Vibrotactile Feedback for Haptics and Telemanipulation: Survey, Concept and Experiment

Péter Galambos

Computer and Automation Research Institute
Hungarian Academy of Sciences
1111 Kende u. 13-17. Budapest, Hungary
E-mail: galambos@sztaki.hu

Abstract: In telemanipulation and 3D virtual interactions it is important to transmit force sensation from the remote or virtual environment to the operator. Due to the weak points (control issues, robustness, cost) of real force feedback devices, methods where force is rendered on non-native sensory channels have grounds. In this paper, a survey of the related literature is presented and the concept of sensor-bridging type cognitive infocommunications based force reflecting schemes is discussed. A complete experimental infrastructure with hardware and software components is built providing a background for the investigation of the proposed methods from practical usability aspects. This environment is utilized in a pilot experiment with human participants providing substantial observations on the usability of sensor-bridging type vibrotactile force feedback methods. The test confirms that vibrotactile glove equipped with shaftless vibration motors can be successfully applied as tactile/haptic feedback device in immersive virtual reality applications.

Keywords: cognitive infocommunications, telemanipulation, force-feedback, vibrotactile feedback

---

1 Introduction

One of the key problem of telemanipulation is to pass sensory information from the remote site to the human operator. The performance of the task can be improved by the complexity and quality of transmitted sensory channels. In most cases, visual and haptic information are the most important however, in robot assisted surgery, for example, it is most challenging to provide transparent force feedback. The difficulties of real haptic feedback are caused by the diverse complexity of the problem. Issues can be sorted into three main categories: Control, Infocommunication and

Cognitive aspects. From the control theory perspective, time delay, parameter uncertainties and nonlinearities all influence the force feedback control performance in a negative way. Infocommunication is also a crucial point because the varying time delay on the packet-switched networks causes an unmanageable problem for the control algorithms. The most complex problems arise around the cognitive process, from the sensation through the understanding of the incoming multi-modal information during the remote or virtual interaction. The complexity of the connection between the human sensory systems and the technical devices forms a challenging research task, namely the development of devices that can be applied to convey all the sensory perceptions from the remote (real or virtual) environment to the human operator. The goal is to develop and optimize methods and tools in order to transmit the remotely measured data to the human brain via the sensory organs.

In this paper, vibrotactile feedback strategies are considered as a possible way to transmit the percept of tactile and grasp forces in human-machine interaction. Two experimental applications are introduced: the first one is a simulated telemanipulation scenario where the operator can grasp virtual remote objects using a master device and then receive visual feedback on a screen, and grasp force feedback via a vibrotactile glove. For telemanipulation, there are many types of devices available on the market that provide force feedback in its native mechanical way; however, the time delay in the infocommunication channels limits their applicability due to control stability issues. In the second application, the human operators can interact in the virtual space as avatars, moved by skeleton-based motion capture device while they are provided with vibrotactile stimulation. Such a virtual interaction can be an alternative way to practice manual operations that require human-robot coexistence in industrial environment which imply significant safety issues [1, 2]. In this scenario, a cognitive adapter computes the vibrotactile stimulus according to the interaction forces between the operator's hand and the manipulated objects. Sensory information must be generated synthetically from the physical model of the virtual environment. The presented experimental software is implemented on the VirCA[1] platform [3].

The proposed experimental setups provide a platform to develop and investigate cognitive infocommunications-based solutions [4]. From the aspect of Cognitive Infocommunications - tactile, force and haptic feedback strategies, where the original sensory information is mapped to alternative sensory channels - it is called *sensor-bridging*. In this abstraction, the communication takes place between the manipulation process and the human operator, so the levels of intelligence are different. Accordingly, the communication is inter-cognitive.

Regarding the similarities of application areas discussed in this paper, the existence of the inter-cognitive sensor-bridging type cognitive adapter is investigated, which gives a solution for both applications.

---

[1] VirCA - **Vir**tual **C**ollaboration **A**rena, developed in MTA SZTAKI (Computer and Automation Research Institute, Hungarian Academy of Sciences). VirCA is free to use for academic purposes and available online at www.virca.hu.

2 Conceptual Background

The first part of this section gives a summary of the goals and perspectives of Cognitive Infocommunications (CogInfoCom) based on [4]. Then a survey of the concerned topics is provided. CogInfoCom, is a newly emerging multi-disciplinary field which is concerned with the analysis of existing and the synthesis of novel forms of communication between humans and electronic devices with various levels of cognitive capabilities (also referred to as artificially cognitive devices). Towards the end of the section, it will become clear that when force feedback in teleoperation is viewed as a channel of communication between the teleoperation process and the human operator, research directions motivated by the philosophy of CogInfoCom brings up novel and useful tools to tackle the problem of providing effective force feedback under various circumstances.

2.1 Cognitive Infocommunications

Cognitive Infocommunications (CogInfoCom) investigates the links between the research areas of infocommunications, informatics and cognitive sciences, as well as the various fields which have emerged as a combination of these sciences. The field of CogInfoCom is sectioned along two dimensions, the mode and the type of the communication. The mode of communication can be intra-cognitive or inter-cognitive according to the level of cognitive capabilities of the endpoints participating in the communication process. The type of communication refers to the type of information that is conveyed between the nodes and the way in which this is done. The communication is a sensor-sharing type when the sensory information is merely transferred on the infocommunication line and thus the same sensory modality is used on both ends to perceive the information. The type of communication is sensor-bridging when the sensory information obtained or experienced is not only transferred to the other end of the line, but also reallocated and transferred to an appropriate sensory modality on the receiver end. The terminology of CogInfoCom is often used within this paper. The definition of CogInfoCom and further introspection can be found in [4].

2.2 Inter-cognitive sensor-bridging in teleoperation

The human brain is able to interpret sensory information even if it is not presented on the naturally coupled sensory modality. This practically means that a blind person might have a real visual experience via receiving tactile stimulation of her skin. This phenomena namely, the cross-modal plasticity of the human brain, is the basis of the sensory substitution as Paul Bach-y-Rita published in the late 1960s [5, 6, 7, 8]. Since early times, the idea of sensory substitution has been tested in various research areas, mainly in the rehabilitation of persons with spinal cord injuries. The first working implementation was the tactile vision substitution system (TVSS) introduced by Bach-y-Rita: A video camera signal was converted into a tactile image and projected onto the blind subject's back. In [9] Bach-y-Rita reviews the theoretical aspects and many applications from the beginning to 1999. In the past decade, further results were published: Bach-y-Rita, Kaczmarek and Tyler introduced the tongue based man machine interface [10]. Danilov et al., using the tongue based interface, got promising results in the rehabilitation of patients with balance disorders [11, 12]. In the case of telemanipulation, the motivation is not the recovery of a lost sensory capability, but the exploiting of unloaded sensory skills of human. In conventional telemanipulators, the force/position input and the position/force display is realized on the same actuated part of a master device (Figure 1).

