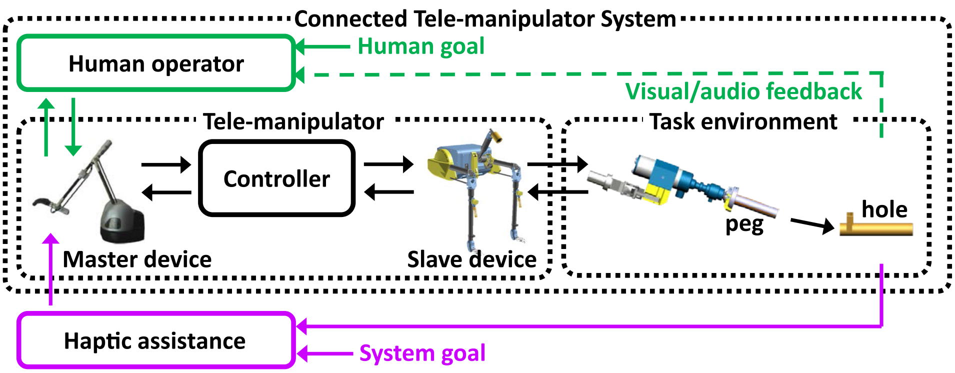

Fig. 4.1: Elements of the Connected Tele-manipulator System combined with haptic assistance. The task has the representation of a peg-in-hole task.

The current research adopts the definition of *haptic shared control*, which "allows both the human and the [assistance] system to exert forces on a control interface, of which its output (its position) remains the direct input to the controlled system [19]." Assistance forces are based on a task model, which contains information about both the remote environment and the system's goal (see Fig. 4.1).

In general, studies report positively on the effect of haptic assistance on task performance [11–18, 20–22]. Research shows that, haptic assistance supports operators to work almost on a similar performance level as in manual manipulation, while control effort is improved[15]. However, all these studies assumed that assistive forces are based on pre-generated, errorless models of the task and remote environment.

Yet in practical implementations of a haptic assistance system, the system might not have perfect knowledge of the environment. Typically the environments, tasks and components are complex, unstructured, unpredictable and, moreover, dynamic [10, 23]. This will introduce *inaccuracies* in the model on which the assistive 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 [24] 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 9 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 [25]. In case the inaccurate models are used as a basis for the haptic assistance system, the operator will be supported incorrectly as indicated in Fig. 4.2.

The effect of inaccuracies in the haptic assistance 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 [16]. Another research shows that if the assistance system is not aware of obstacles, control effort is increased due to human-assistance disagreement [26]. Also, intentionally introduced inaccuracies in the haptic assistance by not avoiding obstacles during car driving, reduced task performance compared to manual control [27]. Our previous study investigated the effect of a 7.5 mm translational inaccuracy during a 30 [mm] diameter peg-in-hole type task [28]. We showed that haptic assistance with small inaccuracies still improves overall task performance compared to conventional tele-manipulation.

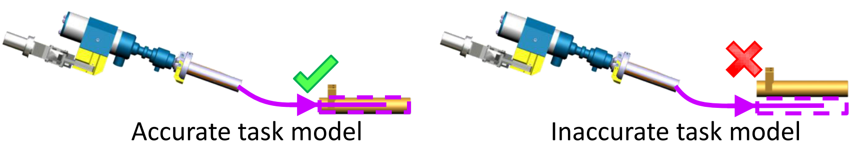

Fig. 4.2: Side view of the peg-in-hole task, showing haptic assistance (arrows) based on an accurate and inaccurate task models (dashed lines).

The goal of the current research is twofold:

The first goal is to quantify the effects of haptic assistance when it suffers from inaccuracies (with different magnitudes and direction) on operator's task performance and control effort. We will consider effects on the overall task, as well as on certain generalisable *task primitives*: Free Space Movement, Contact Transition, Constrained Translational Movement and Constrained Rotational Movement [8]. The task primitives are defined and explained in Section 4.2.3.

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 assistance.

This means that, compared to our previous study [28], 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 assistance *without* inaccuracies improves overall task execution compared to conventional tele-manipulation, as was found in previous research (e.g. [11, 14]). Additionally, the quality of natural haptic feedback (i.e., haptic transparency) will only have a limited effect on task execution [15].

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

Thirdly, 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 assistance. These hypotheses are depicted in Table 4.1.

4.2. Methods

4.2.1. 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.

4.2.2. Experimental setup

The tele-manipulated task is performed in a Virtual Reality environment. The simulation is done by the Interactive Task Simulator [29] where the slave device and

Table 4.1: The hypotheses (H1, H2 and H3) depicted in a table. Here 0, - and + mean respectively similar, degraded and improved task execution compared to the respective baseline (indicated by *).

		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	Without inaccuracies*	0	0
	With small inaccuracies	0	-
	With large inaccuracies	-	- - -

Table 4.2: properties of the tele-manipulator with high and low transparency

property	High quality	low quality
K_{trans} N/m	2000	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	2700
Max force N	35	12
Max torque Nm	3.3	1.2

task are modelled with NVIDIA PhysX^{TM} that simulates real-time rigid body dynamics and contact interaction at 1 kHz. Fig. 4.3 shows an impression of the environment and slave.

The master device is a Haption Virtuose 6D35-45 as shown in Fig. 4.4. This haptic device has a cubic workspace of 450 mm and a rotational workspace of 145° - 115° - 148°. 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 2000 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.

The Virtuose 6D35-45 connects to the (virtual) slave with a 2-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 4.2 specifies the controller parameters in more detail.

4.2.3. Task description

The experimental task is the placement of a welding tool in a tube as shown in Fig. 4.3. The welding tool has the dimensions of 440x70x125 mm (LxWxH), a tip

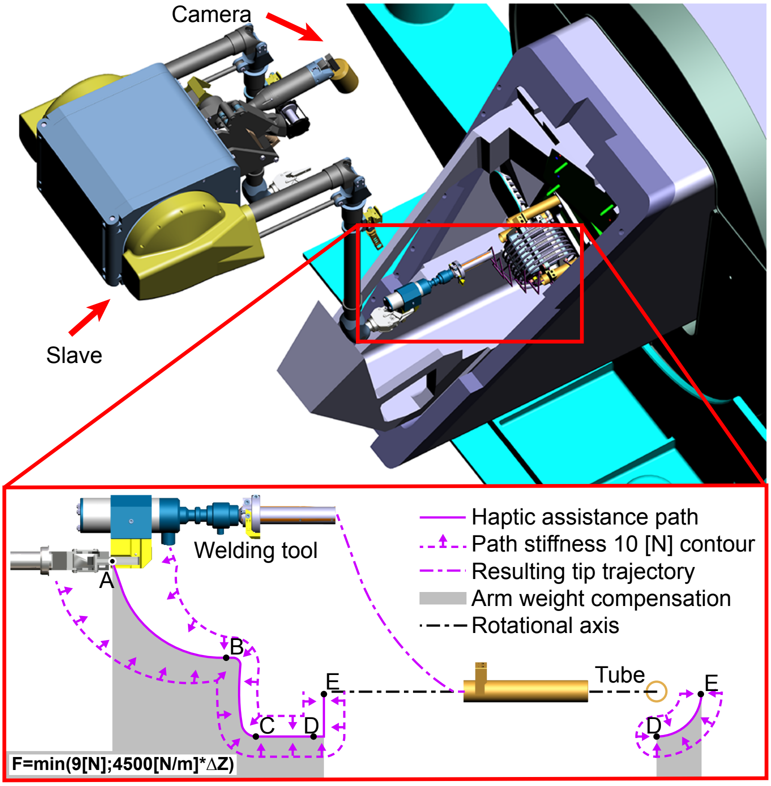

Fig. 4.3: The top part shows the (virtual) slave in the (virtual) environment. The red bordered part shows a side- and front-view of the welding tool placement task. The procedure is to follow the purple path which comprises four subsequent task primitives (as explained in Section 4.2.3): Free Space 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 [28].

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. 4.3. 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 (20°) 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 characterised by a slower, more

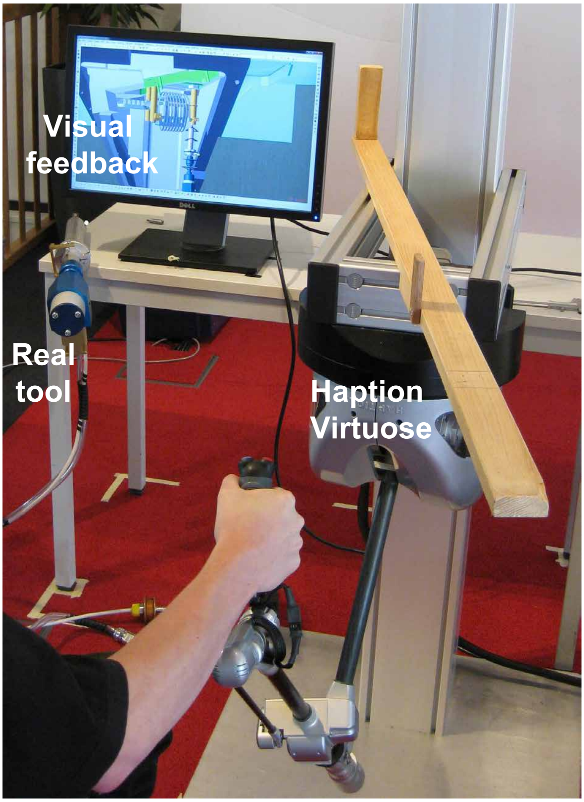

Fig. 4.4: Impression of the experimental set-up with the Haption Virtuose 6D35-45. Also shown is a wooden bar used to define the start position of the master device. Adapted from Oosterhout et al. [28].

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 characterised 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° 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 [30, 31].

4.2.4. Haptic assistance design

This research adapted and modified the proposed haptic assistance design from Boessenkool et al. [15]. The haptic assistance consists of three path segments along which the operator is assisted during the four task primitives (see Fig. 4.3). The segments consist of 23 to 43 discrete points with a defined orientation. The assistive 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 assistance design by [15] where made. Firstly 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 assist operators based on a state they would obtain considering their heading- showed no merit in a pilot study, while it had the potential to destabilise the controller in low transparency. Therefore we omitted it and based the haptic assistance on the operator's present state.

New features were added to the haptic assistance design by [15]. Haptic assistance 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 assistance 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 support path, which therefore carried about half the arm weight. In other words: operators rest their arm on the assistive forces.

To remove the interfering translational inaccuracy, the arm weight is compensated -when the tool sinks below the path- with a stiffness of 4500 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 [32].

4.2.5. Experimental design

Experimental conditions

The experiment consists of four condition being composed of two *operation modes* with two transparency levels as shown in Table 4.3. 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 4.2 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 Hz and 3.7 Hz for high and low transparency, respectively (obtained via the HapticAnalysis package [4]).

The operation modes are conventional tele-manipulation and haptic assistance. The haptic assistance paths were provided with five accuracy levels. Fig. 4.5 shows the used inaccuracies. The magnitudes are set to 7.5 mm (from the previous experiment [28]) and 17.5 mm (between the 15 mm inner and 20 mm outer radius of the tube in an attempt to parameterise it to the order of size of the task). The inaccuracies were applied randomly and in a plus (HA_7.5; HA_17.5) and minus (HA_-17.5; HA_-7.5) direction -together with assistance without inaccuracies (HA_0.0)- in the haptic assistance condition. This randomisation 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.

Table 4.3: The four experimental conditions composed from transparency and operation mode.

Operation mode	Transparency High	Transparency Low
Conventional tele-manipulation	CT_HT	CT_LT
Haptic Assistance (Accurate and -/+ inaccurate)	HA_HT_-17.5	HA_LT_-17.5
	HA_HT_-7.5	HA_LT_-7.5
	HA_HT_0.0	HA_LT_0.0
	HA_HT_7.5	HA_LT_7.5
	HA_HT_17.5	HA_LT_17.5

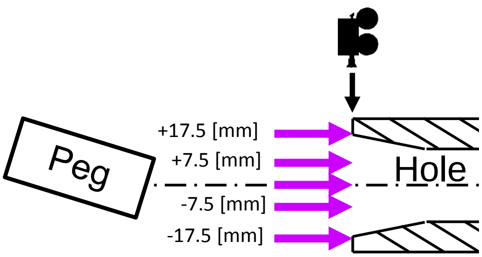

Fig. 4.5: Magnitude of the translational inaccuracy and the relation to the provided visual feedback.

The experiment contains 7 repetitions for the conventional tele-manipulation mode and 35 repetitions for the haptic assistance mode (5 accuracy levels with each 7 repetitions) in 2 transparency conditions. The order with which the four conditions were presented to the subjects was randomised to minimise the influence of order effects.

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 4.2.3.
- 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 assistance (in high transparency) until they were confident with the provided assistive forces. In addition, subjects practised at least three times before the start of each condition, where -in case of haptic assistance- they were told that the system could have some sort of inaccuracies.

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 inaccurate assimilative cues (see Fig. 4.5). This visually occluded the inaccuracy to control this potential confounding variable.

4.2.6. 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 inaccurate assistive cues.

Control effort is evaluated in terms of:

- csa: Cumulative steering angle ° 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.

4.2.7. Data Analysis

The calculated metrics were averaged over the 7 repetitions per subject, for each of the 12 conditions. To analyse the effect of haptic assistance *without* inaccuracies and transparency (first hypothesis), a two-way repeated-measures ANOVA was done with factors F_{a1} operation mode (assisted and conventional tele-manipulation) and F_{a2} transparency (high and low quality). To analyse the effect of haptic assistance *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 assistance (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 ($\alpha \leq 0.05$).

4.3. Results

Figures and tables in this section show the mean and 95% confidence interval (CI) based on 14 subjects, which each performed 7 repetitions. Significant results are denoted with '• • •', '••' and '•' for respectively $p<0.001$, $p<0.01$ and $p<0.05$ (in figures) and in boldface (in tables).

