27. Teleoperation

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This chapter presents an overview of the teleoperation of robotics systems, starting with a historical background, and including the description of an up-to-date specific teleoperation scheme as a representative example to illustrate the typical components and functional modules of these systems. Some specific topics in the field are particularly discussed, for instance, control algorithms, communications channels, the use of graphical simulation and task planning, the usefulness of virtual and augmented reality, and the problem of dexterous grasping. The second part of the chapter includes a description of the most typical application fields, such as industry and construction, mining, underwater, space, surgery, assistance, humanitarian demining, and education, where some of the pioneering, significant, and latest contributions are briefly presented. Finally, some conclusions and the trends in the field close the chapter.

The topics of this chapter are closely related to the contents of other chapters such as those on *Communication in Automation, Including Networking and Wireless* (Chap. 13), *Virtual Reality and Automation* (Chap. 15), and *Collaborative Human–Automation Decision Making* (Chap. 26).

The term *teleoperation* is formed as a combination of the Greek word $\tau\eta\lambda\varepsilon$-, (*tele-*, offsite or remote), and the Latin word *operatĭo*, *-ōnis* (*operation*, something done). So, *teleoperation* means performing some work or action from some distance away. Although in this sense teleoperation could be applied to any operation performed at a distance, this term is most commonly associated with robotics and mobile robots and indicates the driving of one of these machines from a place far from the machine location.

There are of lot of topics involved in a *teleoperated robotic system*, including human–machine interaction, distributed control laws, communications, graphic simulation, task planning, virtual and augmented reality, and dexterous grasping and manipulation. Also the fields of application of these systems are very wide and teleoperation offers great possibilities for profitable applications. All these topics and applications are dealt with in some detail in this chapter.

27.1 Historical Background and Motivation

Since a long time ago, human beings have used a range of tools to increase their manipulation capabilities. In the beginning these tools were simple tree branches, which evolved to long poles with tweezers, such as blacksmith's tools that help to handle hot pieces of iron. These developments were the ancestors of master–slave robotic systems, where the slave robot reproduces the master motions controlled by a human operator. Teleoperated robotic systems allow humans to interact with robotic manipulators and vehicles and to handle objects located in a remote environment, extending human manipulation capabilities to far-off locations, allowing the execution of quite complex tasks and avoiding dangerous situations.

The beginnings of teleoperation can be traced back to the beginnings of radio communication when Nikola Tesla developed what can be considered the first teleoperated apparatus, dated 8 November 1898. This development has been reported under the US patent 613 809, *Method of and Apparatus for Controlling Mechanism of Moving Vessels or Vehicles*. However, bilateral teleoperation systems did not appear until the late 1940s. The first bilateral manipulators were developed for handling radioactive materials. Outstanding pioneers were Raymond Goertz and his colleagues at the Argonne National Laboratory outside of Chicago, and Jean Vertut at a counterpart nuclear engineering laboratory near Paris. The first mechanisms were mechanically coupled and the slave manipulator mimicked the master motions, both being very similar mechanisms (Fig. 27.1). It was not until the mid 1950s that Goertz presented the first electrically coupled master–slave manipulator (Fig. 27.2) [27.1].

Fig. 27.1 Raymond Goertz with the first mechanically coupled teleoperator (Source: Argonne National Labs)

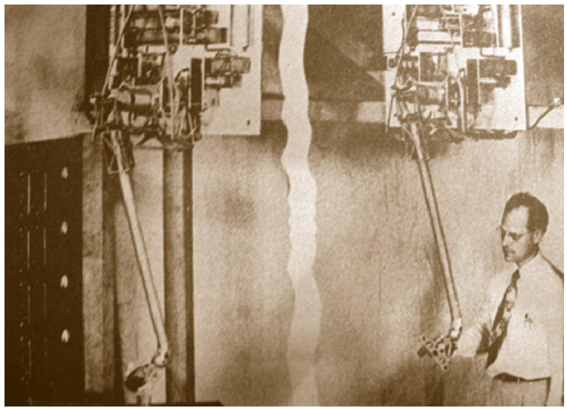

Fig. 27.2 Raymond Goertz with an electrically coupled teleoperator (Source: Argonne National Labs)

In the 1960s applications were extended to underwater teleoperation, where submersible devices carried cameras and the operator could watch the remote robot and its interaction with the submerged environment. The beginnings of space teleoperation dates form the 1970s, and in this application the presence of time delay started to cause instability problems.

Technology has evolved with giant steps, resulting in better robotic manipulators and, in particular, increasing the communication means, from mechanical to electrical transmission, using optic wires, radio signals, and the Internet which practically removes any distance limitation.