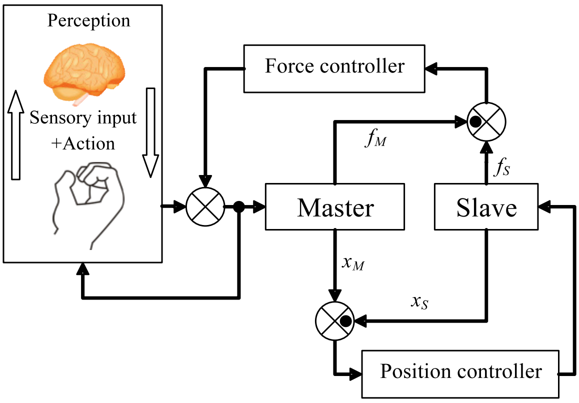


Figure 1
Conventional force-position bilateral control of telemanipulation

This structure - supposing that the bilateral control ensures the stable operation - provides the physical constraint that prevents the unwanted destruction of the remote environment and provides the operator with realistic force feedback in a natural way. Based on the concept of sensory substitution, the author aims to develop intercognitive sensor-bridging methods for force feedback. The proposed architecture is shown in Figure 2 supposing a telamanipulative grasping task.

In this scheme, the master device acts as the position input of the system. The measured master position x_M is the reference signal of the slave side position controller. The interaction between the slave gripper and the remote environment is monitored via force measurement. In the bilateral control, the measured slave force f_s is rendered on the master device (Figure 1), while in the proposed sensor-bridging technique, the interaction force is presented in the form of non-native sensory stimulus (vibrotactile, visual, audio) applying an appropriate coupling algorithm. The separation of the force/position input and output channels opens up the joint closed loops of the traditional bilateral control guarantying the stability of the telemanipulation system.

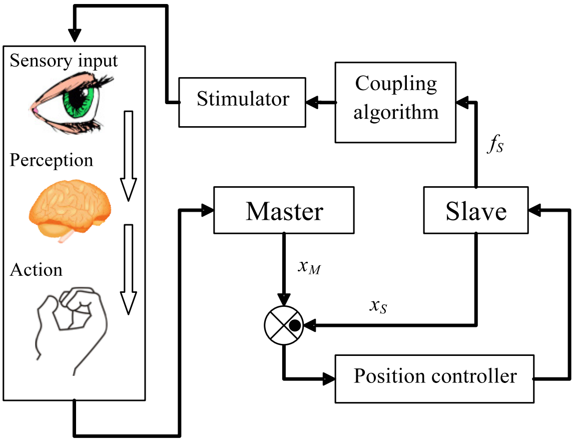


Figure 2
Telemanipulation with sensory substitution

2.3 CogInfoCom in teleoperation

CogInfoCom appears from various points of view – including sensory substitution and multimodal interaction – in existing teleoperation applications. The key motivation for using such approaches is multifold:

- **Contradictory goals in terms of situation awareness and unencumberment**

  Situation awareness (also commonly referred to as telepresence) is a measure of the degree to which the user feels present in the remote or virtual environment [13, 14]. In an early work on the subject, Sheridan outlines 3 key components of telepresence: the extent of sensory information, the control of the relation of sensors to the environment, and the ability to modify the physical environment [15]. Other researchers have conjectured that situation awareness is less quantitative, and that it has both subjective and objective aspects [16].

  Encumberment is a term used often in the literature to describe the extent to which the user is burdened with having to wear various kinds of sensors in order to interact with a system [17, 18]. It is natural to try to reduce encumberment in virtual environments; however, doing this conflicts with the goal of increased situation awareness. In order to resolve these conflicting goals, a widely adopted and natural direction for teleoperation research was to try to use alternative forms of feedback (e.g., [19, 20, 21, 22, 23]).

- **The usefulness of corroboration**

  There is extensive proof in the literature that different sensory channels are not independent of each other. While contradicting information from various senses can cause confusion, simulation sickness or other discomfort, illusions in which stimulation in one sensory channel leads to the illusion of stimulation in another sensory channel can be very powerful in virtual and/or remote teloperation [24]. The ability of human cognition to integrate experience from various sensory channels is referred to as intermodal (or intersensory) integration. According to [25], intermodal integration may be a "*key psychological mechanism contributing to a sense of presence in virtual environments*". It has consistently been proven that information shared by various senses can reinforce each other to create powerful representations of internally consistent worlds [26, 25]

- **Alleviating the negative effects of reduced resolution**

  There are several results in the literature which underline the fact that the use of sensory substitution can be extremely beneficial in cases where the signals that can be provided to the natural sensory modality are reduced in resolution or degrees of freedom.

  For instance, according to Verner and Okamura, providing force feedback that is reduced in degrees of freedom can result in the destabilization of the teleoperation system [27]. In specific applications, such as remote surgical knot-tying in telesurgery, it was shown that the forces applied by the telesurgeon were closer to the normal, manual case when auditory and graphical displays were used instead of direct force feedback [22].

It is important to note that the challenge behind sensory substitution lies not only in the effective mapping of representations from one sensory modality to another, but also in considering the cross-effects between sensory modalities. Researchers long ago discovered that the impression that different sensory modalities are independent of each other is "*more illusory than real*" [28]. Thus, when designing feedback strategies in teleoperation systems, care must be taken so that the operator is not overloaded with sensory information. Although multi-sensory information can help in many cases, its effects can also be counter-productive if the user is burdened with too much information [19, 29]. The question as to whether multi-sensory feedback is productive or not has much to do with the degree of redundancy in the information that is presented [19, 30]. However, Biocca et al in [24, 25] also suggest that it is possible for one sensory modality to yield realistic sensations normally perceived through another modality, while another sensory modality gives no contribution to realistic sensations but significantly increases the user's sense of telepresence.

Besides sensory overload, another key point of interest when designing multi-modal interfaces is how the various sensory modalities relate to one another in terms of importance to human cognition. This is referred to as the question of sensory dominance. There have been a number of studies which show that vision dominates haptic touch and audition [15, 31, 32, 33], but it was also shown that relationships of dominance can become more complex if more than two modalities are under stimulation at the same time [33].

2.4 Force feedback in teleoperation

In force feedback capable haptic or telemanipulator devices, the stability of bilateral control and the realistic force sensation (transparency) are contradicting requirements. Low communication bandwidth, varying time-delay of the communication (jitter), nonlinearities in the mechanisms and the unknown remote environment cause the unstable behavior or degrade the transparency. Among these causes, time delay is crucial because this is an inherent property of distributed control systems. Internet-based teleoperation is a typical example, where communication delay plays an important role [34, 35, 36]. In internet-based telemanipulation, the varying and unbounded time delays represent the main problem, even though the average communication delay is far less than the reaction time of the human operator. The transparency and stability of bilateral teleoperation was studied by Lawrence [37]. Over the past decades several approaches have been published addressing the stability problem of closed loop force reflecting telemanipulation. A comprehensive survey can be found in [38].

Several researchers have attempted to solve the problem of time delays by creating predictive models based on the application. In modalities other than force feedback, two basic approaches – also known as predictor displays – have been proposed: one which involves a Taylor-series based extrapolation based on current state variables and their derivatives, and a second one which involves running a predictive model with time constants that are faster than those of the actual process [39]. The first approach has been shown to yield good results for short-term predictions, while the second approach can be useful in addressing problems caused by nonlinear dynamic properties such as saturation [39].