Fig. 4.6 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 assistance *without* inaccuracies (dark grey). Subjectively seen the results suggest that the haptic assisted trial has improved task performance. Fig. 4.7, presenting the task-completion time of the entire task, shows that haptic assistance *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. 4.7 shows that haptic assistance *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 HA_7.5, inaccuracies degrade

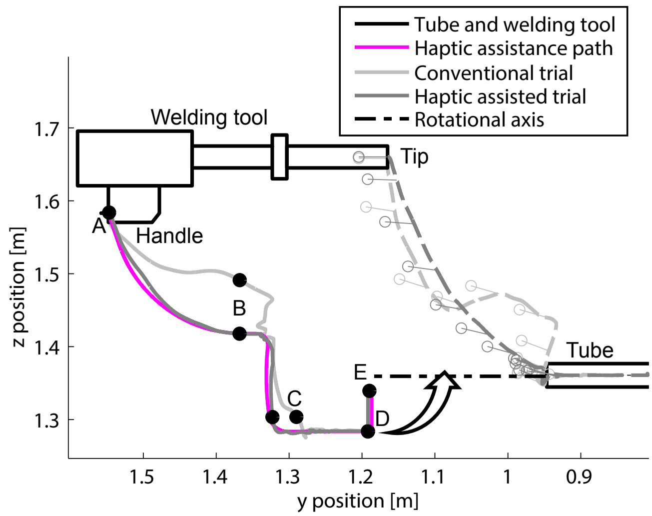

Fig. 4.6: Typical generated trajectories of the handle and tip for the peg-in-hole task, during conventional tele-manipulation (light grey) and haptic assistance without inaccuracies (dark grey) with high transparency. The trajectories for the handle (solid) comprises the four task primitives (as explained in Section 4.2.3): 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.

Table 4.4: Contrast analysis for the entire task for factor F_{b1} inaccuracy level.

	tct Entire task [s]		
HA to	Mean diff. (95% CI)	F(1,13)	p diff.
HA_-17.5	-9.25 (-13.06;-5.45)	27.61	<**0.001**
HA_-7.5	-2.50 (-3.89;-1.10)	14.86	**0.002**
HA_7.5	-0.07 (-1.26;1.11)	0.02	0.894
HA_17.5	-3.58 (-5.62;-1.54)	14.39	**0.002**

task performance (p≤0.002, see Table 4.4). 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 assistance. Therefore this section further describes the results per task primitive.

4.3.1. Effects of haptic assistance and transparency

Table 4.5 summarises the results for haptic assistance *without* inaccuracies and conventional tele-manipulation for both transparency levels. In Free Space Movement, task performance is not affected by haptic assistance or transparency (F(1,13)≤4.42, p≥0.056), while control effort is reduced by both haptic assistance and transparency (F(1,13)≥17.23, p≤0.001).

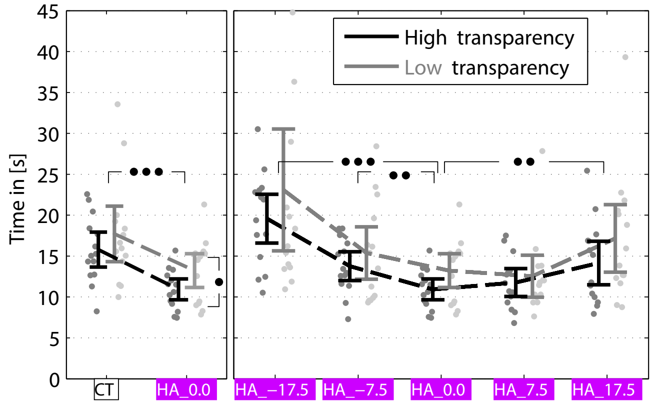

Fig. 4.7: Task-completion time for the entire task showing left Conventional Tele-manipulation (CT) and haptic assistance without inaccuracies (HA_0.0) for both transparencies. Both haptic assistance and transparency improve task performance. Right shows the effect of inaccuracy levels (-17.5; -7.5; 0; 7.5; 17.5) which is that inaccuracies degrade task performance.

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

In the Constrained Translational Movement, haptic assistance 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 assistance 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 ($F(1,13)=84.51$, $p<0.001$).

4.3.2. Effects of inaccuracies and transparency

Table 4.5 summarises the results for haptic assistance *with* inaccuracies for both transparency levels. Table 4.6 summarises the ANOVA results for the effect of haptic assistance *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 HA vs HA_-17.5 increases effort with 2.65 ° ($p=0.014$, see Table 4.7). 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 inaccurate assistive cues do not affect task performance and control effort ($p \geq 0.14$, Greenhouse-Geisser corrected), even though some participants clearly had more trouble with HA_-17.5 provided low transparency, as indicated by the large confidence interval which clearly shows in Fig. 4.8. The results show that there is no interaction between transparency and inaccuracies for both task performance and control effort ($p \geq 0.407$, Greenhouse-Geisser corrected).

During **Constrained Translational Movement**, the inaccurate assistive cues affect task execution (p<0.001, Greenhouse-Geisser corrected). The contrast analysis shows that, except for HA_7.5, inaccuracies result in decreased task execution by at least 2.43 s and 50.93 ° (p≤0.048) as shown in Table 4.7. The results give the impression of a (asymmetric) parabola as shown for task performance in Fig. 4.9. The results show that there is no interaction between transparency and inaccuracies for task performance and control effort (p≥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 Fig. 4.10 and 4.11

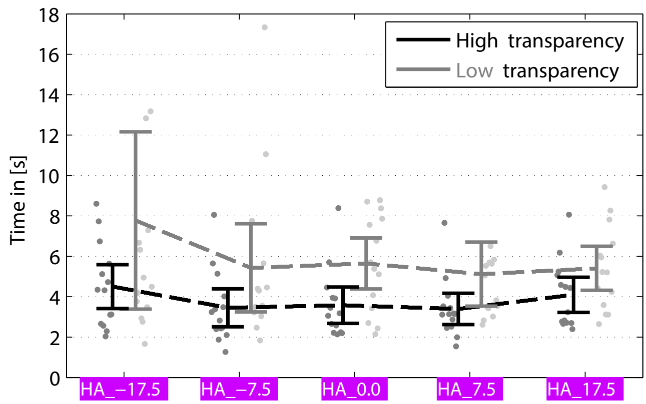

Fig. 4.8: Task-completion time for the Contact Transition showing the effect of inaccuracy levels. There is no significant difference between haptic assistance with and without inaccuracies. A higher quality transparency does not support operators to detect and cope with inaccuracies.

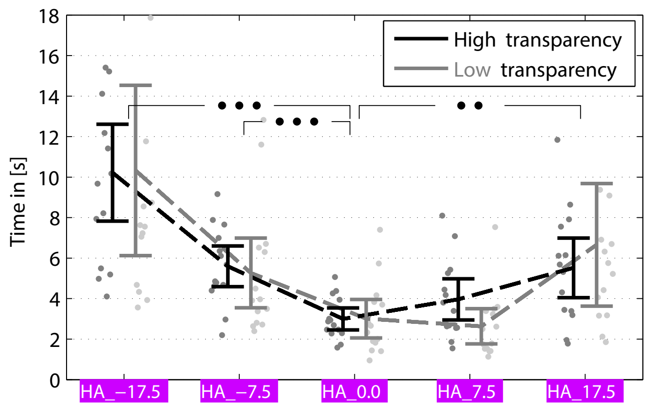

Fig. 4.9: Task-completion time for Constrained Translational Movement showing the effect of inaccuracy levels. Task performance decrees for HA_-17.5, HA_7.5 and HA_17.5. A higher quality transparency does not support operators to detect and cope with inaccurate assistive cues.

respectively. Note that for control effort (shown in Fig. 4.11) the HA_7.5 and HA_17.5 results are excluded from the analysis as will be explained in the discussion. The contrast analysis for task performance shows that HA_-17.5 requires on average 0.13 s more time than haptic assistance without inaccuracies (p=0.002) as shown in Fig. 4.10 and Table 4.7. The results show that there is no interaction between transparency and inaccuracies for task performance and control effort (p≥0.321, Greenhouse-Geisser corrected).

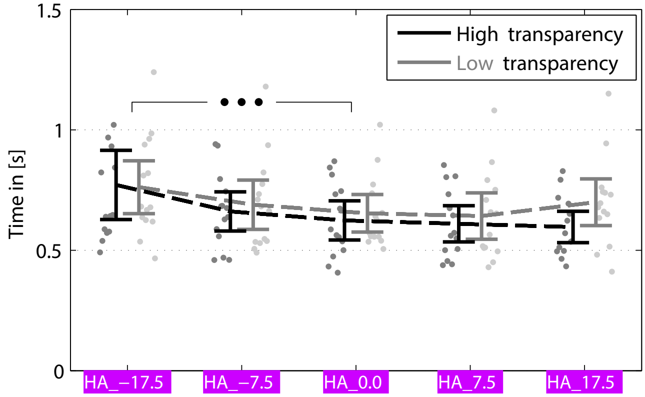

Fig. 4.10: Task-completion time for Constrained Rotational Movement showing the effect of inaccuracy levels. HA_-17.5 requires more time to complete the task. A higher quality transparency does not support operators to detect and cope with inaccurate assistive cues.

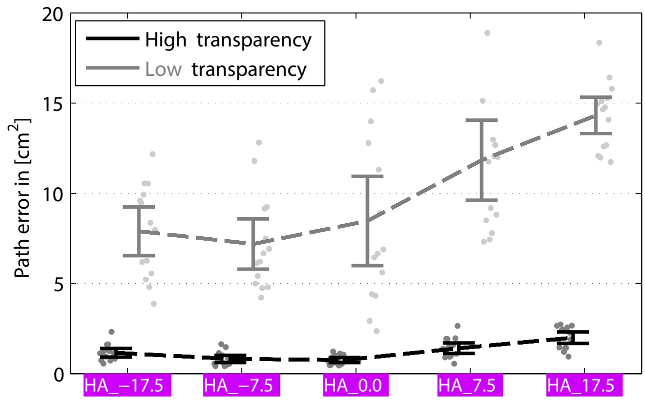

Fig. 4.11: Integrated path error for Constrained Rotational Movement showing the effect of inaccuracy levels. HA_17.5 and HA_7.5 are excluded from the analysis. The other inaccuracies do not affect control effort. A higher quality transparency does not support operators to detect and cope with inaccurate assistive cues.

Table 4.5: The mean (1.96xSD describing +/-95% CI) for task performance and control effort metrics for each of the four task primitives. The grey coloured data are excluded from the analysis as will be explained in the discussion.

	Free Space Movement		Contact Transition	
Metric	tct [s]	csa [°]	tct [s]	csa [°]
CT_HT	4.25 (0.92)	39.50 (0.92)	5.81 (0.83)	66.69 (0.83)
HA_HT_-17.5	4.08 (0.45)	27.00 (0.45)	4.50 (1.09)	43.74 (1.09)
HA_HT_-7.5	4.06 (0.60)	25.96 (0.61)	3.45 (0.94)	33.47 (0.94)
HA_HT_0.0	3.73 (0.37)	25.41 (0.37)	3.58 (0.90)	37.07 (0.90)
HA_HT_7.5	3.80 (0.49)	26.29 (0.49)	3.40 (0.78)	35.95 (0.77)
HA_HT_17.5	3.94 (0.72)	26.20 (0.72)	4.10 (0.87)	40.65 (0.87)
CT_LT	4.23 (0.71)	43.66 (0.71)	9.74 (2.72)	125.39 (2.72)
HA_LT_-17.5	4.22 (0.54)	36.50 (0.53)	7.77 (4.39)	92.48 (4.39)
HA_LT_-7.5	3.99 (0.52)	32.96 (0.52)	5.43 (2.18)	62.85 (2.19)
HA_LT_0.0	3.92 (0.43)	32.79 (0.43)	5.64 (1.27)	64.85 (1.26)
HA_LT_7.5	4.14 (0.59)	32.62 (0.58)	5.12 (1.59)	57.36 (1.59)
HA_LT_17.5	4.40 (0.77)	34.44 (0.77)	5.41 (1.09)	61.16 (1.09)

	Constrained Translation Movement		Constrained Rotational Movement	
Metric	tct [s]	csa [°]	tct [s]	err_{int} [cm^2]
CT_HT	5.06 (1.36)	93.89 (1.36)	0.66 (0.08)	0.87 (0.08)
HA_HT_-17.5	10.22 (2.39)	184.82 (2.39)	0.77 (0.15)	1.16 (0.15)
HA_HT_-7.5	5.59 (1.01)	92.98 (1.01)	0.66 (0.08)	0.82 (0.08)
HA_HT_0.0	3.00 (0.55)	51.91 (0.55)	0.62 (0.09)	0.75 (0.08)
HA_HT_7.5	3.97 (1.02)	57.38 (1.02)	0.61 (0.08)	1.41 (0.08)
HA_HT_17.5	5.52 (1.47)	81.04 (1.48)	0.60 (0.07)	1.99 (0.07)
CT_LT	3.14 (0.76)	64.50 (0.75)	0.60 (0.07)	9.04 (0.07)
HA_LT_-17.5	10.33 (4.21)	198.03 (4.21)	0.76 (0.11)	7.89 (0.11)
HA_LT_-7.5	5.27 (1.72)	106.05 (1.72)	0.69 (0.10)	7.18 (0.11)
HA_LT_0.0	3.01 (0.95)	45.25 (0.95)	0.65 (0.08)	8.46 (0.07)
HA_LT_7.5	2.63 (0.87)	34.88 (0.87)	0.64 (0.10)	11.84 (0.09)
HA_LT_17.5	6.66 (3.03)	131.01 (3.03)	0.70 (0.10)	14.32 (0.09)

4.4. Discussion

The results for the entire task show that haptic assistance *without* inaccuracies improves task-completion time compared to conventional tele-manipulation, as also found by most studies on haptic assistance [11–18, 20–22]. The results also show that improved transparency decreased task-completion time in, while [4, 8] found no effect. For haptic assistance *with* inaccuracies, the benefits of assistance decrease especially for the large inaccuracies. Interestingly, the direction of inaccuracies seems to influence the effect: task performance decrease is larger for HA_-17.5 and HA_-7.5 compared to the HA_17.5 and HA_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 assistance. To better understand what

Table 4.6: 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}). The contrast analysis, for ANOVA results with a significant main effect, can be found in Table 4.7.

