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The Human Role in Telerobotics

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Summary. This chapter introduces the main topics of a telerobotic system. It describes the architecture of such a system from a general point of view and emphasizes the interaction between a human operator and a robot that performs the task in the remote environment. Furthermore it focuses on multi-modal human system interfaces and explains the main features of haptic, auditory, and visual interfaces. Finally important issues for the measurement and evaluation of the attribute telepresence are described.

1.1 Introduction

Telerobotic systems allow human operators to properly interact with a telerobot to telemanipulate objects located in a remote environment. This means that human actions are extended to remote locations allowing the execution of complex tasks and avoiding risky situations for the human operator [1].

In a telerobotic system the human operator plays an important role. He *perceives* information from the remote environment through the human system interface and *acts* accordingly by sending commands to the remote devices. Thus the human system interface has two important functions; first, it has to excite the operator senses so as to show the status of the executed task in the remote environment and second, it has to process the operator commands in order to properly control remote devices. Multi-modal [3] commands are generated by the operator at his or her working site by means of the human system interface using motion, force, voice or symbolic inputs. Such commands are transmitted to the telerobot in order to perform the remote task. Sensors are placed at the remote site to gather data from the task which is then

[3] The term *multi-modal* refers to the different human senses.

transmitted back to the operator and displayed by the multi-modal human system interface.

Designing of multi-modal human system interfaces is one of the key challenges in telerobotics. Vision, audition, and haptics are senses excited by the multi-modal interface. It is thereby important to take into account human perception capabilities so as to obtain a better interaction.

Telepresence is one of the key factors that enhances performance of a telerobotic system. Telepresence means that the information about the remote environment is displayed to the operator in a natural manner, which implies a feeling of presence at the remote site. A good degree of telepresence guarantees the feasibility of the required manipulation task.

The following sections describe the key points of a telerobotic system. Section two shows a general structure of such a system and explains its main components and functions. Section three is focused on the design of multi-modal human system interfaces. Main features of human senses and capabilities are briefly described. It allows defining criteria for a better design of visual, auditory and haptic devices. Section four deals with the concept of telepresence and other performance measurements. Lastly, conclusions of this chapter are summarized in section five.

This chapter is an introduction to the topics of this part of the book. Chapters 2 and 3 describe serial and parallel haptic interfaces respectively. Chapter 4 focuses on exoskeletons. Chapters 5 and 6 describe two different stereoscopic video systems that reproduce human binocular vision. Chapter 7 deals with voice command generation for telerobotics. Chapter 8 describes how to process operator gestures in order to remotely control a robot. Finally, chapter 9 contains a review of the technology in virtual reality applied to telerobotics.

1.2 General Structure of a Telerobotic System

A telerobotic system is comprised of two main parts; the operator environment and the remote environment, as visualized in Fig. 1.1. Both environments are linked by a communication channel that transmits commands from the operator to the remote devices and sends back information of the remote task to the operator. The operator environment is made up of a multi-modal human system interface, which the operator uses in order to control the remote devices. The remote environment consists of teleoperated devices, sensors and objects that take part in the teleoperation task. Each environment contains processing modules which have double functions: first, to transform data transmitted by the communications channel and second, to execute the corresponding local control loops.

A central issue related to the design and operation of telerobotic systems is the degree of coupling between the human operator and the remote robot. It is generally classified as *weak* or *strong*. If the operator gives symbolic commands to the robot by pushing buttons and watching the resulting action in the remote environment, its coupling is rather *weak*. Some degree of ”intelligence” is required for a remote robot to execute such symbolic commands. The coupling is comparably *strong* for the kinesthetic modality in a bilateral teleoperation scenario. Commonly, the motion (and/or force) of the human operator is measured, communicated and used as a set-point for teleoperator motion (and/or force) controller. On the other hand, forces (motions) of the teleoperator in the remote environment are sensed, communicated and fed back to the human operator through the multi-modal human system interface. The degree of coupling is thereby related to the control distribution between operator and remote robot controller. Literature on telerobotics distinguishes among *shared*, *cooperative*, *supervisory*, and *bilateral control*. A comprehensive review of the control modes in telerobotics can be found in [2].