Such predictor displays have proven extremely useful for tasks in which visual feedback is needed [39]. However, due to operator-induced instabilities and problems with closed-loop control (as first demonstrated in [40]), the price of erroneous predictions is much higher in the case of force feedback than in the case of visual feedback. The reason for this is that unexpected disturbances can arise from both the natural inertia of the system, as well as the feedback of erroneous force feedback on the same hand that is operating the master device [41, 42]. Thus, although efforts were made to use predictive force-feedback (e.g., [43]), the importance of alternative approaches also became clear. Such approaches include sensory substitution using visual, audio and vibrotactile feedback [19, 44, 22, 45, 23], wave dissipation and transformation techniques to spread out the negative effects of time delays through time [46, 47], and supervisory control using high-level commands.

2.5 Haptics in Virtual Environment

The importance of haptic rendering in virtual reality applications has continuously grown over the past twenty years. Haptic rendering provides the user with force and tactile feedback during manipulation in the virtual environment. A general survey on haptic rendering was published by Salisbury et al. in [48]. The role of haptics in multimedia is reviewed in [49]. The application of haptics in virtual reality ranges from entertainment to rehabilitation via 3D design, virtual collaboration and different training purposes. Coles et al. investigated the role of haptic feedback in simulators for medical training [50]. Kammerl, Chaudhari and Steinbach introduced a method for efficient haptic data communication for networked virtual environments [51]. Bearing in mind, that the control of haptic devices meets the same difficulties as the bilateral control of telemanipulation [52], the proposed sensor-bridging method helps to overcome the control issues in a variety of applications.

2.6 Solutions for force feedback under the concept of CogInfoCom

The idea to use sensory substitution in order to convey force feedback has been under investigation for several decades [53, 54, 55]. However, the first detailed and conclusive experiments on the subject were carried out by Massimino [19, 56, 44]. In his PhD thesis, Massimino drew the following conclusions regarding sensory substitution for force feedback [19]:

- In the presence of a time delay, sensory substitution may be used, as it does not introduce instabilities
- Auditory displays are useful for representing accurate force direction information

Massimino's results sparked active interest in using sensory substitution through various modalities in order to compensate for compromised force feedback due to lack of equipment and/or time delays.

Through the course of this research, it was found that the use of sensory substitution can be both superfluous and extremely valuable, depending on the application. In an all-encompassing review of the topic, Kaczmarek demonstrated that already in the early 1990s, the use of electrotactile and vibrotactile displays was prevalent in the feedback of various kinds of information, including tactile and force information [20]. At the end of the paper, Kaczmarek concluded that in order to make progress, researchers would have to design more accurate stimulation waveforms for electrotactile feedback, develop smaller, less noisy and less power-consuming vibrator arrays, as well as better understand the correlation between standardized measures such as the just-noticeable-difference (JND) and number of discernible levels.

Today, the most popular forms of sensory substitution for force feedback occur through visual, vibrotactile, and to a lesser extent auditory stimuli [57, 58, 59, 23]. It was shown in [57] and [58] that the use of multi-channel vibrotactile displays results in reduced mean errors and reduced peak forces when users have to trace the outline of a shape at a fixed force. Such results are especially encouraging for the design of remote telesurgical devices, of which even the most prominent are still completely lacking in force feedback [59, 23].

3 Devices

In this section, a vibrotactile glove and a master device for telemanipulative grasping are introduced. Both devices have been developed by the author and his associates in MTA SZTAKI.

3.1 Vibrotactile glove

For sensor-bridging purposes, a vibrotactile glove has been developed (Figure 3). In this glove, one shaftless vibration motor is placed on each finger ending on the nail side, leaving the fingertips free and letting the user to grasp the master device comfortably.

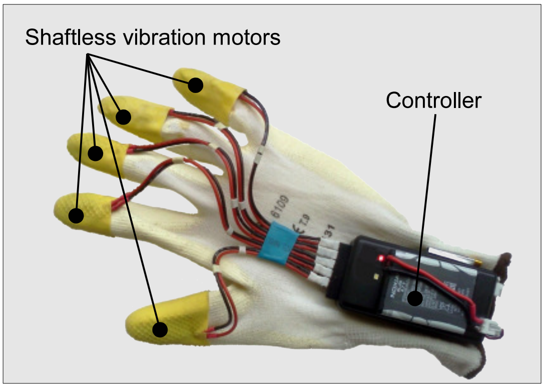


Figure 3
Wireless vibrotactile glove with five shaftless vibration motors

The glove is equipped with a controller board capable of wireless communication with a host PC or embedded system using a bluetooth serial connection. Each vibration motors can be controlled independently with a pulse width modulated (PWM) signal. The PWM duty cycle can be set in 256 steps with serial commands from the host device. A C# API and an RT-Middleware component are available for integrating of the glove into newly developed or existing systems.

3.2 Master device

The master gripper was developed from a commercially available (SCHUNK PG-70) servo-electrical, two-fingered, parallel jaw robot gripper (Figure 4). The below listed properties of the gripper make it well suited to this application.

Stroke per finger	$35mm$
Encoder resolution	$0.001mm$
Max. gripping force	$200N$
Communication	RS-232, CAN-Bus, Profibus DP

The implementation of the real haptic feedback requires a relatively high sampling frequency, so CAN-Bus communication at $1MBaud$ was selected. The gripper internally provides closed-loop velocity and position control and open-loop direct PWM control. The implemented communication is running at approximately $500Hz$ of command frequency. The sampling period is varying due to the non-real-time characteristics of the MS Windows operating system, but during the experiments no malfunction was observed. Because of the large gear-ratio, the gripper is non-back-drivable. It means that without active control the operator cannot move the jaws of the master device, so it is considered as admittance display [60]. To make this gripper applicable as a master device, additional force sensors are necessary. Binocular type load cells are integrated with the fingers of the gripper. Load cells are driven by a commercial instrumentation amplifier circuit providing 12 bit A/D conversion and communication via RS-232 line at 115200 baud rate (electronics was made by Tenzi Ltd.). Raw force data is sent to the host PC at the rate of $2000Hz$.

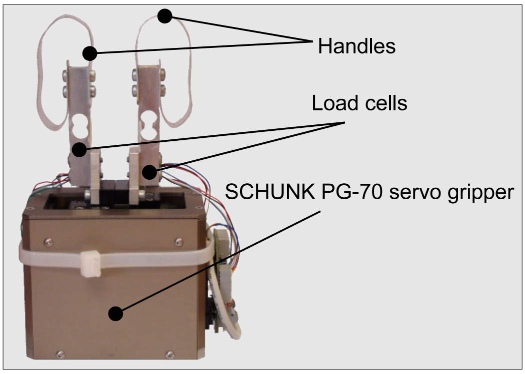


Figure 4
The force feedback capable master gripper

The master device has two operation modes: force feedback and a position input mode without force reflection. Details about the implemented bilateral control scheme can be found in [61]. In position input mode, the master device is controlled in a feed-forward manner. Due to the non-back-drivability of the gripper, its embedded drive system is operating in the open-loop control mode and gets PWM duty value from the host computer according to the following equation:

$$PWM_{duty} = \min(\max(0, \frac{f_1 + f_2}{2} G), 1)), \tag{1}$$

where f_1 and f_2 refer to the measured force on the two fingers respectively and G is a proportional gain. The value of G is tuned so that the master device does not show high resistance against the operator's hand, but does not allow sudden or accidental movements.