	Free Space Movement		Contact Transition	
Performance	tct [s]		tct [s]	
F_{b1} (Inac.)	F(2.2,28.1)=1.40	0.263[1]	F(1.7,21.7)=2.22	0.140[1]
F_{b1}*F_{b2}	F(4,52)=1.26	0.297	F(1.6,20.4)=0.65	0.498[1]
Control effort	csa [°]		csa [°]	
F_{b1} (Inac.)	F(4,52)=4.65	**0.003**	F(1.7,21.8)=1.83	0.188[1]
F_{b1}*F_{b2}	F(4,52)=1.33	0.271	F(1.6,20.1)=0.87	0.407[1]

	Constrained Translation Movement		Constrained Rotation Movement	
Performance	tct [s]		tct [s]	
F_{b1} (Inac.)	F(1.8,23.8)=18.14	<**0.001**[1]	F(2.0,25.9)=10.85	<**0.001**[1]
F_{b1}*F_{b2}	F(2.3,29.8)=0.85	0.452[1]	F(1.7,21.5)=0.82	0.434[1]
Control effort	csa [°]		err_{int} [cm^2]	
F_{b1} (Inac.)	F(1.9,25.2)=11.27	<**0.001**[1]	F(1.3,16.5)=0.86	0.394[1,2]
F_{b1}*F_{b2}	F(1.9,25.0)=1.72	0.199[1]	F(1.4,18.6)=1.14	0.321[1,2]

[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, see discussion.

Table 4.7: Contrast analysis for F_{b1} inaccuracy level for task primitives that had a significant main effect.

	csa Free space [°]		
HA to	Mean diff. (95% CI)	F(1,13)	p diff.
HA_-17.5	-2.65 (-4.66;-0.65)	8.16	**0.014**
HA_-7.5	-0.36 (-1.66;0.938)	0.36	0.560
HA_7.5	-0.36 (-1.44;0.73)	0.50	0.494
HA_17.5	-1.22 (-2.49;0.5)	4.30	0.058
	tct Constrained translation [s]		
HA to	Mean diff. (95% CI)	F(1,13)	p diff.
HA_-17.5	-7.27 (-10.05;-4.50)	31.90	<**0.001**
HA_-7.5	-2.43 (-3.45;-1.40)	26.24	<**0.001**
HA_7.5	-0.30 (-0.97;0.37)	0.91	0.357
HA_17.5	-3.08 (-4.80;-1.37)	15.08	**0.002**
	csa Constrained translation [°]		
HA to	Mean diff. (95% CI)	F(1,13)	p diff.
HA_-17.5	-142.84 (-209.84;-75.85)	21.22	<**0.001**
HA_-7.5	-50.93 (-79.81;-22.05)	14.51	**0.002**
HA_7.5	2.45 (-13.61;18.52)	0.11	0.747
HA_17.5	-57.44 (-114.16;-0.73)	4.79	**0.048**
	tct Constrained rotation [s]		
HA to	Mean diff. (95% CI)	F(1,13)	p diff.
HA_-17.5	-0.13 (-0.20;-0.06)	14.62	**0.002**
HA_-7.5	-0.04 (-0.08;0.01)	3.60	0.080
HA_7.5	0.01 (-0.01;0.04)	1.28	0.279
HA_17.5	-0.01 (-0.04;0.02)	0.62	0.446

task elements contribute to the overall task effects described above, and to be able to generalise and compare with other studies, we subdivided the task in four task primitives [8], and the effects of the experimental conditions on each task primitive will be discussed in the next section.

4.4.1. Effects of haptic assistance and transparency

The effect of haptic assistance *without* inaccuracies and transparency on task performance and control effort shows up differently among the four task primitives. Haptic assistance improves task execution (combined task performance and control effort) during Contact Transition and Constrained Translational Movement tasks. For Free Space Movement, haptic assistance 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 assistance to improve task execution for **Free Space Movement**, assistance only improved control effort (20-30% compared to conventional tele-manipulation). For a similar task in a maze, [26] found a task performance improvement of 30%, while control effort remained unaffected. Boessenkool et al. [15] found a 20-25% reduction in time and a 38-56% reduction in control effort due to haptic assistance in their bolt-and-spanner task.

An explanation for this difference with [15, 26] could be that operators chose a different path during conventional tele-manipulation than the assisted 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. 4.3) this could reduce task-completion time by roughly 7% 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 [15, 26] 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 assistance 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 [33].

For the task primitive **Contact Transition** task execution improves by 20-50% due to haptic assistance compared to conventional tele-manipulation. The reduction in task-completion time (20-40%) agrees with the approximate 32% reduction in earlier research [15]. 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 unassisted 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%) and control effort (43-47%) during Contact Transition, against our expectations. Previous work in our group [4, 8] 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 assistance without inaccuracies improves task performance up to 40% and control effort up to 44% compared to conventional tele-manipulation. This is in agreement with previous research which found reduced contact forces at the remote site [16] and a 42-52% improved task-completion time [15].

Interestingly, low transparency improves task performance with 38% 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 [4]. 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 assistance without inaccuracies does not improve task execution. This is in agreement with previous work [15]. We did however hypothesise improvements as the assistance 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 [8]. 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 assistance. 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%), compared to the low transparency conditions. This suggests that, in this task primitive, operators benefit more from any transparency than from haptic assistance, as assistance did not improve control effort in the low transparency condition.

4.4.2. Effects of inaccuracies

The effect of haptic assistance *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 assistance.

During **Free Space Movement** haptic assistance with inaccuracies degrades control effort by 6-11% for HA_-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 assistance condition were randomised to prevent operators from predicting the size of the inaccuracy.

Haptic assistance with inaccuracies during **Contact Transition** does not affect task execution, which is in contrast to the hypotheses. Yet the large confidence interval of HA_-17.5 under low transparency suggests that this condition was more troublesome. For this HA_-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 assistance 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 assistance gets larger. This originates from the task's potential to jam, which is makes it especially vulnerable to forces tangential to the insertion direction, as the forces due to inaccuracies in the assistance do. Interestingly, though, the effect seems to be larger for the HA_-17.5 and HA_-7.5 compared to the HA_17.5 and HA_7.5, as found for the entire task. Task execution degrades similarly for HA_-7.5, HA_17.5 with 75-134%, while tasks execution for HA_-17.5 degrades with 340-438%. 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. 4.3) 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 assistance with inaccuracies increases task-completion time with 16-24% for HA_-17.5, while HA_17.5 is not affected. This might be explained by the fact that during HA_-17.5 the haptic assistance applies a downward force on the operator hand, therefore counteracting the rotation and decreasing task performance. For HA_17.5 the inverse is observed; the assistive force acts in the direction of movement.

4.4.3. Effects of transparency

The results indicate that haptic transparency does not affect the operator's ability to detect and respond to inaccuracies in the haptic assistance. This could be caused by the simultaneous presentation of assistance and contact forces to the operator. According to Powell et al. [34] our haptic assistance 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 assistive 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.

4.4.4. 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 4500 N/m stiffness) when the tool sinks below the path as shown in Fig. 4.3. 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 HA_17.5 and HA_7.5, while not for the HA_-17.5 and HA_-7.5. By analysing the raw data, we found that, with low transparency, the compensation force pushed the master position upward to roughly the haptic assistance path. This is also the equilibrium in path and tele-manipulator stiffness (4500+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 assistance 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 assistance (also referred to as the level of haptic authority [19, 22]). Using a low stiffness haptic assistance lessens the effect of an inaccuracy (operators can easily overrule the assistive forces) but also provides less clear assistive forces. Increasing the stiffness makes haptic assistance act more like automation in which case small inaccuracies/obstacles will cause increased execution time [12, 26] and increased control effort [26]. Literature suggests to adapt control authority depending on the task, the operator's intention or the criticality of the task [22, 26]. Additionally one can adjust the authority based on accuracy of the assistance's 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 assistance 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 [28] 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 [35]. 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 [29] and that jamming effects appear realistic [36]. Furthermore our results on haptic assistance *without* inaccuracies and transparency closely resemble those of previous research (like e.g. [14, 15, 26]) or can be explained by research (like e.g. benefits of a low or high transparency [4, 33]). 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 assistance system is possible despite small errors in the model on which the assistive forces are based. Haptic assistance 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 assistance 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.

4.5. Conclusion

This chapter investigated how inaccuracies in the model on which haptic assistance 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 assistance 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 assistance *without* inaccuracies as well as by increasing haptic transparency.

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

- 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 assistance, neither during the entire task nor during any of the task primitives.

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5

The Effects of Slave Compliance and Haptic Assistance on Co-operated Tele-manipulated Tasks

I can calculate the motion of heavenly bodies,
but not the madness of people

Isaac Newton

Chapter 3 showed that haptic assistance allowed co-operators to perform tasks faster than without assistance. However, the main underlying assumption was the availability of perfect knowledge of the task and environment. Realistically, moving heavy loads causes dynamic deflections in the dexterous slave due to its compliance. Such deflections cannot be measured and result in dynamic inaccurate assistive cues. It is hypothesised that slave compliance degrades task execution with respect to a theoretical rigid slave. Furthermore, it is hypothesised that, for the compliance slave, dynamic inaccurate assistive cues do not improve task execution. Co-operators (12 pairs) mounted a heavy load via a crane and a dexterous slave with and without assistance. When the dexterous slave was compliant, operators had to perform slower compared to the rigid slave, while they worked equally safe. Haptic assistance allowed the operators to work faster and safer, independently of the slave compliance and the resulting dynamic inaccurate cues.

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5.1. Introduction

Future fusion plants require remote maintenance through tele-manipulation [1, 2]. Many components from these plants weigh more than the typical 15-25 kg lifting capacity of tele-manipulators [3, 4]. Such heavy loads include tools [5], mirror modules [6–8] and shielding modules [1, 3, 9]. These loads require a crane to support the weight, and a dexterous slave to provide accurate sideways positioning [1], as shown in Fig. 5.1. Industrial practice prescribes two operators to handle these asymmetric subtasks: one operator controls the crane via a joystick in rate control [2] and another controls the dexterous slave via a tele-manipulator in position control. In this division of roles, each operator has their own asymmetric (sub)task that must be coordinated precisely with the other, which is defined as co-operation [10, 11]. Putatively, a single operator could control the two subtasks via a hybrid interface. Such a single operator requires 23 times longer (tele-manipulated with respect to hands-on) to complete a task [12]. A similar task controlled by a pair of co-operating operators increases performance by about 20% [11, 13].

Regardless of the improved task performance for the co-operated interface design with respect to the individual approach, tele-manipulation is challenging and an activity for which operators might benefit from a support system. A promising support approach relies on haptic assistance, which essentially informs the human operator (via forces) on the best and safest possible action according to an intelligent automated system. This improves task performance during single-operator single-slave tasks (e.g. [14–24]), and two operator tasks (e.g. [13, 25–28]). Frequently, however, laboratory studies can optimise the assistance system to the

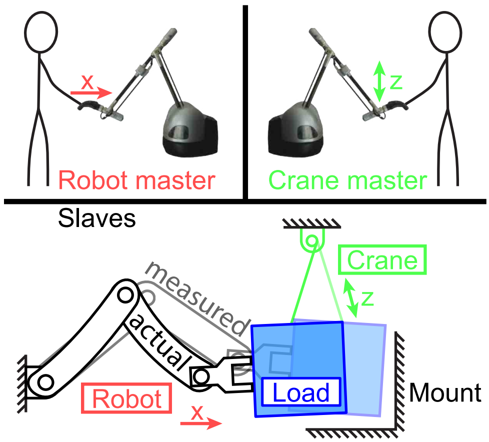

Fig. 5.1: Impression of a heavy load handling task with a crane and a dexterous slave. Top left: the robot operator controls the lateral motion of the load. In this case, the operator makes a movement in the x direction. Top right: the crane operator controls the vertical motion of the load. Lower: The robotic slave (red), the crane (green) and the load (blue) in the task environment. The robotic slave cannot be made of rigid bodies, which implies that the mechanical structure deflects under the forces on it. The joint sensors cannot measure this deflection and register a different position (light blue) from the actual position (dark blue).

experimental task and factor in all kinds of anomalies. Realistically, not all system properties can be measured or modelled perfectly, such as mechanical deflection in the tele-manipulator due to heavy load handling.

Heavy loads, and their manipulators, have the fundamental problem they cannot be made rigid enough to ignore static and dynamic deflections [29]. In essence, mechanical structures are compliant and deflect statically and dynamically due to a weight [29–34] or the operator's input [35–37]. For example, the Mascot 4 tele-manipulator deflects 10 mm at 12 kg (maximum continuous load) [38, 39]. Similarly, the SNS Telerob EMSM-2B tele-manipulator deflects 70-110 mm at 25-45 kg (maximum continuous and peak load) [40, 41]. The issue with such deflections is that they bypass the tele-manipulator's sensors [34, 42] as illustrated in Fig. 5.1. Even an advanced real-time model, of a system that deflects 80 mm from its kinematic model, still has a (static) mismatch of about 5 mm [42]. Realistically, inaccuracies can originate from any compliance in mechanical structures involved in the task. Nevertheless, it is assumed that compliance in the dexterous slave provides a dominant effect while other compliances can be ignored, as explained in the discussion.