Today, the applications of teleoperation systems are found in a large number of fields. The most illustrative are space, underwater, medicine, and hazardous environments, which are described amongst others in Sect. 27.4

27.2 General Scheme and Components

A modern teleoperation system is composed of several functional modules according to the aim of the system. As a paradigm of an up-to-date teleoperated robotic system, the one developed at the Robotics Laboratory of the Institute of Industrial and Control Engineering (IOC), Technical University of Catalonia (UPC), Spain, will be described below [27.2].

The outline of the IOC teleoperation system is represented in Fig. 27.3. The diagram contains two large blocks that correspond to the local station, where the human operator and master robots (haptic devices) are located, and the remote station, which includes two industrial manipulators as slave robots. The system contains the following system modules.

Relational positioning module: This module provides the operator with a means to define geometric relationships that should be satisfied by the part manipulated by the robots with respect to the objects in the environment. These relationships can completely define the position of the manipulated part and then fix all the

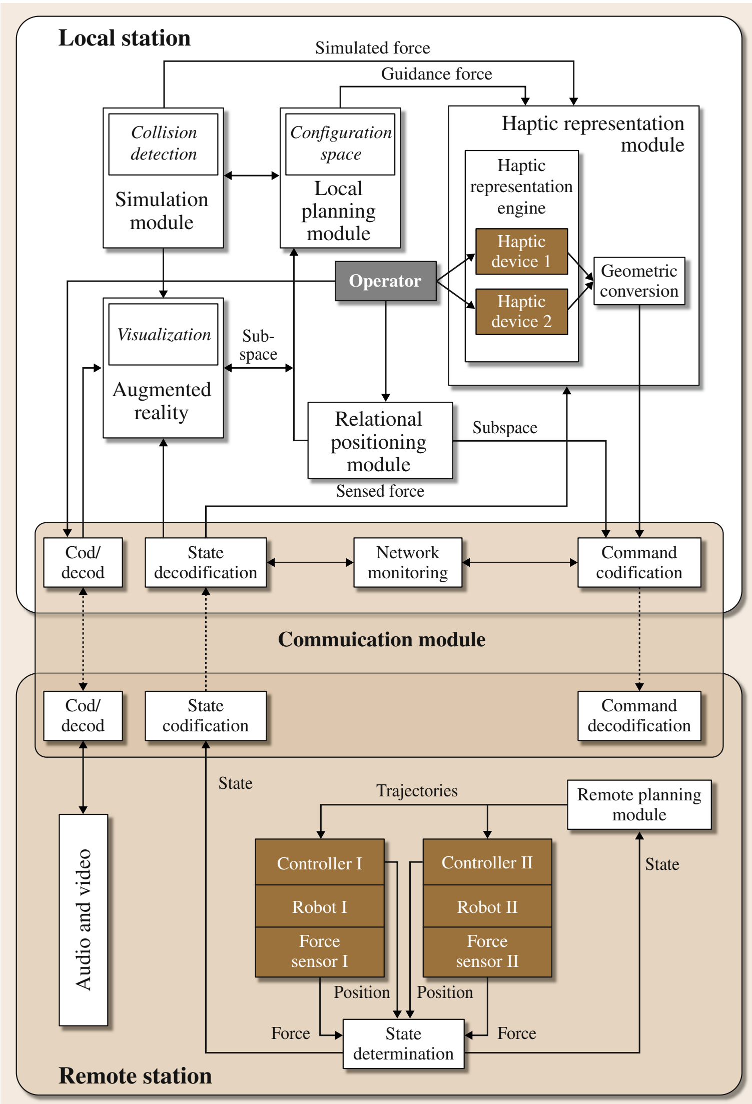

Fig. 27.3 A general scheme of a teleoperation system (courtesy of IOC-UPC)

robots' degrees of freedom (DOFs) or they can partially determine the position and orientation and therefore fix only some DOFs. In the latter case, the remaining degrees of freedom are those that the operator will be able to control by means of one or more haptic devices (master robots). Then, the output of this module is the solution subspace in which the constraints imposed by the relationships are satisfied. This output is sent to the modules of *augmented reality* (for visualization), *command codification* (to define the possible motions in the solution subspace), and *planning* (to incorporate the motion constraints to the haptic devices).

Haptic representation module: This module consists of the *haptic representation engine* and the *geometric conversion submodule*. The haptic representation engine is responsible for calculating the force to be fed back to the operator as a combination of the following forces:

- *Restriction force*: This is calculated by the *planning* module to assure that, during the manipulation of the haptic device by the operator, the motion constraints determined by the *relational positioning* module are satisfied.
- *Simulated force*: This is calculated by the *simulation* module as a reaction to the detection of potential collision situations.
- *Reflected force*: This is the force signal sent from the remote station through the *communication* module to the local station corresponding to the robots' actuators forces and those measured by the force and torque sensors in the wrist of the robots produced by the environmental interaction.

