Visual cues for haptic shared control

Building on the advances of haptic teleoperation

by

A. van den Berg

Literature Study

Delft University of Technology
Faculty of 3mE

October 29, 2019

Student number:	4228391	
Project duration:	March 12, 2019 – October 24, 2019	
Supervisors:	Prof. dr. ir. D. A. Abbink	TU Delft
	MSc. J. Hofland	Heemskerk Innovative Technology

TU Delft

Contents

1
Introduction

1.1. Background

Dangerous, remote or unreachable environments such as nuclear facilities and space stations still require dexterous tasks like maintenance to be performed on site. In these situations direct manipulation is not possible and teleoperation can be a solution for this. Telemanipulation allows humans to perform dexterous tasks in such environments, while maintaining their judgement, skill, attention and ability to resolve unexpected situations [1].
Currently, Heemskerk Innovative Technology (HIT) is working on a project in collaboration with Tata steel to come up with a solution for top dross removal from a zinc bath of a high speed galvanizing line. Dross is a contamination that forms due to iron reacting with the liquid zinc in the galvanizing bath [2]. This dross will have to be removed to maintain the quality of the coating on the steel strips. This dross floats on the surface of the zinc bath and conventionally removed by a worker in protective clothing manually skimming it of the surface using shovel-like tools [3]. Removing dross is an intensive job with poor work conditions, potential safety hazards and difficulty in controlling operating costs and quality [3]. For these reasons, this task could instead be performed using teleoperation, in order to remove the worker from the environment. In teleoperation a human operator interacts with a remote environment using a master manipulator, a slave manipulator and an interactive communication medium between this master and slave manipulator [4]. In these systems the human operator uses the master manipulator to provide position or velocity inputs to the slave manipulator. Using camera systems or simulation software the operator receives visual feedback. The downside of this solution is that teleoperation is much more difficult than direct manipulation due to delays and limited sensory feedback of the task [5][6].

One might argue to opt for full automation. If the automation would be guaranteed to operate flawlessly, it would no longer require any human input and thus reduce workload, prevent human errors and improve efficiency. Even still, Wiener argues that the question is not whether a function can be automated, but whether is should be [7]. Despite great advances in automation, problems existing decades ago still exist [8]. Introducing automation is shown to rarely provide the promised benefits and often fails to bring about the promised safety benefits [9]. A reason for this is that designers often don't take into consideration how people adapt to the introduction of automation, which leads to a decrease in satisfaction, performance and safety [10]. In the discussed application of dross removal, a failure in the automation system would result in a shutdown of the entire production line, and thus, major losses would occur. If these problems were to occur, the human operator will have decreased situational awareness [11] and therefore might not be able to correctly intervene. This could result in problematic situations, especially considering that full automation will also result in a loss of skill in the manual execution of the operation [12]. Furthermore, if full automation is implemented, operators might not be able to react accordingly to sudden changes as they are less familiar with the system due to being out of the loop [12]. Dross removal is an example of where these type of changes can easily occur. Causes of such a change can be, for example, due to the change of steel type, sheet width, sheet thickness, bath composition, temperature fluctuations and constantly varying zinc liquid level. Constant quality assurance is necessary for this dross removal process and therefore automation might not be suitable for automation.

As mentioned before, providing the operator with sufficient sensory feedback is one of the challenges in teleoperation. One way to provide additional feedback to the operator is through haptic technology, which is a fast growing and dynamic area of research in the world of computer interfaces with a wide variety of applications [13][14]. Haptic feedback allows for a sensation of touch when interacting with a remote or virtual object. Haptic information is fed to the operator with the main goal of supplementing visual information without taxing the visual system [15]. Additionally, presenting information haptically typically leads to a faster response, as it enables the operator to react to the forces through fast reflexes [16][17]. Often haptic feedback is used to supplement/offload other modalities. This multimodal interface design approach can lead to many benefits [18]. Specifically introducing haptics into control systems has been shown to lead to improvements in for example learning efficiency [19][20][21], motor learning and rehabilitation [22][23][24], decreasing workload [25][26], task completion-time [27][25], situational awareness [28] and an increased feeling of realism and presence [29][30]. Furthermore, when haptic feedback is incorporated with vision data, it results in a faster response time when compared to vision only stimulus [31][32].

A promising, relatively new, compromise between manual operation and full automation is haptic shared control (HSC) [33][26]. HSC in teleoperation essentially adds guidance forces to a haptic interface with the goal of intuitively combining human intelligence and creativity with the benefits of automation systems [34]. HSC has been proposed as a way to bring benefits similar to those in automation, while avoiding the previously mentioned pitfalls of automation [33]. One implementation of HSC in teleoperation is through virtual fixtures [35][36]. Virtual fixtures can be either pushing the operator away from designated areas (passive assistance) or guiding the operator along some desired path (active assistance) [35]. Shared control is especially useful in environments where changing conditions require human intervention [37], as could be the case for applications like dross removal (dross forming, sheet movement, bath dynamics etc.). It should be noted that there are other types of shared control, a framework for which is described in [37]. In this topology a more general definition of shared control is given. They state that "in shared control human(s) and robot(s) interact congruently in an action-perception cycle to perform a dynamic task that either the human or the robot could execute autonomously under ideal circumstances". The implementation of the target application (teleoperated dross removal) allows us to specify a specific method of shared control. The target application is a task which requires guidance in skill-based behavior, as it is concerning a position based task requiring fine manipulations. Because of this, a haptic interface is a good choice here [15]. Using the (previously mentioned) framework this leads to the decision to investigate HSC, specifically.

1.2. Problem Statement

Currently, HSC brings some of the short-term benefits of automation such as reducing cognitive workload and improving performance in terms of time and accuracy. However, it does not address the long term issues of human automation interaction, such as trust, over-reliance, dependency on the system, and retention of skills [38]. Furthermore, conflicts between the human and automation still occur, which are generally not desired [39]. These conflict can result in a deteriorated situational awareness and reliance [40][41], which is critical for producing effectual robot behavior [42]. It is argued that these issues can be summarized to arise from two separate problems. Either the human does not understand the automation, or the automation does not understand the human [33]. Making the automation understand the human can be done through different methods. One approach is optimizing the control model itself by improving the understanding of the operator behavior [43]. A possible method to do this is to adapt the guidance path trial-by-trial to better fit the humans intention [44]. Another method is to make the system control parameters adapt to the human operator during operation [45][46][47]. For this report, however, the subject will be helping the human understand the automation.

Increasing the level of automation is not necessarily good or bad in itself, however, it is often argued that the problem arises from lies in the lack of information sharing between human and machine. This manifests in a lack of information provided to the human, as the level of automation increases. The idea behind this arises from Ecological Interface Design (EID), in which one of the objectives is ensuring that the human operator remains capable of processing the information required to operate the new technology [48]. However, it is also argued that with increased automation, it is critical that the operator has access to information about

what the automated agents are doing and what they will be doing next [49]. They argued that in order to co-operate with smart technologies, more information is needed, rather than less. Furthermore, providing less information in automation-rich domains may cause operators to experience difficulty in getting the automation do to what they and have a poor understanding of how the automation works.
Even with correctly matched automation, the way the information is presented to the operator is important and incorrect design of feedback plays a role in many of the problems with automation [50]. When feedback is poorly presented or the human operator is overloaded with information, this can increase operator *workload* and diminish the benefits of automation [51]. Because of this, a critical design challenge is to provide the operator with sufficient feedback without overwhelming them. Furthermore, this feedback needs to be presented with proper context, abstraction and integration, or the information regarding the behavior of complex automation might not be understandable [9]. In this report, it will be investigated how this can be achieved for HSC, using only visual feedback.

The deliberate choice has been made here to specifically investigate visual feedback. Other feedback modalities such as audio, (vibro)tactile, haptic and even olfactory feedback are also available and have possible advantages [15]. These modalities are used largely to supplement and/or offload the visual channel, while visual feedback is (almost) always already integrated in teleoperation systems and is often essential to teleoperation interfaces [15][9]. Furthermore, visual feedback has been more thoroughly studied and plays a major role in sensory perception [52]. Even still, a complete overview of the influence of visual feedback on HSC does not yet seem to exist.

Besides the discussed issue of conflicts in HSC there are other important factors in which improving the visual feedback could prove useful. One of these is *trust* in the automated system. Our trust in the automation plays an important role in the degree to which we are willing to rely on information or actions provided by the automated system [41]. Inappropriate reliance in the automation can cause problems such as misuse and disuse of the automation [53][54][55]. Moreover, supplying the user with information about the reliability of the automation and its performance helps to form the appropriate user reliability, which in turn helps to improve the interaction between the user and automation [56][9][55]. The trust we have in the automation can be properly calibrated by giving appropriate feedback about how the automation works and what its limitations are [53][9][57][58]. Trust tends to increase when the presented information is detailed, consistent and clearly organised [9].
Furthermore, research has shown that in some cases haptic interfaces lead to lower *user acceptance*, as the operators don't always understand the system's intentions [59][60]. Visual feedback is a way of providing this understanding and with that may increase this user acceptance in HSC.

Cue weighting is also an important aspect when considering multi-modal feedback systems. Our experience of the world inherently involves the simultaneous processing of information from multiple sensory modalities [61]. The different senses interact with each other so that what is perceived by one sense, is affected by what is perceived by another [62]. Humans integrate sensory information across different modalities by weighing different cues based on their perceived uncertainty (both within and in-between trial errors) [63][64][65]. It has been shown that this cue weighting mechanism extends to augmented haptics, as used in HSC [65]. Using this mechanism users are able to find their target with an improved or equal performance by utilizing two different cues across different modalities, as opposed to only one [65][66]. Additionally, having knowledge about the performance of the automation speeds up the adjustment for this cue weighting mechanism [66], which is in line with the previously made points regarding trust.
Even if all cues are accurate, supplying information through different modalities simultaneously (*information redundancy*) can result in an increase in performance [67][68][69]. Important to note here however is that this can lead to an increased task execution time (potentially due to an increased workload) if the information is not displayed in an ergonomic way, as was the case with reference [67]. Furthermore, this model seems to break down when the inputs do not appear to originate from the same physical source location [69]. In these type of sensory conflicts vision is weighted greater when geometric properties are being judged [70].The geometric properties are especially of interest in teleoperation tasks such as the target application, which is another reason that the vision has been chosen as the target modality for this report.

1.3. Research Question

In conclusion the chosen solution for the problem of dross removal is to employ a visuo-haptic teleoperation interface that is augmented using HSC. Though HSC has a lot of potential, it can still be improved. One approach to improving HSC is by improving the visual feedback to help the human understand the automation better. This could help by for example reducing conflicts, appropriately calibrating trust and supplying complementary (redundant) feedback to improve performance. Visual cues have been used in HSC in many different ways. However, a complete overview of these, and how they affect the performance does not yet exist. This literature report aims to fill this gap with the following research question:

What visual cues are used in shared control teleoperation interfaces?

The following sub-questions will be addressed, in order to extend this main question:

A: How does each visual cue influence the performance?
B: Can these cues effectively be applied to support haptic shared control teleoperation?

1.4. Method

To get a set of literature to review an initial search was done in the digital library of Web of Science. The search terms that were used are shown in table 1.1.

Table 1.1: The search terms used for the literature search. The horizontal terms were combined using the AND operator, while the vertical terms were combined using the OR operator. Additionally, the right column contains the terms that were used to filter out papers using NOT.

	← AND →			NOT
	Visual	**Feedback**	**Shared Control**	**Unwanted**
	vision*	feedback	"shared control*	cutaneous
	visual*	cue*	"shared auto*"	kinesthetic
↑		support*	"shared tele*"	vibrotactile
OR		guid*	"virtual guid*"	"vis* based"
↓		augment*	"virtual fixture*"	"visual servo*"
		imag*		
		present*		
		aid*		

These search terms gave a total 176 search results. These were then further filtered on the basis of the following criterion:

- The visual cue must at least be shown graphically or be explained in some form for the paper so that the cue can be explained and categorized in this report.
- The discussed visual cue is or has been used in a shared control teleoperation setup.

The initial screening resulted in a total of *27* papers, which were more thoroughly investigated. Besides the papers resulting from the database search some papers gathered from references and the more general initial search were also included. These papers were fully analyzed and included in this report.

It is worth noting is that some of the cues that are discussed are not specific to shared control systems. For example, a system that visually presents a virtual fixture is not necessarily a shared control system, as defined in [37], as the (robot) controller is not necessarily participating in the perception-action cycle. Nonetheless, these cues are used in shared control systems and thus contribute to answering the research question. Because of this, papers discussing such cues are still represented in this report, regardless of if the specific system they have been implemented in is a shared control system.
Another important thing to note is that this report is not about the type of screen or its properties on which these cues or information is displayed. Some will be said about the importance of these parameters, however, the design of the display itself falls outside the scope of this literature study.

1.5. Report structure

In order to structure the report in a logical way, a categorization has been done based on the information about the type of signal that the visual cue represents. A shared control setup can be represented by the relatively simple control scheme, shown in Figure 1.1. The control scheme consists of the human and the controller acting simultaneously on a system (e.g. a vehicle), which interacts with the environment. The reference signal represents the outside environment in which the operator is going to work, for example a road, which may or may not be augmented by additional guidance information (for example an optimal path). This environment can often be shown directly or through a camera feed, however, this is not always the case. Furthermore, it can be useful to visually show this additional guidance information visually. The visualization methods for the reference signal that have been found in the literature search are discussed first, in Chapter 2. The state (Chapter 6) and the reference signal are combined into a guidance signal which guides the user and the controller in performing some desired task. One method of presenting this information to the operator is by displaying it visually. The visual cues in which this is done are discussed in chapter 3. The signal coming from the human is the human output, which comprises of the direct movements performed by the human. Since this is information is directly perceived by the (human) operator, additional cues to represent this information are not required. The output of the controller, in contrast to the human output, is not directly perceived by the operator. The controller output comprises of the state of the controller, but also its dynamic properties, like its limits and intentions. The visual cues found in the literature search in which this is done, are the subject of Chapter 4. The subsequent block is the system, which has the system output as an the output signal. This system output comprises of the intended goal and movements as a result of the (weighed) inputs by the human and controller, before interacting with the environment. Therefore, in a way this signal is a prediction of the future state of the system. Showing this information visually to the operator can be useful in some cases. The visualization of this system output is the subject of Chapter 5. The final signal is the state of the system, after interacting with the environment. A large part of this information is often directly observed through for example a camera stream, though this isn't always sufficient. A solution can be to implement additional visual cues to display information about the system state to the operator. These type of cues are the subject of Chapter 6.

It is worth mentioning that this control scheme serves as a way to give a general idea of the type of signals in a shared control system and to give a general structure to this literature report. In order to keep this structuring clear, it has helped to keep this control scheme as simple as possible. Therefore, it is not a fully comprehensive framework for any shared control cue or implementation (for this the reader is referred to [37]). One example of where this signal is not completely accurate is when the augmented reference signals (Chapter 2) are generated interactively or in real time, based on the environment (e.g. [71], [72], [73], [74]). This particular type of implementation would change the control scheme so that the augmented reference signals are influenced by the feedback loop. However, the focus of this report is not the different control schemes for visual cues in shared control but rather the cues themselves, for which the control scheme shown in figure 1.1 will be sufficient.

The rest of the report is structured as follows. Chapter 7 will discuss these previous five chapters containing all the visual cues, by giving a more complete overview and relating this to the research question (section 1.3. Furthermore, it will draw some conclusions and relate the discussion to the intended use case of dross removal. Finally, in Chapter 8 the future work and recommendations will be discussed.

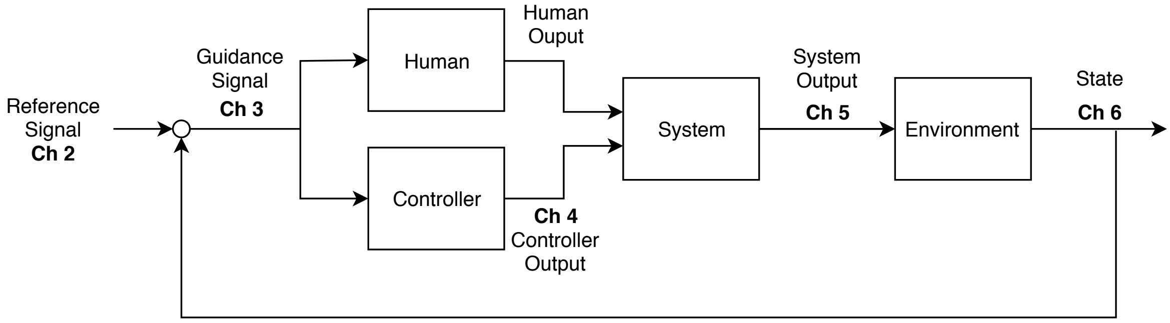


Figure 1.1: A simple control scheme showing the types of signals around which the separate chapters are based. The human and controller are acting simultaneously onto system, which reacts with the environment. The reference signal (Ch 2) and the current system state (Ch 6) are combined to form a guidance signal (Ch 3). This guidance signal is used by the human and controller (Chapter 4), from which they both generate an output signal. These output signals are sent to the system which plans a certain system output (Chapter 5). The system then interacts with the environment resulting in the system state (Chapter 6).

2

Reference Signal Cues

This chapter discusses the visualization of the reference signal, as shown in Figure 1.1. This chapter is split up into two sections. The first one discusses the visualization of the environment, and the system inside of it. Often this part of the signal can just be shown to the operator directly or through a camera feed. However, this is not always possible and might not be the best solution. For this reason, in some cases environments, and the system inside it get represented virtually, through a method called virtualization. This virtualization is the subject of Section 2.1. The other part of this signal are the augmentations that are overlaid onto this outside environment. An example of this can be some optimal path on a road. Such a signal is not actually in the environment but is added to it as a reference signal that gives the human operator and the controller additional information to guide them in operation. The visual cues designed to represent this information are discussed in Section 2.2.

2.1. Virtualization

As mentioned, showing the environment, and the system inside it simply through a camera feed is not always the best solution. It should be noted that the virtualization of the controlled system is not strictly part of the reference signal, but could be better represented in Chapter 6, discussing the system state. However, the virtualization of the environment, and the system inside it are closely related to each other, and are often done using the same method. Because of this, discussing them separately doesn't make much sense, which is why both parts of this cue have been included in this section.

One reason that simply showing a camera stream to the operator is not feasible can be that there is not enough bandwidth to allow for quality communication in two directions, for example in space teleoperation. In [75] a system that is proposed which uses Virtual Reality (VR) and Augmented Reality (AR) techniques to deal with this problem in a pick and place task. Using a model and the End-Effector (EE) pose a virtual robot model can be visualized. This reduces the required bandwidth, and can also enable predictive control strategies to deal with time delays (explained further in section 5.1). The advantage of VR is that it can give real-time feedback, even though there are large delays in the system. The disadvantage is that it doesn't allow the operator to see what is actually going on in the environment. This becomes important when the goal is to manipulate this environment in some way (for example in a pick and place task), as the operator needs to see if his actions have the desired results. To overcome this issue an additional screen shows the AR scene, used for the placement part of the task. A disadvantage of this interface is that is requires the operator to shift his attention between the two screens. In [76] the same problem of large delays and limited bandwidth is solved by combining VR and AR into Augmented Virtuality (AV). In this AV visualization the virtual model is augmented by the projection of real images taken from the robot EE (shown in figure 2.1). This eliminates the second screen and prevents the operator from having to constantly shift his/her attention.