The inability to measure dynamic deflections implies that the assistance system has inaccurate information, which results in inaccurate assistive cues. The effects of such inaccurate cues on operator control behaviour are presently unknown. Therefore, this chapter aims to quantify the effects of slave compliance and haptic assistance on operator control behaviour.

We hypothesise that slave compliance forces operators to move more slowly whilst having a higher control activity with respect to a theoretical rigid slave, especially for in-contact tasks. For haptic assistance, we hypothesise that task performance improves with equal or reduced control activity for the rigid slave compared to having no assistance. Such benefits of assistance are not hypothesised for the compliant slave, in particular not during in-contact tasks.

To investigate these hypotheses we designed an experimental setup to cooperatively interact in a virtual planar environment. The operators used a haptic manipulator to either control a dexterous slave or a crane. Both remote devices were connected to a heavy load that needed to be moved and mounted, with and without haptic assistance. The dexterous slave could be rigid or compliant.

5.2. Methods

5.2.1. Participants

Twenty-six right-handed persons (two of which were female) volunteered for this experiment without receiving a financial compensation. Participants had no experience with the task and formed 13 impromptu teams. They were between ages 19 and 38 years. The experiment followed the guidelines of the Human Research Ethics Committee of Delft University of Technology and all participants gave their informed consent.

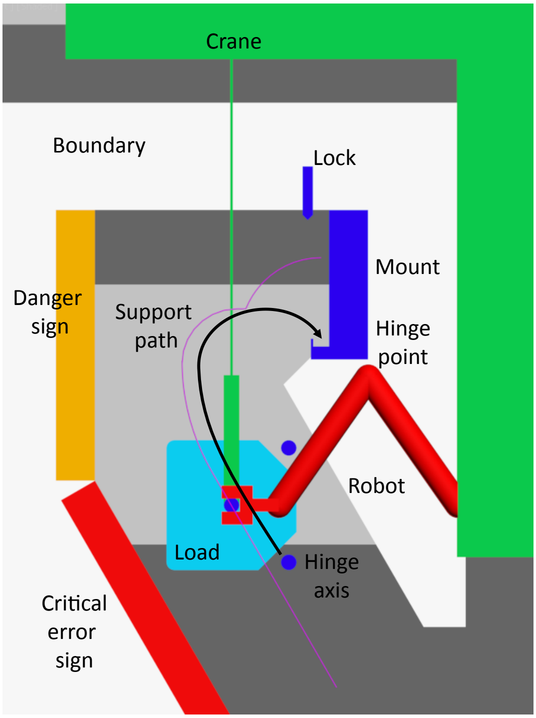

Fig. 5.2: The experimental mounting task consisted of three phases. First, operators performed a Free Space Movement between the boundaries. Then, operators made a Contact Transition to make the hinge axis meet its hinge point. For this phase, operators tilted the load about 30°. Finally, operators completed a Constrained Rotational Movement to rotate the load upright. Once upright, the blue lock pin engaged the load. Contact with the boundaries was not allowed in any phase and would trigger a critical error, which showed by a red sign on the contacted boundary. Nearly contacted bounds turned orange to indicate a near critical event.

5.2.2. Experimental setup

The mounting task was simulated in virtual reality with the Interactive Task Simulator [43]. The slave devices were a crane and a robotic slave as shown in Fig. 5.2. The crane consisted of a cable with a constant length (20 m) with simulated hoisting dynamics (1 Hz second order low-pass Butterworth filter). The crane lowered and raised the load. The robotic slave was a planar, three degrees of freedom device. The robot's base displaced vertically with the crane. Its tool-centre-point was at the centre of rotation of the load.

The slave devices were visualised with Unity 3D on a 43-inch TV screen. Co-operators received a camera view of the dexterous slave holding the load with approximately one meter of space above and below. The camera view moved up and down with the crane movement.

The master devices were two Haption Virtuose 6D devices [44], one for each operator, as shown in Fig. 5.3. The first Virtuose controlled the lateral and rotational motion of the robotic slave via a position-error controller, rendering force feedback

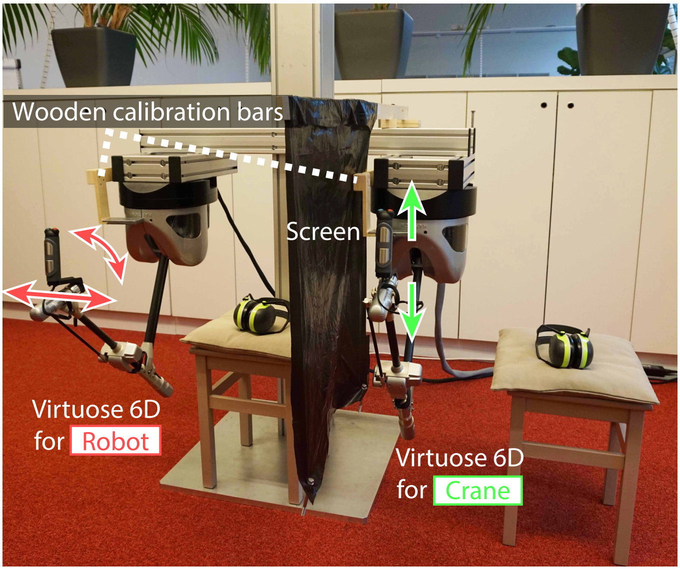

Fig. 5.3: Two Haption Virtuose 6D devices control the robotic slave and crane. The retractable wooden bars defined the starting position of the devices. The screen and ear caps served to exclude potential visual and auditory communication from influencing operator control behaviour. Adapted from Oosterhout et al. [13].

to the operator at 1 kHz. Its lateral stiffness and damping were 2000 N/m and 10 Ns/m respectively, with a maximum of 30 N. The in-plane rotational stiffness and damping were 20 Nm/rad and 0.05 Nms/rad with a maximum of 3 Nm. The second Virtuose's vertical motion provided the set-point velocity to rate-control the crane. The Virtuose itself fed back a force to a zero vertical offset with a 50 N/m spring and a 0.01 Ns/m damper. An additional stiffness (700 N/m) and damping (0.1 Ns/m), till max 3 N, made the centre tangible.

Unused translational degrees of freedom on both Virtuose devices were constrained by presenting 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.

A screen separated the co-operators, as shown in Fig 5.3, and prevented 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.

5.2.3. Task description

Co-operators had to mount a 0.5 m square load with a weight of 50 kg and inertia of 0.9 kg/m^2. The mounting procedure was subdivided into three phases, or fundamental subtasks, which allows detailed analysis and provides a better comparison with other studies [45]. First, operators manoeuvred the load through a bounded path to the mounting place. Near the end they tilted the load about 30°.

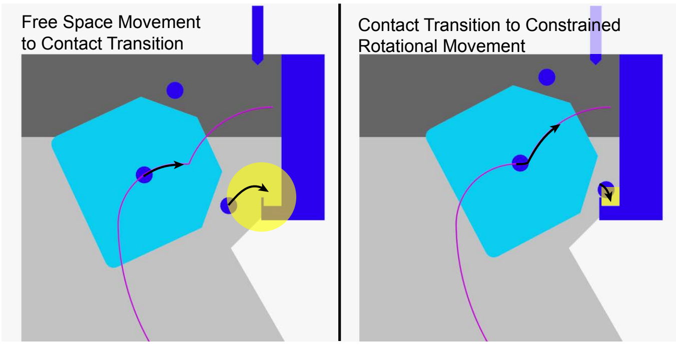

Fig. 5.4: The transitions between the three fundamental subtasks visualised in the overall mounting task. The left shows that the Contact Transition started when the hinge axis enters the yellow translucent circle for the first time (r=0.12 around the hinge point). The right shows that the Constrained Rotational Movement starts when the hinge axis entered, and stayed inside, the yellow translucent box.

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As touching the boundaries was not allowed, there were no external forces on the load, meaning that this was a Free-Space Movement [45]. Second, the load had to contact the mount: a Contact Transition [45]. Finally, operators placed and held the hinge axis in the hinge point while they moved the load upwards and turned it straight again. This was a Constrained Rotational Movement [45]. Once straight, an automatic system moved the lock pin down, fixing the load. The transitions between the fundamental subtasks are illustrated in Fig. 5.4. An example of a similar mounting task, proposed for fusion plant maintenance, can be found in e.g. [9].

The mounting location changed between trials. It could appear on the top right, like in Fig 5.2, or mirrored along the vertical and/or horizontal axis. This presented a top left, lower right and lower left mounting location. These were provided in a balanced order such that no subsequent locations were the same and each appeared twice in a sequence of 8 trials. This approach prevented operators from optimising their control strategy (by e.g. feed-forward) to a single mount procedure.

5.2.4. Experimental design

Experimental conditions

The experimental design consisted of two factors, assistance level and compliance level, each of which had two conditions. The assistance level could be either 'on' (with haptic assistance) or 'off' (conventional tele-manipulation). The compliance level was either rigid (no compliance) or compliant. Combined, these levels resulted in four conditions, which were performed by all co-operators according to a Latin square design to mitigate order bias.

Compliance design

Slave compliance was simulated in the task environment. As there exist no generic models to simulate compliance, structure dynamics were captured in a linear second order system model. To enable the operator to easily excite the structure's

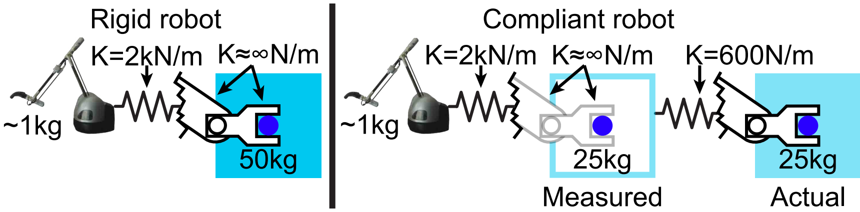

Fig. 5.5: Illustration of the simulated compliance modelling for the translational degree of freedom.

dynamics, while having limited control over it, the natural frequency was modelled below the natural frequency of the tele-manipulator control system. The task and control systems had the following proximate natural frequencies:

$$\omega_{linear} = \sqrt{k/m} = \sqrt{2000/50} = 6.3 rad/s \Rightarrow 1.0 Hz$$

$$\omega_{rotational} = \sqrt{k/I} = \sqrt{20/0.9} = 4.7 rad/s \Rightarrow 0.8 Hz$$

$$\omega_{pendulum} = \sqrt{g/l} = \sqrt{9.81/20} = 1.4 rad/s \Rightarrow 0.1 Hz$$

The system dynamics in the second order system consisted of two coupled objects of 25 kg and 0.45 kg/m^2 (half the load) via a 600 N/m and a 10 Nm/rad spring with zero damping, as illustrated in Fig. 5.5. Only one of the objects, the *actual load*, was visible to the operators. The other object, the *measured load*, was invisible and the slave of the tele-manipulator system, as shown in Fig. 5.1 and Fig. 5.5.

Haptic assistance design

The assistance system haptically links the co-operators through the joint task. Therefore it had one task definition in the form of a path, as shown by the purple line in Fig. 5.2. The system predicted the load's state with a look-ahead controller [14, 46] of 0.4 seconds, based on the load's heading. There it calculated the shortest vector of the load to the path in global coordinates as a measure of the desired heading. The systems split this heading into a vertical and horizontal component for the crane and robot interfaces respectively. Finally, it sent these components to their respective interfaces as intuitive tangible cues. The robot operator received sideways force based on a 400 N/m (and 4 Nm/rad) spring towards the path (orientation). The crane operator received vertical force feedback by shifting the neutral position of the joystick interface. These basics were explained in more detail in chapter 3. The present study extends this assistance system with two additions.

Firstly, the assistance provided a snapping force and torque to keep the axis in its hinge point during the Constrained Rotational Movement. The snapping force and torque were set to 3 N and 0.15 Nm respectively.

Secondly, the assistance had stiffness feedback, on top of force feedback, for the crane operator during the Constrained Rotational Movement. Stiffness feedback helped operators to stop hoisting in a timely manner by making the narrow margin (only 0.025 m with the upper or lower bound) more tangible. It did this by multiplying the joysticks' stiffness with the actual distance, not the predicted distance from the look-ahead controller, in millimetres towards the path. Additionally, this was multiplied by a factor of 1, from the start of the rotation, up till 4, at the end of the rotation. This applied to both the 100 N/m and 700 N/m spring on the joystick, while the multipliers were caped at 10 and 2 respectively to keep the total stiffness at a stable limit. Similar stiffness and force feedback implementations were used in, for example [24, 47–49].

Experimental protocol

Participants had eight familiarisation trials in the compliant condition without haptic assistance. The familiarisation trials aimed not only at getting the operators acquainted with the overall task, but also with each interface and its corresponding subtask. Therefore, co-operators switched roles after the first four trials. They attained their permanent roles randomly after the familiarisation trials.

Before the experiment, each participant received written and spoken instructions to mount the load, as explained in section 5.2.3, as fast as possible, while doing this gently and without hitting the boundary. Completing this gently meant to make each new contact with the mount soft. By hitting the mount too hard or hitting the boundaries they made a critical error, after which they still had to complete the task as fast as possible.

After the instructions, operators performed 24 training trials (three blocks of eight trials). Finally, operators performed the four conditions, each of which had two blocks of eight trials. After each block participants had a one-minute break. Participants were motivated to freely test each condition in the first two paths of the first block 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 by the purple line in Fig. 5.2, for training purposes during the first two paths.

Participants received feedback on their performance. They saw their critical error instantaneously: the screen blanked for 6 second and the part of the boundary they contacted became red (see Fig. 5.2). Sections they approached closer than 0.01 m, turned orange (only during familiarisation and training). After each trial, they saw the task-completion time.