The *geometric conversion submodule* is in charge of the conversion between the coordinates of the haptic devices and those of the robots.

Augmented-reality module: This module is in charge of displaying to the user the view of the remote station, to which is added the following information:

- *Motion restrictions imposed by the operator*. This information provides the operator with the understanding and control of the unrestricted degrees of freedom can be commanded by means of the haptic device (for example, it can visualize a plane on which the motions of the robot end-effector are restricted).
- *Graphical models of the robots in their last configuration received from the cell*. This allows the operator to receive visual feedback of the robots' state from the remote station at a frequency faster than that allowed by the transmission of the whole image, since it is possible to update the robots' graphical models locally from the values of their six joint variables.

This module receives as inputs: (1) the image of the cell, (2) the state (pose) of the robots, (3) the model of the cell, and (4) the motion constraints imposed by the operator. This module is responsible for maintaining the coherence of the data and for updating the model of the cell.

Simulation module: This module is used to detect possible collisions of the robots and the manipulated pieces with the environment, and to provide feedback to the operator with the corresponding force in order to allow him to react quickly when faced with these possible collision situations.

Local planning module: The planning module of the local station computes the forces that should guide the operator to a position where the geometric relationships he has defined are satisfied, as well as the necessary forces to prevent the operator from violating the corresponding restrictions.

Remote planning module: The planning module of the remote station is in charge of reconstructing the trajectories traced by the operator with the haptic device. This module includes a feedback loop for position and force that allows safe execution of motions with compliance.

Communication module: This module is in charge of communications between the local and the remote stations through the used communication channel (e.g., Internet or Internet2). This consists of the following submodules for the information processing in the local and remote stations:

- *Command codification/decodification*: These submodules are responsible for the codification and decodification of the motion commands sent from the local station and the remote station. These commands should contain the information of the degrees of freedom constrained to satisfy the geometric relationships and the motion variables on the unrestricted ones, following the movements specified by the operator by means of the haptic devices (for instance, if the motion is constrained to be on a plane, this information will be transferred and then the commands will be the three variables that define the motion on that plane). For each robot, the following three qualitatively different situations are possible:
  – The motion subspace satisfying the constraints defined by the relationships fixed by the operator