There are additional benefits to this virtualization of the robot and its environment, besides the already mentioned reduction in required bandwidth. The first one is the possibility of using multiple viewing angles. The angle at which these virtual models are viewed can be chosen at will, whereas in the case of a camera

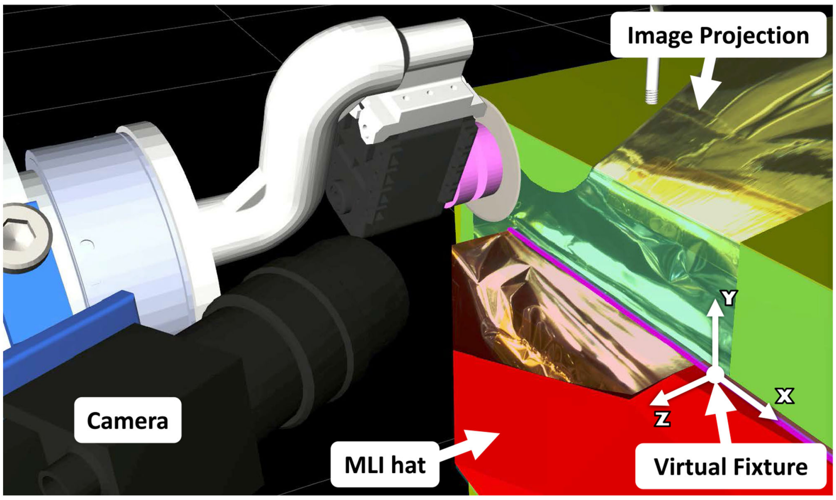


Figure 2.1: Augmented Virtuality (AV) for a space teleoperation system, adopted from [76].

feed the camera itself will have to be moved. This moving of the camera would take time and comes with some system requirements that would enable this movement in the first place. The changing of viewing angles allows for a better situational awareness, depth perception and enables the operator to reliably perform otherwise infeasible teleoperation tasks in camera blind spots [77][78][76]. Another advantage is that it allows the implementation of virtual guides, further explained in Section 2.2. Something that won't be thoroughly investigated in this report, but is worth mentioning, is that this viewing of multiple angles can become easier and more intuitive when using a head-mounted display (HMD). Using this hardware, the operator can physically move his/her head around to investigate the situation, just as if he/she would when standing next to it. This is something that is really only useful if the scene is virtualized in some way, as it requires depth information. The use of such a HMD also improves depth perception, as they posses stereo vision. Furthermore, they have been shown to improve telemanipulation performance, as they allow for faster and more precise movements [79].

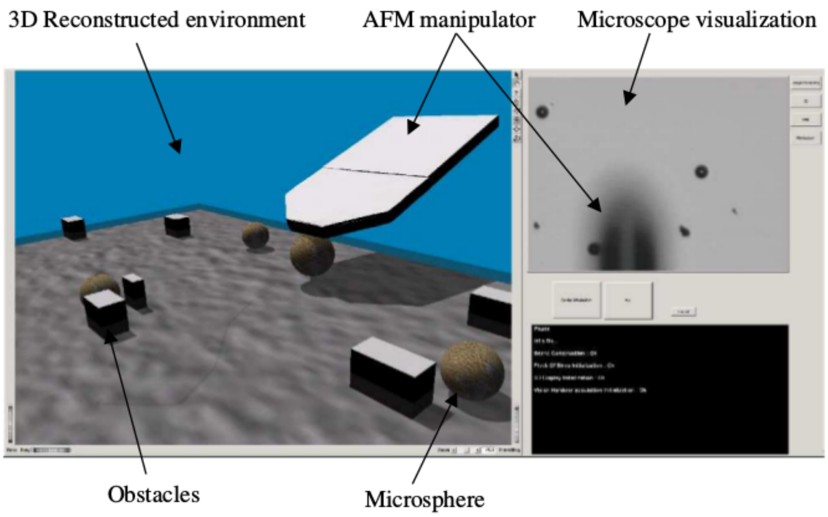


Figure 2.2: Screenshot of the interface for a tele-micromanipulation system in which the real microscope image (top right) is virtually reconstructed (left side), adopted from [80].

Another situation in which showing the operator a camera feed is not feasible is when this view is difficult to interpret. An example of this is discussed in [78], which describes a tele-micromanipulation system. In the paper a virtualization of the scene is suggested, as the alternative is a 2D microscope view which is hard to observe in 3D (a comparison can be seen in the interface screenshot in Figure 2.2).

It could also be that the view of the region of interest is obstructed, and a camera feed is simply not possible. This is the case in Minimally Invasive Surgery (MIS), like in the system described in [81]. MIS has the advantage of minimizing incisions in the patient's body, but have the drawback of restricted vision. Because of this, imaging techniques can be applied to get a sort of *X-Ray vision* into the body. These imaging methods can be used to make a 3D model of the patients body and its internal organs. This model can then be used by the surgeon to navigate and potentially benefit from the the advantages mentioned in this section (with the exception of the reduction of required bandwidth). Unfortunately, neither of these papers have evaluated the effects of this specific visual cue.
Finally, in [82] different feedback modes are investigated for an assembly task. One of the things investigated is the virtualization of task environment. It was found that a virtual presentation outperforms a realistic camera view in completion time and applied contact forces. It is stated that this is because the virtual image limits the presentation to the most relevant elements for the task, which is another advantage of this visual cue.

This shows how when this visual cue is combined with HSC it can help in improving the performance, as well as decreasing workload

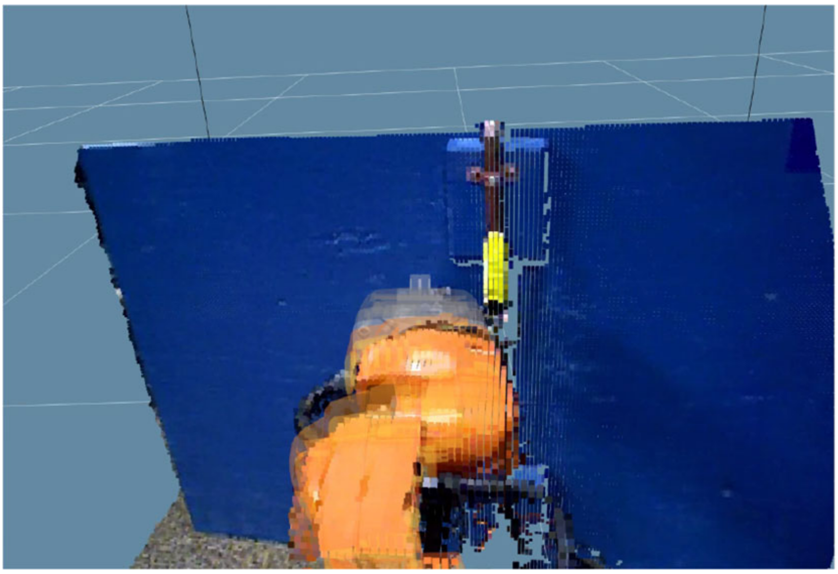


Figure 2.3: A voxel-based 3D map based on RGB-D data, adopted from [83].

The methods with which these virtualization have been generated have not been elaborated on until now. These methods will be discussed now, as they influence the properties and effects of the virtualization. In the first few papers mentioned in this section ([75],[76],[77]) the virtual scenes were built using sensor information about the joint positions and a model of the system. This has the advantage that is takes up less bandwidth (as mentioned before), but has the drawback that it is not always accurate as small errors in the sensor data and model information can cause errors. Another option is to generate the virtual scene in based on vision of the real system. This does not allow the reduction of data transfer to cope with limited bandwidth, but does prevent errors based on incorrect sensor data and doesn't require sensors on every joint. This is the technique applied the tele-micromanipulation system, described in [78]. This technique is also similar to that applied in [81], but is different in that the virtual model is not generated in real-time but is predefined in a separate interface, based on medical imaging techniques (such as MRI or CT). There are several drawbacks to this method: it is computationally more expensive, and it requires some assumptions or predefined models to be made, as the depth information is not available in this case. This last drawback can be prevented if a depth sensor is implemented in this system, as is done in [83] describing a tele-manipulation task. In this system a special camera is used that captures depth data, along with RGB data, called an RGB-D camera. The combination of this data allows for the rendering of voxel-based 3D maps resulting in a 3D image of the scene, as shown in Figure 2.3. This method allows the preservation of previously observed, now occluded geometries. Combining this with the free changing of viewing angles allows an improved depth perception and the possibility of viewing areas that would otherwise be occluded. The use of this 3D visualization resulted in fewer collisions and improved path smoothness. Furthermore, it decreased workload but did not affect situational awareness. A reason for this decrease in workload, as stated before, is that the rendering can be limited to only the parts that are relevant for the task. In [84] a similar approach has been taken, but applied to a navigation task. It was shown that for this task in most situations the 3D visualization of the environment resulted in a less collisions, reduced completion times, decreased workload, higher situational awareness, and higher accuracy of mental models of the remote environment. A possible drawback of this method is that errors in the distance sensor can deteriorate the quality of the feedback, resulting in confusion for the operator. These errors can for example be related to the resolution of the camera, the recorded material (for example transparent material can be harder to detect), and measurement distance. Something else that should be noted is that these methods that virtualize the scene based on visual feedback are not practical when dealing with large delays. This is because they can't directly be used for predictive controllers, as is the case with the first method discussed.

The main advantages and disadvantages, along with the situations in which these methods can be useful have been summarized for each method in Table 2.1. The situations in which all three methods can be useful, when compared to a camera stream, have not been included in the table. Instead, these situations are listed below:

- Improving depth perception
- *Potentially* improving performance parameters (completion time, collision avoidance, movement smoothness, accuracy, workload, situational awareness), depending on the specific environment and task conditions
- Enabling viewing from multiple angles
- Enabling the use of HMDs
- Limiting the presentation to the elements relevant to the task

Something else that is worth noting is that in some of these papers (e.g. [83]) HSC has also been applied, showing that this technique can be and is combined with HSC. However, the comparison between haptic feedback with the virtualization compared to haptic feedback alone was not done in any of these papers. This shows a gap present for many visual cues discussed in this report. Another reason why this combination could be useful is that having the scene virtually, allows for the easy implementation of VFs (as discussed in Section 2.2).

Table 2.1: Table summarizing the advantages and disadvantages of the virtualization methods and in which situations they are useful.

Method	Main advantages	Main disadvantages	Useful when	Papers
Joint sensor and model	Requires less bandwidth	Errors (sensor noise, modeling) Requires models/assumptions	Dealing with large delays or limited bandwidth	[77] [78] [76]
Vision and model	Less prone to error, Requires less sensors	Computationally expensive Requires models/assumptions	Unclear vision Higher accuracy required	[78] [81]
Vision and distance sensor	Doesn't require models/assumptions	Computationally expensive Errors (distance sensor)	No sensors/models available	[83] [84]

2.2. Augmentation

The environment around the controlled system can be augmented by perceptual overlays guiding the operator in performing a task. An example of this is displaying a guidance path, which guides the operator over some optimal path. The name that is often used in literature to describe these overlaid guidance signals is Virtual Fixtures (VFs). Out of all the visual cues found in the literature search, the visualization of VFs is the most common one. In his seminal work, Rosenberg [35] defined VFs as "abstract sensory information overlaid on top of reflected sensory feedback from a remote environment". VFs are often compared to rulers in the sense that they help to perform a certain task (such as drawling a line) by overlaying sensory information. Using a ruler reduces the mental workload required to draw a line, as well as speeding up the operation and allowing the operator to draw a significantly better line compared to if no ruler would be used. They have been developed and implemented to provide assistance across a wide variety of applications, which range from the microscopic (biological) operations [80][85] to the macroscopic industrial operations [86]. VFs have been found to be an effective method of improving operator performance by enhancing speed, precision and/or the reduction of mental workload [87][88][89].

A distinction is often made between forbidden region virtual fixtures (FRVFs, discussed in subsection 2.2.1) and guidance virtual fixtures (GVFs, discussed in subsection 2.2.2). FRVFs indicate a region that the operator is not supposed to move into, as the name suggests. GVFs supply guidance to help the operator stay on a desired path or surface. Virtual fixtures can consist of "haptic, visual, auditory, and tactile sensations, used alone or in cross-modal combinations" [87]. However, VFs are most frequently implemented with haptic feedback. A reason for this could be that the majority of the work done on VFs has been applied to telemanipulation [36]. In telemanipulation one of the main problems is the lack of transparency as there is a decrease in sensory information (when compared to direct manipulation) [6] and haptic feedback has been shown to effectively fill this gap [90][5]. Even still, VFs are found with different feedback modalities in literature, of which the visual implementations will be discussed in this chapter.

2.2.1. Forbidden Region Virtual Fixtures (FRVFs)

FRVFs are a type of augmented guidance which indicate a region that the operator shouldn't (soft FRVFs) or can't (hard FRVFs) move into. These can be implemented in a shared control interface for example to prevent collisions. As mentioned, these are often only displayed haptically, though they do exist in different (combinations of) modalities one of which is vision. Unfortunately, in the literature search there were no papers that specifically investigated the effects of the individual implementation of a visual FRVF. Instead, the research that applies this visual cue focuses on the comparison of modalities for showing this cue. One issue with this is that the information that is displayed haptically slightly differs to the information that is shown visually. The haptic version of this cue is the application of a force to the control device used by the operator in the direction away from the forbidden region. This force directly informs the operator of an action or correction recommended by the controller, while the visual cue informs the operator of the region the operator is being steered away from. This is not always the case, as in some cases these corrective actions are displayed to the operator in some way, which is the subject of Chapter 3. These points should be kept in mind for the remainder of this section, as they slightly limit the discussion about the effect of this visual cue.

In [71] two FRVFs are used with a slight offset between them so that a tool can slide between and cut an isolation sheet in a space teleoperation system. These fixtures were displayed both haptically and visually, though not separately. This resulted in a more accurate and faster task operation, especially when large delays are present. The reason for this is that this cue has been combined with a predictive control strategy (described in Chapter 6). Unfortunately, not much can be said about the contribution of the visual cue to these performance improvements, as this was not investigated.
In [80] the same virtualized micromanipulation teleoperation system as described in [78] in Section 2.1 is extended with a form of FRVF. An important part of this task is that the micro object are avoided in the manipulation task, to prevent interference due to adhesive microforces. To achieve this, repulsive potential fields (acting as FRVFs) are implemented around these objects using visual and/or haptic feedback. The visualized potential fields are shown in Figure 2.4. The haptic potential field is combined with the visual cue and compared to only the visual cue. When the haptic field is also implemented the control effort and the completion time are reduced, and the safety is improved.

In [91] a more advanced system is shown, in which a more complex FRVF is manually generated inside an artery. The process through which this is done is illustrated in figure 2.5, showing the finished visualized FRVF in image (c). Besides the visualization of the FRVF, an additional visual cue was implemented which is the highlighting of the currently active FRVF, indicating the position of the tool. The visual feedback was compared to haptic feedback and to both. The haptic feedback resulted in a better accuracy resulting in fewer collisions. The visual feedback contributed most to a lower task completion time. Furthermore, the users preferred the test conditions in which the visual cues were visible, along with the haptic guidance. Though this shows the potential importance of visual cues in general, it must be noted that this does not necessarily

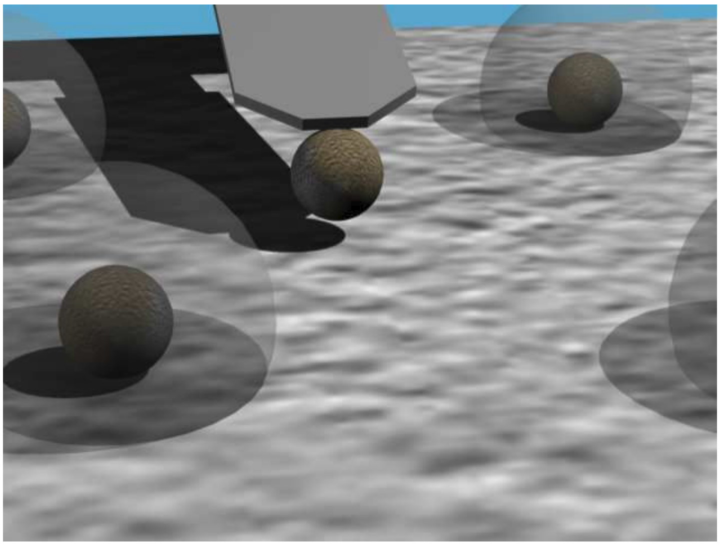
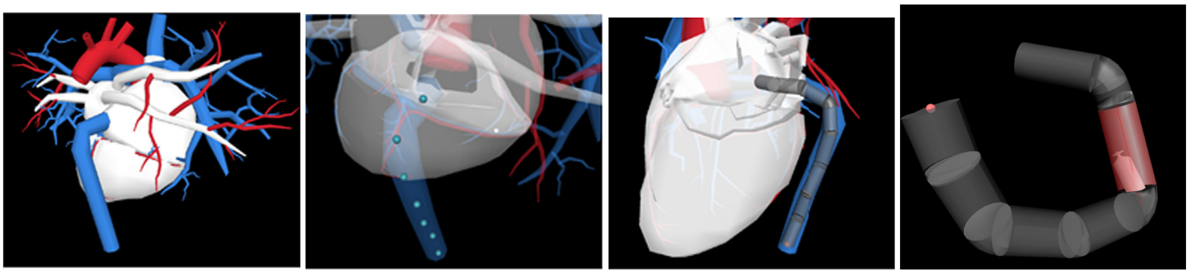


Figure 2.4: Potential fields in tele-micromanipulation task, from [80]

show the usefulness of the visualization of FRVFs. This is because the cue was simultaneously implemented with the highlighting cue, though this can be seen as an extension onto the visualization of FRVFs. Other cues related to this are further discussed in Chapter 4.



(a) (b) (c) (d)

Figure 2.5: The interactive design of a FRVF inside an artery for MIS, adopted from [91]. The design process is illustrated here, where: (a) shows the original model, (b) shows midpoints added to the model and (c) shows the VF elements generated from these midpoints. Finally, (d) shows the additional visual cue of highlighting the currently active FRVF segment.

In [92] a no fly zone is implemented for a remotely piloted vehicle (RPV) acting as a kind of FRVF. This no-fly zone is implemented for a region in which the RPV is not allowed to go outside of, and also for other aerial vehicles flying in that area, like shown in figure 2.6. Besides simple visualizing these visualized FRVFs, the shape, curvature and color of the fence change depending on the current vehicle state. These cues will be further discussed in Chapter 3, though it should be noted that the possibility of showing these cues can be seen as an important reason for visualizing FRVFs in the first place. The implementation of all the cues have been shown to improve the situational awareness and safety of operation of the system. This idea was later implemented in combination with haptic feedback in [93], where it was shown that the visual-haptic display outperformed the visual only display in helping the pilot keep a safe distance from the indicated no-fly zoned and other vehicles.

In [94] a similar cue was implemented. The paper described the design and evaluation of a safety augmentation system to prevent an aircraft from entering a no-fly zone. The focus of the study is to investigate what combination of modalities is the most beneficial. One of the visual cues introduced is the visualization of this no-fly zone, acting as a kind of FRVF. Once again, there were other visual cues implemented simultaneously. Similarly to [91] the visualized FRVF changes color when it is activates due to the aircraft being sufficiently close by. Furthermore, there is a predicted flight trajectory shown visually, which changes color based on predicted risk (further explained in Section 5.1). The results reveal that the combined implementation of the additional visualized information leads to increased safety, secondary-task performance (lower workload) and risk awareness. The visual interface was well-received, which was not the case for the haptic cues. Furthermore, it was concluded that visual feedback made the haptic cues easier to understand, causing 70% of the pilots to state that they understand the cues, instead of 40%. The results found in the paper show the potential of the communication of additional information through the visual channel. Though, once again it is not clear to what degree this can be attributed to the visualization of the FRVF, as this was not explicitly tested in the research.

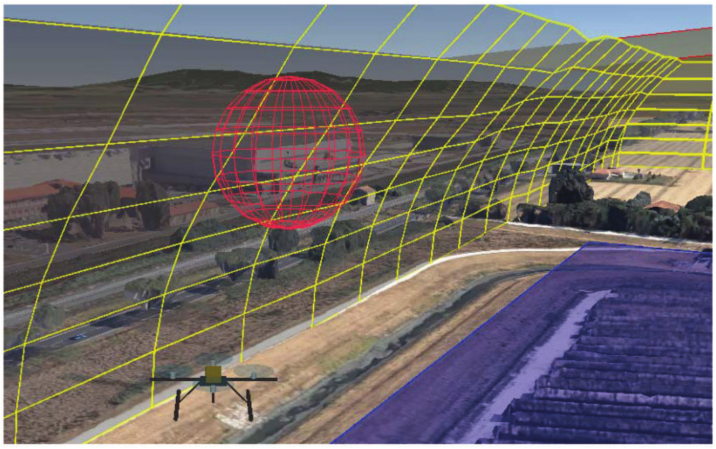


Figure 2.6: FRVFs for an RPV indicating no-fly zones, adopted from [92].

In conclusion, the visualization of FRVFs can be useful in improving the performance, though this was never explicitly tested. One clear advantage is that the cue can be extended with other visual cues for example for guidance signals (Chapter 3) or controller state signals (Chapter 4). Furthermore, it seems this visual cue is mostly used in situations where the actual forbidden region is not directly clear from the camera feed. Haptic feedback used in combination with the visual cue almost always outperforms the visual cue in performance. The visual information seems to contribute most to the acceptance/understanding ([94]) of the haptic cues and increasing the situational awareness and safety of operation ([92][94]). The reason for this could be that the visual information allows the operator to look ahead and react earlier to when only haptic information would be available. The comparison between haptic feedback and haptic combined with only visual feedback was not done in any of these papers. This comparison could be useful in determining if the additional visual cues can have a supportive effect on the haptic feedback. Furthermore, the effect of individual implementation was not evaluated so these conclusions are speculative and remain to be verified.