A competition motivated participants to move at a fast pace, whilst upholding safety. The team with the fastest average task-completion time would win €10 per participant. Notably, each critical error added six seconds to a trial, and training blocks were excluded. Teams were disqualified when five trials per block (including training blocks) contained at least one critical error. Disqualification occurred once. The experiment for this pair of operators was discontinued and the data replaced by measurements from a new pair. The competition encouraged a realistic tele-manipulation speed-accuracy trade-off. During real tele-manipulation, operators must minimise task-completion time while upholding safety and reliability that otherwise might result in expensive downtime [1].

5.2.5. Data acquisition & metrics

Force, position and velocity data were recorded for the master, 'rigid' slave, 'compliant' slave and load at 1 kHz. This data was down-sampled to 100 Hz and served to evaluate task performance, control activity and task safety as listed below.

- tct: Task-completion time [s], for performance measures as the time in seconds to complete the task.
- sal: Spectral arc length [-], for performance expressed by quantifying the smoothness of movement for the lateral (robot, sal_L) or vertical (crane, sal_v) Virtuose motion. It measures the arc length of the amplitude and frequency-normalised Fourier magnitude spectrum of the speed profile [50]. Smooth vs. un-smooth movements relates to expert vs. novice performance [51].
- tim: Total input movement [m], for control activity represented as the total path length that the operator moved with the Virtuose in either the lateral (robot, tim_L) or vertical (crane, tim_v) direction.
- ce: Critical errors [-], for safety expressed as the number of critical errors made during the last block (eight trials).
- ttc: Shortest time to contact [s], for safety expressed as the time left before the load would hit the bounds considering the load's heading at each instance. It mitigates extremes by taking the shortest fifth percentile time to contact. This metric is also known as time-to-lane crossing (TLC) for car driving [52].
- dtc: Shortest distance to contact [m], for 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 shortest fifth percentile distance to contact.

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5.2.6. Data Analysis

The calculated metrics were averaged over four trials from the second (last) block per condition per participant. These four trials were the last repetition of each mounting quadrant that had no critical error. In two cases both trials of one quadrant had a critical error (a top left and a top right mount). Here the second instance of the opposite top mount was used instead. No other data treatments or transforms were applied.

A two-way repeated measures ANOVA was applied to the metrics, except for the critical errors. The later was tested with the non-parametric two-way repeated measures ezPerm test (with perms = 1e3) [53] via R statistics [54]. In case of an interaction effect between the factors, a simple effects Post Hoc analysis (with Bonferroni correction of 4) was completed. Differences in the metric were considered significant at p-values of 0.05 or below.

Furthermore, the power spectral density was calculated for the master positions during conventional tele-manipulation with the rigid and compliant slaves. The dynamic inaccuracies between the measured and actual position of the load were

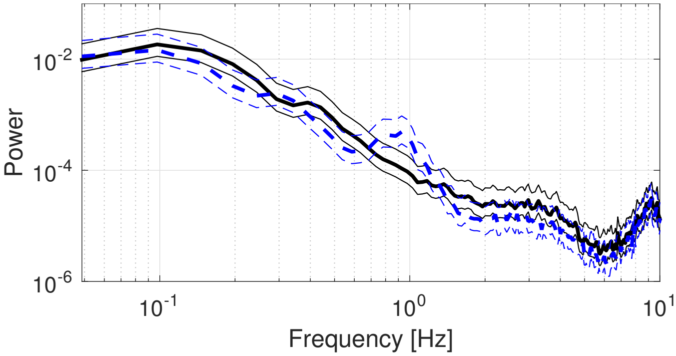

Fig. 5.6: Power spectral density plot (mean and 95% confidence interval) of the master device movements to control a rigid (black) and compliant (blue dashed) slave during unassisted bilateral tele-manipulation. It shows that there is more power near 1 Hz, related to the natural oscillation frequency due to the compliant slave.

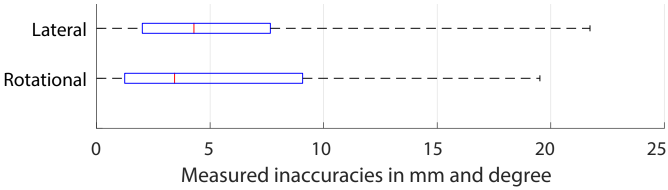

Fig. 5.7: Measured dynamic inaccuracies in lateral (upper) and rotational (lower) direction presented in box plots showing the minimum, the maximum and the 25th, 50th and 75th percentile.

quantified by the minimum, the maximum and the 25th, 50th and 75th percentiles, see Fig. 5.5. These were calculated based on measure positions from the simulated environment for the condition with haptic assistance and a compliant slave.

5.3. Results

Fig. 5.6 shows the power spectral density of the master device movements to illustrate the effects of slave compliance on the task during unassisted tele-manipulation. The plot shows more power around 1 Hz on the master device for the compliant slave compared to the rigid slave. Compliance also caused dynamic inaccuracies in the endpoint translations and rotations assumed by the haptic assistance. A measure of size for these inaccuracies is presented in Fig. 5.7.

Other figures and tables in this section provide the mean and 95% confidence interval based on 12 teams of co-operators. The levels of assistance are indicated by CT (Conventional Tele-manipulation) and HA (Haptic Assistance). Significant main effects or interactions are presented in figures by a bride with either '• • •', '••' or '•' for $p<0.001$, $p<0.01$ and $p<0.05$, respectively. A bridge above the data indicates a main effect for compliance level. A bridge below indicates a main effect for assistance level. A bridge between the data presents an assistance-compliance interaction. The F- and p-values are presented in the text.

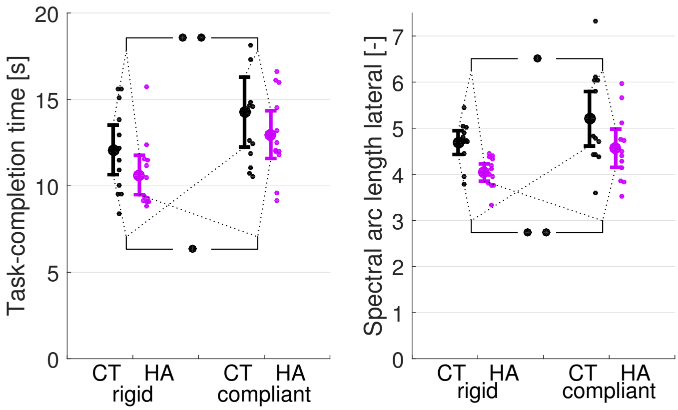

Fig. 5.8: Task-completion time (left panel) and the spectral arc length of the lateral control input (right panel). The dots represent the means per team while they performed the task conventionally (CT, black) or haptically assisted (HA, purple) with the rigid and compliant slaves.

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5.3.1. Task performance

The results show that the mean task-completion time differs significantly between the rigid and compliant slaves ($F_{1,11}$=10.94, p=0.007), such that operators work faster with a rigid slave, see Fig. 5.8 and Table 5.1. Assistance level also affects task performance significantly ($F_{1,11}$=7.04, p=0.022), such that assisted operators can shorten task-completion time with respect to unassisted operators. There is no interaction between the two factors ($F_{1,11}$=0.02, p=0.885).

Table 5.2 shows that both slave compliance and assistance level affects the Free-Space Movement ($F_{1,11}\geq$=8.18, p≤0.016) such that compliance increases and assistance reduces the required time. There is no interaction between the factors for Free-Space Movement ($F_{1,11}$=0.88, p=0.368). The Contact Transition subtask holds no significant differences at all ($F_{1,11}\leq$2.79, p≥0.123). The Constrained Rotational Movement is not affected by the assistance level ($F_{1,11}$=0.18, p=0.680), but slave compliance significantly affects the observed task-completion time ($F_{1,11}$=17.30, p=0.002). There is also no interaction between the factors for the Constrained Rotational Movement ($F_{1,11}$=4.21, p=0.065).

Fig. 5.8 and Table 5.1 show a significant main effect in the lateral spectral arc length for both the slave compliance ($F_{1,11}$=6.04, p=0.032) and assistance level ($F_{1,11}$=12.92, p=0.004). The results indicate that operators control the rigid slave more smoothly than the compliant slave, and that they benefit from the assistance with respect to the conventional condition. The movement smoothness of the crane operator is not changed under either condition ($F_{1,11}\leq$0.10, p≥0.754). Neither interface has an interaction between the factors ($F_{1,11}\leq$0.65, p≥0.436).

5.3.2. Control activity

Lateral control activity has a significant main effect between the compliance levels to control the dexterous slave ($F_{1,11}$=19.85, p=0.001), with less activity for the

Table 5.1: Results for the metric on the entire mounting task. The signs ↔ and ↕ in the centre column indicate a significant main effect for slave compliance and support level respectively. Similarly, ⤧ denotes a significant interaction. In that case, ↔ or ↕ in-between data present significant results from the simple effects Post Hoc analysis.

	Task-completion time [s]		
	rigid mean (95% CI)		compliant mean (95% CI)
CT	12.09 (10.65;13.52)		14.27 (12.24;16.29)
		✥	
HA	10.63 (9.49;11.77)		12.96 (11.58;14.34)
	Spectral arc length lateral [-]		
	rigid mean (95% CI)		compliant mean (95% CI)
CT	4.69 (4.43;4.95)		5.20 (4.61;5.80)
		✥	
HA	4.04 (3.85;4.23)		4.57 (4.15;4.98)
	Spectral arc length vertical [-]		
	rigid mean (95% CI)		compliant mean (95% CI)
CT	3.69 (3.39;3.99)		3.60 (3.21;3.99)
HA	3.58 (3.40;3.76)		3.74 (3.58;3.90)
	Lateral master movement [m]		
	rigid mean (95% CI)		compliant mean (95% CI)
CT	0.448 (0.413;0.482)		0.510 (0.463;0.558)
		✥	
HA	0.495 (0.473;0.517)		0.542 (0.509;0.574)
	Vertical master movement [m]		
	rigid mean (95% CI)		compliant mean (95% CI)
CT	0.133 (0.099;0.167)		0.145 (0.107;0.184)
HA	0.159 (0.123;0.195)		0.170 (0.121;0.218)
	Fifth percentile time to contact [s]		
	rigid mean (95% CI)		compliant mean (95% CI)
CT	0.813 (0.712;0.915)		0.957 (0.761;1.152)
HA	0.849 (0.743;0.955)		0.932 (0.742;1.122)
	Fifth percentile distance to contact [m]		
	rigid mean (95% CI)		compliant mean (95% CI)
CT	0.099 (0.090;0.108)		0.119 (0.103;0.135)
	↕	↕ ⤧	
HA	0.125 (0.115;0.134)		0.128 (0.114;0.142)

rigid than the compliant slave, as shown in Fig. 5.9 and Table 5.1. The vertical control activity for the crane is not affected by compliance ($F_{1,11}$=0.91, p=0.360). Assistance increases lateral control activity ($F_{1,11}$=7.81, p=0.017), while the results on the vertical movements are not significant ($F_{1,11}$=4.70, p=0.053). There are no interactions between the two factors for either the lateral or vertical control activity ($F_{1,11}\leq$0.49, p$\geq$0.498).

Compliance level does not affect lateral control activity during Free-Space Movement ($F_{1,11}$=3.65, p=0.082), but it does during Contact Transition and the Con-

Table 5.2: Task-completion time for the three fundamental subtasks. The signs ↔ and ↕ in the centre column indicate a significant main effect for slave compliance and support level respectively.

	Free-Space Movement time [s]		
	rigid mean (95% CI)		compliant mean (95% CI)
CT	5.54 (4.96;6.12)		7.05 (5.81;8.30)
		↔ ↕	
HA	4.64 (4.27;5.01)		5.66 (4.82;6.50)
	Contact Transition time [s]		
	rigid mean (95% CI)		compliant mean (95% CI)
CT	2.30 (1.86;2.74)		2.74 (2.14;3.35)
HA	2.04 (1.51;2.57)		2.33 (1.79;2.86)
	Constrained Rotational Movement time [s]		
	rigid mean (95% CI)		compliant mean (95% CI)
CT	4.25 (3.49;5.01)		4.47 (3.90;5.04)
		↔	
HA	3.95 (3.38;4.53)		4.98 (4.23;5.73)

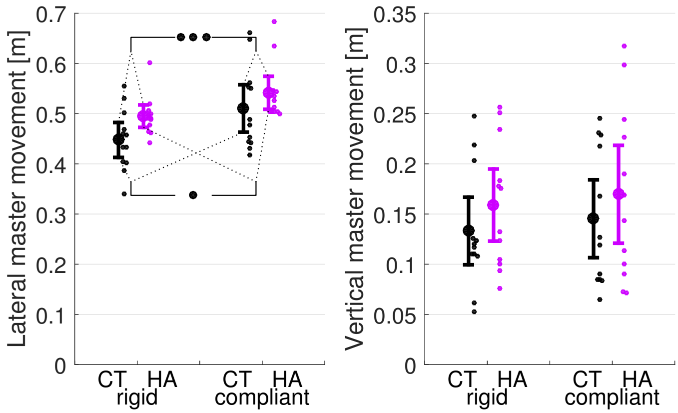

Fig. 5.9: Total master device movements during the entire task: lateral input to control the dexterous slave (left panel) and vertical input to control the crane (right panel). The dots represent the means per team-member while they performed the task conventionally (CT, black) or haptically assisted (HA, purple) with the rigid and compliant slaves.

strained Rotational Movement ($F_{1,11}$≥8.34, p≤0.015). The compliant slave requires more activity than the rigid slave, see Table 5.3. Lateral control activity has a significant main effect for assistance level during Free-Space Movement ($F_{1,11}$=19.43, p=0.001), such that assisted operators required more activity than unassisted operators. There were no other significant differences for the lateral control activity ($F_{1,11}$≤0.75, p≥0.406).