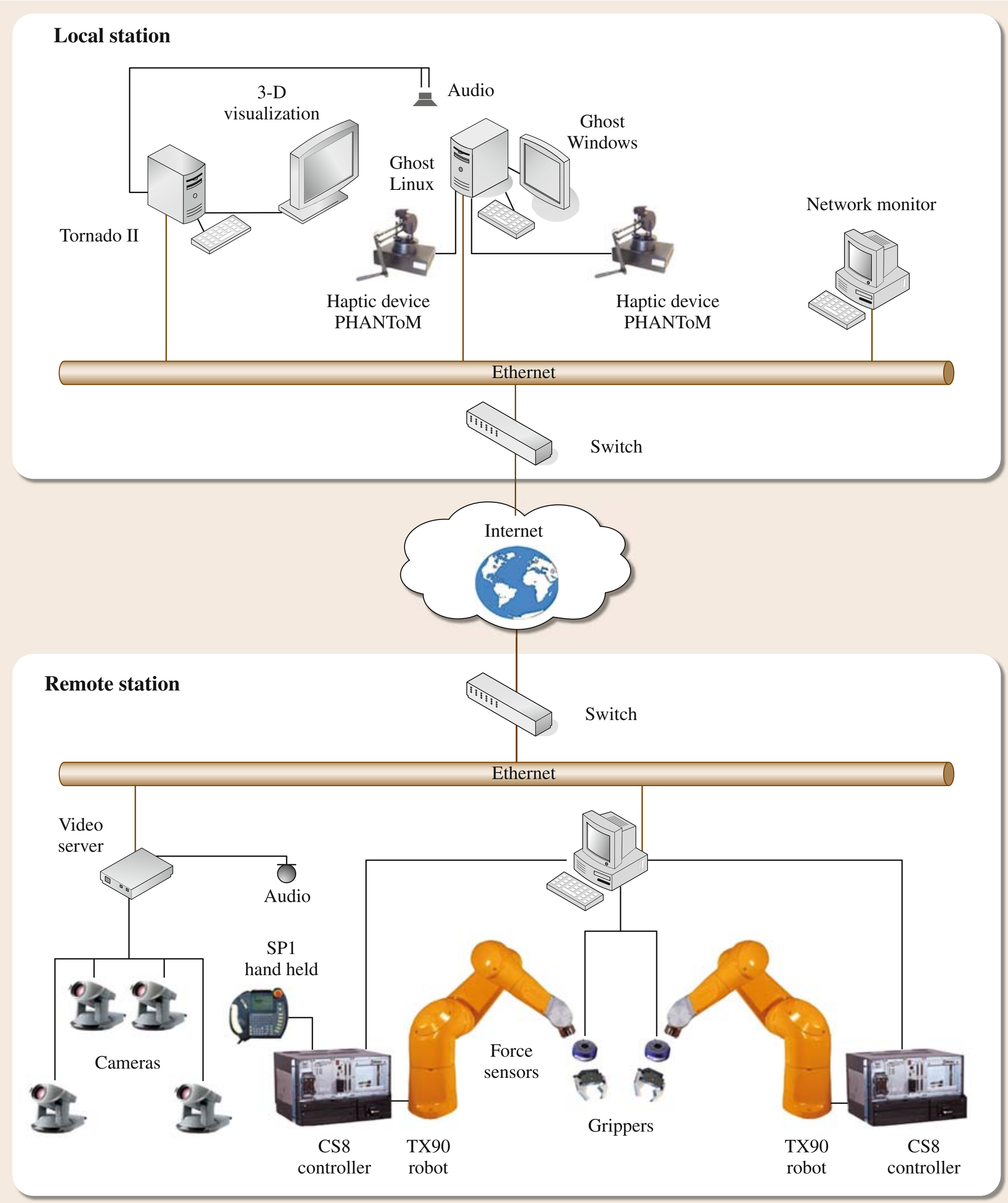

Fig. 27.4 Physical architecture of a teleoperation system (courtesy of IOC-UPC)

has dimension zero. This means that the constraints completely determine the position and orientation (pose) of the manipulated object. In this case the command is this pose.

  - The motion subspace has dimension six, i. e., the operator does not have any relationship fixed. In this case the operator can manipulate the six degrees of freedom of the haptic device and the command sent to the remote station is composed of the values of the six joint variables.
  - The motion subspace has dimension from one to five. In this case the commands are composed of the information of this subspace and the variables that describe the motion inside it, calculated from the coordinates introduced by the operator through the haptic device or determined by the local planning module.
- *State codification/decodification*: These submodules generate and interpret the messages between the remote and the local stations. The robot state is coded as the combination of the position and force information.
- *Network monitoring system*: This submodule analyzes in real time the quality of service (QoS) of the communication channel in order to properly adapt the teleoperation parameters and the sensorial feedback.

A scheme depicting the physical architecture of the whole teleoperation system is shown in Fig. 27.4.

27.2.1 Operation Principle

In order to perform a robotized task with the described teleoperation system, the operator should carry out the following steps:

- Define the motion constraints for each phase of the task, specifying the relative position of the manipulated objects or tools with respect to the environment.
- Move the haptic devices to control the motions of the robots in the subspace that satisfies the imposed constraints. The haptic devices, by means of the force feedback applied to the operator, are capable of:
  - guiding the operator motions so that they satisfy the imposed constraints
  - detecting collision situations and trying to avoid undesired impacts
- Control the realization of the task availing himself of an image of the scene visualized using three-dimensional augmented reality with additional information (like the graphical representation of the motion subspace, the graphical model of the robots updated with the last received data, and other outstanding information for the good performance of the task).

27.3 Challenges and Solutions

During the development of modern teleoperation systems, such as the one described in Sect. 27.2, a lot of challenges have to be faced. Most of these challenges now have a partial or total solution and the main ones are reviewed in the following subsections.

27.3.1 Control Algorithms

A control algorithm for a teleoperation system has two main objectives: telepresence and stability. Obviously, the minimum requirement for a control scheme is to preserve stability despite the existence of time delay and the behavior of the operator and the environment. 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 (immersion). Good telepresence increases the feasibility of the remote manipulation task. The degree of telepresence associated to a teleoperation system is called *transparency*.

Scattering-based control has always dominated the control field in teleoperation systems since it was first proposed by *Anderson* and *Spong* [27.3], creating the basis of modern teleoperation system control. Their approach was to render the communications passive using the analogy of a lossless transmission line with scattering theory. They showed that the scattering transformation ensures passivity of the communications despite any constant time delay. Following the former scattering approach, it was proved [27.4] that, by matching the impedances of the local and remote robot controllers with the impedance of the virtual transmission line, wave reflections are avoided. These were the beginnings of a series of developments for bilateral teleoperators. The reader may refer to [27.5, 6] for two advanced surveys on this topic.