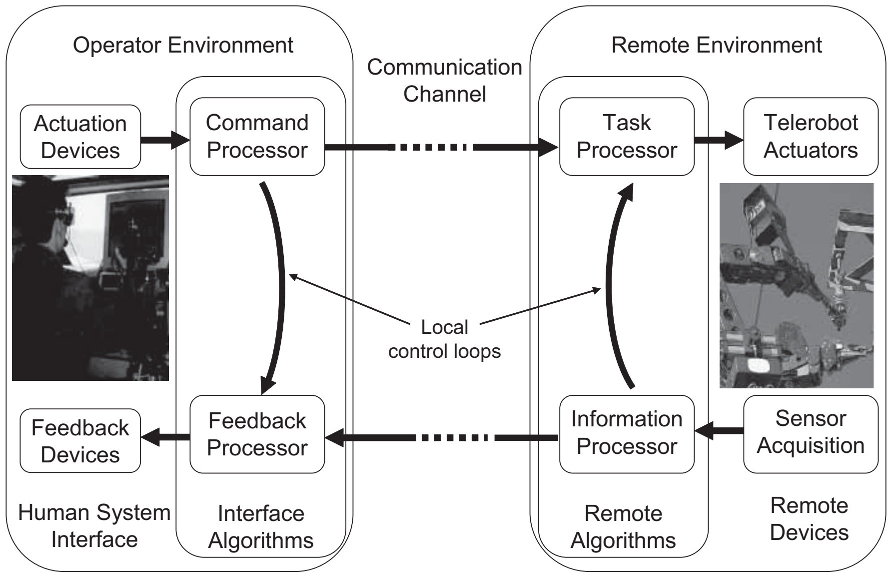

Fig. 1.1. Main modules of a telerobotic system

1.2.1 Operator Environment

The human system interface plays an important role in a telerobotic system. It provides input devices that are used to generate operator commands and display devices that are used to monitor the interaction between remote robot and environment. Telerobot commands are generated by input devices that identify the operator actions. According to the control mode, commands have to be processed to a greater or lesser degree before they are transmitted to the remote environment. For example, when an operator executes a guidance task using a master-slave system, i.e. with strong coupling, motion (force) commands are continuously processed. They could be scaled or transformed to different coordinates. This is an example for a rather simple processing. More complex processing would be required if commands were symbolic, like e.g. ”picking an object”. Symbolic commands have to be transformed - on operator or remote site - to the corresponding sequence of remote device actions.

Simultaneously, multi-modal sensor information is received from the remote environment. This multi-modal feedback consists of 2D or 3D visual, mono/stereo acoustic, haptic (force, motion, tactile, temperature) and symbolic information which is generated by feedback information processors and displayed by the corresponding interface devices. The purpose of a feedback device is to excite the operator’s senses in order to show him the remote task status. Force feedback master-arms and stereoscopic screens are typical examples of devices used as human system interfaces. The former informs the operator about applied contact forces during telemanipulation, while the latter gives a 3D visual impression of the remote environment.

Whereby low level control loops executed at the operator site ensure a good tracking behavior of the haptic interface, high level control loops show additional information about the remote task. *Augmented reality* and *predictions* may thereby significantly improve the task performance. A common example of such an augmented reality assisted system is a graphic display that shows safe region for operation and arrows indicating virtual forces for collision avoidance. Prediction is usually applied in improving performance by lowering the effect of long time delays and non-reliability in signal transmission. Photo-realistic scene prediction [3, 4] and the prediction of environment forces [5] are typical examples. Sensory substitution as e.g. in [6], where force is replaced by artificially generated sound, may reduce complexity and cost of a human system interface.

1.2.2 Remote Environment

When the operator commands reach the remote environment, the task processor transforms them into actions. Once again, the complexity of data processing depends on the type of command and the degree of coupling. Complex data processing is required when the operator and the telerobot are weakly coupled, i.e. in cases where the robot has some degree of autonomy or when the robot only receives symbolic commands. Simple data processing is required when the operator and the telerobot are strongly coupled.

The information captured by sensors is used in obtaining data from the remote task and sending them to the operator environment via the communication channel. Computer vision recognition and object localization algorithms are good examples of sensor processing. They obtain information from the objects located at the remote site and thereby define spatial positions of telemanipulated objects.

Local control loops that are executed at the remote site, ensure the motion (force) tracking of the robot. Trajectories are provided by the operator or generated from symbolic commands. Several researchers have looked into human skill and expertise modelling so as to supplement control from the local teleoperator, e.g. [7–12]. The main concept is to have an intelligent teleoperator that performs tasks by demonstration. Such operator can acquire expert control knowledge (skills) from measured data and apply skills in performing tasks in semi-autonomous teleoperation control.