2.2.2. Guidance Virtual Fixtures (GVFs)

As opposed to FRVFs, GVFs guide the operator to a predefined position and/or orientation, or along a certain path. As previously mentioned, this guidance is often offered haptically but is sometimes (also) shown visually. Often a comparison is made between (combinations of) these modalities. These comparisons will be discussed in this section and summarized in a table in its conclusion.
In [95] one of the earliest works is shown in which visualization is implemented. The described task is the unhooking of an object from a stand using a robotic manipulator, shown in figure 2.7. In the interface the GVF is visually overlaid only if the controlled EE is sufficiently close, which is a visual cue in itself, further explained in Chapter 4. Additionally, a model of the controlled system is superimposed onto the camera stream (further described in Section 2.1). Interestingly, simply showing the GVF increased the completion time, though not much is said about this in the paper. One reason this could be the case is that the visual cue causes too much cluttering of the screen making it harder to navigate.

In [89] a pick and place task is described in which GVFs are applied and visualized. In this work, the effect of the visual GVF was not explicitly investigated, as it was combined with haptic guidance. Two separate GVFs are described. The first is that of a position to which the operator is guided. Once this position is reached, the used GVF switches to an *approach* GVF which guides to operator to along a path suitable for grasping the to be picked object. This switching of visual cues is a visual cue in itself, as it informs the operator of a change in the controller. Other cues like this are described in Chapter 4, though they are mentioned here briefly, as

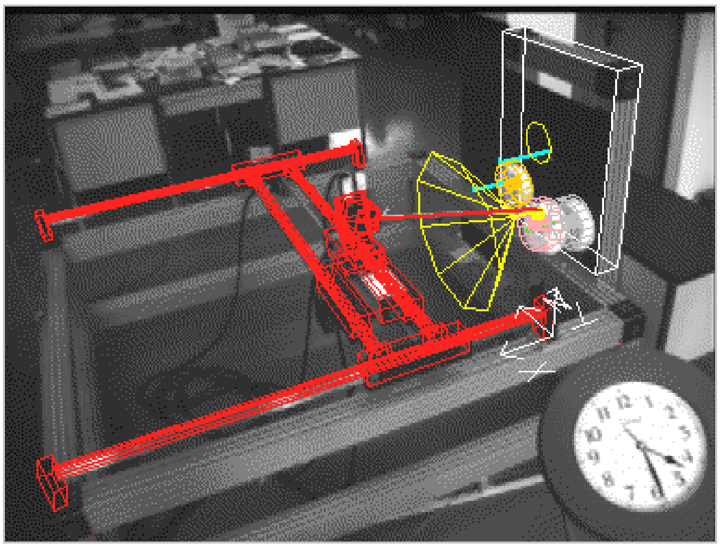
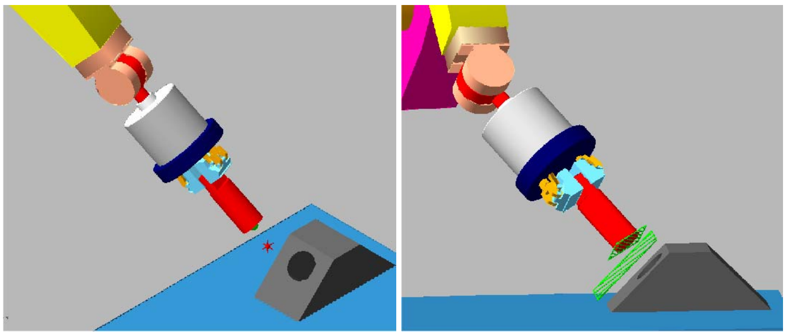


Figure 2.7: Visualized GVF for unhooking an object from a stand, adopted from [95]

these are a direct extension of the visualization of GVFs. The multimodal implementation of the GVF was shown to improve the completion time and reduce the operator workload, when compared to manual control.

A similar system is applied to a peg-in-hole task, described in [96]. There are a wide range of cues that are applied in the auditory, haptic and visual modalities. Relevant to this section are the visual GVF cues, though once again, the cues aren't separately evaluated. After the robot picked up the peg, a visual cue guides the robotic end-effector to the goal position in front of hole in which it is to be inserted, as shown in figure 2.8a. A haptic cue is also activated once the peg is sufficiently close to the goal position. The next cue helps the operator align the peg in the correct orientation before it can be inserted, using haptic and visual feedback. The visual cue for this part of the operation this consists of two planes that are to be aligned, as shown in figure 2.8b. Not much can be said about the effect of these specific cues as they are not individually evaluated. However, this paper does show another way in which this cue can be implemented and combined in teleoperation interfaces.



(a) (b)

Figure 2.8: Visual cues for GVFs to aid in peg in hole task, from [96]

From these early studies we can identify two distinct types of guidance fixtures. The first is the alignment to a certain position or orientation, and the second is the following of a certain path. Like done in [89], these two cues are often combined as a position or an orientation fixture can be used to guide the operator to the beginning of a path fixture. The rest of the visualized GVFs that have been found are path GVFs. One of these is described in [97], which specifically investigates multimodal path GVFs. In it a comparison is made of all the combinations of haptic and visual feedback (including the baseline case with no guidance at all). The results indicate that in terms of completion time the combination of haptic and visual feedback outperform

all other cases, where haptic outperforms visual feedback, and visual feedback outperforms no feedback at all. The path deviation was reduced significantly by the combination of haptic and visual feedback, though either one separately did not have the same effect. Interestingly, the haptic feedback increased the number of collisions, whereas when just visual feedback was present this was not the case. Haptic instabilities have been stated as a possible reason for this.
In [98] several haptic and visual cues were evaluated for the guided control of a nonholonomic vehicle. In one of the test conditions an optimal path was shown visually, along with a predicted vehicle trajectory (explained in Chapter 6). This can be compared to the case where only the predicted vehicle trajectory was shown in order to investigate the effect of the visualized guidance path. The visualized GVF did improve the performance time slightly. There were no significant differences in workload, control effort, collisions and preference. Unfortunately, a combination of haptic and visual feedback was not investigated. It is suggested that in real applications the benefits of haptic cues might be larger (compared to visual), as in that case the visual workload is higher (compared to the relatively simple experiment environment). Because of this, it is important to consider the workload when deciding which cues to give to the operator.

In [99] the teleoperation of a robotic arm in the presence of time delays is desribed. A GVF is applied in different modalities for the following of a circular trajectory. It was found that the haptic feedback greatly reduces the position error and completion time when compared to visual feedback. The addition of visual feedback to this haptic feedback does further decrease the completion time, though the position error also increases. This could be because the visual feedback encourages the operator to move the EE at a higher speed, and thus less accurately.
Another paper which has already been discussed in Section 2.1 is [83]. The focus of this previous mention is 3D voxel based virtualization of the scene. An advantage which arises from this virtualization is that the operator can draw on a GVF in this 3D space. This GVF is used to aid the operator in opening a valve. This path is displayed haptically and visually. It was found that this combined implementation improved collision avoidance, though it did not have a significant effect on the performance, workload, situational awareness, and path length or smoothness. In [72] a similar method is described, which allows the drawing of a path GVF, which is then displayed haptically and visually. It was shown that the execution time and accuracy of the movements were improved by the implementation of the fixture.

In [100] a dynamic GVF is described for telesurgery on a beating heart. Up until this point the GVFs that have been described in this section have been static GVFs. Dynamic GVFs differ from static ones in that they change shape, size or position depending on the state of the system or the environment. Since a beating heart is constantly moving, so should the GVF. A cycle of the visualized GVF changing shape is shown in Figure 2.9. The three test cases have either no feedback, only visual feedback or visual feedback combined with haptic feedback. It was found that the completion time was not reduced by the GVFs. However, the average error was reduced by visual feedback, and was further reduced when both feedback modalities were used.
In [74] a unique system in shown in which the GVF is automatically generated by the use of a deep learning algorithm. A specific reason to visualize this GVF in this system is that this automatic generation is likely not always fully accurate, and a visual implementation of the GVF can help the operator identify this. Unfortunately, the effect of this GVF has not been evaluated.

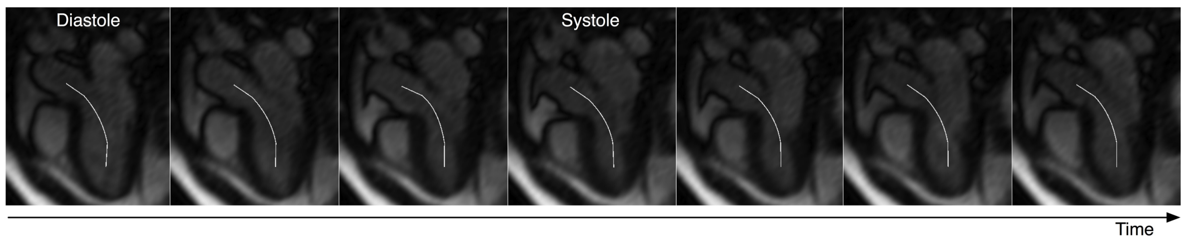


Figure 2.9: Heart beat cycle showing the dynamic changing of a GVF for telesurgery, adopted from [100].

There is some more work in which these path GVFs have been visualized, namely: [71][76][74][101][102]. However, they don't explicitly evaluate the effect of this cue and the methodology of the visualization doesn't differ from the other papers described in this section. For this reason, the choice has been made to only mention them here to give a more complete overview of the literature, but refrain from introducing information not relevant to answering the research questions.

All the results discussed in this section (10 papers total) have been summarized in Table 2.2. In the table modalities and effects are compared for the visualization of GVFs. This cue is the only cue for which a substantial amount of research exists that compares the effects between display modalities. For this reason this table has been created to make an attempt to use this cue to make some conclusions (and speculations) about the potential of visual feedback in shared control interfaces. It is important to note that for [95] and [89] there is an additional visual cue present indicating the active GVF by the appearing/disappearing of the visualization (Chapter 4). However, for simplicity, and completeness, the decision has been made to leave these papers in the overview. Furthermore, only combinations and comparisons containing visual feedback have been included, as this is the focus of this report. The criteria that the cue has been evaluated on are:

- T: Completion **T**ime, positive effect means decreased completion time.
- A: **A**ccuracy, positive effect means increased accuracy.
- P: User **P**reference, positive effect means the users preferred this modality.
- W: **W**orkload, positive effect means a decreased workload.
- E: Control **E**ffort, positive effect means a decreased control effort.

From this table we can see that when visual feedback is compared to no feedback, the results differ quite a lot between papers. A reason for this can be that the design of the visual cue varies a lot between implementations, as can been seen from the few images showing these cues in this section. This design is very important as a bad design can have a negative impact on workload and potentially clutter the workspace [95]. Furthermore, like stated in [98] it is important to consider workload when deciding which cues to display to the operator, since haptic cues can result in a lower visual workload, whereas visual cues can improve the performance and reduce the control effort. This reduction for control effort was not shown for the displaying of the GVFs, but has been shown for the other additional visual cues presented in the paper (further discussed in Chapter 5).
Nonetheless, most papers that implemented visualized GVFs indicate a positive effect on the performance criteria. Furthermore, it has not been shown that visual feedback can outperform haptic feedback, rather, two papers have shown the opposite. When vision is combined with haptic feedback, all criteria are either positively affected or no difference is found, when compared to no feedback (none), or only vision.
Unfortunately, only one paper ([99]) makes the comparison between haptic and the combination of vision and haptic. This shows a gap in literature that is resurfaces in most cues discussed in this report. Making this comparison can give an answer to the question of can vision be useful in supplementing haptic feedback in HSC, as is suggested in the introduction of this report. The paper that has done this comparison found a positive effect on the completion time, but at the cost of accuracy. This suggests that operators will tend to increase their speed when they can look ahead due to additional information, but this decreases the accuracy of the operation. This speculation is similar to that made in [98], which has also found this improved completion time at the cost of a decrease in safety/accuracy due to the addition of a visualized path GVF (although no haptic feedback was present in this task). It is stated that operators get more stubborn in creating their own optimal path, taking more risks, by deviating from the optimal path but get manage to get a better completion time because of this. This is in line with [103], which investigates Ecological Interface Design (EID) in an air traffic control task. It is stated that in EID all feasible control actions within the work domain are revealed, which causes that chance that people disagree with this automation to increase.
There is very little research on the last three criteria: preference, workload and control effort. However, the results that do exist indicate that there is no significant effect on these criteria. Generally, the addition of vision positively influences completion time and accuracy, however, haptics seem to have a larger contribution in both these criteria. This can be seen from the table as haptic feedback almost always outperform visual feedback, and there were no results found that show the opposite.

One important advantage that is a direct result of the implementation of this cue is that it can be extended with other cues, like the ones discussed in Chapter 4. This advantage can't be captured in this table,

Table 2.2: Table showing a comparison of different criteria for displaying of GVF in different modalities for the papers discussed in this section. The criteria are: Completion **T**ime, **A**ccuracy, User **P**reference, **W**orkload, and Control **E**ffort.

		None					Haptic					Vision				
	Effect	**T**	**A**	**P**	**W**	**E**	**T**	**A**	**P**	**W**	**E**	**T**	**A**	**P**	**W**	**E**
Vision compared to:	Positive	[98][75]	[95][100]													
	Negative	[95]	[98]				[99][75]	[99]								
	Neutral	[100]	[75]	[98]	[98]	[98]		[75]								
Vision+Haptic compared to:	Positive	[89][72][75]	[72][100][83][75]		[89]		[99]					[99]	[99][100]			
	Negative							[99]								
	Neutral	[100][83]			[83]	[83]						[100]				

but should be kept in mind nonetheless. Similarly, the visualization of the cue can be useful in properly calibrating the operator trust in the system, which might be especially useful when the fixtures are dynamic and/or generated in real-time (e.g. [100][74]). However, this is something that remains to be verified.

3
Guidance Signal Cues

In this chapter the visualization of the guidance signal is discussed. This guidance signal in a shared control setup provides additional information about a corrective action to both the controller and the human operator that helps to execute a certain task. An important distinction is made between the reference signal that is used to form this guidance signal, which is discussed in chapter 2, and the guidance signal itself (discussed here). This guidance signal directly informs the operator about the input that results in some optimal/recommended position, orientation and/or path. This could for example be the showing the distance to a certain point optimal for grasping an object, instead of just visualizing the point itself.
Something that is worth noting is that these cues are not acting on the system directly, as can be seen from Figure 1.1. This can be different when dealing with haptic interfaces. An example of this is described in [34], which discusses the implementation of the haptic steering wheel. In the described system the controller applies a force to the input device (steering wheel) which directly influences the system input. If these guidance forces would be visually displayed to the operator, this would theoretically part of Chapter 4, as this visual cue directly represents the controller output. This is different when this information is only displayed visually, as this information does not necessarily need to be represent a change of system input, but can be used merely as a recommendation to the operator. However, since the visual implementation of both signals can serve both applications, the decision has been made to group these signals in this chapter in order to prevent the repetition of information.

These guidance cues can be divided into two categories based on what type of augmentation, or virtual fixture, the cue is guiding to. This division is the same as that made in Section 2.2. The first category contains the guidance cues for FRVFs, and is discussed in Section 3.1. The second category contains the guidance cues for GVFs, and is discussed in Section 3.2.

3.1. Guidance cues for FRVFs

In this section the guidance cues are discussed for the use with a FRVFs (discussed in Section 2.2.1). Visual guidance cues for FRVFs give some kind of warning to the operator about incorrect or unsafe positioning. When a FRVF is visually displayed, this guidance cue can be given by changing the color of this FRVF, like done in [92]. The paper has already been mentioned in Section 2.2.1, and the FRVF is a virtual fence indicating a no-fly zone, as shown in Figure 2.6. When the remotely piloted vehicle is expected to violate the no-fly zone, based on a predicted future position, this virtual fence's color changes from yellow to green. As the distance to the fence decreases, and the plane is less able to manoeuvre away from the zone the color of the fence changes smoothly from green to orange and finally to red. The cue isn't explicitly evaluated, though the complete set of cues was said to be easy to detect, interpret and exploit. It should be noted that this visual cue is an extension of the visualization of the FRVF. This shows how cues can be extended so that they contain more information in a single cue.

A similar cue is implemented in [94], which also deals with a no-fly zone. Besides this no-fly zone, a path-prediction line is also visualized (further discussed in Section 5.2). In this implementation, the color of the path-predictor line smoothly shifts from white to red, as the risk of entering this no-fly zone increases. The

results indicate a positive effect on performance, though the changing of color cue was not explicitly evaluated.
This approach is extended and applied to automotive control in [104]. In this thesis, EID inspired visual feedback is designed to complement automotive HSC. This visual feedback comprises of several trajectory curves (discussed in Section 5.2), which all have a certain (non-visualized) look-ahead point. If this look-ahead point falls outside the road boundaries, the color of its trajectory curve changes to red, like shown in Figure 3.1. Once again, the effects of this changing of color are not explicitly investigated. The effects of the implementation of the complete set of visual cues significantly affected the performance. It was stated that the color changing cue resulted in larger road margins, even in time-critical tasks (improved safety). Since they are more appropriate there, the rest of the results of the implementation the sets of cues for these two papers ([94][104]) will be discussed in Section 5.2. Something that is worth noting here is that in both these papers overshoot behavior is reduced by the addition of the visual cues to the haptic feedback. This effect is most likely the result of this FRVF guidance cue, as it shows the operator when it is safe to move back around the obstacle. Using this visual information, operators can plan ahead further than when just relying on the haptic cues only.

Figure 3.1: Guidance cue in which a trajectory line changes red when it leads outside the road boundaries, adopted from [104].

In the guidance cues in the previous three papers it is possible to see when a risk is present, though it is not directly visible where this risk is coming from. With haptic feedback this information is inherently available, as operators are pushed in some optimal direction. However, this information can also be given visually instead, like done in [105]. The paper describes a microsurgery task for deep and narrow spaces. To avoid collisions a FRVF has been implemented. The feedback for this FRVF is compared between different feedback modalities. The haptic feedback consists of force feedback, but only to avoid collisions that are out of view, at the very edges of the area of operation. They state that this is done because these forces may disturb the surgeon. The visual feedback provides feedback in the whole workspace using a specialized visual cue. This visual cue comprises of a semicircle positioned on the edge of the screen in the direction that the upper part of the tool is closest to the FRVF, as shown in Figure 3.2. The color of the semicircle changes from yellow to red depending on the proximity to the FRVF. Finally, a motion scaling feedback is implemented which scales down the motion the closer the tool gets to the FRVF.
All combinations of feedback methods (including no feedback) were evaluated in an tracing task. It was shown that the methods that included visual feedback had the best results in terms of safety, in which the combination of force and visual feedback showed the best results. The force feedback and motion scaling feedback were said to be more difficult to understand and interfere with the manipulations, when compared to the visual feedback method. The combination of force and visual feedback received the highest (subjective) evaluation score by the operators. There were no significant differences found for the completion time of the operation apart from the motion scaling feedback, which increased the completion time.

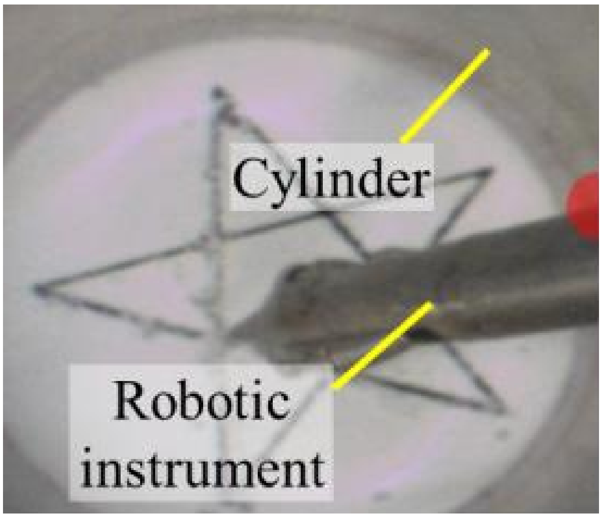
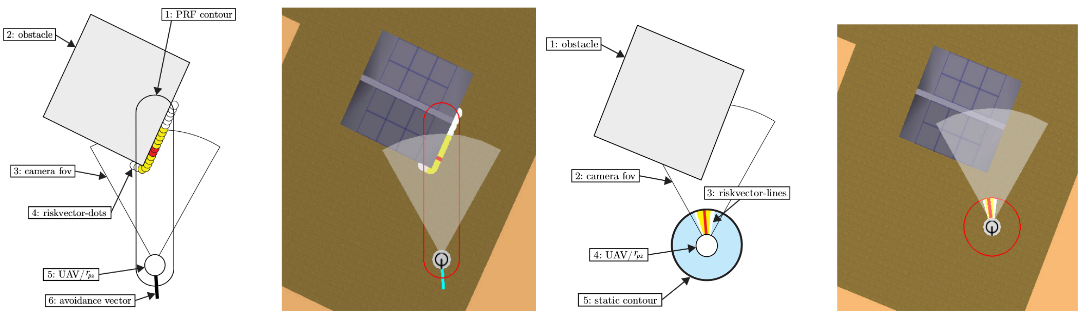


Figure 3.2: Guidance cue showing the proximity to a FRVF for collision avoidance in a microsurgery task in deep and narrow spaces, adopted from [105].