4 The cognitive adapter

The cognitive adapter transforms a force-like quantity into a vibration pattern that is executed on the vibrotactile glove. In our investigation, grasping force in telemanipulation and elastic force in virtual manipulation are considered as input data. The vibration pattern means the way of control of the vibration motors according to a given force value. In a simple case, the rule can be formulated as a scalar-vector function $\mathbf{p} = \mathbf{g}(\mathrm{f})$, where the elements of $\mathbf{p}$ are real numbers between zero and one representing the vibration intensity of each motors. A more complicated method is when the motors are controlled with periodic signals because the characterization of periodic patterns requires more parameters. Considering, that the vibrotactile stimulator device is equipped with vibro-actuators in discrete positions (e.g. at the fingertips), different types of stimulation strategies can be distinguished. Figure 5 schematically illustrates six possible control modes. In diagram (a) the upper plot means the measured or computed force data as a function of time. The other diagrams show the control signals driving the vibro-actuators, m_1, m_2, m_3, m_n are the time plots of motor voltages. In our experiments, homogeneous and inhomogeneous amplitude modulated strategies are implemented. The following subsections introduce these two methods.

4.1 Homogeneous linear vibration function

As an obvious approach, the homogeneous linear mapping was implemented (Figure 5/a). In this case, all five vibro-actuators are controlled in the same way in a linear function of the input force.

Figure 6 shows the function $p(f) = g \cdot f$ where g is a properly selected proportional gain. As p saturates at the force value $f = 1/g$, the linear section should be arranged into the typical force range of the application.

4.2 Inhomogeneous radiating vibration function

More sophisticated mapping can be defined with the inhomogeneous stimulation (Figure 5/b). In this mode, the vibration radiates from the thumb to the little finger by the increasing force value.

Figure 7 shows how the motors are controlled in the function of input force. The thumb and index fingers stimulated in the same way and after the two motors reach

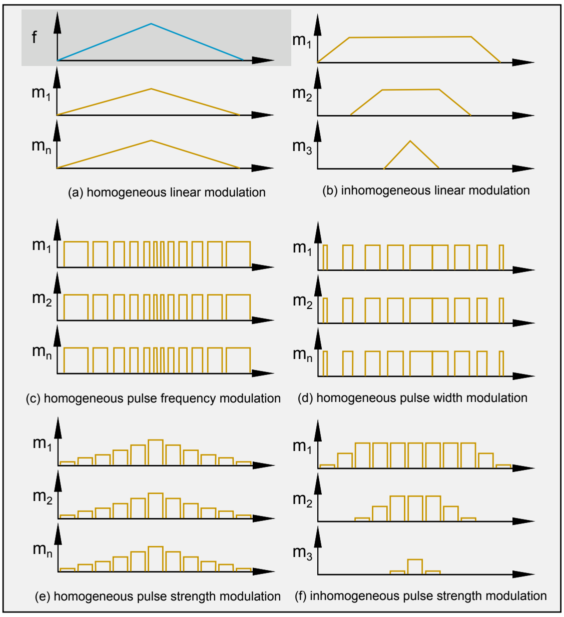


Figure 5
Various stimulation strategies

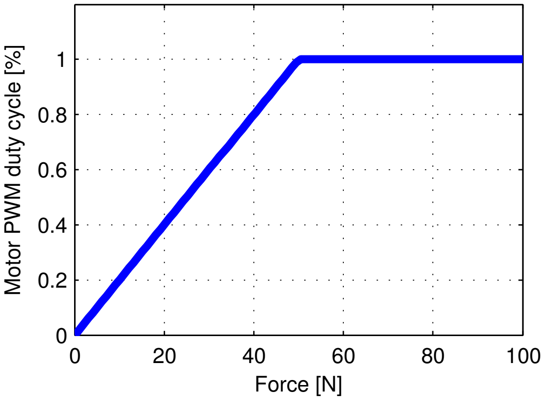


Figure 6
Homogeneous linear vibration function

the 100% PWM duty, further fingers come in to action. In this way the dynamic range of the stimulus is much higher than in the homogeneous case.

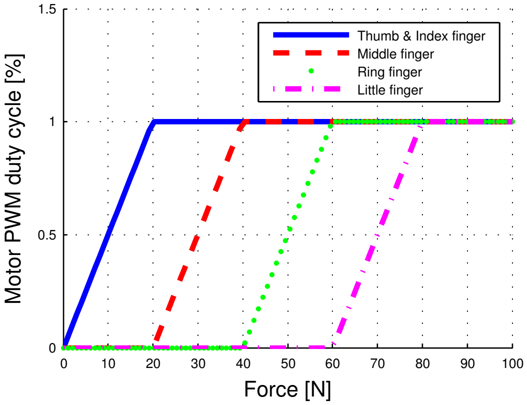


Figure 7
Inhomogeneous radiating vibration function

5 Applications

5.1 Telemanipulative Grasping

In this application, inter-cognitive sensor-bridging is applied to display force information to the user in a telemanipulative grasping task. The testbed incorporates the force feedback capable master device, a simulated remote environment and the vibrotactile glove.

In the course of the experiment, the human subject uses the master device to grasp a simulated remote object with a certain force. During the task, the subject is provided with visual feedback regarding the vision as primary sensory modality. Optionally, real haptic feedback, sensor-bridging type feedback or both can be enabled.

Figure 8 shows the experimental setup. A PC is serving as the controller of the active devices (master gripper, vibrotactile glove) and provides the simulated virtual remote environment. Two types of remote objects can be selected in the software: a helical spring with adjustable linear stiffness and a breathing chicken. The chicken's size changes periodically due to a breathing motion which has time varying periodicity in order to make it more realistic. The non-rigid character of the chicken is defined by its stiffness, while other details of mechanical behavior, such as viscous damping and stress relaxation, were neglected. During the tests, several system parameters such as grasping force and gripper finger position can be recorded. This setup makes possible the comparative investigation of native and sensor-bridging type force feedback in telemanipulative grasping tasks. An earlier version of this setup was applied for the experimental investigation of peripheral vision-based grasping force feedback [62].

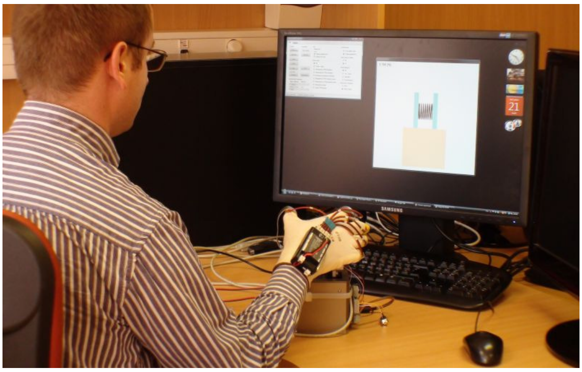


Figure 8
Telemanipulative grasping experiment to investigate sensor-bridging type feedback methods

5.2 Interaction in Virtual Environment

In this experimental scenario, a human operator represents himself in an immersive virtual environment and manipulates objects using his humanoid avatar. The operator can receive vibrotactile feedback according to the interaction between the avatar and the manipulated objects. VirCA and the immersive 3D visualisation laboratory of MTA SZTAKI is applied as background infrastructure for this setup.