1.3 Multi-modal Human System Interfaces for Telerobotic Applications

The interaction with a remote robot is done through the human system interface, which transmits operator's actions and excites human senses according to the information received from the remote environment. Multi-modal human system interfaces refer to the perceptual modalities of human beings, such as visual, auditory, and haptic [4] modalities. Thus designing new devices the human sensing ability must be taken into account.

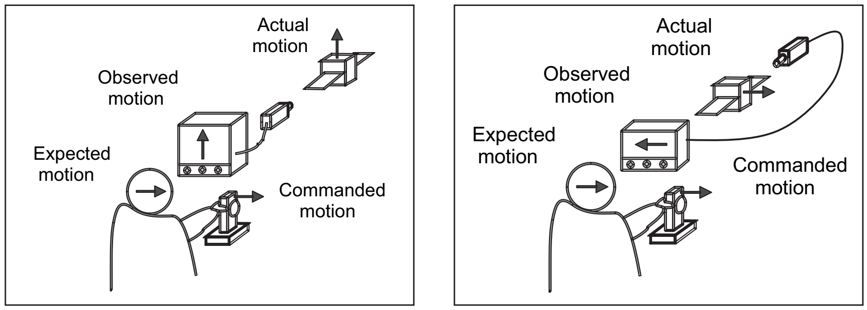

Fig. 1.2. Examples of visual disadjustment due to kinematic transformations (left) or observational reasons (right)

Furthermore operator *teleproprioception* have to be considered. Operator telepropioception implies coherence between operator's commands and their execution. Fig. 1.2 describes some examples that show disadjustments between commanded and observed motions. Such disadjustments are due to kinematic transformations, observational reasons or relative movements between object and camera, which make the guidance references incoherent to the given visual references. Moreover aspects such as information redundancy and stimulus fidelity of the information provided to the human operator are essential in obtaining an accurate perception of the remote environment. The following sections review the human sensing abilities and provide a classification of state-of-the-art human system interfaces.

1.3.1 Sense of Vision

The sense of vision informs us about shapes, colours and distances of the objects that can be seen by the human eye. The retina consists of a large number of photoreceptor cells. The two main types are rods and cones. They are excited by light and transmit signals to the brain through the optic nerve. The brain processes this information in several layers in order to properly interpret visual excitation.

[4] Haptics refers to the feeling of force, motion, and vibration. It is divided into kinesthetic, proprioreceptive, and tactile submodalities.

Table 1.1. Main features of signals transmitted in a telerobotic system

Channel	Type of signals	Sample size (pixels or n. of bits)	Samples per second	Bandwidth
Visual				
	TV video (PAL/NTSC)	720x480 - 720x576	25 - 30 frames/s	165,9 Mbps
	TV Video compres. (DVD quality)	720x480 - 720x576	25 - 30 frames/s	5,2 Mbps
	Stereo video (uncompressed)	640x480	30 - 70 frames/s	147 - 344 Mbps
	Stereo video compres. (DVD quality)	640x480	30 - 70 frames/s	6,3 - 14,6 Mbps
Auditory				
	Stereo sound quality CD	16 bits x 2 channels	44,1 kHz	1,4 Mbps
	Mono sound quality telephone	12 bits x 1 channel	8,0 kHz	96 kbps
Haptics				
	Tactile	10 bits (per point)	0-10 kHz	0-100 kbps/point
	Soft contact forces	10 bits (per DoF) (6 DoF)	0,1-1,0 kHz	6-60 kbps
	Hard contact forces	10 bits (per DoF) (6 DoF)	10-100 Hz	0,6-6 kbps

Numerous studies and experiments have been performed to compare monoscopic effectiveness of images versus stereoscopic images [13–15]. These studies show that stereoscopic images are better than monoscopic images when performing a telemanipulation task. Other studies, such as [16, 17] highlight the complexity of the mechanisms applied in stereoscopic image perception. These works demonstrate that monoscopic data such as shadows and reflections could be as important as stereoscopic data [18].