In [106] a haptic support system for an Unmanned Aerial Vehicle (UAV) was implemented. The system was shown to reduce the number of collisions, but resulted in lower user acceptance as the operators had difficulty in understanding the haptic cues. In order combat this complementary visual feedback is implemented which visualized this haptic guidance. Two designs are tested and are shown in Figure 3.3. The first design is called the Parametric Risk Field-Contour Risk Field (PRF-CRF), and is shown in Figure 3.3a. It shows the PRF in a red oval which signifies the area which is scanned for obstacles. When an object falls within this region, forces are generated to guide the operator away from the object. The points from which these forces originate are visualized and color coded based on the risk they represent (white is low risk, yellow is medium risk, and red is high risk). Furthermore, the resulting avoidance vector is also visualized which shows the resulting direction and magnitude of the repelling force. The second design is called the Static Circular Risk Field (SCRF), and is shown in Figure 3.3b. It comprises of lines representing the risk in a certain direction, color coded in the same way as the PRF-CRF design. Neither of the visual cues resulted in a significant difference in performance, safety or workload. However, the user preference did show significant differences in which the PRF-CRF design was preferred over the SCRF design, which was preferred over no visualization at all. Furthermore, the visualizations led to an (small but significant) increase in user acceptance. The users stated that they could better anticipate the haptic feedback and time their actions.
It is also worth noting that the cue was most useful in the subtasks with more space to maneuver, and the visual overlays were appreciated most in these situations. In the subtask with narrow spaces the visual overlay caused more collisions, as the haptic forces cancelled out causing the visual display to become cluttered. This highlights a challenge in the designing of visual cues, which is that they are often specialized to a certain situation and might not work in others.



(a) (b)

Figure 3.3: Visualized haptic guidance designs for an Unmanned Aerial Vehicle (UAV). (a) shows the Parametric Risk Field (PRF) Countour Risk Field (CRF) visualization. (b) shows the Static Circular Risk Field (SCRF) visualization. Adopted from [106].

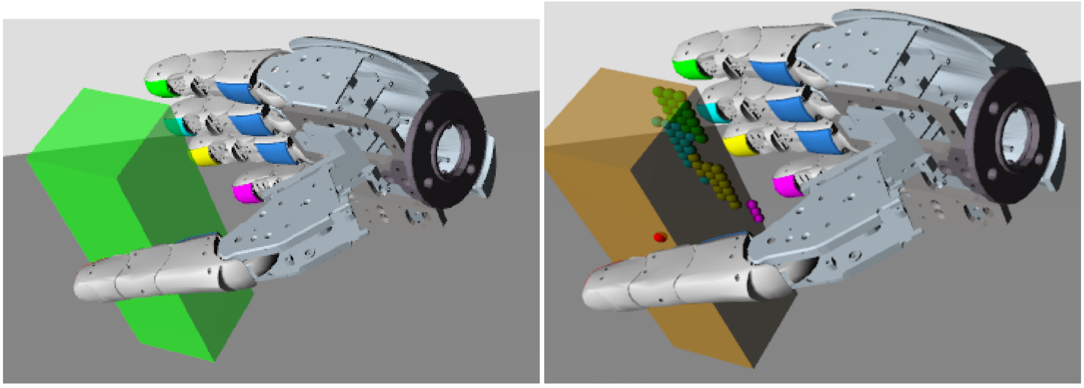
Guidance cues for FRVFs seem to be used in situations where the situational awareness is relatively low and safety is relatively important, like in UAV control, telesurgery or driving. They are useful in improving the safety of the operation by reducing the risk of collisions, even in time-critical situations as shown in [104]. Furthermore, these cues can be used when accuracy is critical and haptic feedback would cause too much of a disturbance [105]. Another important use of this cue is to make haptic cues easier to understand, and with that potentially improve acceptance and performance [106][105], showing that it can be used to support HSC. The cue is often implemented by changing the color of another cue (for example a visualized FRVF or a predicted trajectory). A reason for this can be that the operators can observe the information of several signals simultaneously, without having to switch their visual attention between them. Additionally, it is worth noting that special care should be taken to consider the workload that comes with these cues and to design the visual cue so that it does not clutter the screen. This is seen in [106], where in one of the subtasks the visual cue would take up a lot of space on the screen causing a significant decrease in performance with the implementation of that visual guidance cue.

3.2. Guidance cues for GVFs

This section discusses the guidance cues that guide the operator for the correct alignment with a GVF (discussed in Section 2.2.2). Instead of warning the operator about some unsafe positioning, like in the previous section, these cues do the opposite by guiding the operator to a certain position or orientation, or notifying them when they have reached it. One implementation of this is through a simple, binary, change of color, for example when the correct position has been reached, like done in [107]. The paper describes a virtual peg in hole task in which the peg is brought to the target position (as shown in Figure 3.4), after which it can be released when it is within an acceptable region near the goal (acceptability zone). This reaching of the acceptability zone is what triggers the guidance cue, indicating that the peg can be released. This guidance cue is displayed in different modalities and a comparison is made between them. The visual cue for this is the changing of the peg color, which is shown in Figure 3.4. The other cues to which this is being compared are a vibration (haptic cue) and a sound (auditory cue). Furthermore, the task difficulty varies based on the varying size of the acceptability zone. It was found that the vibration feedback results in the smallest improvements in performance, as the vibration interfered with the positioning of the task (especially with the most difficult tasks, with the smallest acceptability zone). For the easier tasks the visual (color) cue resulted in the best completion time, whereas for the more difficult tasks this was the sound cue. A reason for this could be that with a more difficult task the visual workload required to execute the task increases, so that the visual cue is less effective. There was no significant difference in accuracy between the sound and color cue, although both improved because of the cue. On average the users preferred the (visual) color cue.

Figure 3.4: Peg in hole task with visual indicator to see when the correct position is reached, adopted from [107].

A similar cue was investigated in [108], which described a teleoperated grasping task. One of the cues that is evaluated is a guidance cue which notifies the operator when he/she is in a position from which an object can be grasped. There are two different designs that are implemented and evaluated, the binary cue and the regions cue. In Figure 3.5a the binary cue is shown, in which the object turns green if a force closure grasp is possible. In Figure 3.5b the regions cue is shown, in which the regions in which object will be grasped are visualized, indicating the robustness of the grasp and the potential contact locations. The completion time, grasping quality, and workload were all found to improve with the implementation of the guidance cues (when compared to no feedback). Especially the fact that workload decreases is interesting here as even though extra information is given, the feedback is well designed and simple to interpret so that the operator requires less workload to execute the task. There was no significant difference in these results found between the two cues. The operators were more confident of a good grasping quality (before grasping) with the guidance cues present. Here the regions cue resulted in a higher confidence than the binary cue, and the operators stated that they did not know how to move the hand to obtain an optimal grasp. This shows that a more advanced cue might be helpful in calibrating the operators trust in the automation.



(a) (b)

Figure 3.5: Guidance signal cues that visually display to an operator when he/she is in position to grasp an object. (a) shows the binary cue. (b) shows the regions cue. The Figures are adopted from [108].

Another GVF guidance signal cue is the showing of the shortest distance to some goal position, like done in [96]. This shows the operator the change in position that results in the optimal position, in this case for the grasping of a peg for a peg-in-hole task. In [81] this guidance cue is combined with the previous cue, in that this shortest distance line also changes color when the controlled tool is aligned with this shortest distance line. Unfortunately, neither of these cues are explicitly evaluated, as they are only used as part of a larger set of cues that are implemented simultaneously.

This idea is further extended in [102], which discusses the implementation of a special visual cue that guides the operator over a predetermined path through tissue using flexible needle, shown in Figure 3.6. This cue is a little different in that it doesn't directly show when the alignment is correct, like the previous cue ([81]). Instead, a special cue is designed that shows the difference in alignment between the tool-tip and the guidance path. Furthermore, it shows the distance to the next node along this guidance path. This is done by displaying two lines, one of which is current orientation, of the tool-tip, and the other one is the orientation that results in following an optimal path GVF. The size of the lines represents the distance until the next landmark node along this path. At this point it is worth considering whether this cue is indeed a guidance signal cue, or perhaps a combination of other cue types. At first glance it could seem that the showing of the target orientation is a special way of displaying a GVF, and would be more suited for Section 2.2.2. However, this wouldn't be completely accurate as the orientation and distance are relative to the current state of the tool-tip. This means that the cue is dependent on the current state of the tool-tip and therefore can't be a reference signal. Furthermore, the cue is specifically designed to show the difference in alignment, and directly shows the operator the change in orientation and position that results in the following of some optimal path. This agrees with the definition of the guidance signal cues stated in the introduction of this chapter, which is why it has been included in this chapter. The visual cue did not improve the completion time significantly though users did indicate that they preferred the test case with the visual cues present. However, the accuracy did improve because of the visual cue.

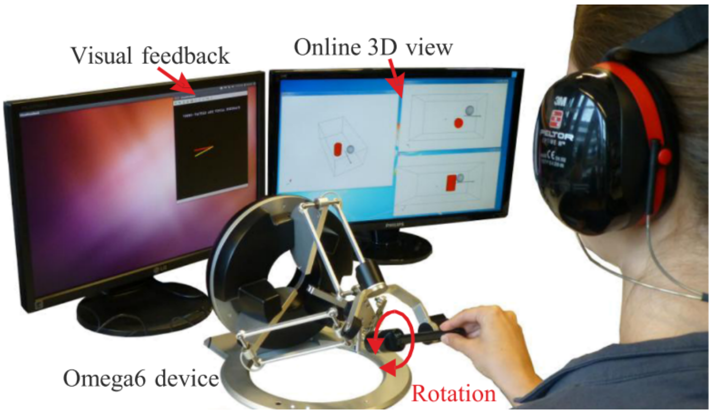


Figure 3.6: Alignment guidance cue for flexible needle steering in MIS, adopted from [102].

One final guidance cue is that discussed in [109] which discusses a bolting task for maintenance work at ITER. It employs a specialized visual cue to aid in the placement of the bolt runner, mainly because of the limited depth perception. The cue comprises of a a shortest-distance line, along with an error bar. The operator needs to minimize this error and move the bolt-runner (EE-tool) along the shortest distance line to end up on the bolt-head. It was shown that this cue did not result in a significant difference in performance. Furthermore, the operators commented that the cue obstructed the view of the bolt-head. Therefore, this cue is likely not useful as it only takes up workload, without offering any performance improvements in return.

In conclusion, guidance cues can be useful in showing the operator when a goal position has been reached. These cues can result in better completion times, accuracy, workload and trust in the automation. Supplying additional information can help to further improve this trust, as shown in [108]. Though special care should be taken that the cues don't obstruct the view in any way. Like with guidance cues for FRVFs, visual cues for GVFs seem to be preferable when high accuracy is required, as shown in [107]. The reason for this is that a haptic feedback cue can interfere with the positioning, which could be a problem when very high accuracy is required. However, it should be noted that this was only shown in one paper which is relatively old (2005), and newer hardware might not show such a problem.
Also similar to guidance cues for FRVFs is that this visual cue is often combined with other visual cues. In this way more information can be obtained without needing to shift visual attention between cues. The visual cue does not always improve performance, however, the visual cue is preferred in all cases (where it was evaluated). With the exception of the cue described in [109], which was said to obstruct the view of the situation. Unfortunately, none of the papers investigated if this visual cue can be used to support haptic feedback. Furthermore, it is worth noting that this visual cue is not applied very often, compared to FRVF guidance cues (discussed in the previous section). A reason for this could be that haptic feedback effectively fills this gap so that there is not enough need for visual guidance cues. This could enforced by the fact that the design and implementation of these cues could take a lot of effort since they are very specialized towards the application in which they are applied. This is evident from the large variation in design between each visual cue discussed in this section. Nonetheless, it could be worth to investigate how this visual cue can be used to improve HSC. One aspect in which they can especially be useful is in improving the acceptance or understanding of HSC, as is seen for FRVF guidance cues in the previous section.

4

Controller Output Cues

This chapter discusses the various visual cues informing the operator about the state of the controller. The direct output of the controller, such as the visual representation of a haptic guidance force, could also be part of this chapter. However, like explained in Chapter 3, these exact same cues can be used to represent the guidance signal itself. Because of this, the decision has been made to include all these cues Chapter 3, to prevent the repetition of information.

One part of the controller state that is shown using visual cues is whether the automation is currently active or not. This can be very simple, for example by turning on a LED to notify the operator when the automation is active, like done in [110]. The paper describes a pick and place task in which the goal is to minimize the contact forces of the gripper and the picked object. To achieve this multiple feedback modes were investigated, in combination with automated agents. One of these is that when the contact force reached a certain threshold, the controller will actively maintain this force so that it will not surpass this threshold value. When the controller activates, LEDs on the robot are illuminated. It was shown that when the LEDs are implemented the average contact forces were lower than when this was not the case.

When an interface contains VFs, it might be useful to show the operator which VF is currently active. This was been done in [89], which visualized the currently active GVF. When the controlled EE is in the proximity of the GVF, it will be visually displayed. The first GVF guides the operator towards a starting position from which the path can be followed. Once this position has been reached, a guidance path GVF is activated and visualized. This shows the operator what the automation is doing, as well as that the starting position has been reached. Both of the visualized GVFs are displayed in Figure 4.1. Additionally, this potentially limits the workload by only showing the visual cues that are relevant to the task at that point in time. However this wasn't explicitly investigated.
This cue is also applied in [96], where four different visual cues are used. The paper described a peg in hole task in which the peg has to be picked up first. For each part of the task the operator is guided in a different way. When the next part of the task has been reached, the automation switches modes, which is visualized by the displaying of a visual guidance cue guiding the operator though the next part.
In [91] this idea is applied to FRVFs for an artery surgery task. To avoid collision with the artery walls, a segmented tube FRVF is implemented. When the surgical tool EE is within a certain segment of the tube it colors red, to show the operator that this is the currently active segment, as shown in Figure 2.5d. It was noted that this showing of the active segment caused a significant improvement in completion time. They note that this is because the cue makes it easier to find the location of the tool EE. It should be noted that the effect of this highlighting was not explicitly investigated in any of these papers.

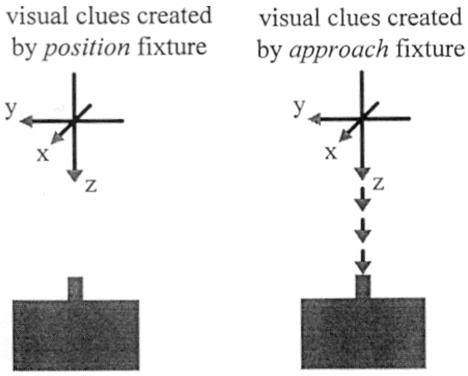


Figure 4.1: Two different GVFs which get visualized when activated at a different point during the operation. This informs the operator of the current state of the automation. Adopted from [89].

Besides showing the state of the automation, visual cues exist to show the uncertainty of automation. Unfortunately this cue has not been found to be used in any shared control interface. Nonetheless, it has been shown that showing uncertainty can help in calibrating trust in automation, which can help to prevent misuse and disuse [111]. In attempt to investigate the potential of these cues for shared control interfaces, these cues will be briefly discussed here even though they don't strictly belong in this report. An example of an application in which uncertainty is displayed is for Adaptive Cruise Control (ACC) systems. For example in [112], when the automation is uncertain, a special icon is displayed like seen in Figure 4.2. When the uncertainty display was enabled the Time To Collision (TTC) was significantly larger compared to the control group. It was also found that the situational awareness increased with the implementation of the uncertainty display. Furthermore, the participants in the group with the uncertainty display enabled noted that they would keep the automation significantly more often than the participants in the control group would.
In [113], this cue is extended and it also shows the limits of the automation through EID inspired cues. The display promoted faster and more consistent braking responses when the system was outside the indicated automation limits, resulting in safer following distances and no collisions. From this, we can see that providing the driver with continuous information about the state of the automation is a promising alternative to simply providing warnings when the automation fails.

Figure 4.2: Icon shown in the middle to indicate when the ACC is uncertain, adopted from [112].

In conclusion, showing the state of the automation seems to be useful in improving performance, for example in decreasing the max force applied. One of the reasons for this can be in many cases a lot of other information can be extracted from these cues, as when something changes in the state of the automation, this is most likely a result of a change in the state of the system. For example the position can be determined very quickly when a certain VF lights up, showing that it is active, as seen in [91]. Another example is when a LED lights up to show that the automation activated, as this informs the operator the threshold force has been applied. Nonetheless, not many cues showing information about the controller properties or state have

been implemented in shared control interfaces. Furthermore, workload wasn't investigated for these cues. This is important to consider when a cue brings marginal advantages it might not be worth to implement this cue if it comes at the cost of an increase in workload.
To explore some of the possible cues relating to the controller output a brief look has been taken at visual cues used in ACC systems, which visualize the uncertainty and the limits of the automation. These cues are proven to be useful in calibrating trust, and in improving situational awareness and user preference in different types of automation. However, they have not found to be explored for shared control. Perhaps a reason for this is that the development of shared control has not been developed far enough to be in the position to integrate these cues. Another likely reason is that with a shared control interface the operator will not have to take over from the automation, as he/she is always in the loop already. Because of this the operator is more aware of what the automation is doing and can already react more quickly and appropriately when the automation fails. This is a reason that HSC has been suggested as an alternative to ACC, e.g. in [114]. Even still, it might be worth exploring the effects of these type of cues in shared control interfaces to see if similar effects can be found.

5
System Output Cues

This chapter contains the cues representing the system output. The system output is the result of the combined inputs by the human and the controller, after being processed by the system, and before reacting with the environment (see figure 1.1). This means that this signal is in fact a prediction of the actual state. There is a clear distinction in the designs of this cue based on whether or not the controlled system is holonomic or not, though the reasons behind this will be further elaborated in the separate sections. For holonomic systems the commanded position is directly visualized, often referred to as *ghosting*, which is the subject of Section 5.1. In nonholonomic system a predicted trajectory is visualized, which is based on the current heading direction and velocity. This visual cue is discussed in Section 5.2

5.1. Ghosting

This section discusses the "ghosting" visual cue. The systems in which this cue was found are all industrial robots. This cue is very different from that described in the next section, which is mostly due to the fact that these systems are holonomic (as opposed to nonholonomic, in the next section). In holonomic systems the final state of the system does not depend on the path taken to achieve it. Because of this property an operator can choose a goal position, and simply have the robot move straight towards this point, generally without having to worry about how this will be achieved (as long as the path is unobstructed). This is not really useful in (close to) real-time control, as the commanded position will be closely followed by the actual robot position so showing them separately won't provide any additional information (it might even cause confusion as it could clutter the screen). However, if there are time delays in the system this cue can become quite useful.

The advantage of this cue when dealing with large time delays is that an operator can see the commanded position, without having to wait for the real system to move there, which is called a predictive display [115]. This makes control more time efficient and can prevent instabilities caused by these delays. This visualization is often done by displaying a virtual representation of the system (a "ghost") in the commanded position that is overlaid on top of the display of the real system (either a virtualized version or a camera feed), like shown in Figure 5.1. This cue has been shown to save time during the operation by reducing the influence of large time delays [75].