A variety of motion capture devices (MoCap suits, MS Kinect$^{\mathrm{TM}}$) can be used to track the motion of the operator in nearly real-time. A 3 by 3 meters area was available for the user to manage his movements, but the virtual room can be any size. Three walls of the room are 3D projected, and hence the users have to wear passive 3D glasses. the operator's motion is reproduced by a humanoid avatar in the virtual space; thus the user can observe his own activity from an out-of-body perspective [63]. The avatar has the look and skeleton structure of the widely used NAO humanoid robot. An abstract contact sensor device is attached onto the robot's hand in order to detect the contact with other objects. This sensor is capable of providing the description of the contacted object and the contact state. Feedback to the user is computed by the cognitive adapter according to this description. The user receives the vibrotactile feedback via the vibrotactile glove on his right hand. Figure 9 shows the operator and his avatar in the virtual arena.

Technically, the application is implemented as an assembly of RT-Middleware components (RTCs) involving VirCA. The components and connections are shown in Figure 10. VirCA core component serves as the central management module and provides the 3D virtual environment. Other components are stringed to VirCA via RT-Middleware connections.

The first branch consist of an RTC for the motion capture device (Measurand) that is connected to an RTC, which performs transformation between the MoCap suit data

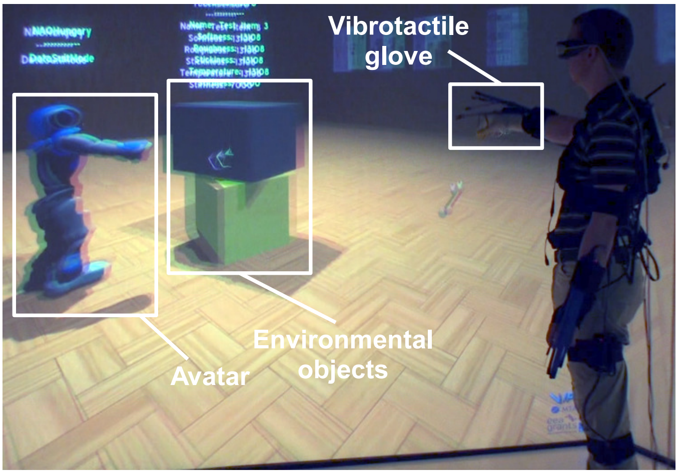


Figure 9
Manipulation in the immersive 3D Virtual reality

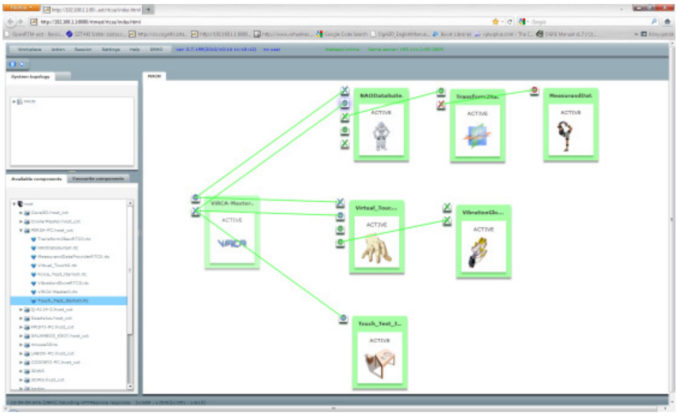


Figure 10
VirCA assembly for manipulation in a shared virtual space

type and the input format of the robot and a Cyber Device that represents the NAO humanoid robot in VirCA. In the next branch, the abstract sensor device is connected directly to VirCA. The vibrotactile glove gets force information from the sensor. Environmental objects can be connected to the virtual room. They are able to react with the contact sensor and handle surface and stiffness information characterizing their physical behavior. Over the vibrotactile force feedback, the cognitive adapter can transform tactile information into auditory icons [64]. This scenario illustrates a possible application of inter-cognitive sensor-bridging to achieve effective haptic feedback avoiding control instability using low-cost and lightweight devices.

6 Experimental Study

A pilot experiment has been done to investigate the vibrotactile feedback in interaction with virtual objects in an immersive virtual reality. The motivation of the experimental study is twofold. Firstly, to gain initial experience in this quite new area of human computer interaction. And to reveal how many grade of hardness/stiffness can be distinguished based on the vibrotactile stimulus that displays the interaction force.

6.1 Participants

Ten people participated in the experiment. Their age varied between 24-42 years and three of them were female. All the participants are well experienced computer users and half of them also play 3D video games. The vibrotactile glove that was used in the experiment is only available in one size; thus it did not fit equally well for everyone. Participants with smaller palms had problems with the improper alignment of vibro-actuators on the fingers.

6.2 Method

The experimental environment was arranged similarly as was described in subsection 5.2. The only difference is that the motion of the participants was tracked by a Kinect^{TM}sensor, so they did not have to wear any disturbing gadgets. Three type of stimulation strategies were examined: the first one was the linear homogeneous vibration function (Figure 6). The second strategy was the inhomogeneous radiating vibration function (Figure 7). The third was a modified version of the second wherein all fingers were treated individually.

Each subject passed two tests with each vibration modes. In both tests, the stiffness/hardness of visually uniform objects should have been discriminated. In the first test, a given stiffness range was equally sectioned in five discrete values, while in the second one, only three grades were assigned on the same range. This means that the first (softest) and the last (hardest) grades meant the same hardness, while the medium (2) on the second scale was equal to the third grade of the first scale. The two scales are illustrated in figure 11.

The gain parameter of the first strategy was set so that the covered stiffness range to be between the lower and upper bound of the linear part of the vibration function (Figure 6). The second strategy (Figure 7) was also tuned in such a way that the interaction forces vary in the valid input range. In the third strategy, the parameters

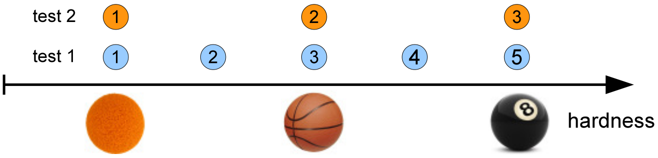


Figure 11
Stiffness grades in the first and second tests

and the stiffness of the objects were adjusted to set the saturation point of the fingers to coincide with the total overlapping of the test object and the virtual touch sensor.

The test process was the following: In the first part of the test - before the actual probes -, the participants practised 5-10 minutes on the sample objects, which were five uniform boxes in a row with increasing stiffness in five grades. After the practice, the participants had to judge the stiffness of an unknown object (test object) five times consecutively. The subjects were asked to tell the number of the stiffness grade (1-5) that they felt. In the five consecutive tests, the stiffness of the test object was selected randomly in order to exclude any possibility of deducing the subsequent answer. In the second part, the same process (5-10 minutes practice, 5 probes) was executed with three grades. Figure 12 shows a moment when a subject is practising on the sample objects.