The vertical control activity has significant effects on assistance levels in all fundamental subtasks ($F_{1,11}$≥5.81, p≤0.035), see Table 5.4. Assisted crane operators control the vertical axis with less activity compared to unassisted operators during

Table 5.3: Lateral master movement for the three fundamental subtasks. The signs ↔ and ↕ in the centre column indicate a significant main effect for slave compliance and support level respectively.

	Free-Space Movement lateral control activity [m]		
	rigid mean (95% CI)		compliant mean (95% CI)
CT	0.201 (0.179;0.222)		0.211 (0.189;0.233)
		↕	
HA	0.235 (0.229;0.241)		0.241 (0.230;0.253)
	Contact Transition lateral control activity [m]		
	rigid mean (95% CI)		compliant mean (95% CI)
CT	0.138 (0.131;0.146)		0.154 (0.143;0.165)
		↔	
HA	0.142 (0.136;0.147)		0.150 (0.144;0.157)
	Constrained Rotational Movement lateral control activity [m]		
	rigid mean (95% CI)		compliant mean (95% CI)
CT	0.109 (0.098;0.119)		0.146 (0.123;0.169)
		↔	
HA	0.118 (0.101;0.134)		0.150 (0.127;0.173)

Table 5.4: Vertical master movement for the three fundamental subtasks. The signs ↔ and ↕ in the centre column indicate a significant main effect for slave compliance and support level respectively.

	Free-Space Movement vertical control activity [m]		
	rigid mean (95% CI)		compliant mean (95% CI)
CT	0.079 (0.052;0.107)		0.080 (0.058;0.102)
		↕	
HA	0.065 (0.053;0.077)		0.061 (0.042;0.080)
	Contact Transition vertical control activity [m]		
	rigid mean (95% CI)		compliant mean (95% CI)
CT	0.022 (0.016;0.027)		0.024 (0.012;0.037)
		↕	
HA	0.034 (0.020;0.048)		0.032 (0.019;0.045)
	Constrained Rotational Movement vertical control activity [m]		
	rigid mean (95% CI)		compliant mean (95% CI)
CT	0.032 (0.025;0.039)		0.041 (0.028;0.054)
		↕	
HA	0.059 (0.040;0.079)		0.077 (0.049;0.104)

Free-Space Movement, while they use more activity during the other two fundamental subtasks. Compliance level does not cause significant differences in the vertical control activity during Free-Space Movement ($F_{1,11}$=0.09, p=0.766), Contact Transition ($F_{1,11}$=0.00, p=0.989) and Constrained Rotational Movement ($F_{1,11}$=4.30, p=0.062). None of the fundamental subtasks have an interaction effect ($F_{1,11}\leq$0.40, p$\geq$0.541).

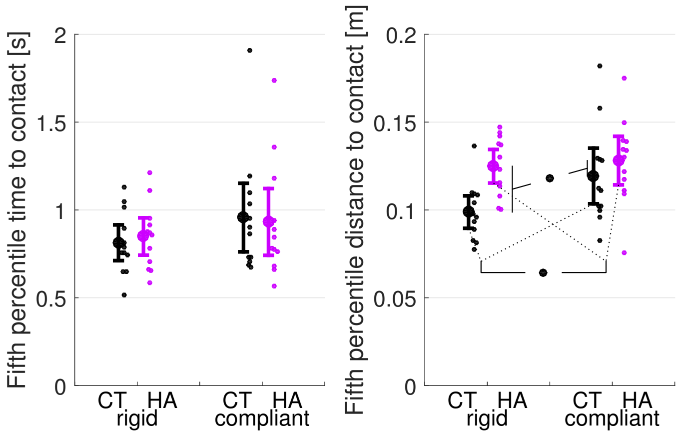

Fig. 5.10: Time (left panel) and distance (right panel) to contact for the Free-Space Movement. The dots represent the means per team while they performed the task conventionally (CT, black) or haptically assisted (HA, purple) with the rigid and compliant slaves.

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Table 5.5: Total number of critical errors made per subtask

	CT rigid	HA rigid	CT comp	HA comp
Total	17	7	25	13
FSM	1	0	2	0
CT	9	6	11	4
CRM	7	1	12	9

5.3.3. Safety

The fifth percentile shortest time to contact has no significant differences or interaction at all ($F_{1,11} \leq 2.53$, $p \geq 0.140$), as shown in Fig. 5.10 and Table 5.1. Compliance level also does not affect the fifth percentile shortest distance to contact ($F_{1,11}=4.05$, p=0.069), while assistance level does ($F_{1,11}=9.38$, p=0.011). Notably, there is an interaction effect between the factors ($F_{1,11}=5.69$, p=0.036). The Bonferroni corrected simple effects show a significant effect between the assistance levels for the rigid slave (p=0.005), while it does not for the compliant slave (p=1.000). Compliance level does not change the distance for both the conventional (p=0.082) and assisted (p=1.000) tele-manipulation.

The number of critical errors, during the last 8 trials of each condition, present no significant difference between the compliance levels (p=0.050), see Fig. 5.11 and Table 5.5. The number of critical errors changes significantly for assistance level (p=0.012), with fewer errors for assisted than unassisted operators. The interaction effect (p=0.790) of ezPerm may not be trustworthy [53]. A fundamental subtask analysis shows that most critical errors are made during the in-contact subtasks. Furthermore, assistance reduces the number of errors in each subtask, see Table 5.5.

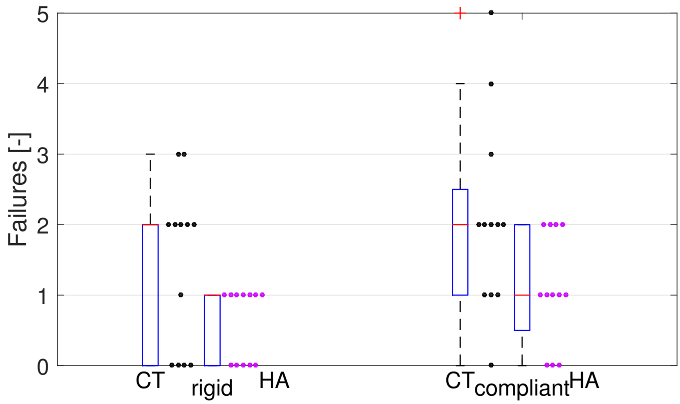

Fig. 5.11: Number of critical errors made in the last 8 trials presented in box plots showing the minimum, the maximum and the 25th, 50th and 75th percentiles. The dots represent the number of critical errors teams made, while they performed the task conventionally (CT, black) or haptically assisted (HA, purple) with the rigid and compliant slaves.

5.4. Discussion

5.4.1. Effects of slave compliance

It would be interesting to discuss the outcomes of the evaluation study with respect to other work in the field though, to the best of our knowledge, only Christiansson investigated the effects of slave compliance in human-factors studies [55]. Interestingly, he drew a parallel between slave compliance and the quality of haptic information that passes through a tele-manipulator (for example, expressed in terms of transmitted impedance, bandwidth or transparency [55–57]). Both a compliant slave and tele-manipulator filter and degrade the position and force information that the master device has to render to the operator. This parallel does not necessarily mean that observed effects are comparable, but provides an interesting perspective in this discussion.

It was hypothesised that slave compliance would decrease task performance while it would increase control activity with respect to a theoretical rigid slave, especially for in-contact tasks. In agreement with this hypothesis, task performance decreases due to the compliance in the slave. The results show a 20% worse task-completion time, which originates from the Free-Space Movement (24%) and Constrained Rotational Movement (15%). This is consistent with the results found in literature where compliance forces operators to wait up to 1/3 of the operation time for structure vibrations to decay [35, 36], while it creates no positioning difficulties [37]. Furthermore, the results show 12% less smooth lateral movement for the dexterous slave. It is no surprise that the spectral arc length of the vertical crane shows no significant differences: the crane is uncoupled from the slave's compliance. Curiously, the Contact Transition is not affected by slave compliance, even though this was expected. Other studies, that vary the quality of haptic feedback, show mixed results for the Contact Transition: high transparency did improve performance during a peg-in-hole task [18], while it did not during a bolt-and-spanner task [45]. Possibly, there is an effect of visual feedback, which was perfect (present and [45]) vs. occluded ([18]). Alternately, literature shows that beyond a certain slave/tele-manipulator stiffness, task performance does not further improve accordingly [45, 55, 58]

Control activity results show that slave compliance increases the lateral master activity by 12%, while the vertical activity remains similar. Likely, the slave's compliance degrades the operator's ability to control the dynamics. Another explanation could be the reflected vibration added to the master's motion, as shown by the peak near 1 Hz in Fig. 5.6. Increased control activity is, however, also reported for telemanipulation with poor haptic feedback [18, 59]. The control activity results for the fundamental subtasks show that slave compliance increases the lateral activity during Contact Transition (9%) and Constrained Rotational Movement (30%). This is consistent with previous work where poor haptic feedback increased the human control activity in these subtasks [18], although other studies show no effect of transparency [45]. Slave compliance does not affect safety.

5.4.2. Effects of haptic assistance

For haptic assistance, we hypothesised that task performance would improve while control activity would remain equal or be reduced with respect to having no assistance. Haptic assistance improves both the task-completion time (10%) and the lateral movement smoothness (13%). For the subtasks, task-completion time is only reduced (18%) during Free-Space Movement. This subtask was also performed faster in other studies: 30% in a maze task [60], 20-25% in a bolt-and-spanner task [14] and 38.8% in a peg-in-hole task [61]. Some studies also show improvements in an in-contact task [14, 18, 61], which was expected for the present study.

The lateral movement of the robot operator increases by 8% due to haptic assistance, which originates from Free-Space Movement (16%). This contradicts the hypothesised reduction in control activity, but makes sense. The assistance path in Free-Space Movement spaciously avoided the spike in the bounds, as illustrated in Fig. 5.2. Probably, operators tolerated a detour while being assisted, but cut corners in the unassisted condition.

Haptic assistance affects vertical crane control activity in all subtasks, but not in the overall task. Interestingly, vertical input decreases (20%) in Free-Space Movement, while it increases in Contact Transition (43%) and Constrained Rotational Movement (86%). For Free-Space Movement it was subjectively observed that unassisted crane operators tend to slow down (make extra movements) near critical situations. For the in-contact subtasks, control activity might have increased due to the haptic link between operators that facilitated action coordination. The assistance system suggested one fixed height to the crane operator for the Contact Transition. This means that crane operators had to accurately accommodate their height, whilst in the unassisted condition robot operators did that by rotating the load. For Constrained Rotational Movement it was subjectively observed that the hinge axis regularly lost contact. Then, the assistance informed the crane to stop, or even revert hoisting, i.e. make extra movements, to reduce chances of a critical error.

Assistance reduces the number of critical errors in the entire task (from 42 to 20), which recurs in all subtasks. Additionally, the distance to contact increased (16%) for the rigid slave. Such an increase in safety was not found in our previous work [13], although improved safety for two operator tasks due to assistance is observed more often in literature [25, 27].

5.4.3. Effects of dynamic inaccurate haptic cues

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During the condition with the compliant slave and haptic assistance, the assistance controller did not obtain the true position of the load. The assistance system merely obtained the position based on the slave's sensors that did not account for its compliance. For this case, it was hypothesised that haptic assistance would not improve task performance as assistance does for controlling a rigid slave, in particular for in-contact tasks. To validate the hypothesis there has to be at least a significant interaction effect between assistance level and slave compliance. The only tested metric with a significant interaction was the distance to contact. However, its result is multi-interpretable. On one hand, the inaccurate cues could have obstructed operators from being able to increase their safety margin. On the other hand, there could have been no need to increase the safety margin beyond 0.128 m in either assisted condition, but were the unassisted operators forced to attain a bigger margin for the compliant slave than the rigid slave, due to the load's oscillation.

There are some explanations for the robustness of haptic assistance against dynamic inaccuracies. First of all, the dynamically inaccurate haptic cues could simply pose no major obstructions for operators to perform their task. Similar results were found in studies that considered static, rather than dynamic, inaccuracies. Some of these studies investigate the effects of inaccuracies with a binary nature: the assistance has/receives no information, such that it turns off, or fails to notice something (e.g. [60–63]). Others studies investigated the effects of inaccuracies with a static systematic nature: the assistance has/receives incorrect in information, such that there is an offset (e.g. [15, 17–19, 64]). Interestingly, the implication of the previous and present studies is that haptic assistance does not have to be perfectly accurate to support operators.

Alternatively, the present inaccuracies could have been too small to observe any effect. This would be an issue if the inaccuracies did not reach realistic magnitudes. The present inaccuracies arose due to a 600 N/m spring between two masses of 25 kg that had an Eigen frequency of 1.1 Hz. In a realistic case, the stiffness and frequency would be higher making it harder to reach higher magnitudes of inaccuracies. For example, the estimated stiffness and Eigen frequency for the Mascot 4 (the tele-manipulator system at the fusion reactor JET [38, 39]) are 12 kN/m and 2.5 Hz for a 50 kg load. Similarly, the estimated stiffness and frequency for the Telerob EMSM-2B (the tele-manipulator system at the neutron spallation source SNS [40, 41]) are 4 kN/m and 1.4 Hz for a 50 kg load. Meanwhile, the present task used novice operators while real tasks rely on highly trained operators. Here expert vs. novice performance has been related to smooth vs. un-smooth movements [51], where un-smooth movements have a higher potential for disturbing a dynamic system. Finally, the assistance did not model nor correct for slave compliance. Corrections, by predicting, estimating or even modelling the dynamics, can already reduce static inaccuracies up to 94% [42]. As such, the present inaccuracies posed a worst-case scenario for haptic assistance, to which the assistance was robust.