In [76] and [71] this cue is also applied, though the real robot is not displayed. The described task is to cut a layer of isolation while dealing with large time delays. To aid in this a virtualization method is applied (as explained in Section 2.1). In [76] a camera stream from the EE is projected onto the virtual model. If the operator wants an update of the actual state of the task, the operator should wait for the stream to catch up and update. The effects of this predictive display were not explicitly investigated.
In [71] VFs are implemented to achieve real-time feedback for the virtual model. This is an important advantage of combining these two cues (VFs and predictive displays), which is that immediate feedback can be given to the operator without requiring the real-life robot arm to move and interact with the environment. The overall system resulted in better accuracy and completion times, especially when large delays were present. However, the effect of the predictive control itself was not explicitly investigated.

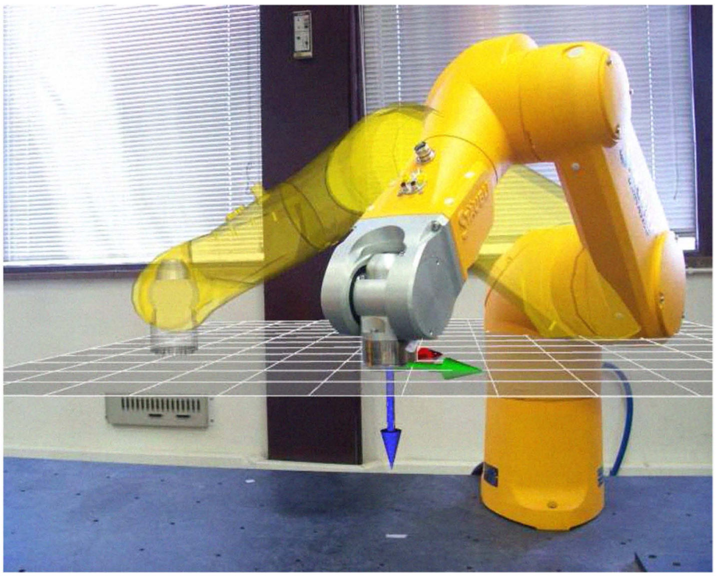


Figure 5.1: Virtual representation of the controlled system showing the commanded system output, adopted from [99].

Something worth noting is that this cue is not only applied in systems with large time delays. Another reason to implement this cue is to enable programming by demonstration, for example as done in [116]. A model of a welding robot is controlled via a teleoperation interface to plan a path for applying a weld. In this way a path can be planned using a virtual model of the robot and its environment, without having to move the real robot. Furthermore, as the environment is also virtualized using a depth camera (like described in Section 2.1), this method has the additional advantage of immediate haptic feedback. Because of these properties, the described method has been found to be useful in assisting the programming of a welding path.

In conclusion, this cue is useful for reducing completion time when used as predictive displays if large time delays are present in the system. Without delays this cue would only clutter up the display without providing any additional information. Sometimes the state of the real robot is also displayed to the operator, though this is not always the case. Showing the this information as well can be helpful as it allows the operator the see the commanded position relative to the real position of the robot (though this difference was not explicitly evaluated). This cue can be extended by combining it with virtual fixtures allowing immediate feedback, even with large delays. Finally, this cue can be used for programming by demonstration interfaces, in which it provides the advantage of not having to move the real robot during the planning phase. What is missing in the design of these cues is a workload comparison. This could help in improving the design of the overall cue and determine the associated (workload) cost of its implementation.

5.2. Predicted Trajectory

In this section visual cues are discussed that represent the current system output in the form of a predicted trajectory curve. This type of cue is used only for nonholomic systems. These differ from holonomic systems in that the final state of the system depends on the path taken to achieve it. For this reason, it is not practical to select a goal state and have some controller figure out how to move here, as is done in the previous section. This does not mean that the predicted position is not visualized, but the design is quite different and so is they way in which it is used.

The visual cue that is used for these systems is the visual displaying of the predicted trajectory of the system, based on its current state. This predicted trajectory is based on the current angle of the controlled system and its velocity. A very simple implementation of this cue is discussed in [94]. The paper discusses a safety augmentation system for aircrafts which, among other cues, implements a visualization of the predicted trajectory, as shown in Figure 5.2. This can be used to identify early on if the aircraft is at risk of entering the visually indicated no-fly zones (discussed in Section 2.2.1). Additionally, this trajectory line shifts color, depending on the risk, further described in Section 3.2. This points to another advantage of this cue which is that other information can be shown in the same cue, so that the operator doesn't have to shift attention between cues. The effects of this cue weren't explicitly investigated. However, the implementation of the full set of cues resulted in higher operator acceptance, improved safety, decreased workload and higher risk awareness. Additionally it is shown that the introduction of this cue reduced overshoot behavior, which is most likely the result of the changing of the color of the predicted trajectory line, informing the operator when it is safe to move back around the forbidden region.

Another way in which this cue can be extended is by visualizing the system limits. By showing the system limits the operator can see the predicted trajectory in the context of the possible range of options and can make a more informed decision about which direction will be optimal. This visual cue gives information about the actual state of the system, which is discussed in Chapter 6. The rest of the papers found in which this predicted trajectory has been visualized, have also visualized these system limits (simultaneously). Therefore, the discussion of this cue will be continued in Section 6.1.
From this we can't conclude much about the effects of this visual cue in itself, as it is always extended with cues containing additional information. This shows that the cue in itself it perhaps not useful enough to justify taking up the workload for the operator. However, by extending it with other cues the operator can advantages, without having to shift his attention to other areas on the display. These advantages comprise of improvements in performance and user experience, as shown in [94] and as explained in Section 6.1.

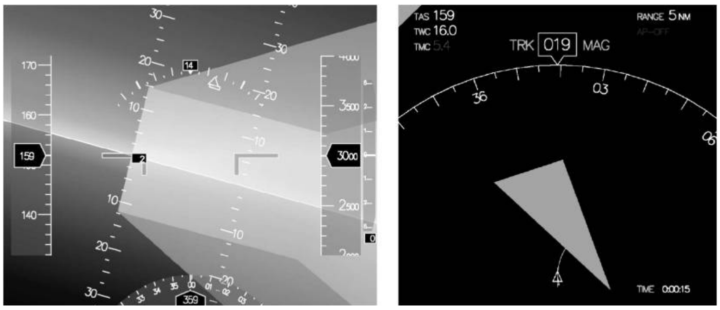


Figure 5.2: The flight display for a safety augmentation system for an aircraft. The right image shows the predicted trajectory, which currently intersects with the visualized no-fly zone signified by the triangle. Adopted from [94].

6

State Cues

In this chapter the visual cues are described that represent information about the actual state of the controlled system, while interacting with the environment surrounding it. This information, and the cues relating to it, can be divided into two categories: the actual state of the system in relation to the environment or reference signal (e.g. spatial cues), and the interaction with the environment itself, for example the visualization of interaction forces. The visual cues related to the system state are discussed in Section 6.1, and in Section 6.2 the visual cues representing information about the interactions with the environment are discussed.

6.1. System State

In this section the visual cues representing the system state are being discussed. This is the current system state, while interacting with the environment, for example velocity, position, or the system limits. The actual visualization of the interactions with the environment will be discussed in Section 6.2.

Often, a lot of information can be derived by observing the system itself through a camera stream, or virtualized model. The viewing of the system as a virtualized model could be seen as part of this section. However, the decision was made to include this in Section 2.1. This section discusses the virtualization of the environment, as well as the system that exists in it together. The reason for this is that these two parts are too closely related to explain them in separate sections. Therefore, for this specific state cue the reader is referred to Section 7.1.
There are not many visual cues (used in shared control) that give additional information about the system state. A logical reason for this is that, as stated already, most of this information can easily be derived by simply observing the system in some way. One problem that could surface is that the pose of a (part of) the system is difficult to observe. A solution that was used in [99] and [75] is to visually display the axes of the EE that stand out from the rest of the image. This clearly shows the current pose of the EE, as seen in Figure 5.1. However, this would only be useful if the pose is not obvious from the viewing of the system. In this example this is the case because the EE is symmetric around one of its axes. Unfortunately, the effects of this visual cue were not evaluated.

Something that is not as easy to observe from camera streams are the limits of a system. In Section 5.2 it was discussed that predicted trajectories for non-holonomic systems are often visualized in the context of the system limits, so that the operator can make a more informed choice. One of the papers in which this was done is [98], which is shown in Figure 6.1. A green dashed line shows the predicted position after translating a certain distance, given the current orientation. The area in which this green line is placed represents the possible steering angels, taking into account the maximum steering angle. It was shown that this cue resulted in significant decrease in completion time and control effort, though no significant difference was found in accuracy. Furthermore, the subjective measures show that users preferred the cue to be present, and they experienced increased comfort and decreased effort.

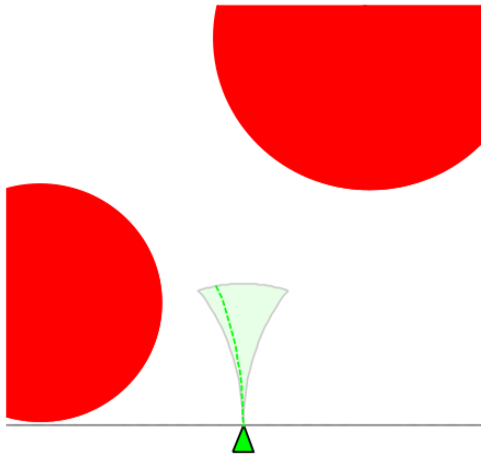


Figure 6.1: Visual display of the predicted trajectory along with the system limits, adopted from [98]. The dashed green line shows the predicted trajectory, and the grey lines show the possible range of trajectories (system limits).

A similar cue was more extensively discussed for the design of a flight display, in [117]. In this thesis paper the cue was further extended with some intermediate curve lines to facilitate heading estimation, as shown in Figure 6.2. To do this the pilot can mentally interpolate between the curves and choose the optimal trajectory. It was also explained that it is important to select the appropriate prediction time, as a too large window would cause the envelope to curve in on itself resulting in a cluttering of the screen. Furthermore, it is worth noting that showing this many intermediate lines is most likely only useful when dealing with asymmetric limits, as is the case here. When this is not the case interpolating will be more trivial and showing this extra information will probably only take up workload and clutter the screen without providing any additional benefits. Possibly due to the limited sample size, the results that were found bear limited statistical significance. However, the results indicate slight overall improvements resulting from this cue. The pilots were more confident, operated safer and experienced a lower workload. Additionally, it was found that the pilot behavior was more consistent. A reason for this can be that the pilots were more confident, which caused them to opt for the most optimal trajectory, without hesitating and flying around the runway first. Furthermore, they reported they preferred the cue to be present (rather than not having it) and stated that with the cue, they experienced less frustration.

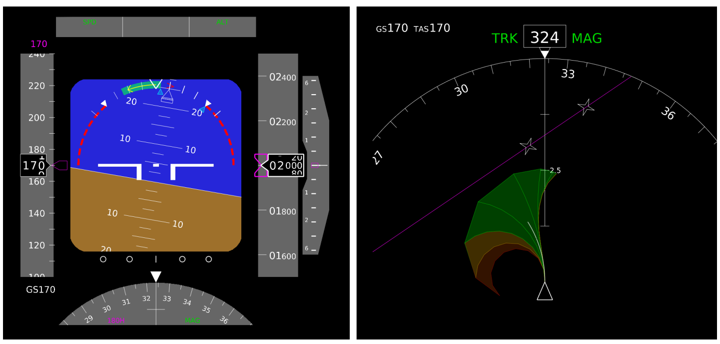


Figure 6.2: Another visual display of the predicted trajectory for an aircraft. The system limits and intermediate curves were included to facilitate heading estimation, adopted from [117].

This cue was also evaluated in the driving domain, in [104]. In the thesis paper this visual cue was designed to complement HSC for obstacle avoidance. It contains the the same cue of the predicted trajectory, along with the current system limits with two intermediate lines, as shown in Figure 3.1. This cue was further extended by showing the operator which trend vectors falls outside of the road boundaries at a certain look-ahead time, further discussed in Chapter 3. The results show that the cue causes a reduction in obstacle margins, indicating that with the visual information present drivers tend to approach the boundary of "safe" behavior. However, previous research has shown that this will not necessarily imply a larger likelihood of accidents [118]. Contrarily to the obstacle margins, the road margins were increased. It was noted that this could be caused by the guidance cue of the change of color of the trajectory lines. Furthermore, an increased variability in road position was found. This could be explained by the fact that drivers have access to more information which show options, instead of simply suggesting an optimal strategy. Moreover, the visual cue caused a tendency for the drivers to disagree with the haptic feedback, though torque conflicts were reduced. Once again, an explanation for this can be that drivers can see which options they have, instead of seeing one optimal path. Finally, the drivers preferred the combination of the visual cue and the HSC over HSC only, which was preferred over the visual cue only. Finally, the combination of the two feedback forms was shown to be beneficial in reducing overshoot behavior. In critical situations drivers receiving only haptic feedback tend to overshoot in avoiding an obstacle. Visual feedback reduced this effect. This was most likely because of the changing of the color of the trajectory lines also, as this shows when the predicted trajectory falls outside of the road boundaries. This was also found in [94], which employs a similar FRVF guidance cue, though it doesn't show the system limits.

In conclusion, not many visual cues are used in shared control to indicate the actual state of the system. As mentioned already, a reason for this can be that a lot of this information can be deduced by observing the system through a camera stream, or virtualized model. Some cues to provide this information more clearly do exist but are only really useful if the rest of the display is inadequate, in which case a better, more straightforward solution might be to simply improve this display, though this is not part of this report. One thing that should be noted that the display of the controlled system in a virtual way (called virtualization) has been included in Section 2.1, while it could be represented here instead since it technically represents the system state. As mentioned before, the reason behind this is that the virtualization of the environment and the system inside it are closely related. Therefore, discussing them separately does not make sense, and would make the discussion of the cue less clear.
System limits, on the other hand, are harder to obtain just by observation of the system, and these have been shown visually with specialized cues. This cue can be useful as it allows the operator to view the current system output (Section 5.2) in the context of the system limits. However, special care should be taken that the screen does not get too cluttered. This visual cue has been found to result in performance improvements in terms of completion time and control effort. Furthermore, subjective improvements were found in a decreased perceived effort and workload, and improved confidence. Once again, another advantage of this cue is that it can be extended with other cues, for example guidance cues as done in [104]. The cue causes operators to disagree with haptic guidance more often, though interestingly this does not result in an increase in control effort, rather a reduction of it. This disagreement can be explained by operators having access to information about the options they have revealing valid options that might not always agree with what the automation suggests. The reduction in control effort can be explained by the fact that operators can use the visual information to make longer predictions and correct the steering input in time without having to make as much adjustments later. Lastly, operators preferred the visual cue to be present in all cases, though they did not prefer only the visual cue over the haptic one in [104].
Showing these system limits was shown to improve the consistency of pilot behavior in [117], however, increased the variability of driver behavior in [104]. This disagreement could be explained by the fact that with the driving task there are more valid options of which one is not necessarily better than the other, where the chosen option is probably decided by operator preference. However, with the flight task, there is one option that is obviously optimal (flying directly to the runway), though when operators are not confident enough, they choose to fly away first. It seems that this visual cue improves confidence, so that operators more often choose the path they feel most comfortable with.

6.2. Environment Interaction

In this section the visual cues are discussed that give information about the interactions with the environment. In teleoperation this type of information is hard perceive for the operator. To overcome this an option can be to implement haptic feedback, though this is not always possible (for example the harware is not available or when high precision is required, as the force feedback could interact with the task accuracy [105]). Furthermore, problems can arise when it is not clear where this force feedback comes from, for example when dealing with guidance forces as well as contact forces. The visual cues that have been found that could play a role in these situations are discussed here.

One way to show collisions is by highlighting (changing the color of) the controlled system when it collides with the environment. This cue is investigated in [90], which describes a virtual assembly task. Visual, vibrotactile and haptic (force) feedback modes were evaluated and compared. The visual collision feedback comprises of the displaying of a red copy of the controlled peg being displayed upon collision, as shown in Figure 6.3. The direction and intensity of the collision are also indicated, by the distance between the manipulated object and its copy. Furthermore, the object and its copy are rendered transparently to improve visibility. It was found that haptic feedback is the most helpful in decreasing the collision forces and operator workload, followed by visual feedback. Vibrotactile feedback was said to be ambiguous, which was not the case for haptic and visual feedback. Because of this vibrotactile feedback resulted in the highest collision forces but the best completion times, as operators took a 'quick-and-dirty' approach. The workload of the visual feedback was significantly higher than that of the haptic feedback. This makes sense as the operators have to constantly pay attention to the copy as well as the controlled object, whereas haptic (force) feedback is an intuitive way of perceiving collisions and thus requires little additional workload. This relatively high workload that comes with visualizing forces has been confirmed in earlier studies [82].

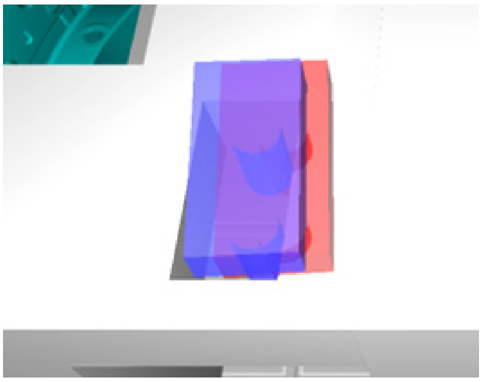


Figure 6.3: Visual cue to indicate collisions in virtual assembly task. Upon collision a virtual copy of the object gets visualized. Adopted from [90].

In [81] collisions are indicated by changing the color of the shortest distance line to the target (Guidance cue described in Chapter 3). The paper describes a MIS task in which a surgeon needs to move a needle-like tool to a goal position. When the controlled tool intersects with another organ this guidance line changes color as shown in figure 6.4. Unfortunately, this cue was not explicitly evaluated. However, it shows another example of how other visual cues can be extended to provide additional information to the operator.

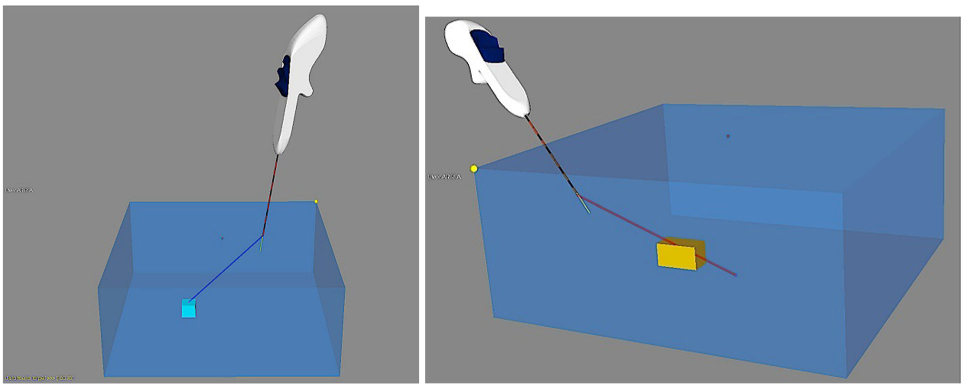


Figure 6.4: Shortest distance line changing color from blue (left) to red (right) when the tool collides with an organ. Adopted from [81].

A more straightforward way to show collision forces is to represent this force using an arrow, indicating the direction and magnitude of the force. This was applied in [96] as well as [74], though neither described the cue in much depth or evaluated its effects explicitly. In [119] this force arrow cue was investigated more in-depth and compared in between modalities for an insertion task. When the controlled object collides with the environment, a force arrow shows up that indicates the origin, direction and magnitude of the collision force, as shown in Figure 6.6. It was found that the visual feedback actually increased the task completion time. However, the response time to contact decreased (insignificantly) indicating that perhaps operators were more aware of collisions and moved more slowly because of it. It is worth noting that this is a relatively old study (don in 2002) which might play a role, as these setups have changed a lot in design and quality of feedback.

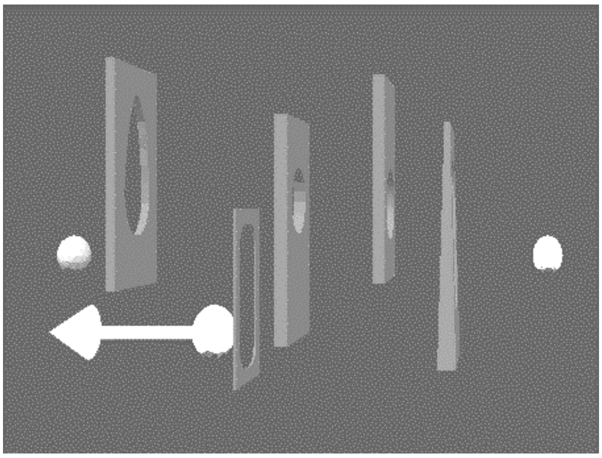


Figure 6.5: Visual cue to indicate collisions in insertion task. Upon collision a force arrow is shown indicating the origin, direction and magnitude of the collision force. Adopted from [119].