Human visual perception has three mechanisms to perceive spatial information, which are binocularity, motion parallax and image realism. Binocularity is due to having two points of view which are 6 to 7 centimeters apart. Spatial information received by this mechanism has a predominant effect for closer objects, which is less than 1 meter. Many visual interfaces such as head-mounted displays, shutter glasses, parallax barrier, etc. imitate this effect providing users with different images for each eye. The motion parallax effect is predominant for objects farther than 1 meter and refers to relative movements between objects. As everybody knows nearer objects move faster than farther objects. An example can be clearly stated out when driving: trees located next to the car move faster than the mountains in the background that can be seen without any motion. As a consequence, a monoscopic camera in motion informs about spatial positions because different points of view of the scene are provided. Finally the third mechanism, the image realism is related to our manner of perceiving environments, which is based on texture gradients, object projections, light reflections, shadows and so on. Features of these data imply transmitting high quality images that require a large bandwidth. According to table 1.1 the minimum bandwidth is 5,2 Mbps. It corresponds to monoscopic compressed images. The maximum bandwidth is 344 Mbps, which corresponds to stereoscopic images with 70 frames per second and a resolution of 640*480 pixels per image.

Visual Interfaces

Teleoperation visual interfaces show images from the remote site. Cameras observe the scene of the remote environment and the captured images are displayed on the corresponding interfaces that provide visual information to the human operator.

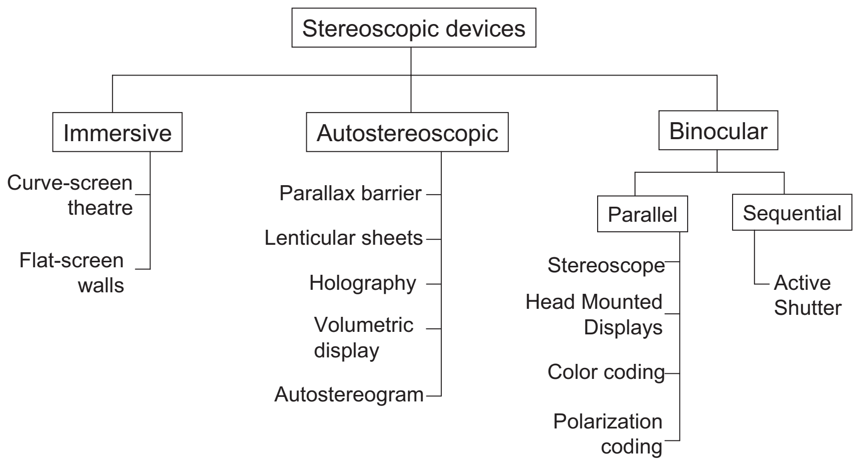

Fig. 1.3. Stereoscopic device classification

Simulating full human binocular vision requires better technology than what is currently available. No current display can meet all the specifications required in order to reproduce human depth perception properly. Therefore, a great variety of stereoscopic devices are available for specific applications, as is shown in Fig. 1.3. Stereoscopic devices can be divided into the following categories: binocular, autostereoscopic and immersive (according to its purpose). Binocular devices require an additional component such as glasses or a helmet in order to show a different image to each eye. Head Mounted Displays and systems based on shutter or polarized glasses are representatives of these devices. Autostereoscopic devices show a different image to each eye without needing any additional device, such as lenticular sheets or parallax barrier. Immersive devices make use of broad scenes where the sensation of depth is attained by covering the whole visual field, such as flat-screen walls and curve-screen theatres.

The number of images displayed per second is an important parameter for visual devices. Common visual interfaces usually show 25 or 30 frames per second, while stereoscopic devices based on shutter glasses display more than 60 frames per second. This high frequency is to avoid flicking problems upon visualization of stereoscopic images and it implies a large bandwidth as shown in table 1.1.

1.3.2 Sense of Hearing

Auditory cues are also important for teleoperation interfaces since they increase the situation awareness, attract visual attention and covey a variety of complex information without overwhelming the visual system. Auditory cues are particularly usefull when the visual channel is saturated or in the case of a limited field of view. Since the response to the auditory stimulus is fast (30-40 ms faster than for visual signals) sounds are also very suitable for alarms and sporadic messages from the computer interface.