5.4.4. Limitations and future work

Modelling the compliance by a linear second order system, and applying that to only one of the asymmetric slaves simplified the real situation considerably. First of all, realistic deflections of mechanical structures occur in all components of a telemanipulated task. It was assumed the load, its mount and the crane were rigid, while these may contribute to the inaccuracies. Their effect was considered to be relatively small, as exemplified by a fictive steal crane cable with a length of 1 m, a cross area of 1 mm^2 and a Young's modulus of 200 GPa, constituting a stiffness of 200 kN/m. This differs more than one order of magnitude from the estimate 12 kN/m and 4 kN/m for the Mascot 4 and Telerob EMSM-2B (see the previous section). Secondly, real compliance behaves in a non-linear manner, while the present system behaves linearly. However, if a study could reveal differences in task performance between alternative types of compliance (i.e. linear vs. non-linear), these differences are probably much smaller than their differences with respect to a rigid slave. Finally, the simulated slave compliance hardly changes during the in-contact tasks, while extra contact points usually increase stiffness, as shown for parallel manipulators [65] and micro-macro manipulators [66]. Nevertheless, this underlines that the presently observed inaccuracies represent a worst-case condition.

The present study used impromptu teams of naïve participants, which complicates the extrapolation of the results to the highly trained operators used in practice. Although the studied teams received training, a real team will probably have better skills in controlling the task and the interfaces, while they also learn to co-operate better. Additionally, operators were not allowed to communicate about the task to exclude it as confounding factor on the effects of haptic assistance and the dynamic inaccurate cues. Therefore, only a longitudinal study with real teams could reveal the effectiveness of haptic assistance.

Real operators perform tasks in 6 DoF from which they receive suboptimal camera feeds. This makes real operators probably more reliant on the haptic information they receive via their interface [45]. This increase in reliance on haptic information makes haptic assistance, which provides support cues inherently in 6 DoF, probably more valuable for task performance than presently observed. The perfect visual feedback from the planar task showcased the dynamic inaccuracies to the operators, while suboptimal camera feeds from 6 DoF tasks could occlude inaccuracies. As such, future studies should perform real 6 DoF task to identify the effects of haptic assistance and inaccurate assistive cues.

5.5. Conclusion

This chapter quantified the effects of slave compliance and haptic assistance on a co-operated heavy load handling task with two asymmetric slaves. Therefore, twelve pairs of co-operators controlled a crane and a dexterous slave to manoeuvre and mount a 50 kg load with and without haptic assistance. The dexterous slave was either rigid or compliant. Haptic assistance produced dynamically inaccurate cues in case of the compliant slave due to the inability to measure the slave's exact position. The task contained three fundamental subtasks: Free-Space Movement; Contact Transition; and Constrained Rotational Movement.

The results show that haptic assistance supports operator control behaviour similarly for the rigid and compliant slaves, despite the dynamic inaccurate assistive cues caused by compliance. Task performance degrades 12-20% for the compliant slave with respect to the rigid slave. Similarly, control activity degrades in lateral direction by 12%, while task safety is not changed statistically. Haptic assistance improves task performance by 10-13%, mainly during Free-Space Movement (18%), compared to unassisted operators. The required vertical control activity for the crane reduces (20%) during Free-Space Movement for assisted operators with respect to unassisted operators, while vertical control activity increases (43-86%) for the in-contact subtasks. Haptic assistance does not change the required lateral control activity during in-contact subtasks, but during Free-Space Movement assistance increases lateral control activity (16%) with respect to unassisted operators. Finally, haptic assistance increases task safety by 52%.

In short, haptic assistance improved task performance and safety. Slave compliance, on the other hand, negatively affected task execution. Moreover, compliance caused worst-case dynamic inaccurate assistive cues, which, however, did not constitute changes in the efficacy of haptic assistance. This means that, for the experimental conditions studied, the benefits of haptic assistance are robust against dynamic inaccuracies.

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6

Discussion

Should you find a wise critic to point out your faults,
follow him as you would a guide to hidden treasure

Buddha | Dhammapada

This thesis investigates how to design a control interface to facilitate the operator's action coordination between two asymmetric subtasks. The aim is to quantify the impact of interface design and haptic assistance to facilitate action coordination between two asymmetric slaves, a crane for lifting and a dexterous robot for accurate positioning, that handle a single heavy load. In that, it focusses on the three aspects of the connected tele-manipulator system: the human, the tele-manipulator and the task environment. These are briefly described below and the results are discussed afterwards.

Considering the human aspect, this thesis investigated whether different interface designs for control of the two asymmetric slaves could improve operator control behaviour. Therefore it first discusses and extends an existing framework for human-human interaction. Via a human-factors study, this thesis assesses task performance, control activity and acceptance between the industrial practice of two co-operating operators and both a single bi-manual operator approach and a single uni-manual operator approach. The study concludes that co-operators perform asymmetric interactive tasks better than one individual.

Despite knowing the preferable interface design, a tele-manipulator degrades task performance. Haptic assistance could both support task execution and facilitate action coordination between the asymmetric subtasks. Due to the fact that the knowledge to build such a haptic assistance is not available, this thesis proposes a novel assistance system. The novelty consists of a haptic link between the interfaces of the slaves through the joint task space. A human-factors study aims to identify the effects of this support with respect to conventional tele-manipulation for co-operators and for uni-manual operators. It concludes that haptic assistance improves task execution of asymmetric interactive tasks.

Haptic assistance improves task performance under the assumption of perfect knowledge of the task and environment. This especially breaks down for real-world heavy load handling tasks. In real-world environments, elastic deflection of mechanical structures, referred to as compliance, cannot be ignored when handling heavy loads. These deflections cannot be measured or modelled in sufficient detail, giving the assistance system an inaccurate impression of the real world and resulting in inaccurate assistive cues. Such inaccuracies can have a static or dynamic nature. The specific question is if, and to what extent, such inaccuracies would reduce task performance.

This thesis assesses the impact of static inaccurate assistive cues on a single-operator single-slave task. Individual operators performed a task with and without haptic assistance in a low and high haptic transparency mode. The impact of dynamic inaccurate assistive cues is assessed during a co-operated mounting task. Dynamic inaccuracies arise when external factors (i.e., operator input or contact events) perturb the compliant robotic slave. The study investigates the effects of a compliant and rigid slave, with and without haptic assistance, on co-operated control behaviour. The study concludes that the benefits of haptic assistance remain in the face of static or dynamic inaccuracies.

6.1. Co-operators perform asymmetric interactive tasks better than one individual

Control over two asymmetric interactive subtasks was hypothesised to be challenging for a pair of co-operating operators, as they must accurately synchronise with each other's movements. Task execution was therefore hypothesised to improve when control over the asymmetric subtasks was performed by a single operator by means of a hybrid uni-manual interface. This is because synchronisation with one's own movements should be far easier. Additionally, bi-manual control by a single operator, having one hand for each slave interface, was hypothesised to be even harder than co-operated control, because performance deteriorates when motion and timing between limbs are not in coalition (i.e. asymmetric) [1].

Contrary to our hypothesis, uni-manual operators completed the asymmetric tasks 20% to 36% slower than co-operators, (chapters 2 and 3). Apparently, uni-manual control was plagued by difficulties that outweigh the potential synchronisation issues for co-operators. One of the explanations may be that simultaneous control over the asymmetric slaves with a single device resembles the difficulties encountered during multi-axis control [2]. Operators who must divide their attention over several control axes had a lower crossover frequency than for single-axis (full-attention) control, while the remnant, closed-loop system performance (error) and phase margin increased. This corresponds to the observed increase in vertical (crane) input for uni-manual operators (25% to 73% more with respect to co-operators, as shown in chapters 2 and 3).

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As expected, bi-manual operators performed 59% slower than co-operators for the conditions studied (chapter 2). This is consistent with the literature that shows that successful bi-manual control greatly depends on spatial and temporal constraints (like relative rhythm, amplitude or direction) [1]: performance of bi-manual operators deteriorates when these constraints do not act in coalition, which is the case for the asymmetric subtasks. Note that for *symmetric* interactive subtasks, constituting equal roles among subtasks, constraints do act in coalition, which generally allows bi-manual operators to outperform dual operators [3–7].

6.2. Haptic assistance improves task execution of asymmetric interactive tasks

Haptic assistance was hypothesised to improve co-operated control over two asymmetric interactive tasks, partly as a result of the novel haptic link between the operators through the joint task. The same assistance was also hypothesised to improve control behaviour of a single operator with a hybrid uni-manual interface. Potentially the uni-manual operator could benefit more from the assistance than the co-operators.

As expected, assisted co-operators completed tasks 10-18% faster with respect to conventional tele-manipulation (chapters 3 and 5). This is consistent with the results for symmetric interactive tasks where two operators were assisted [8–11]. Haptic assistance also improved the interface acceptance (chapter 3) and task safety (chapter 5). While manoeuvring through a bounded path, the assistance reduced lateral control activity for the robot by 4% (chapter 3) and vertical control activity for the crane by 20% (chapter 5). However, assistance increased vertical control activity by 43-86% during in-contact tasks (chapter 5). Potentially, this increase indicates that, with assistance, the crane operator is better engaged in the task compared to the conventional condition. Moreover, both crane and robot operators reported reduced cognitive workload (chapter 3).

Uni-manual operators with haptic assistance completed tasks 21% faster and made movements 3-7% smoother with respect to conventional tele-manipulation (chapter 3), which supports the hypothesis. At the same time, haptic assistance decreases lateral control activity by 4%, decreased cognitive workload, and increased interface acceptance. Interestingly, unassisted uni-manual operators performed less than co-operators, but with assistance, there was virtually no difference between co-operators and uni-manual operators (chapter 3). In essence, haptic assistance enables operators to perform complex dynamic tasks better than without assistance, as is consistent with the results from O'Malley et al. [12].

6.3. Benefits of haptic assistance remain in the face of static or dynamic inaccuracies

The benefits of haptic assistance do not merely occur when the assistance is based on perfectly accurate information pertaining to the task environment, but also when this information contains inaccuracies. Task performance with static inaccurate assistive cues, which could not be seen by the operator, in the support trajectory for a 6-DOF tele-manipulated peg-in-hole task, was similar to that of accurate haptic assistance in three out of four subtasks (chapter 4). Only for the Constrained Translational Movement, the subtasks that had potential for jamming, task performance degraded (75-438%) and increased control activity (105-295%; chapter 4). These results were recently supported for a peg-in-hole task by Lee et al. [13]. Remarkably, the effect of static inaccuracies does not depend on the quality of the haptic transparency, indicating that transparency does not change the operator's ability to detect or cope with inaccuracies (chapter 4). Furthermore, haptic assistance facilitates similar benefits to operators controlling a compliant slave (resulting in dynamic inaccurate assistive cues) as it does to operators controlling rigid slaves (resulting in accurate assistive cues) when they manoeuvred a box through a bounded path and mounted it to the wall in a planar 3-DOF task.

The inaccuracies in haptic assistance were substantial. The static inaccuracies could be as large as 17.5 mm, being equivalent to the radius of the hole (chapter 4). The dynamic inaccuracies were induced by contact events and the operator's input. These inaccuracies exceeded 4.3 mm for 50% of the task time and exceeded 15.5 mm for 5% of the task time (chapter 5). Hypothetically, larger inaccuracies might lead to an increasingly negative impact, but might also be detected earlier. Regardless, inaccuracies in haptic assistance systems, resulting in conflict forces or torques, should be avoided wherever possible.

6.4. Limitations and recommendations

This section discusses the limitations of the methods and recommendations for improvement.

6.4.1. Use of virtual reality

The studies in this thesis investigated human control behaviour in interaction with a simulated task environment. The simulation provided several advantages over a hardware task environment. For example, with respect to a hardware environment, a simulated task environment can be (re)built with more flexibility, in a fraction of the time and with minimal financial and material resources required. Additionally, any virtual object can be tracked, actuated or linked easily: object tracking allowed the measurement of the position of both the real slave and the compliant slave in chapter 5; object actuation allowed a constant length cable by moving the crane up and down instead of actual hoisting in chapters 2, 3 and 5; and object linking allowed the slave manipulator to follow the exact vertical movements of the crane in chapters 2, 3 and 5.

Using a simulation includes several limitations. A simulation is by definition an abstraction of reality, based on models that balance realism and computational efficiency [14]. The simulated contact interactions, object dynamics and kinematics were based on NVIDIA PhysX^{TM}, in which the simulated dynamics and friction resemble real-world behaviour [15] and jamming effects appear realistic [16]. Operator behaviour measured in the simulated environment is difficult to generalise to real-world tasks. However, several results compare well to real-world studies. As discussed in chapter 4, operators who manually control a remote tool in 6DOF in a simulated environment have substantial variability in positional accuracy. This is similar to the variability found in studies with realistic environments [17–19]. Furthermore, the positional accuracy improves due to haptic assistance compared to manual control [17–19]. Meanwhile, the effects of haptic assistance on task completion time in chapter 4 are also consistent with other studies. For example, in virtual reality [20], in a simplified 2D real-world tele-manipulation [17, 21], and in a real-world task environment [19, 22].

6.4.2. Use of naïve participants and impromptu teams

All studies in this thesis used naïve participants, who performed the experimental tasks for a relatively short period of time. This complicates the extrapolation of the results to real operators, who have had months of training or even years of experience [23, 24]. Moreover, the co-operator teams were impromptu, whilst in reality, teams will probably not only improve skills with their own subtask, but will also learn to co-operate better with each other. Therefore, only a longitudinal study could reveal the true effects of interface design, haptic assistance and inaccuracies.

6.4.3. Choice of task and instructions

Participants were given the instruction of moving the heavy load as fast as possible without making collisions, in order to resemble the constraints in nuclear fusion maintenance where down-time needs to be minimised, but collisions are unacceptable. Note that participants were not disqualified from the experiment if they made a collision. However, they were novices, and permitting some errors allowed them to learn their limits, which experienced operators would already know.