Grasp forces are another type of environment interaction. These are different from collisions as there no need to indicate the direction of the forces. In [120] the grasp force is shown using the density of lines displayed at the border of the screen. The reason for this is that this cue can then be viewed using peripheral vision, so that the central vision can be used for the executed task. It was shown that this visual feedback gives less precise feeling of the remote side than realistic force feedback. However, after a learning period operators were able to hold a predefined grasping force so that the grasped object was not crushed or dropped. The cue is shown to be usable but once again, not as effective as haptic feedback.

Another task in which forces have been visualized is the task of suturing. In these visual cues the direction of the force is also not displayed as it is not as important to since the surgeon can easily derive this information by observing the system. However, in basic suturing skills such a knot tying applying an appropriate amount of force is essential, as tissue can be damaged or the suture can end up being loose or broken. For this reason it is important that the surgeon/operator to be able to perceive the magnitude of the applied force. When this force is hard to perceive, for example due to a lack of experience or due to a loss of transparency in teleoperation, one way to potentially improve this is through visual feedback. In [121] visual feedback was used to show the applied force to novices in a knot tying task. The feedback comprises of a set of LEDs changing color from green to red, as the applied force increases. It was shown that the visual feedback significantly reduces the reaction force, task time and improves the suture strength for novices.

Figure 6.6: LEDs shifting color from green to red depending on the applied force during a knot tying task. Adopted from [121].

The same task, but executed through a surgical robotic system is discussed in [122]. In surgical robotic systems direct haptic feedback is negligible and robot assisted haptic feedback is controversial, therefore, visual feedback is suggested as an alternative to aid in a knot tying task. A colored dot is visualized on the controlled EEs, which shift color from green to red depending on the applied force. It was found that for novices the visual feedback resulted in reduced suture breakage, lower forces and decreased force inconsistencies. Though no significant difference was found in completion time and knot quality. However, for surgeons experienced with the system, the metrics remained unaffected. This shows that experienced surgeons are able to derive this information from the camera stream alone and it is probably not worth it to show this cue to these surgeons, as it might increase the workload (though this was not investigated).

Finally, in [123] another suturing task is described that's divided into the tissue puncturing and knot tightening subtasks. It compares the different combinations of haptic and visual force feedback (including no additional feedback). The visual cue consists of a bar for each manipulator which grows with an increasing applied force. Furthermore, this bar is color coded in different sections for different (experimentally determined) magnitudes of force, as shown in Figure 6.7. The first part of the bar is green for low forces, the next part is orange for higher forces and the third part is red for forces that are too high and cause a risk of tissue damage or suture breakage. These forces were determined for the knot tightening task and bear less relevance to the tissue puncturing, as for this task the required force depends on the penetration depth. It was found that in this case, there was no significant difference found between the novices and the experts (contrary to what was found in [122]). A reason for this can be that the system that the experts used here (Haptic Wands) was not the same as the one they were used to (Da Vinci). Furthermore, it was found that the visual feedback did not have any significant effects for the tissue puncturing subtask. A reason for this is that (as mentioned already) the amount of force required to insert the needle varied depending on how deep the needle is being inserted into the tissue. Another reason could be that the color coding in the bars in the visual cue were calibrated for the knot tightening task, and the force needed to penetrate the tissue was always within the green region of the bars during the puncturing task. Therefore, no additional information was provided about the correctness of the force. Conversely, for the knot tightening task it was found that the force applied was more accurate and consistent, compared to haptic or no feedback.
It was found that haptic feedback is effective in reducing the number of collisions with the tissue and reducing the applied pressure as a result of collisions, and take a shorter period of time for completing the task for both tasks, whereas the visual feedback did not result in significant differences for any of these metrics. However, for the case of knot tightening the visual feedback resulted in a more accurate forces being applied, which results in better knots. A reason for this is likely that the visual cue was specified towards this goal and showed information (the required amount of force) that was not present in the haptic feedback alone.

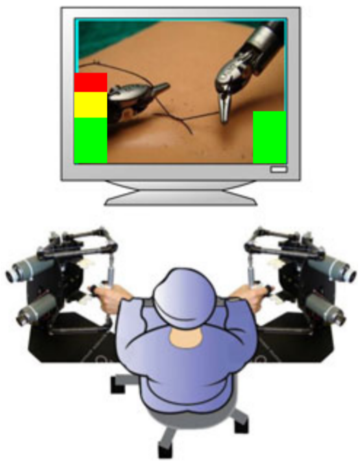


Figure 6.7: Visual force feedback for a suturing task using a surgical robotic system. Adopted from [123].

In conclusion, showing visual force feedback has been found to decrease collision forces and completion time when forces are hard to perceive and operators are not experienced. However, it was found that haptic (force) feedback outperforms visual feedback in these criteria and it said to be more intuitive. Moreover, it was found that this visual cue increases workload, though this was not evaluated for all papers. It could be

especially interesting to make a workload comparison for a visual cue like the one described in [123]. Here, colors are used to indicate the correctness of the force, which could make it easier to know if the correct amount of force is applied, potentially lowering the workload. Visually indicating which objects are colliding was only evaluated in one paper, in which it was compared to force and vibrotactile feedback. There were no significant differences found in completion time. The visual feedback outperformed vibrotactile feedback, but got outperformed by haptic feedback in terms of collision forces.
However, visual force feedback was found to be useful in controlling the amount of force that is applied both in grasping and suturing tasks. A reason force this can be that these visual cues can be specialized towards a certain task so that the operator knows exactly how much force is required, something which is more difficult to convey using haptic feedback. This is most apparent in [121] which has direct haptic feedback. Here, providing additional visual feedback resulted in reduced completion times, reduced maximum applied force and an improved quality of the suture. This shows how visual cues can be used to convey more information than using only haptic feedback, which can help in improving performance. However, it should be noted that a workload comparison was not done for these cues (as mentioned already).

7

Discussion and Conclusion

This literature studies visual cues used in shared control interfaces for the purpose of complementing HSC teleoperation. The use case and reason behind this study is the implementation of teleoperated dross removal from the galvanizing bath of a continuous galvanizing line. Although HSC brings many benefits over regular or fully automated teleoperation, several problems can be identified, as outlined in Section 1.2. One approach to mitigate some of these problems is to implement complementary visual cues. In shared control interfaces many different visual cues have been implemented, however, an overview of these and their effects did not yet exist. This literature study aims to fill this gap by answering the main research question of: *What visual cues are used in shared control teleoperation interfaces?*. This question is answered in the five main chapters, Chapter 2 to 6, structured around a relatively simple control scheme shown in figure 1.1. The control scheme contains five signals for which visual cues can be used to represent them, where each signal is contained within its dedicated chapter.

The categorization of visual cues, although relatively simple, helps to bring some structure in the wide range of visual cues that are used in shared control. This structure aids in describing the effects of a certain type of cue and identifying gaps that are present. However, even within the same signal type the cues can vary a lot in design, as they are often specialized towards that specific situation or task. Furthermore, in many studies visual cues relating to different types of information are simultaneously implemented which means that the effects of any one of these cues is difficult to identify. Despite these weaknesses in this method, it has proven to provide a structured overview of what visual cues are used in shared control teleoperation interfaces. The combined results of this literature study are summarized in Table 7.1.

The first two columns list the cues for each chapter, and are based on the sections contained within that chapter. Underneath each cue, the papers are listed that have implemented this cue, and are discussed in that specific section. The effects of each cue along with the situations in which they are most useful are presented in the two columns after this, and will be discussed in more depth in Section 7.1. The column after this shows in which way the visual cue has been shown to support HSC, which is further elaborated on in Section 7.2. The gaps in literature that limit the complete answering of the research question are highlighted in the final column will be used as part of the discussion in both section where they are relevant. Finally, in Section 7.3 this table is applied to the use case of teleoperated dross removal to select a set of visual cues that could have the most potential for this specific application.

Table 7.1: Summary Table of the entire literature study. For each type of cue it tells in which situation it is most useful and what effects it has on the operation and operator experience. Effects printed in italic are not found through explicit evaluation but usually for the implementation of a combination of cues. These are only stated as supplementary information if little or no other results are available. It is also stated if the cue has been found to support HSC, and if so, in what way it influences the performance. Finally, the last column shows the gaps in literature that prevent the complete answering of the research questions of this literature study.

Chapter	Cue	Useful in situation	Effects	Supporting HSC?	Gaps?
2 Reference	Virtualization [75][76][77][78][79][81][82][83][84]	• Large time delays • Limited bandwidth • occluded or unclear vision • using HMDs	• Improved depth perception • Improved situational awareness • Reduced collisions • Reduced task completion time • Decreased workload	Done, but not explicitly evaluated	• Support for HSC not evaluated
	FRVFs [71][80][91][92][93][94]	• Forbidden region not clear • Extension to other cues	• *Improved situational awareness* • *Increased safety* • *Reduced task completion time*	Done, but not explicitly evaluated. Was said to increase understanding and acceptance.	• Support for HSC not investigated • Cue never explicitly evaluated
	GVFs [95][89][96][97][98][99][83][72][100][74]	• Haptic feedback is not an option • Uncertainty in GVFs • Dynamic GVFs • Extension to other cues	• Increasing accuracy • Reduced task completion time	Yes, reduces completion time, but decreased accuracy [99]	• Support for HSC needs more research • Workload rarely evaluated
3 Guidance	FRVF Guidance [92][94][104][105][106]	• Haptic feedback is not an option • Situational awareness limited but important	• Improving safety • Increases Accuracy	Yes (without influencing workload), • improves safety [105] • Improves user acceptance and preference [106] • *Reduces overshoot* [104][94]	
	GVF Guidance [107][108][96][81][102][109]	• Haptic feedback is not an option • Very high accuracy required	• Reduced task completion time • Increased accuracy • Decreased workload	Done, but not explicitly evaluated. Was said to improve trust and acceptance.	• Support for HSC not investigated • Not all implementations evaluated (though they vary a lot in design)
4 Controller	Controller Output [110][89][91]	• When multiple VFs are used	• Reduced maximum applied force[110] • *Reduced task completion time*	Used for showing active VF, though not evaluated explicitly, was said to help in positioning, resulting in reduced task completion time [91].	• Support for HSC not evaluated • Uncertainty displays potentially interesting but not yet implemented in shared control • Workload not evaluated
5 System	Ghosting [75][76][71][116]	Always used for controlling holonomic systems: • in the presence of large time delays • for programming by demonstration	• Reduced task completion time • *Increased accuracy*	Yes, allows immediate haptic feedback in presence of large time delays [71]	• Workload not investigated
	Predicted Trajectory [94][98][117][104]	• Always used for controlling nonholonomic systems • Extension to other cues	• Reduced task completion time • Decreased control effort (objective and subjective) • Increased safety • Increased confidence • Decreased workload	Yes, though also combined with FRVF guidance • *improved operator experience[94]* • *Disagree with automation more often[94][104]* • *Increased variability in control[104]* • *Increased safety [94]*	• Cue never explicitly evaluated
6 State	System state [99][75][98][117][104]	• Showing system limits for nonholonomic systems			• Few cues available, mainly system limits are shown, which are always displayed together with the predicted trajectory (though this cue is partially included in Section 2.1)
	Environment Interaction [90][81][96][74][119][120][121][122][123]	• Haptic feedback is not an option • Forces are hard to perceive (e.g. lack of transparency or experience)	• Decreased peak reaction force • Improved suture knot quality • Less suture breakage • Workload higher than for haptic feedback [90] (though not evaluated in other papers)	Yes, when forces are hard to perceive due to lack of transparency and experience. Especially useful when color coded to indicate correctness of force. Results in more accurate applied force and higher user acceptance[123].	• Workload rarely evaluated.

7.1. Effects of Visual cues

This section discusses the third and fourth column of Table 7.1, containing the situations in which a specific cue is useful, and what the effects of this cue are. With this, an answer is given to the first subquestion of: *How does each visual cue influence the performance?*. Although this question has been largely answered throughout the main chapters of the report already, it will be answered here in a broader sense.

In order to discuss the effects of the visual cues, it makes sense to first discuss the situations in which these cues can and should be applied, shown in the third column of Table 7.1. An interface designer looking to implement visual cues in a shared control system can use this list to find out if there are specific situations that match the intended situation. For some of these cues their applicability is strictly tied to those situations, for example the predicted trajectory cue in Chapter 5 only makes sense to be used for nonholonomic systems. However, most cues have certain situations in which they make the most sense and are used most often, though they aren't restricted to these situations.
One situation that is reoccurring is the situation in which haptic feedback is not an option. For many cues haptic feedback has been found to outperform visual feedback as is most evident in Section 2.2.2, in which a direct comparison is made between modalities. Reasons that haptic feedback is not an option can be due to restrictions in hardware, but also because in some fields (for example the medical field) haptic feedback is still quite controversial. Furthermore, in some instances haptic feedback was found to disturb the accuracy of certain positioning tasks, like described in Chapter 3.
Another situation which is found multiple times in this list is the extension to other cues. It was found that cues are often combined to give information about multiple types of signals simultaneously. An example of this is found in [92], in which the visualization of a FRVF is shifted in color to indicate the safety of the predicted trajectory. Some cues are implemented with these extensions more often than not. A reason for this can be that these cues on themselves don't bring enough advantages to justify the effort of implementation and workload it takes up. However, when they are combined with other cues they can bring information (for example about the safety of a movement) in an intuitive way, and might be a lot more useful because of this, without taking up a lot of additional workload. The other situations that are listed are quite specific to the individual cues, and are better left to be discussed only in the chapters/sections they refer to.

Furthermore, a situation in which the implementation of a certain cue can be useful is to achieve the effects that it brings, listed in the fourth column of Table 7.1. Some of these effects are quite specific to a certain application (like less suture breakage for environment interaction cues), but most are more general effects (like a reduced task completion time). Furthermore, some effects have been printed in *italic*. These cues have not been found explicitly, but rather due to the implementation of multiple cues simultaneously. These results are only listed to supplement the effects if little to no other effects have been identified explicitly. In one specific case, cues from two separate signal types are always used together (predicted trajectory and system limits), which is why the cells about their effects have been combined as well. Investigating the overall list reveals how visual cues influence the performance, answering the first sub-question of this literature search in a broader, more general sense.

The most common effect is the reduction of the task completion time. A reason for this can be that operators are able to optimize their strategy, because they have access to more information. Perhaps, because of this operators can plan ahead further and operate with more confidence, resulting in better task completion times, as was found in [117]. Another reason completion times were reduced is a little more situation specific, namely when dealing with large time delays, as described in 5.1. In these situations the effect of these time delays can be mitigated using predicted control strategies.
Another common effect is an increase in safety/reduction of collisions. This means that operators operate in a safer way, for example by staying further away from a forbidden region. The reason for this is likely that operators simply are more aware of unsafe behavior due to visual cues warning them. Additionally, visual cues contribute to increasing the situational awareness as found for some cues, which results in safer operation [124]. Furthermore, the displaying of GVFs and the guidance for them results in an increase in accuracy. In this situation the operator is likely more aware of when deviations from some optimal pose/position occur (compared to without the visual cue), resulting in a higher accuracy.
It has also been found that visual cues make other parts of the automation easier to understand, accept, and trust. This effect is found explicitly for the FRVF guidance cue, in which it was specifically investigated in [106]. For several other cues these improvements were found to be a result of the implementation several vi-

sual cues. This means not much can be said about one cue specifically, though it is clear that visual feedback can contribute to these criteria.
Lastly, workload has been found to be reduced for some visual cues, or is unaffected (FRVF guidance) contrarily to what might be expected. A reason for this can be that visual cues can be used to make information simpler to interpret, so that less attention is required to perform an operation. A good example of this is found in [108] where a visual cue indicates if an object is 'graspable', something which is more difficult to determine by just observing the situation. Another reason can be that visual feedback can be manipulated to only show the parts relevant to a certain task, like done in some virtualization methods, described in 2.1. However, visually displaying environment interactions has been shown to increase workload in one case [90]. Furthermore, there were several papers ([109][106][95]) in which the visual cue could clutter the workspace, potentially increasing workload and reducing performance in certain situations. Additionally, it should be noted that the workload was not investigated for all the visual cues, as this could influence the overall outcome of these conclusions.

The categorization of cues done in this report reveals more gaps that limit the complete answering of the research questions. The system state has a relatively small number of visual cues that have been used in shared control. However, this can be explained by the fact that a lot of the information about the system state can be observed by simply looking at the system (for example position, velocity, etc.). Things like the system limits are more difficult to directly observe, and they have been visualized but this is only done for the the maximum steering angle. Additionally, it might be interesting to look at observing other types of limits, for example the workrange of an industrial robot. Furthermore, the controller output has relatively little visual cues. Part of this chapter is represented in Chapter 3, as explained there. However, there are other parts of the controller output signal that might be worth visualizing. One example that has been investigated in the chapter is the visualizing of the controller uncertainties. It has been found that in other types of automation this helps to calibrate trust and prevent misuse and disuse. It could be interesting to see if this extends to shared control systems as well.
The visually displaying of FRVFs is never explicitly investigated but always used together with other cues, whereas with GVFs this is opposite, as the visual display of the GVF is researched quite a lot. An explanation for this difference could be that perhaps just showing forbidden regions isn't thought to be useful enough to justify the occupied screen space and visual workload that could come with it. Instead they often come with additional cues, like FRVF guidance cues or highlighting of the currently active fixture (discussed in Chapter 4), or are implemented in combination with haptic feedback. Visually displaying GVFs often takes up a lot less space on the screen, which likely results in a smaller increase in visual workload. Additionally, they have been shown to result in performance improvements in some cases, as shown in Table 2.2. Though, visualized GVFs are mostly implemented in combination with haptic feedback as well.

7.2. Supporting HSC

In this section the fifth column of Table 7.1 will be discussed, which shows if the cue has been shown to support HSC and if so, in what way. In this way an answer will be given to the second sub-question of: *Can these cues effectively be applied to support haptic shared control teleoperation?*. This question has been partially answered in the separate chapters, however, a more general conclusion will be formed in this section.

Only a handful of papers make the comparison of only haptic feedback to visual- with haptic feedback combined. This comparison is essential as it directly investigates this research question. The way in which these cues have been found to support HSC mostly vary completely in between cues, however, this is not the case for all effects.
The one effect that is almost unanimous between papers are improvements in user experience. In [94] 40% of the operators said having the only the visual cues present just introduced clutter with redundant information, and when only haptic feedback was present the cues were difficult to understand. When the two were combined all operators preferred this feedback type and no such statements were made. Additionally frustration and workload was found to be reduced because of this. Furthermore, in [105] it was found that the understandability and operability of the system increased with the addition of visual cues to the haptic feedback. In [106] it was found that the operator acceptance increased and operators preferred the cues to be present. However, these improvements are only found if the visual cues are relevant to the task. In [123] a suturing task is described in which it was stated that both visual cues and haptic cues were necessary for

the (knot-tying) subtask to be executed by most operators, which was confirmed by improvements in performance. The visual cue was color coded for that specific subtask. However, for a tissue puncturing subtask the visual cue was said to be redundant and didn't bring any performance improvements, as the color coding wasn't relevant to this subtask.
The strength of the visual feedback in these cues seems to be that it can show the operator the correctness, or conversely, the danger of the current action. This is often done by changing the color of other visual cues, for example of a force display in a suturing task [123] or a predicted trajectory for controlling an airplane [106]. This kind of information can not be given using haptic feedback only and thus additional visual information provides context for the haptic feedback. These properties could be the reason that the improvements described above are found.
Something else which is seen, is that overshoot behavior is reduced in [104] and [94], as well as an increase in safety in [106] (insignificant), [94] and [104] (road margins increased, though obstacle margins decreased). Additionally, it was found in [104] and [94] that operators followed the haptic feedback less often. One reason for these effects could be that operators are more aware of the valid options they have. Because of this, they are able to plan ahead further and optimize their own strategy, using the haptic feedback as support instead of a guide. This could also play a role in the reduction of task completion time in [99], though this was at the cost of accuracy.