Sound can be described by its physical properties frequency, intensity, and complexity. These properties correspond to the perceptual analogues pitch, loudness, and timbre. Designing auditory displays it is important to consider physical as well as perceptual properties. It is known that humans are able to hear sounds with frequencies from 20 Hz to 22.000 Hz, whereby the absolute sensitivity varies with frequency. Humans perceive sound intensity on a logarithmic scale, which spans over a range of 110-120 dB from just detectable sounds to sounds that cause pain. The physical measure ”‘intensity”’ is not linear dependent on the perceptual measure ”‘loudness”’ of a sound: The same increase in intensity can result in different increments in loudness, depending on the frequency of the signal. As the intensity of a signal is correlated to the loudness of a signal, the frequency correlates to the pitch. While for periodic signals the perceived pitch of a signal is directly dependent on the frequency of a signal, for nonperiodic signals the perceived pitch is affected by several stimulus attributes as e.g. harmonicity and loudness. Also the perception of timbre, which enables us to distinguish between different speakers or instruments depends on a number of physical parameters as spectral content and temporal envelope. Well known are also masking effects, which appear when multiple acoustic sources are presented to the listener simultaneously or in rapid succession.

Another important characteristic is the spatial acuity of the auditory system. While humans are able to distinguish sounds which are displaced by one degree from the median plane, this ability decreases drastically for sound sources located directly to the side of the human such that lateral displacements of about 10 degrees can be just detected. The human perception of spatial hearing is based on the evaluation of binaural, spectral, anechoic and dynamic cues as well as reverberation and the prior knowledge about the environment.

Auditory Interfaces

As already mentioned designing auditory interfaces it is important to consider physical as well as perceptual properties. E.g. it is known that the intensity of everyday sound has a range of about 80 to 90 dB. Thats why typical sound systems use 16 bits to represent the pressure of an acoustic signal (see table 1.1). Further it is known that speech information is characterized by frequencies of 200 to 5000 Hz. Hence acoustic interfaces must be designed to cover at least this range of frequencies.

In order to enable a high immersion signals should be replayed by providing an accurate spatial information. Spatial auditory cues can be generated either by using headphones or loudspeakers. While headphones allow a more precise control of the different auditory cues, a loudspeaker-system doesn't interfere with the human's head.

Depending on the different level of spatial immersion diotic, dichotic and spatialized headphone displays can be distinguished. Diotic displays present identical signals to both ears, dichotic displays simulate frequency independent interaural time and intensity differences and spatialized audio displays coupled with a head-tracking system can provide several spatial cues available in the real world. So called Head-Related-Transfer-Functions (HRTFs) are used to describe how an acoustic signal is transformed on the way from its source to the ear drum of the listener.

A similar impression to that generated with headphones can also be produced by using speakers arranged around the listener. In this case the signals of all speakers must be controlled in such a way, that the sum of all signals generates the appropriate spatial cues. Since all signals influence each other, the signals for each ear cannot be manipulated independently and complex calculations are necessary in order to get a real spatial impression. Even here nonspatial, stereo displays and spatial displays can be distinguished. While nonspatial displays correspond to the diotic, stereo displays (using only two speakers) correspond to the dichotic headphones. Most commercial available stereo headphones are based on this last mentioned two speaker system, which is able to control the lateral sound location. Using more than two speakers the spatial simulation increases. The most common Surround sound systems available at the market are 5.1, 6.1 and 10.1 systems.

1.3.3 Sense of Touch

The sense of touch is another complex sense which can be divided into two main components: the tactile and the kinesthetic component. Integration of both is known as haptics, which is a Greek word meaning ”science of touch”.

The tactile receptors are located directly under the skin and the stimulation of such receptors has a high frequency (up to 10 kHz). They participate in the first contact when the interaction with an object occurs. Furthermore they make it possible to perceive texture, geometry, and temperature of manipulated objects. Four different mechanoreceptors are distinguished according to the velocity of adaptation as well as the size of the receptive fields: FA II receptors (Pacinian Corpuscles) which are acceleration sensitive, FA I receptors (Meissner Corpuscles) which are velocity dependent, SA I receptors (Merkel's cells) which react on pressure, and SA II receptors (Ruffini endings) which are sensitive on stretching the skin. More information about tactile receptors and the tactile sensation of human beings can be found in [19, 20].

The kinesthetic excitation is related to the receptors located in muscles, sinews, and joints. They inform us about pose and motion, contact forces, weight and object deformability. This interaction has a lower frequency (less 1 kHz), and its reproduction is thus more realistic. A good description of this stimulus can be found in [19, 20].