Communication between co-operators was restricted, even though real-world tele-manipulation would allow, or even mandate, communication. Chapter 2 only allowed communication between trials as part of the co-operation interface. Communication within a trial was prohibited to prevent interference with the task (e.g. halting to discuss future actions). Chapters 3 and 5 completely forbade spoken communication to eliminate it as potential confounding factor and put the focus on communication via the haptic link of the assistance system.

Chapters 2, 3 and 5 tested operator control behaviour during 2D manoeuvring through a bounded path with a single and optimal camera view, while real tasks occur in 3D with multiple cameras that may provide suboptimal views. The mounting task in chapters 2 and 5 aimed to force interaction between the asymmetric slaves. Despite that similar mounting procedures have been proposed, the ITER organisation favours gravity assisted mounting and object alignment above any other approach [25].

The peg-in-hole task in chapter 4 was in 3D to facilitate a camera view in line with the static inaccuracies to eliminate visual sight on them as confounding factor. This made inaccuracies only haptically detectable. As a result, a crane operator would have been completely blind to the inaccuracies: joystick do not provide haptic feedback from the environment. This could misrepresent the effect of the inaccuracies. Therefore, the study in chapter 4 relied on a single haptic tele-manipulator setup. This limited generalisability regarding co-operation, but increased generalisability regarding other existing studies on haptic assistance for tele-manipulation.

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6.4.4. Haptic assistance system design

The haptic assistance system design in this thesis was inspired by the design principles of haptic shared control [26]: to use a look-ahead controller to predict future errors with respect to a predefined trajectory and translate this to assistive forces on the control interface, thereby essentially sharing the control over a slave robot with the human operator. However, other haptic assistance principles exist (e.g, virtual fixtures [27, 28]), which might yield different operator behaviours. Additionally, the tuning of the controller parameters could result in different operator behaviour. The studies in this thesis used heuristically tuned parameters for look-ahead time, stiffness, damping, force feedback and stiffness feedback. Notably, the resulting stiffness gains (300 to 600 N/m) were relatively high compared to gains observed in literature (e.g., 150 N/m [17] and 200 N/m [19, 20]). This stiffness is also referred to as the level of haptic authority [26, 29], suggesting that the assistance in this thesis had more authority than those from literature. However, heavy loads (50 kg in this case) require higher operator control force with respect to light loads (e.g. 1.2 kg [20] and 5 kg [12]), meaning that the support force and stiffness had to be higher as well.

6.5. Future directions

To gain better insights into operator control behaviour of asymmetric interactive subtasks, future studies should include tasks with real slave hardware. Real-world environments introduce realistic static and dynamic inaccuracies in haptic assistance, instead of the simplified assumptions of this thesis. Preferably these studies should evaluate expert operators to investigate to what extent co-operating and haptic assistance provide real-world benefits. A comparison with novice operators could quantify the extent to which haptic assistance simplifies a task, and if less trained operators consequently behave more like experts. Realistic tasks in 6 degrees of freedom (such as those performed in chapter 4) may result in additional difficulties when controlling two asymmetric slaves: orienting objects with sub-optimal viewing angles severely complicates task execution. Notably, in human-robot teamwork with two operators, high-quality team communication (goal-directed versus not) contributed to nine times better performance [30].

It would be interesting to extrapolate the effects of haptic assistance and the team-choices (one or two operators) to other tasks than those studied in this thesis. Ideally, a comparable task would allow quantification of task performance and control activity for all four classes of the extended Jarrassé's framework. Preferably, all classes use the same tasks in 6 degrees of freedom, because most existing studies consider tasks in, at most, 2 classes, with only one or two degrees of freedom. Potentially, the framework provides valuable insights for human-robot teams as well. Interestingly, some studies assign humans and robots in symmetric interactive roles, for example, to move a table [31–33]. This appears to be one of the least favourable human-human team configurations (chapter 2). Alternatively, Johnson proposes a Coactive Design approach, which aims for interdependence between team members and acknowledges that humans and robot have different (asymmetric) qualities [34]. Essentially, interdependence suggests that the strengths of one team member to perform the task still allows for contributions from the 'weaker' member when this member has an interface that supports assistance.

The support path design could have influenced the effect of the haptic assistance. The present study used one fixed support path (the centre-line of the bounded path) for all participants. This 'one-size-fits-all approach' has been shown to work in general, but also may have small conflicts in the trajectories. This can lead to annoyance [29], and increased force, discomfort or even reduced performance [35]. Adapting the assistance to the individual would probably improve acceptance and performance of operators [36]. Future research should explore how to adapt the support path towards two co-operating operators controlling two asymmetric subtasks.

Modelling and predicting mechanical compliance could further improve haptic assistance. This would reduce the magnitude of the static and dynamic inaccuracies. It could also provide operators with cues to help them to moderate excitations of the mechanical Eigen Frequency. Additionally, an assistance system could be made to automatically compensate for potential oscillations. Hypothetically, such enhanced haptic assistance could allow operators to control a compliant slave in free space as well as they control a rigid slave.

The examined interfaces were relatively close to the standard industrial approach: a joystick-crane and master-slave interface. More advanced interfaces, such as different master devices, controllers or slave devices, may present different outcomes. One interesting approach would be to remove the asymmetry from the control interface for uni-manual operators, for example, by controlling both slaves in either rate- or position control. The problem is that rate-control might not be accurate enough, while position control cannot cover the large crane workspace. An interesting fusion of these controllers exists as the bubble technique [37, 38]. This technique presents a position control mode in a (centre) part of the workspace, being the bubble, and switches automatically back and forward to rate-control near the edges of this bubble. This technique improves single-operator task execution in large workspaces, while allowing for accurate manipulation [37, 38]. Interestingly, sub-sea ROV operators work with the bubble technique in a co-operative mode: one operator controls motor trust (large movements), and the other operator controls the robotic manipulator (fine movements) [39]. Experimenting with such, and other, sophisticated (assistive) interfaces could reveal even better ways to remotely interact with the advanced systems, such as fusion plants, that we use to facilitate our modern lives.

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- **J. van Oosterhout**, C.J. Heemskerk, H. Boessenkool, M.R. de Baar, F.C.T. van der Helm, D.A. Abbink, *The Effects of Slave Compliance and Haptic Assistance on Co-operated Tele-manipulated Tasks*, IEEE Transactions on Human-Machine Systems (prepared for submission).

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… all of time is a great wheel that turns in a track of predetermined events. Left to itself, time turns endlessly, and all the world is doomed to repeat the cycle of events that lead us all ever deeper into darkness and degradation… … In partnership with [his] Catalyst, the White Prophet labors to divert the turning of time into a better path.

Robin Hobb | The Tawny Man Trilogy: Fool's Fate

Propositions

accompanying the dissertation

Co-operation and Haptic Assistance for Tele-manipulated Control over Two Asymmetric Slaves

by

Jeroen van Oosterhout

1. Many hands make light work, even during asymmetric tasks.
2. Haptic assistance does not have to be perfect to be effective.
3. Selection and training of operators results in greater improvements in task performance than haptic assistance.
4. For tasks with haptic assistance, the operator is the biggest source of inaccuracies.
5. Haptic transparency of a tele-manipulator degrades when adding haptic assistance.
6. Contrary to a human slave, the slave of a haptic tele-manipulator is able to command its master.
7. Researchers must change the offensive master-slave metaphor [1] in order to prevent years of subjective discussions to harm the objective and ethically neutral nature of science.
8. Good virtual reality does not require a head mounted display.
9. For system engineering the divide-and-conquer strategy leads to an overhead in communication.
10. Dyslexia inspires the scientist in generating ideas and results, but frustrates the co-authors.

These propositions are regarded as opposable and defendable, and have been approved as such by the promotors Prof. dr. ir. D.A. Abbink, Prof. dr. F.C.T van der Helm and Prof. dr. M.R. de Baar.

[1] Reuters. (26 November 2003) "'master' and 'slave' computer labels unacceptable, officials say,". [Online]. Available: http://www.cnn.com/2003/TECH/ptech/11/26/master.term.reut/index.html. [Accessed: 05 - December - 2017].

Stellingen

behorende bij het proefschrift

Co-operation and Haptic Assistance for Tele-manipulated Control over Two Asymmetric Slaves

door

Jeroen van Oosterhout

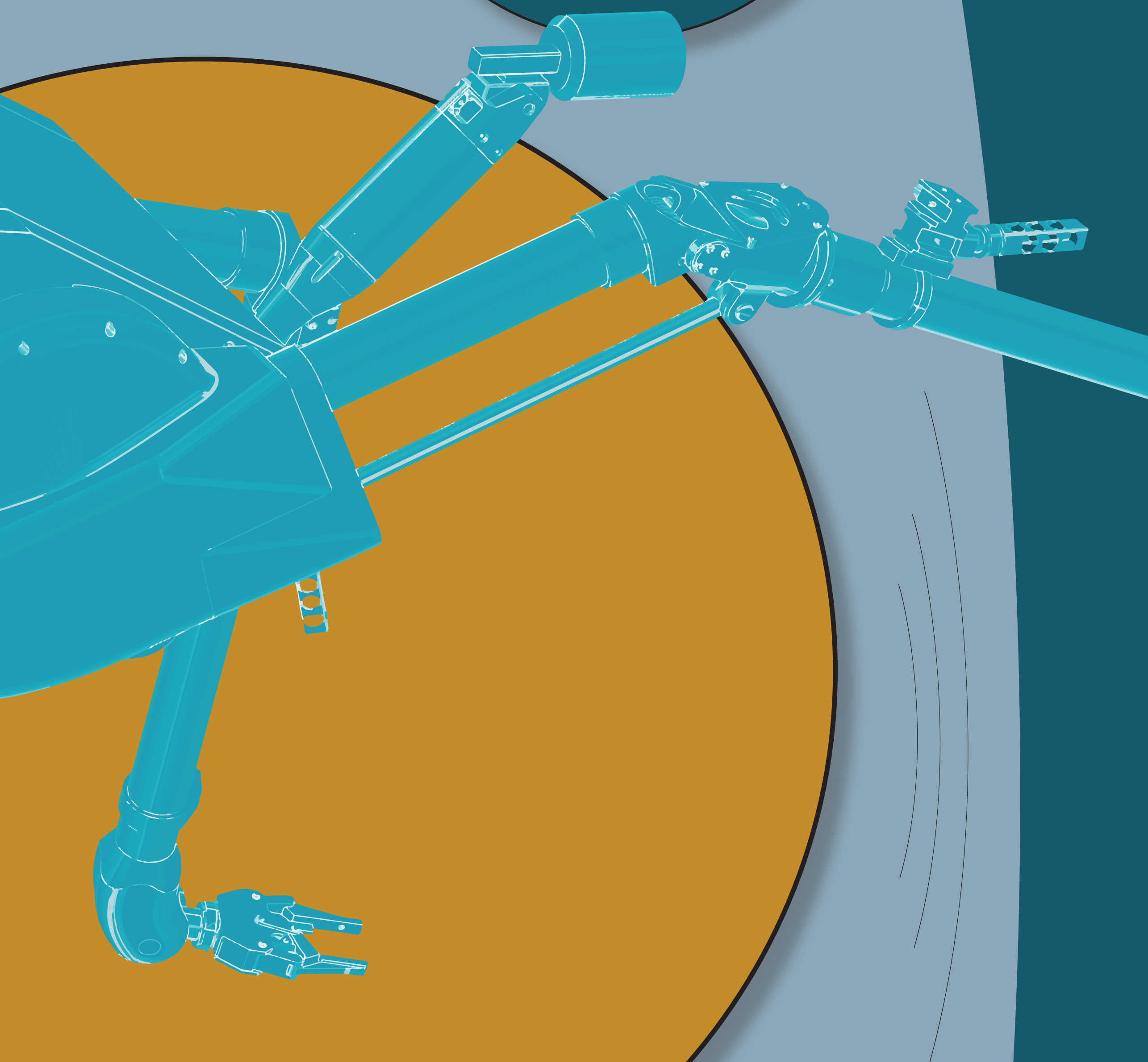
1. Vele handen maken licht werk, zelfs tijdens asymmetrische taken.
2. Haptische assistentie hoeft niet perfect te zijn om effectief te zijn.
3. Selectie en training van operators leidt tot een grotere verbetering van de taakprestatie dan haptische ondersteuning.
4. Bij taken met haptische ondersteuning is de operator de grootste bron van onnauwkeurigheden.
5. Haptische transparantie van een tele-manipulator verslechtert door toevoeging van haptische ondersteuning.
6. In tegenstelling tot menselijke slaven kan, de slave van een haptische tele-manipulator weldegelijk zijn master commanderen.
7. Onderzoekers moeten de beledigend bevonden master-slave metafoor [1] spoedig veranderen om te voorkomen dat een jarenlange subjectieve discussie het objectieve en ethisch neutrale karakter van wetenschap schaadt.
8. Goede virtual reality vereist geen head mounted display.
9. In de systeem engineering leidt de verdeel-en-heers strategie tot een overhead in communicatie.
10. Dyslexie inspireert de wetenschapper in het genereren van ideeën en resultaten, maar frustreert de co-auteurs.

Deze stellingen worden opponeerbaar en verdedigbaar geacht en zijn als zodanig goedgekeurd door de promotoren Prof. dr. ir. D.A. Abbink, Prof. dr. F.C.T van der Helm en Prof. dr. M.R. de Baar.

[1] Reuters. (26 November 2003) "'master' and 'slave' computer labels unacceptable, officials say,". [Online]. Available: http://www.cnn.com/2003/TECH/ptech/11/26/master.term.reut/index.html. [Accessed: 05 - December - 2017].

Ka was like a wheel, its one purpose to turn, and in the end it always came back to the place where it had started.

Stephen King | The Dark Tower III: The Waste Lands



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