In conclusion, there are some synergies found in literature in the use of visual cues to support HSC. However, there is not much research available yet. Out of the effects that have been found the improving of user experience is the most common one. Operators seem to be able to understand the haptic information better with the addition of (relevant) visual cues, which leads to various performance improvements. Additionally, operators seem to be able to plan further ahead using visual cues, resulting in a potential increase in disagreements with the automation, however, safety increases and overshoot behavior is reduced.
Most of the research is focused on FRVF guidance in controlling nonholonomic vehicles. In this situation the effects on performance and operator experience are promising and are worth exploring further. Additionally, it might be worth it to investigate these cues for GVFs as well, as somewhat similar results are found in [99]. The greatest strength of visual feedback seems to be that it is able to provide additional information, giving context to the haptic feedback. This shows the operators the correctness of their actions, as well as allow them to form their own strategy using the haptic feedback more as support instead of a guide. This seems to lead to various performance improvements, though additional research is needed to have the research to properly back this up. Furthermore, some of the visual cues have not been investigated as support for HSC at all. A reason for this could be that the design of visual cues is quite difficult as they are often specialized towards a certain situation and need to be designed well so that they provide the information in an intuitive way, without introducing more workload than necessary. Nonetheless, seeing how the results of the existing research give promising improvements, similar results might be found by investigating these visual cues.

7.3. Teleoperated Dross Removal

In this section the summary table will be applied to the use case of teleoperated dross removal. This use case has briefly been discussed in the introduction, but will be reiterated here in a little more depth. This is done to get a good grasp on what is important in the process that we seek to improve.

In high speed galvanizing lines a steel strip goes through a bath containing liquid metal (mostly zinc) where it receives its galvanizing layer. In the this process the bath gets contaminated as the metals oxidize and iron dissolves in the bath, forming dross. A part of this dross floats to the top of the bath, called top dross, and its removal is the process of interest for this report. The removal of this dross is important and is performed 24/7, because when dross gets in contact with the steel strip small defects will occur, deteriorating the quality of the steel strip. The quality of this steel strip is of the utmost importance as a decrease in quality can result in big financial losses. This fact is important to consider also in the removal of the dross, as when this is done incorrectly the quality of the galvanizing layer can also deteriorate. One important consequence of this is that when removing the dross, the bath surface should have as little fluctuations as possible. Additionally, the steel strip should never be touched by the tools as, besides the deterioration in quality, this can result in damage in the tools and equipment.

Conventionally this task is done by a worker that removes this dross manually with a shovel like tool. The plan is to remove this worker from the environment, and perform the operation through the teleoperation of an industrial robot with implemented HSC. To find visual cues that might be useful in improving this set-up, first the important criteria are listed:

- *Low Workload*: Task will have to be executed 24/7. To prevent operators from getting burned out too quickly, a low workload is required.
- *High Safety*: Touching the steel strip will result in big financial losses. Therefore, it is very important that this will not happen.
- *High Situational Awareness*: It is important the operator knows where the dross is located, how the controlled robot is positioned, and what is going on in the environment, for the operation to be executed safely and efficiently.
- *High Accuracy*: The bath should experience minimal fluctuations, as this will deteriorate the quality of the steel strip. For this a high (movement) accuracy is required so that the tool isn't inserted deeper than necessary and the task is executed with the minimal amount of movement.
- *High Movement Smoothness*: Similar to the high accuracy requirement, smooth movements are required to minimize the fluctuations in the bath surface (minimal overshoot, corrective behavior, reaction forces etc.).

With these criteria the table can be used to select which cues have the most potential for improving the interface. To do this, Table 7.1 has been copied and its entries have been color coded in Table 7.2 based on the criteria above. First the properties that are not desired are color coded in red. For three cues this results in their immediate elimination as the situation in which they are useful does not match the use case. There are more red boxes, though these are unwanted effects, which might be worth considering if the advantages outweigh these.

After this, green boxes are placed indicating effects that are sought after. The positive effects that are color coded green are simply the criteria that have been listed above. The situations that have been color coded green might require some explanation and insight. Dross might form in places that are slightly out of view (behind the steel strip, behind tools and structures in the bath etc.) so being able to see these areas can be useful. There are certain regions that are forbidden to work in as they are too close to the steel strip, these might not be obvious for every operator so visually showing them could be helpful. Situational awareness can be limited since the operator has a lot to take into account and as stated it is an important quality to have. Furthermore, high accuracy is required to maintain the quality of the coating. Because of this using visual GVF guidance cues instead of haptic ones (if any) can be beneficial as haptic cues have been shown to be detrimental to positioning task in high accuracy tasks.
Additionally, some parts have been colored blue. These are the parts that are not necessarily sought after but could be useful, so are seen as a bonus. Understanding, trust and acceptance of the system are useful qualities as they improve the operator experience and prevents misuse and disuse, which is important as the operation will have to be performed continuously. Depth perception is useful since the operations will have to be performed in three dimensions and having a lack of depth perception could cause problems in operation. Furthermore, it might be interesting to look at using an HMD (head mounted display) to perform the operation, as they have been found to be useful in improving performance in some situations.
Finally, yellow boxes are inserted, which indicate warnings that the designer should be aware of. These are all things that have not yet been (sufficiently) investigated but might play a role in the performance in using the visual cue.

From this it can be concluded that the following cues are worth investigating for the implementation in this system:

- *Virtualization*: Interesting for improving performance, allowing viewing of occluded areas, and using HMDs.
- *FRVFs*: Indicating which areas are forbidden, which might not always be clear.

- *FRVF guidance*: Improves performance as well as (possibly) reducing overshoot, which could result in smoother movements.
- *GVF guidance*: Found to be useful when very high accuracy is required, as haptic feedback can interfere with positioning in this case. Also has other performance enhancements that are important.
- *Controller output*: Though there is not much research available on cues for this signal, a reduction in maximum applied force and help in positioning can be beneficial for this application. So these cues may be worth investigating.
- *Environment interaction*: The color coding of forces could be used to show the interactions with the bath. This could reduce the peak reaction force, and with that reduce the fluctuations in the bath. Though this might come with additional workload.

In conclusion, Table 7.1 can be used to identify which visual cues have the most potential for improving performance in a chosen situation. This process is shown in this section, using the use case of teleoperated dross removal as an example. This results in a selection of cues that are worth investigating, though the interface designer should be wary of the gaps in literature that belong to these cues. Nonetheless, this selection of visual cues (and the corresponding papers that use them) can provide guidance in the development of the visual interface, given the vast range of visual cues used in shared control systems that was previously unstructured.

Table 7.2: Summary table (previously shown in Table 7.1) color coded for the specific case of teleoperated undesired features, green boxes indicate desired features, blue boxes indicate bonus features and yellow boxes indicate warnings for potential problems.

Chapter		Cue	Useful in situation	Effects	Supporting HSC?	Gaps?
2	Reference	Virtualization [75][76][77][78][79][81] [82][83][84]	• Large time delays • Limited bandwidth • occluded or unclear vision • using HMDs	• Improved depth perception • Improved situational awareness • Reduced collisions • Reduced task completion time • Decreased workload	Done, but not explicitly evaluated	• Support for HSC not evaluated
		FRVFs [71][80][91][92][93][94]	• Forbidden region not clear • Extension to other cues	• *Improved situational awareness* • *Increased safety* • *Reduced task completion time*	Done, but not explicitly evaluated. Was said to increase understanding and acceptance.	• Support for HSC not investigated • Cue never explicitly evaluated
		GVFs [95][89][96][97][98][99] [83][72][100][74]	• Haptic feedback is not an option • Uncertainty in GVFs • Dynamic GVFs • Extension to other cues	• Increasing accuracy • Reduced task completion time	Yes, reduces completion time, but decreased accuracy [99]	• Support for HSC needs more research • Workload rarely evaluated
3	Guidance	FRVF Guidance [92][94][104][105][106]	• Haptic feedback is not an option • Situational awareness limited but important	• Improving safety • Increases Accuracy	Yes (without influencing workload), • improves safety [105] • Improves user acceptance and preference [106] • *Reduces overshoot* [104][94]	
		GVF Guidance [107][108][96][81][102] [109]	• Haptic feedback is not an option • Very high accuracy required	• Reduced task completion time • Increased accuracy • Decreased workload	Done, but not explicitly evaluated. Was said to improve trust and acceptance.	• Support for HSC not investigated • Not all implementations evaluated (though they vary a lot in design)
4	Controller	Controller Output [110][89][91]	• When multiple VFs are used	• Reduced maximum applied force[110] • *Reduced task completion time*	Used for showing active VF, though not evaluated explicitly, was said to help in positioning, resulting in reduced task completion time [91].	• Support for HSC not evaluated • Uncertainty displays potentially interesting but not yet implemented in shared control • Workload not evaluated
5	System	Ghosting [75][76][71][116]	Always used for controlling holonomic systems: • in the presence of large time delays • for programming by demonstration	• Reduced task completion time • *Increased accuracy*	Yes, allows immediate haptic feedback in presence of large time delays [71]	• Workload not investigated
		Predicted Trajectory [94][98][117][104]	• Always used for controlling nonholonomic systems • Extension to other cues	• Reduced task completion time • Decreased control effort (objective and subjective) • Increased safety • Increased confidence • Decreased workload	Yes, though also combined with FRVF guidance • *improved operator experience[94]* • *Disagree with automation more often[94][104]* • *Increased variability in control[104]* • *Increased safety [94]*	• Cue never explicitly evaluated
6	State	System state [99][75][98][117][104]	• Showing system limits for nonholonomic systems			• Few cues available, mainly system limits are shown, which are always displayed together with the predicted trajectory (though this cue is partially included in Section 2.1)
		Environment Interaction [90][81][96][74][119][120] [121][122][123]	• Haptic feedback is not an option • Forces are hard to perceive (e.g. lack of transparency or experience)	• Decreased peak reaction force • Improved suture knot quality • Less suture breakage • Workload higher than for haptic feedback [90] (though not evaluated in other papers)	Yes, when forces are hard to perceive due to lack of transparency and experience. Especially useful when color coded to indicate correctness of force. Results in more accurate applied force and higher user acceptance[123].	• Workload rarely evaluated.

8 Future work

The result of this literature research is a summarizing table (Table 7.1), summarizing the information gathered about visual cues used in shared control systems. In Section 7.3, this table was applied to the use case of teleoperated dross removal. The result of this process is a selection of visual cues that have the most potential in improving the performance of this set-up. From these cues the I have chosen to work on the virtualization cue for my MSc thesis. Besides this, I will investigate the effects of the implementation of a HMD in combination with the virtualization cue. I made this choice because this cue is very versatile in how it can be applied, and has been shown to improve the performance in the criteria relevant to this application. Additionally, it can be extended with most of the visual cues found, and with the implementation of HMDs. Furthermore, there has been no research yet that explicitly investigates the effects that virtualization brings when it is used to support HSC. This combination has been found to be beneficial in several situations, as discussed in Section 7.2. Therefore, it is interesting to see if these benefits can also be found for this specific visual cue.
This visual cue will be applied to the same use case of teleoperated dross removal, focusing on the same criteria as described in Section 7.3. The reason for this is that this allows me to further develop this use case, as well as re-apply additional knowledge that I've gathered in the making of this literature report.

Bibliography

[1] M. K. O'Malley, A. Gupta, M. Gen, and Y. Li, "Shared control in haptic systems for performance enhancement and training," *Journal of Dynamic Systems, Measurement, and Control*, vol. 128, no. 1, pp. 75–85, 2006.

[2] M. A. Bright, G. C. Becherer, and R. L. Grodeck, "Galvanizing bath apparatus," 7 2013, uS Patent 8,475,594.

[3] X. Hao, L. Bai, C. Yue, X. Xu, Z. Yin, and M. Zhang, "The research and application of zinc dross removing robot in galvanized production line," 2018.

[4] J.-y. Lee and S. Payandeh, *Haptic Teleoperation Systems.* Springer, 2015.

[5] M. J. Massimino and T. B. Sheridan, "Variable force and visual feedback effects on teleoperator man/machine performance," 1989.

[6] J. G. Wildenbeest, D. A. Abbink, C. J. Heemskerk, F. C. Van Der Helm, and H. Boessenkool, "The impact of haptic feedback quality on the performance of teleoperated assembly tasks," *IEEE Transactions on Haptics*, vol. 6, no. 2, pp. 242–252, 2012.

[7] E. WIENER and R. CURRY, "FLIGHT-DECK AUTOMATION - PROMISES AND PROBLEMS," *ERGONOMICS*, vol. 23, no. 10, pp. 995–1011, 1980.

[8] R. Parasuraman and C. D. Wickens, "Humans: Still vital after all these years of automation," *Human factors*, vol. 50, no. 3, pp. 511–520, 2008.

[9] G. Salvendy, *Handbook of human factors and ergonomics.* John Wiley & Sons, 2012.

[10] J. D. Lee, "Review of a pivotal human factors article: "humans and automation: Use, misuse, disuse, abuse"," *Human Factors*, vol. 50, no. 3, pp. 404–410, 2008, pMID: 18689046. [Online]. Available: https://doi.org/10.1518/001872008X288547

[11] N. B. Sarter and D. D. Woods, "How in the world did we ever get into that mode? mode error and awareness in supervisory control," *Human Factors*, vol. 37, no. 1, pp. 5–19, 1995. [Online]. Available: https://doi.org/10.1518/001872095779049516

[12] M. R. Endsley and E. O. Kiris, "The out-of-the-loop performance problem and level of control in automation," *Human factors*, vol. 37, no. 2, pp. 381–394, 1995.

[13] B. Hannaford and A. M. Okamura, *Haptics.* Cham: Springer International Publishing, 2016, pp. 1063–1084. [Online]. Available: https://doi.org/10.1007/978-3-319-32552-1_42

[14] M. Sreelakshmi and T. Subash, "Haptic technology: A comprehensive review on its applications and future prospects," *Materials Today: Proceedings*, vol. 4, no. 2, pp. 4182–4187, 2017.

[15] J. Y. C. Chen, E. C. Haas, and M. J. Barnes, "Human performance issues and user interface design for teleoperated robots," *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, vol. 37, no. 6, pp. 1231–1245, 2007.

[16] S. D. Stigter, M. Mulder, and M. Van Paassen, "Design and evaluation of a haptic flight director," *Journal of guidance, control, and dynamics*, vol. 30, no. 1, pp. 35–46, 2007.

[17] D. Abbink and M. Mulder, "Exploring the dimensions of haptic feedback support in manual control," *Journal of Computing and Information Science in Engineering*, vol. 9, no. 1, p. 011006, 2009.

[18] K. E. Maclean and V. Hayward, "Do it yourself haptics: Part ii [tutorial]," *IEEE Robotics Automation Magazine*, vol. 15, no. 1, pp. 104–119, 2008.

[19] M. Reiner, “Seeing through touch: The role of haptic information in visualization,” in *Visualization: Theory and practice in science education.* Springer, 2008, pp. 73–84.

[20] S. Deng, J. A. Kirkby, J. Chang, and J. J. Zhang, “Multimodality with eye tracking and haptics: a new horizon for serious games?” *International Journal of Serious Games*, vol. 1, no. 4, pp. 17–34, 2014.

[21] F. L. Engel, P. Goossens, and R. Haakma, “Improved efficiency through i-and e-feedback: A trackball with contextual force feedback,” *International Journal of Human-Computer Studies*, vol. 41, no. 6, pp. 949–974, 1994.

[22] D. Kaber, L. A. Tupler, M. Clamann, G.-H. Gil, B. Zhu, M. Swangnetr, W. Jeon, Y. Zhang, X. Qin, W. Ma *et al.*, “Evaluation of an augmented virtual reality and haptic control interface for psychomotor training,” *Assistive Technology*, vol. 26, no. 1, pp. 51–60, 2014.

[23] H. Wu, S. Liang, W. Hang, X. Liu, Q. Wang, K.-S. Choi, and J. Qin, “Evaluation of motor training performance in 3d virtual environment via combining brain-computer interface and haptic feedback,” *Procedia Computer Science*, vol. 107, pp. 256–261, 2017.

[24] J. G. Wildenbeest, D. A. Abbink, and J. F. Schorsch, “Haptic transparency increases the generalizability of motor learning during telemanipulation,” in *2013 World Haptics Conference (WHC).* IEEE, 2013, pp. 707–712.

[25] B. Hannaford, L. Wood, D. A. McAffee, and H. Zak, “Performance evaluation of a six-axis generalized force-reflecting teleoperator,” *IEEE transactions on systems, man, and cybernetics*, vol. 21, no. 3, pp. 620–633, 1991.

[26] P. G. Griffiths and R. B. Gillespie, “Sharing control between humans and automation using haptic interface: Primary and secondary task performance benefits,” *Human Factors*, vol. 47, no. 3, pp. 574–590, 2005, pMID: 16435698. [Online]. Available: https://doi.org/10.1518/001872005774859944

[27] J. Draper, W. Moore, J. Herndon, and B. Weil, “Effects of force reflection on servomanipulator task performance,” Oak Ridge National Lab., TN (USA), Tech. Rep., 1986.

[28] M. Barnes, K. Cosenzo, D. Mitchell, and J. Chen, “Human robot teams as soldier augmentation in future battlefields: An overview,” in *Proc. 11th Int. Conf. Hum*, 2005.

[29] G. C. Burdea, *Force and Touch Feedback for Virtual Reality.* New York, NY, USA: John Wiley & Sons, Inc., 1996.

[30] C. Passenberg, A. Peer, and M. Buss, “A survey of environment-, operator-, and task-adapted controllers for teleoperation systems,” *Mechatronics*, vol. 20, no. 7, pp. 787 – 801, 2010, special Issue on Design and Control Methodologies in Telerobotics. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0957415810000735

[31] M. Eimer and J. Driver, “An event-related brain potential study of cross-modal links in spatial attention between vision and touch,” *Psychophysiology*, vol. 37, no. 5, pp. 697–705, 2000.

[32] C. H. Park and A. M. Howard, “Vision-based force guidance for improved human performance in a teleoperative manipulation system,” in *2007 IEEE/RSJ International Conference on Intelligent Robots and Systems.* IEEE, 2007, pp. 2126–2131.

[33] D. A. Abbink, M. Mulder, and E. R. Boer, “Haptic shared control: smoothly shifting control authority?” *Cognition, Technology & Work*, vol. 14, no. 1, pp. 19–28, 2012.

[34] M. Mulder, D. A. Abbink, and E. R. Boer, “Sharing control with haptics: Seamless driver support from manual to automatic control,” *Human Factors*, vol. 54, no. 5, pp. 786–798, 2012, pMID: 23156623. [Online]. Available: https://doi.org/10.1177/0018720812443984

[35] L. B. Rosenberg, “Virtual fixtures: Perceptual tools for telerobotic manipulation,” in *Proceedings of IEEE Virtual Reality Annual International Symposium*, 9 1993, pp. 76–82.

[36] J. J. Abbott, P. Marayong, and A. M. Okamura, "Haptic virtual fixtures for robot-assisted manipulation," in *Robotics Research*, S. Thrun, R. Brooks, and H. Durrant-Whyte, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2007, pp. 49–64.

[37] D. A. Abbink, T. Carlson, M. Mulder, J. C. de Winter, F. Aminravan, T. L. Gibo, and E. R. Boer, "A topology of shared control systems—finding common ground in diversity," *IEEE Transactions on Human-Machine Systems*, no. 99, pp. 1–17, 2018.

[38] H. Boessenkool, D. A. Abbink, C. J. M. Heemskerk, F. C. T. van der Helm, and J. G. W. Wildenbeest, "A task-specific analysis of the benefit of haptic shared control during telemanipulation," *IEEE Transactions on Haptics*, vol. 6, no. 1, pp. 2–12, 1 2013.

[39] M. Itoh, F. Flemisch, and D. Abbink, "A hierarchical framework to analyze shared control conflicts between human and machine," *IFAC-PapersOnLine*, vol. 49, no. 19, pp. 96 – 101, 2016, 13th IFAC Symposium on Analysis, Design, and Evaluation ofHuman-Machine Systems HMS 2016. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S2405896316320584

[40] F. Flemisch, J. Kelsch, C. Löper, A. Schieben, and J. Schindler, "Automation spectrum, inner/outer compatibility and other potentially useful human factors concepts for assistance and automation," *Human Factors for assistance and automation*, no. 2008, pp. 1–16, 2008.

[41] R. Parasuraman and V. Riley, "Humans and automation: Use, misuse, disuse, abuse," *Human factors*, vol. 39, no. 2, pp. 230–253, 1997.

[42] M. A. Goodrich, J. W. Crandall, and E. Barakova, "Teleoperation and beyond for assistive humanoid robots," *Reviews of Human factors and ergonomics*, vol. 9, no. 1, pp. 175–226, 2013.

[43] D. A. Abbink, D. Cleij, M. Mulder, and M. M. v. Paassen, "The importance of including knowledge of neuromuscular behaviour in haptic shared control," in *2012 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, 10 2012, pp. 3350–3355.