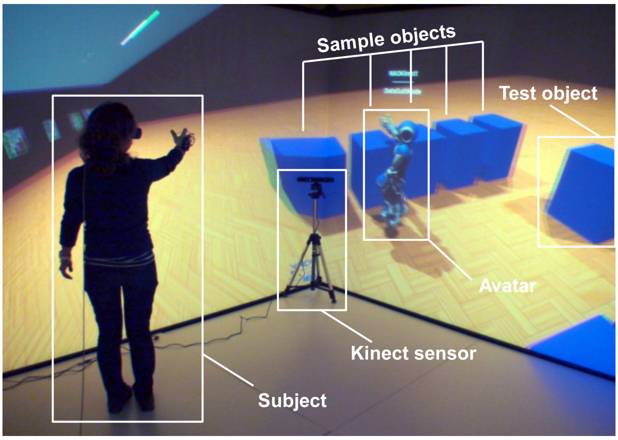


Figure 12
Experimental setup in the immersive virtual reality

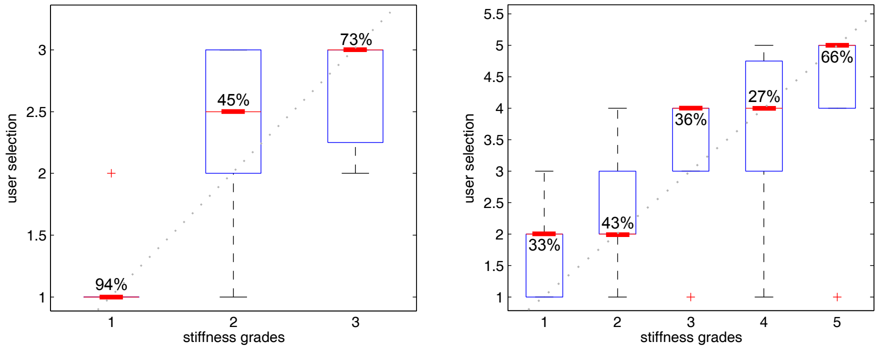
6.3 Results

The previously described test was completed by the ten participants; thus, overall 300 test events were registered. In this subsection, these events are evaluated using standard statistical methods. The results are presented in figure 13 with box plots for each stimulation strategy, separately for the 3-grade and 5-grade cases. In the diagrams, six numerical quantities are presented: The thick horizontal line shows the median; the lower and upper bound of the boxes means the lower and upper quartile respectively; the horizontal lines connected to the boxes with dashed lines show the minimum and maximum values of guesses; while the small crosses shows the judgements that are considered as outliers. The numbers in the boxes mean the percentage of correct guesses.

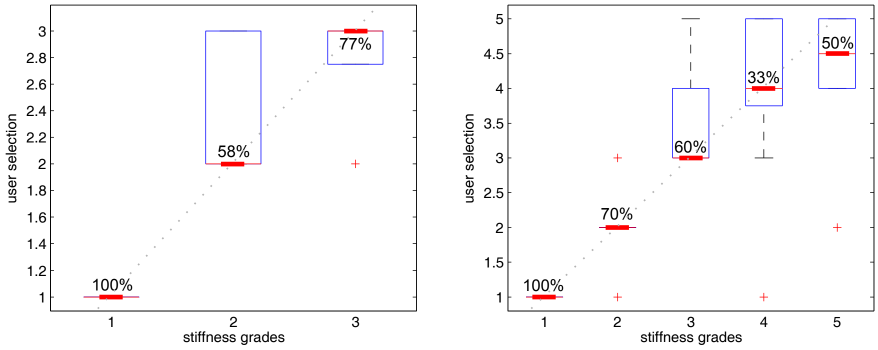
The diagrams show that the ratio of correct guesses and the variance is improves in the second and also in the third stimulation strategy compared to the first one. In the tests with the first strategy, the discrimination of three grades (Figure 13/a) were already ambiguous even though the first grade was recognized in 94% of the cases. In the five-grade test of the first strategy (Figure 13/b), the uncertainty was even larger as the median values illustrate. The picture is much better in case of the second stimulation strategy (Figure 13/c,d) as the medians are lying on the expected grade. We got the best results with the third vibration function (Figure 13/e,f). Both 3-grade and 5-grade tests were passed with a low number of mistakes. With each strategy, the discrimination at lower stiffnesses (1,2) was better than at higher (3,4,5) grades, which shows that the discrimination is better at lower vibration intensities (and frequencies). In conclusion, we can state that the linear homogeneous vibration function (strategy 1) is not applicable to display multi-grade information precisely using vibrotactile gloves with shaftless vibration motors where the amplitude and the frequency of the vibration are coupled. Strategies that implement different stimulation for each finger, such as strategies 2 and 3 are more applicable to transmit such information to the user. The investigation shows that with a properly tuned inhomogeneous radiating vibration function, five different stiffness grades can be precisely discriminated.

Conclusion

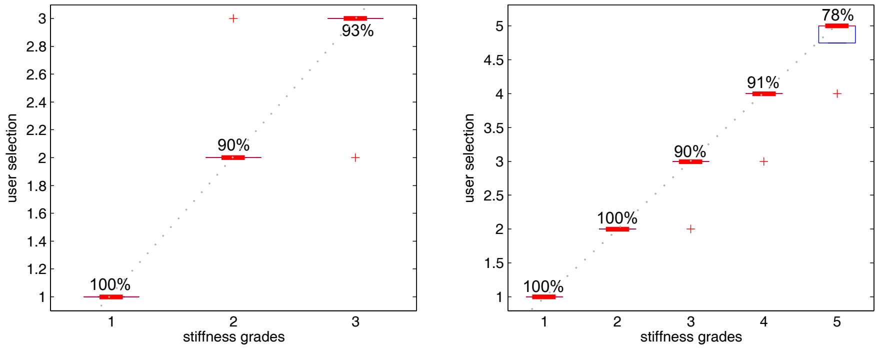
In this work, a sensor-bridging type force feedback scheme has been discussed with the conceptual background of cognitive infocommunications and the affected literature has been surveyed. A complete experimental infrastructure is developed for the investigation of vibrotactile force feedback strategies in two current applications: The first setup provides a test environment for telemanipulative grasping, where the operator can grasp a simulated remote object using a master device and receive force feedback via a vibrotactile glove. The second setup implements vibrotactile feedback for immersive 3D environments serving the user with the sense of interaction forces. Initial tests show promising perspectives in both application fields; however, the im-



(a) Strategy 1 / three-grade test (b) Strategy 1 / five-grade test



(c) Strategy 2 / three-grade test (d) Strategy 2 / five-grade test



(e) Strategy 3 / three-grade test (f) Strategy 3 / five-grade test

Figure 13

Experimental comparison of three stimulation strategies provement of the tele-grasping setup with real remote side is reasonable. The paper introduces a pilot experiment in immersive 3D virtual world conducted with ten participants and reports substantial observations on the usability of different vibrotactile feedback strategies. As a main conclusion of the experiment, it is shown that five stiffness grades can be distinctly discriminated with a properly tuned vibrotactile feedback produced by a vibrotactile glove equipped with shaftless vibration motors.