To summarize it can be stated that bandwidth and location of receptors are the main differences between tactile and kinesthetic sensation. This has to be taken into account when developing new haptic interfaces.

Haptic Interfaces

Haptic interfaces cover a very extensive variety of devices. Their classification could be based on two main criteria which are predominant feedback component and device portability. The predominant feedback component criterion permits classifying haptic devices into two categories, which are kinesthetic predominant devices and tactile predominant devices. According to the other criterion which is portability, haptic interfaces can be classified as portable and non-portable devices. Non-portable haptic interfaces are devices that are bolted to a desk, a wall, the ceiling, or the floor. Portable haptic interfaces are devices that are worn by the operator. An overview of typical types of haptic interfaces can be found in [21–24].

Table 1.2. Classification of haptic interfaces

	Portable	Non-portable
Kinesthetic predominant	exoskeletons	joysticks, pen/string-based systems, robot-like systems
Tactile predominant	gloves with vibrotactile and temperature feedback	pin actuators, general vibrotactile and temperature devices

Table 1.2 shows the most important representatives according to the classification mentioned above. Exoskeletons are usually worn devices mounted to the arm or leg. They reproduce the human body motions and the feedback is predominantly kinesthetic. Such a kind of interface is presented in chapter 4. Non-portable and kinesthetic predominant devices are devices that have a serial or parallel kinematic configuration and are manipulated by the operator's fingers or hands. Chapter 2 and 3 describe such systems in more detail. Gloves are common interface devices that highlight tactile interaction. Examples of them are described in [25, 26]. Finally, tactile and non-portable displays provide information about object features such as surface structure, geometry and temperature. An overview of the principles of vibrotactile and electrotactile displays can be found in [27] and [28]. Examples for temperature feedback systems are presented in [29] and [26].

1.4 Measuring and Evaluating Telepresence

A telepresence system allows a human operator to operate in a remote environment using the superior motor and sensor skills of a robot and the unrivalled cognitive skills of a human being. Teleoperation provides the means to successfully achieve telepresence.
Technically as well as philosophically telepresence is a difficult concept. Hence, defining an *ideal* telepresence system results in many different, partly contradictory, conditions. For example, reducing feedback may improve the performance of a fatigue operator. However, as common ground a telepresence system should enable the operator to feel *immersed* and *involved* in the remote environment. Immersion and involvement are psychological states that depend on the display of the remote environment. High *immersion* means that the user is enveloped by all stimuli necessary to provide a congruent picture of the remote environment. High *involvement* means that the user is provided by all stimuli essential to interact with the remote environment [30]. Both conditions are accommodated by reflecting a high extent of sensory information to the human operator and by enabling her/him to naturally explore and manipulate the remote environment [31].
A basis that structures different evaluation methods is given by the distinction between *objective* and *subjective* telepresence. Objective telepresence is defined by the pure capability of the human operator to successfully complete a given task in the remote environment. Subjective telepresence is more strict emphasizing that the operator must feel as if physically being present in the remote environment [32]. Objective performance measures are *task completion time* or *reaction time* to a remote stimulus. Subjective performance can be measured by *presence questionnaires* asking the human operator about her/his individual feelings [30, 33, 34].
Another way to evaluate the performance is offered by the *transparency* paradigm. A telepresence system is transparent if it exactly reproduces the remote environment. Hence the operator can 'look through' the telepresence system sensing only the remote environment [35]. That results in a number of performance measures for the different channels of the telepresence system. The quality of haptic telepresence, for example, can be judged by comparing positions and forces at operator and teleoperator side [36]. Another possibility is to compare the displayed mechanical impedance with the impedance of the remote environment [37]. For the other modalities transparency criteria also result in comparisons between the operator and the teleoperator site.

1.5 Conclusions

Telerobotics implies linking a human operator and a robot in order to execute a remote task. The coupling between the operator and the robot is considered as strong, when most of the remote control loops are closed by the operator, or considered as weak, when symbolic commands are sent by the operator to be processed by the remote robot control loops.

Teleoperation multi-modal human system interfaces have a double function; first, to process the operator commands and second, to excite operator sense with the information coming from the remote environment. Visual, auditory and haptic interfaces as described are natural manners in controlling a remote task.

Many factors as e.g. acting and human sense capabilities have to be taken into account upon designing a multi-modal interface properly. The goal is to achieve the maximum possible degree of telepresence in order to increase the performance of the telerobotic system.

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