[44] A. W. de Jonge, J. G. W. Wildenbeest, H. Boessenkool, and D. A. Abbink, "The effect of trial-by-trial adaptation on conflicts in haptic shared control for free-air teleoperation tasks," *IEEE Transactions on Haptics*, vol. 9, no. 1, pp. 111–120, 1 2016.

[45] R. Boink, M. M. van Paassen, M. Mulder, and D. A. Abbink, "Understanding and reducing conflicts between driver and haptic shared control," in *2014 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, 10 2014, pp. 1510–1515.

[46] W. Scholtens, S. Barendswaard, D. Pool, R. Van Paassen, and D. Abbink, "A new haptic shared controller reducing steering conflicts," in *2018 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, 10 2018, pp. 2705–2710.

[47] A. H. Ghasemi, M. Johns, B. Garber, P. Boehm, P. Jayakumar, W. Ju, and R. B. Gillespie, "Role negotiation in a haptic shared control framework," in *Adjunct Proceedings of the 8th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, ser. AutomotiveUI '16 Adjunct. ACM, 2016, pp. 179–184. [Online]. Available: http://doi.acm.org.tudelft.idm.oclc.org/10.1145/3004323.3004349

[48] J. M. Flach, F. Tanabe, K. Monta, K. J. Vicente, and J. Rasmussen, "An ecological approach to interface design," in *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 42, no. 3. SAGE Publications Sage CA: Los Angeles, CA, 1998, pp. 295–299.

[49] K. Christoffersen and D. D. Woods, "How to make automated systems team players," in *Advances in human performance and cognitive engineering research.* Emerald Group Publishing Limited, 2002, pp. 1–12.

[50] D. A. Norman, "The 'problem'with automation: inappropriate feedback and interaction, not 'over-automation'," *Philosophical Transactions of the Royal Society of London. B, Biological Sciences*, vol. 327, no. 1241, pp. 585–593, 1990.

[51] E. B. Entin, E. E. Entin, and D. Serfaty, "Optimizing aided target-recognition performance," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 40, no. 4, pp. 233–237, 1996. [Online]. Available: https://doi.org/10.1177/154193129604000419

[52] H. B. Barlow, H. B. Barlow, and J. Mollon, *Senses.* CUP Archive, 1982, vol. 3.

[53] P. A. Hancock, D. R. Billings, and K. E. Schaefer, "Can you trust your robot?" *Ergonomics in Design*, vol. 19, no. 3, pp. 24–29, 2011.

[54] K. A. Hoff and M. Bashir, "Trust in automation: Integrating empirical evidence on factors that influence trust," *Human Factors*, vol. 57, no. 3, pp. 407–434, 2015.

[55] M. T. Dzindolet, S. A. Peterson, R. A. Pomranky, L. G. Pierce, and H. P. Beck, "The role of trust in automation reliance," *International Journal of Human-Computer Studies*, vol. 58, no. 6, pp. 697 – 718, 2003, trust and Technology. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1071581903000387

[56] J. LEE and N. MORAY, "Trust, control strategies and allocation of function in human-machine systems," *Ergonomics*, vol. 35, no. 10, pp. 1243–1270, 1992, pMID: 1516577. [Online]. Available: https://doi.org/10.1080/00140139208967392

[57] E. J. de Visser, M. Cohen, A. Freedy, and R. Parasuraman, "A design methodology for trust cue calibration in cognitive agents," in *Virtual, Augmented and Mixed Reality. Designing and Developing Virtual and Augmented Environments*, R. Shumaker and S. Lackey, Eds. Cham: Springer International Publishing, 2014, pp. 251–262.

[58] J. M. McGuirl and N. B. Sarter, "Supporting trust calibration and the effective use of decision aids by presenting dynamic system confidence information," *Human Factors*, vol. 48, no. 4, pp. 656–665, 2006, pMID: 17240714. [Online]. Available: https://doi.org/10.1518/001872006779166334

[59] T. Lam, M. Mulder, M. Van Paassen, J. Mulder, and F. Van der Helm, "Force-stiffness feedback in uav tele-operation with time delay," in *AIAA Guidance, Navigation, and Control Conference*, 2009, p. 5977.

[60] T. M. Lam, "Haptic interface for uav teleoperation," 2009.

[61] A. R. Seitz, R. Kim, V. van Wassenhove, and L. Shams, "Simultaneous and independent acquisition of multisensory and unisensory associations," *Perception*, vol. 36, no. 10, pp. 1445–1453, 2007.

[62] C. Spence and J. Driver, *Crossmodal space and crossmodal attention.* Oxford University Press, 2004.

[63] M. O. Ernst and M. S. Banks, "Humans integrate visual and haptic information in a statistically optimal fashion," *Nature*, vol. 415, no. 6870, p. 429, 2002.

[64] D. Alais and D. Burr, "The ventriloquist effect results from near-optimal bimodal integration," *Current Biology*, vol. 14, no. 3, pp. 257 – 262, 2004. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0960982204000430

[65] T. L. Gibo, W. Mugge, and D. A. Abbink, "Trust in haptic assistance: weighting visual and haptic cues based on error history," *Experimental Brain Research*, vol. 235, no. 8, pp. 2533–2546, 9 2017. [Online]. Available: https://doi.org/10.1007/s00221-017-4986-4

[66] T. L. Gibo, M. A. Plaisier, W. Mugge, and D. A. Abbink, "Reliance on haptic assistance reflected in haptic cue weighting," *IEEE Transactions on Haptics*, vol. 12, no. 1, pp. 68–77, Jan. 2019.

[67] P. Richard and P. Coiffet, "Human perceptual issues in virtual environments: sensory substitution and information redundancy," in *Proceedings 4th IEEE International Workshop on Robot and Human Communication*, 7 1995, pp. 301–306.

[68] M. J. Massimino and T. B. Sheridan, "Sensory substitution for force feedback in teleoperation," *Presence: Teleoperators and Virtual Environments*, vol. 2, no. 4, pp. 344–352, 1993. [Online]. Available: https://doi.org/10.1162/pres.1993.2.4.344

[69] H. B. Helbig and M. O. Ernst, “Optimal integration of shape information from vision and touch,” *Experimental Brain Research*, vol. 179, no. 4, pp. 595–606, Jun. 2007. [Online]. Available: https://doi.org/10.1007/s00221-006-0814-y

[70] S. LEDERMAN, G. THORNE, and B. JONES, “Perception of texture by vision and touch - multidimensionality and intersensory integration,” *JOURNAL OF EXPERIMENTAL PSYCHOLOGY-HUMAN PERCEPTION AND PERFORMANCE*, vol. 12, no. 2, pp. 169–180, 5 1986.

[71] T. Xia, S. Leonard, A. Deguet, L. Whitcomb, and P. Kazanzides, “Augmented reality environment with virtual fixtures for robotic telemanipulation in space,” in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2012, pp. 5059–5064.

[72] V. Pruks, K.-H. Lee, and J.-H. Ryu, “Shared teleoperation for nuclear plant robotics using interactive virtual guidance generation and shared autonomy approaches,” in *2018 15th International Conference on Ubiquitous Robots (UR)*. IEEE, 2018, pp. 91–95.

[73] K.-H. Lee, V. Pruks, and J.-H. Ryu, “Development of shared autonomy and virtual guidance generation system for human interactive teleoperation,” in *2017 14th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI)*. IEEE, 2017, pp. 457–461.

[74] K. Cho, K. Ko, H. Shim, and I. Jang, “Development of automatic virtual guidance visualization system for teleoperation using object detection,” in *2018 15th International Conference on Ubiquitous Robots (UR)*. IEEE, 2018, pp. 63–66.

[75] Y. Wang, F. Sun, L. Hu, Z. Li, and H. Liu, “Space teleoperation with large time delay based on vision feedback and virtual reality,” in *2009 IEEE/ASME International Conference on Advanced Intelligent Mechatronics*. IEEE, 2009, pp. 1200–1205.

[76] B. P. Vagvolgyi, W. Pryor, R. Reedy, W. Niu, A. Deguet, L. L. Whitcomb, S. Leonard, and P. Kazanzides, “Scene modeling and augmented virtuality interface for telerobotic satellite servicing,” *IEEE Robotics and Automation Letters*, vol. 3, no. 4, pp. 4241–4248, 2018.

[77] S. Otmane, M. Mallem, A. Kheddar, and F. Chavand, “Ariti: an augmented reality interface for teleopeation on the internet,” in *Advanced Simulation Technologies Conf.(ASTC2000)*. Wyndham City Center Hotel Washington, DC (USA), 2000, pp. 254–261.

[78] M. Ammi, A. Ferreira, and J.-G. Fontaine, “Virtualized reality interface for tele-micromanipulation,” in *IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA’04. 2004*, vol. 3. IEEE, 2004, pp. 2776–2781.

[79] V. Falk, D. Mintz, J. Grunenfelder, J. Fann, and T. Burdon, “Influence of three-dimensional vision on surgical telemanipulator performance,” *Surgical endoscopy*, vol. 15, no. 11, pp. 1282–1288, 2001.

[80] M. Ammi and A. Ferreira, “Robotic assisted micromanipulation system using virtual fixtures and metaphors,” in *Proceedings 2007 IEEE International Conference on Robotics and Automation*. IEEE, 2007, pp. 454–460.

[81] L. T. De Paolis and V. De Luca, “Augmented visualization with depth perception cues to improve the surgeon’s performance in minimally invasive surgery,” *Medical & biological engineering & computing*, vol. 57, no. 5, pp. 995–1013, 2019.

[82] B. Petzold, M. F. Zaeh, B. Faerber, B. Deml, H. Egermeier, J. Schilp, and S. Clarke, “A study on visual, auditory, and haptic feedback for assembly tasks,” *Presence: Teleoperators & Virtual Environments*, vol. 13, no. 1, pp. 16–21, 2004.

[83] K. Huang, D. Chitrakar, F. Rydén, and H. J. Chizeck, “Evaluation of haptic guidance virtual fixtures and 3d visualization methods in telemanipulation—a user study,” *Intelligent Service Robotics*, pp. 1–13, 2019.

[84] M. Mast, M. Španěl, G. Arbeiter, V. Štancl, Z. Materna, F. Weisshardt, M. Burmester, P. Smrž, and B. Graf, “Teleoperation of domestic service robots: effects of global 3d environment maps in the user interface on operators’ cognitive and performance metrics,” in *International conference on social robotics*. Springer, 2013, pp. 392–401.

[85] A. Ghanbari, X. Chen, W. Wang, B. Horan, H. Abdi, and S. Nahavandi, “Haptic microrobotic intracellular injection assistance using virtual fixtures,” in *2010 11th International Conference on Control Automation Robotics & Vision*. IEEE, 2010, pp. 781–786.

[86] K. Zarei-nia, N. Sepehri, T. Olson, and W. Mueller, “Haptic-enabled control of hydraulic manipulators applied to power line maintenance: Concept & implementation,” in *2010 1st International Conference on Applied Robotics for the Power Industry*. IEEE, 2010, pp. 1–6.

[87] L. B. Rosenberg, “Virtual haptic overlays enhance performance in telepresence tasks,” in *Telemanipulator and Telepresence Technologies*, vol. 2351. International Society for Optics and Photonics, 1995, pp. 99–109.

[88] C. P. Sayers and R. P. Paul, “An operator interface for teleprogramming employing synthetic fixtures,” *Presence: Teleoperators & Virtual Environments*, vol. 3, no. 4, pp. 309–320, 1994.

[89] S. Payandeh and Z. Stanisic, “On application of virtual fixtures as an aid for telemanipulation and training,” in *Proceedings 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. HAPTICS 2002*. IEEE, 2002, pp. 18–23.

[90] B. Weber, M. Sagardia, T. Hulin, and C. Preusche, “Visual, vibrotactile, and force feedback of collisions in virtual environments: effects on performance, mental workload and spatial orientation,” in *International Conference on Virtual, Augmented and Mixed Reality*. Springer, 2013, pp. 241–250.

[91] O. Halabi and Y. Halwani, “Design and implementation of haptic virtual fixtures for preoperative surgical planning,” *Displays*, vol. 54, pp. 9–19, 2018.

[92] F. Giulietti, L. Pollini, and G. Avanzini, “Visual aids for safe operation of remotely piloted vehicles in the controlled air space,” *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, vol. 230, no. 9, pp. 1641–1654, 2016.

[93] M. Razzanelli, S. Aringhieri, G. Franzini, G. Avanzini, F. Giulietti, M. Innocenti, and L. Pollini, “A visual-haptic display for human and autonomous systems integration,” in *International Workshop on Modelling and Simulation for Autonomous Systems*. Springer, 2016, pp. 64–80.

[94] C. Borst, F. Grootendorst, D. Brouwer, C. Bedoya, M. Mulder, and M. Van Paassen, “Design and evaluation of a safety augmentation system for aircraft,” *Journal of Aircraft*, vol. 51, no. 1, pp. 12–22, 2013.

[95] S. Otmane, M. Mallem, A. Kheddar, and F. Chavand, “Active virtual guides as an apparatus for augmented reality based telemanipulation system on the internet,” in *Proceedings 33rd Annual Simulation Symposium (SS 2000)*. IEEE, 2000, pp. 185–191.

[96] Z. Cui, Y. Liu, and Z. Gong, “Research on multi-sensory virtual guides based robotic teleoperation system,” in *2006 International Conference on Mechatronics and Automation*. IEEE, 2006, pp. 1447–1452.

[97] F. Wang and S. Payandeh, “A study of hybrid virtual fixtures in assistive path following problems,” in *2012 IEEE International Conference on Development and Learning and Epigenetic Robotics (ICDL)*. IEEE, 2012, pp. 1–2.

[98] R. J. Kuiper, D. J. Heck, I. A. Kuling, and D. A. Abbink, “Evaluation of haptic and visual cues for repulsive or attractive guidance in nonholonomic steering tasks,” *IEEE Transactions on Human-Machine Systems*, vol. 46, no. 5, pp. 672–683, 2016.

[99] A. Rodriguez, E. Nuño, L. Palomo, and L. Basañez, “Nonlinear control and geometric constraint enforcement for teleoperated task execution,” in *2010 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2010, pp. 5251–5257.

[100] N. V. Navkar, Z. Deng, D. J. Shah, K. E. Bekris, and N. V. Tsekos, “Visual and force-feedback guidance for robot-assisted interventions in the beating heart with real-time mri,” in *2012 IEEE international conference on robotics and automation*. IEEE, 2012, pp. 689–694.

[101] Z. Liu, P. Huang, Z. Lu, and J. Pan, “A compound virtual fixture for dexterous space teleoperation,” in *2015 12th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI)*. IEEE, 2015, pp. 261–266.

[102] M. Abayazid, C. Pacchierotti, P. Moreira, R. Alterovitz, D. Prattichizzo, and S. Misra, "Experimental evaluation of co-manipulated ultrasound-guided flexible needle steering," *The International Journal of Medical Robotics and Computer Assisted Surgery*, vol. 12, no. 2, pp. 219–230, 2016.

[103] C. Borst, V. A. Bijsterbosch, M. van Paassen, and M. Mulder, "Ecological interface design: supporting fault diagnosis of automated advice in a supervisory air traffic control task," *Cognition, Technology & Work*, vol. 19, no. 4, pp. 545–560, 2017.

[104] W. Vreugdenhil, "Complementing automotive haptic shared control with visual feedback for obstacle avoidance," 2019.

[105] A. Nakazawa, K. Nanri, K. Harada, S. Tanaka, H. Nukariya, Y. Kurose, N. Shono, H. Nakatomi, A. Morita, E. Watanabe *et al.*, "Feedback methods for collision avoidance using virtual fixtures for robotic neurosurgery in deep and narrow spaces," in *2016 6th IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob)*. IEEE, 2016, pp. 247–252.

[106] V. Ho, C. Borst, M. M. van Paassen, and M. Mulder, "Increasing acceptance of haptic feedback in uav teleoperation by visualizing force fields," in *2018 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*. IEEE, 2018, pp. 3027–3032.

[107] J. Aleotti, S. Caselli, and M. Reggiani, "Evaluation of virtual fixtures for a robot programming by demonstration interface," *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans*, vol. 35, no. 4, pp. 536–545, 2005.

[108] K. Hertkorn, B. Weber, P. Kremer, M. A. Roa, and C. Borst, "Assistance for telepresence using online grasp planning," in *2013 13th IEEE-RAS International Conference on Humanoid Robots (Humanoids)*. IEEE, 2013, pp. 507–513.

[109] C. Heemskerk, P. Eendebak, G. Schropp, H. Hermes, B. Elzendoorn, and A. Magielsen, "Introducing artificial depth cues to improve task performance in iter maintenance actions," *Fusion Engineering and Design*, vol. 88, no. 9-10, pp. 1969–1972, 2013.

[110] W. B. Griffin, W. R. Provancher, and M. R. Cutkosky, "Feedback strategies for telemanipulation with shared control of object handling forces," *Presence: Teleoperators & Virtual Environments*, vol. 14, no. 6, pp. 720–731, 2005.

[111] M. T. Dzindolet, S. A. Peterson, R. A. Pomranky, L. G. Pierce, and H. P. Beck, "The role of trust in automation reliance," *International journal of human-computer studies*, vol. 58, no. 6, pp. 697–718, 2003.

[112] J. Beller, M. Heesen, and M. Vollrath, "Improving the driver–automation interaction: An approach using automation uncertainty," *Human factors*, vol. 55, no. 6, pp. 1130–1141, 2013.

[113] B. D. Seppelt and J. D. Lee, "Making adaptive cruise control (acc) limits visible," *International journal of human-computer studies*, vol. 65, no. 3, pp. 192–205, 2007.

[114] D. A. Abbink, "Neuromuscular analysis of haptic gas pedal feedback during car following," 2006.

[115] A. K. Bejczy and W. S. Kim, "Predictive displays and shared compliance control for time-delayed telemanipulation," in *EEE International Workshop on Intelligent Robots and Systems, Towards a New Frontier of Applications*. IEEE, 1990, pp. 407–412.

[116] D. Ni, A. Yew, S. Ong, and A. Nee, "Haptic and visual augmented reality interface for programming welding robots," *Advances in Manufacturing*, vol. 5, no. 3, pp. 191–198, 2017.

[117] T. Rijndorp, C. Borst, C. C. de Visser, O. Stroosma, M. Mulder, and M. van Paassen, "Aviate, navigate: Functional visualizations of asymmetric flight envelope limits," in *AIAA Information Systems-AIAA Infotech@ Aerospace*, 2017, p. 1297.

[118] C. Borst, J. M. Flach, and J. Ellerbroek, "Beyond ecological interface design: Lessons from concerns and misconceptions," *IEEE Transactions on Human-Machine Systems*, vol. 45, no. 2, pp. 164–175, April 2015.

[119] A. Lécuyer, C. Mégard, J.-M. Burkhardt, T. Lim, S. Coquillart, P. Coiffet, and L. Graux, "The effect of haptic, visual and auditory feedback on an insertion task on a 2-screen workbench," in *Proceedings of the Immersive Projection Technology Symposium*, vol. 2, 2002.

[120] P. Galambos, A. Róka, G. Sörös, and P. Korondi, "Visual feedback techniques for telemanipulation and system status sensualization," in *2010 IEEE 8th International Symposium on Applied Machine Intelligence and Informatics (SAMI)*. IEEE, 2010, pp. 145–151.

[121] T. Horeman, M. D. Blikkendaal, D. Feng, A. van Dijke, F. Jansen, J. Dankelman, and J. J. van den Dobbelsteen, "Visual force feedback improves knot-tying security," *Journal of surgical education*, vol. 71, no. 1, pp. 133–141, 2014.

[122] C. E. Reiley, T. Akinbiyi, D. Burschka, D. C. Chang, A. M. Okamura, and D. D. Yuh, "Effects of visual force feedback on robot-assisted surgical task performance," *The Journal of thoracic and cardiovascular surgery*, vol. 135, no. 1, pp. 196–202, 2008.

[123] A. Talasaz, A. L. Trejos, and R. V. Patel, "The role of direct and visual force feedback in suturing using a 7-dof dual-arm teleoperated system," *IEEE transactions on haptics*, vol. 10, no. 2, pp. 276–287, 2016.

[124] F. Flemisch, M. Heesen, T. Hesse, J. Kelsch, A. Schieben, and J. Beller, "Towards a dynamic balance between humans and automation: authority, ability, responsibility and control in shared and cooperative control situations," *Cognition, Technology & Work*, vol. 14, no. 1, pp. 3–18, 2012.