Acknowledgement

The research was supported by the Hungarian National Development Agency, NAP project NKTH-KCKHA005 (OMFB-01137/2008).

References

[1] O. Ogorodnikova, "Creating an active awareness system for humans in robotic workcell," *Acta Polytechnica Hungarica*, vol. 5, no. 2, pp. 113–126, 2008.

[2] ——, "How safe the Human-Robot coexistence is? theoretical presentation," *Acta Polytechnica Hungarica*, vol. 6, no. 4, pp. 51–74, 2009.

[3] P. Galambos and P. Baranyi, "Virca as virtual intelligent space for rt-middleware," in *Advanced Intelligent Mechatronics (AIM), 2011 IEEE/ASME International Conference on*, july 2011, pp. 140 –145.

[4] P. Baranyi and A. Csapo, "Cognitive infocommunications: CogInfoCom," in *2010 11th International Symposium on Computational Intelligence and Informatics (CINTI)*, Budapest, Hungary, Nov. 2010, pp. 141–146.

[5] P. Bach-y-Rita, "Sensory plasticity. applications to a vision substitution system." *Acta Neurol Scand*, vol. 43, no. 4, pp. 417–426, 1967.

[6] ——, "Various neurophysiological findings of sensory substitution," *Acta Neurol Latinoam*, vol. 14, no. 1, pp. 125–131, 1968.

[7] P. Bach-y-Rita, C. C. Collins, F. A. Saunders, B. White, and L. Scadden, "Vision substitution by tactile image projection," *Nature*, vol. 221, no. 5184, pp. 963–964, 1969.

[8] P. Bach-y-Rita, *Brain mechanisms in sensory substitution.* New York: Academic Press, 1972.

[9] ——, "Theoretical aspects of sensory substitution and of neurotransmission-related reorganization in spinal cord injury," *Spinal Cord: The Official Journal of the International Medical Society of Paraplegia*, vol. 37, no. 7, pp. 465–474, Jul. 1999.

[10] P. Bach-y-Rita and M. E. Tyler, “Tongue man-machine interface.” *Stud Health Technol Inform*, vol. 70, pp. 17–19, 2000.

[11] Y. Danilov, M. Tyler, K. Skinner, and P. Bach-y-Rita, “Efficacy of electrotactile vestibular substitution in patients with bilateral vestibular and central balance loss,” in *2006 International Conference of the IEEE Engineering in Medicine and Biology Society*, 2006, pp. 6605–6609.

[12] Y. P. Danilov, M. E. Tyler, K. L. Skinner, R. A. Hogle, and P. Bach-y-Rita, “Efficacy of electrotactile vestibular substitution in patients with peripheral and central vestibular loss.” *J Vestib Res*, vol. 17, no. 2-3, pp. 119–130, 2007.

[13] T. Sheridan, “Musings on telepresence and virtual presence,” *Presence: Teleoperators and Virtual Environments*, vol. 1, no. 1, pp. 120–126, 1992.

[14] M. Endsley and D. Garland, *Situation Awareness: Analysis and Measurement*. Routledge, 2000.

[15] T. Sheridan, “Human factors considerations for remote manipulation,” in *Advanced Guidance and Control Aspects in Robotics*, 1994.

[16] M. Slater and S. Wilbur, “A framework for immersive virtual environments (five): Speculations on the role of presence in virtual environments,” *Presence*, vol. 6, no. 6, pp. 603–615, 1997.

[17] S. Ellis, “Nature and origins of virtual environments: a bibliographical essay,” *Computing Systems in Engineering*, vol. 2, no. 4, pp. 321–347, 1991.

[18] R. Adams and B. Hannaford, “Stable haptic interaction with virtual environments,” *IEEE Transactions on Robotics and Automation*, vol. 15, no. 3, pp. 465–474, 1999.

[19] M. Massimino, “Sensory substitution for force feedback in space teleoperation,” Ph.D. dissertation, MIT, Dept. of Mechanical Engineering, 1992.

[20] K. Kaczmarek, J. Webster, P. Bach-y-Rita, and W. Tompkins, “Electrotactile and vibrotactile displays for sensory substitution systems,” *IEEE Transactions on Biomedical Engineering*, vol. 38, no. 1, pp. 1–16, 1991.

[21] H. Tan and A. Pentland, “Tactual displays for sensory substitution and wearable computers,” in *ACM SIGGRAPH 2005 Courses*, ser. SIGGRAPH ’05, 2005.

[22] M. Kitagawa, D. Dokko, A. Okamura, and D. Yuh, “Effect of sensory substitution on suture-manipulation forces for robotic surgical systems,” *Journal of Thoracic and Cardiovascular Surgery*, vol. 129, no. 1, pp. 151–158, 2005.

[23] A. M. Okamura, L. N. Verner, T. Yamamoto, J. C. Gwilliam, and P. G. Griffiths, *Force Feedback and Sensory Substitution for Robot-Assisted Surgery*. Springer, 2011, pp. 419–448.

[24] F. Biocca, J. Kim, and Y. Choi, “Visual touch in virtual environments: An exploratory study of presence, multimodal interfaces and cross-modal sensory illusions,” *Presence: Teleoperators and Virtual Environments*, vol. 10, no. 3, pp. 247–265, 2001.

[25] F. Biocca, Y. Inoue, H. Polinsky, A. Lee, and A. Tang, “Visual cues and virtual touch: Role of visual stimuli and intersensory integration in cross-modal haptic illusions and the sense of presence,” in *In Proceedings of Presence*, F. Gouveia, Ed., 2002.

[26] R. Welch and D. Warren, “Immediate perceptual response to intersensory discrepancy,” *Psychological Bulletin*, vol. 88, no. 3, pp. 638–667, 1980.

[27] L. Verner and A. Okamura, “Sensor/actuator asymmetries in telemanipulators: Impliations of partial force feedback,” in *In Proc. 14th Symposium on Haptic Interfaces for Virtual Environments and Teleoperator Systems*, 2006, pp. 309–314.

[28] B. Stein, M. Wallace, and A. Meredith, “Neural mechanisms mediating attention and orientation to multisensory cues,” in *The Cognitive Neurosciences*, M. Gazzaniga, Ed. MIT Press, Cambridge, 1995, pp. 683–702.

[29] L. Williams, “Bisensory force feedback in telerobotics,” Ph.D. dissertation, University of Houston, 2001.

[30] J. Rochlis, “Human factors and telerobotics: Tools and approaches for designing remote robotics workstation displays,” Ph.D. dissertation, Massachusetts Institute of Technology, 2002.

[31] R. Welch and D. Warren, “Intersensory interactions,” in *Handbook of Perception and Human Performance*, L. Boff and J. Thomas, Eds. John Wiley, 1986, vol. 1, pp. 25–36.

[32] F. Pavani, C. Spence, and J. Driver, “Visual capture of touch: Out-of-the-body experiences with rubber gloves,” *Psychological Science*, vol. 11, no. 5, pp. 353–359, 2000.

[33] D. Hecht and M. Reiner, “Sensory dominance in combinations of audio, visual and haptic stimuli,” *Experimental Brain Research*, vol. 193, pp. 307–314, 2009.

[34] S. Munir and W. J. Book, “Internet-based teleoperation using wave variables with prediction,” *IEEE/ASME Transactions on Mechatronics*, vol. 7, no. 2, pp. 124–133, 2002.

[35] I. G. Polushin, P. X. Liu, and C. Lung, “A Force-Reflection algorithm for improved transparency in bilateral teleoperation with communication delay,” *Mechatronics, IEEE/ASME Transactions on*, vol. 12, no. 3, pp. 361 –374, Jun. 2007.

[36] N. Ando, P. Korondi, and H. Hashimoto, “Development of micromanipulator and haptic interface for networked micromanipulation,” *Mechatronics, IEEE/ASME Transactions on*, vol. 6, no. 4, pp. 417 –427, Dec. 2001.

[37] D. A. Lawrence, “Stability and transparency in bilateral teleoperation,” *IEEE Transactions on Robotics and Automation*, vol. 9, no. 5, pp. 624–637, 1993.

[38] P. F. Hokayem and M. W. Spong, “Bilateral teleoperation: An historical survey,” *Automatica*, vol. 42, no. 12, pp. 2035–2057, Dec. 2006.

[39] T. Sheridan, “Space teleoperation through time delay: Review and prognosis,” *IEEE Transactions on Robotics and Automation*, vol. 9, no. 5, pp. 592–606, 1993.

[40] W. Ferrell, “Delayed force feedback,” *Human Factors: The Journal of the Human Factors and Ergonomic Society*, vol. 8, no. 5, pp. 449–455, 1966.

[41] H. Das and H. Zak, “Operator performance with alternative manual control modes in teleoperation,” *Presence*, vol. 1, no. 2, pp. 201–217, 1992.

[42] H. Kazerooni and T. Snyder, “Case study on haptic devices: Human-induced instability in powered hand controllers,” *Journal of Guidance, Control and Dynamics*, vol. 18, no. 1, pp. 108–113, 1995.

[43] F. Buzan and T. Sheridan, “A model-based predictive operator-aid for telemanipulators with time delay,” in *In proc. of the IEEE International Conference on Systems, Man and Cybernetics*, 1989, pp. 14–17.

[44] M. Massimino, “Improved force perception through sensory substitution,” *Control Engineering Practice*, vol. 3, no. 2, pp. 215–222, 1995.

[45] M. Tavakoli, A. Aziminejad, R. Patel, and M. Moallem, “High-fidelity bilateral teleoperation systems and the effect of multimodal haptics,” *IEEE Transactions on Systems, Man, and Cybernetics, Part B: Cybernetics*, vol. 37, no. 6, pp. 1512–1528, 2007.

[46] R. Anderson and M. Spong, “Hybrid impedance control of robotic manipulators,” *IEEE Journal of Robotics and Automation*, vol. 4, pp. 549–556, 1988.

[47] G. Niemeyer and J.-J. E. Slotine, “Stable adaptive teleoperation,” *IEEE Journal of Oceanic Engineering*, vol. 16, no. 1, 1991.

[48] K. Salisbury, F. Conti, and F. Barbagli, “Haptic rendering: introductory concepts,” *Computer Graphics and Applications, IEEE*, vol. 24, no. 2, pp. 24–32, march-april 2004.

[49] N. Magnenat-Thalmann and U. Bonanni, “Haptics in virtual reality and multimedia,” *Multimedia, IEEE*, vol. 13, no. 3, pp. 6–11, july-sept. 2006.

[50] T. Coles, D. Meglan, and N. John, “The role of haptics in medical training simulators: A survey of the state of the art,” *Haptics, IEEE Transactions on*, vol. 4, no. 1, pp. 51–66, jan.-feb. 2011.

[51] J. Kammerl, R. Chaudhari, and E. Steinbach, “Combining contact models with perceptual data reduction for efficient haptic data communication in networked ves,” *Instrumentation and Measurement, IEEE Transactions on*, vol. 60, no. 1, pp. 57–68, jan. 2011.

[52] R. Adams and B. Hannaford, “Control law design for haptic interfaces to virtual reality,” *Control Systems Technology, IEEE Transactions on*, vol. 10, no. 1, pp. 3–13, jan 2002.

[53] A. Bejczy, R. Dotson, J. Brown, and J. Lewis, “Manual control of manipulator forces and torques using graphic display,” in *IEEE International Conference of Cybernetics and Society*, 1982, pp. 691–698.

[54] P. Bach-y-Rita, J. Webster, W. Tompkins, and T. Crabb, “Sensory substitution for space gloves and for space robots,” in *In Proceedings of the Workshop for Space Telerobotics*, vol. 2, 1987, pp. 51–57.

[55] W. Kim and A. Bejczy, “Graphics displays for operator aid in telemanipulation,” in *IEEE International Conference on Systems, Man and Cybernetics*, 1991, pp. 1059–1067.

[56] M. Massimino and T. Sheridan, “Sensory substitution of force feedback for the human-machine interface in space teleoperation,” in *43rd Congress of the International Astronautical Federation*, 1992.

[57] T. Debus, T. Becker, P. Dupont, T.-J. Jang, and R. Howe, “Multichannel vibrotactile display for sensory substitution during teleoperation,” in *SPIE International Symposium on Intelligent Systems and Advanced Manufacturing*, 2001.

[58] T. Debus, T.-J. Jang, P. Dupont, and R. Howe, “Multichannel vibrotactile display for teleoperated assembly,” in *IEEE International Conference on Robotics and Automation*, 2002, pp. 592–597.

[59] C. Reiley, T. Akinbiyi, D. Burschka, D. Chang, A. Okamura, and 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.

[60] T. Yoshikawa, Y. Yokokohji, T. Matsumoto, and X.-Z. Zheng, “Display of feel for the manipulation of dynamic virtual objects,” *Journal of Dynamic Systems, Measurement, and Control*, vol. 117, no. 4, pp. 554–558, 1995.

[61] P. Galambos, M. Boleraczki, A. Juhász, A. Tóth, J. Püspöki, and G. Arz, “Development of the prototype of a master-slave servoelectrical gripper with

forcefeedback for telemanipulation tasks," in *Proceedings of the Fifth Conference on Mechanical Engineering*, K. L. Penninger A, Ed. BME OMIKK, May 2006.

[62] P. Galambos, A. Róka, P. Baranyi, and P. Korondi, "Contrast vision-based grasp force feedback in telemanipulation," in *Advanced Intelligent Mechatronics, 2010 IEEE/ASME International Conference on*, Montreal, Canada, Jun. 2010.

[63] M. Slater, B. Spanlang, M. V. Sanchez-Vives, and O. Blanke, "First person experience of body transfer in virtual reality," *PLoS ONE*, vol. 5, 05 2010.

[64] A. Csapo and P. Baranyi, "An interaction-based model for auditory substitution of tactile percepts," in *2010 IEEE 14th International Conference on Intelligent Engineering Systems*, Las Palmas, Spain, 2010, pp. 271–276.