Various control schemes for teleoperated robotic systems have been proposed in the literature. A brief description of the most representative approaches is presented below.

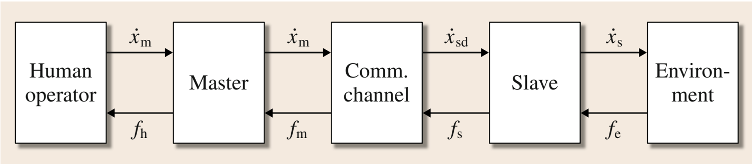

Fig. 27.5 Traditional force reflection

Traditional force reflection. This is probably the most studied and reported scheme. In this approach, the master sends position information to the slave and receives force feedback from the remote interaction of the slave with the environment (Fig. 27.5). However, it was shown that stability is compromised in systems with high time delay [27.3].

Shared compliance control. This scheme is similar to the traditional force reflection, except that on the slave side a compliance term is inserted to modify the behavior of the slave manipulator according to the interaction with the environment.

Scattering-based teleoperation. The scattering transformation (wave variables) used in the transmission of power information makes the communication channel passive even if a time delay T affects the system (Fig. 27.6). However, the scattering transformation presents a tradeoff between stability and performance. In an attempt to improve performance using the scattering transformation, several approaches have been reported, for instance, transmitting wave integrals [27.7, 8] and wave filtering and wave prediction [27.9].

Four-channel control. Velocity and force information is sent to the other side in both directions, thereby defining four channels. In both controllers a linear combination of the available force and velocity information is used to fit the specifications of the control design [27.10].

Proportional (P) and proportional–derivative (PD) controllers. It is widely known that use of the classic scattering transformation may give raise to position drift. In [27.11] position tracking is achieved by sending the local position to the remote station, and adding a proportional term to the position error in the remote controller. Following this approach, [27.12] proposed a symmetric scheme by matching the impedances and adding a proportional error term to the local and remote robots, such that the resulting control laws became simple PD-like controllers. Stability of PD-like controllers, without the scattering transformation, has been proved in [27.13] under the assumption that the human interaction with the local manipulator is passive. In [27.14] it is shown that, when the human operator applies a constant force on the local manipulator, a teleoperation system controlled with PD-like laws is stable.

Variable-time-delay schemes. In the presence of variable time delays, the basic scattering transformation cannot provide the passivity needed in the communications [27.15]. In order to solve this issue, the use of a time-varying gain that is a function of the rate of change of the time delay has been proposed [27.16]. Recently it has been shown [27.17] that, under an appropriate dissipation strategy, the communications can dissipate an amount of energy equal to the generated energy. Applying the strategy of [27.15], in [27.18] it was proven that, under power scaling factors for microteleoperation, the resulting communications remain passive.

27.3.2 Communication Channels

Communication channels can be classified in terms of two aspects: their physical nature and their mode of operation. According to the first aspect, two groups can be defined: physically connected (mechanically, electrically, optically wired, pneumatically, and hydraulically) and physically disconnected (radiofrequency and optically coupled such as via infrared). The second aspect entails the following three groups:

- *Time delay free*. The communication channel connecting the local and the remote stations does not affect the stability of the overall teleoperation system. In general this is the kind of channel present when the two stations are near to each other. Examples of these communication channels are some surgical systems, where the master and slave are lo-

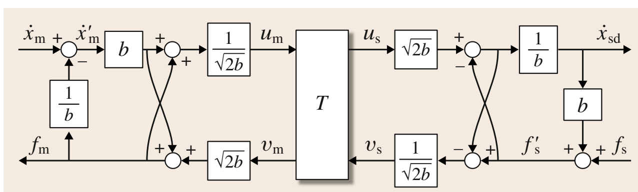

Fig. 27.6 Scattering transformation with impedance adaptation

cated in the same room and connected through wires or radio.

- *Constant time delay*. These are often associated with communications in space, underwater teleoperation using sound signals, and systems with dedicated wires across large distances.
- *Variable time delay*. This is the case, for instance, of packet-switched networks where variable time delays are caused by many reasons such as routing, acknowledge response, and packing and unpacking data.

One of the most promising teleoperation communication channels is the Internet, which is a packet-switched network, i. e., it uses protocols that divide the messages into packets before transmission. Each packet is then transmitted individually and can follow a different route to its destination. Once all packets forming a message have arrived at the destination, they are recompiled into the original message. The transmission control protocol (TCP) and user datagram protocol (UDP) work in this way and they are the Internet protocols most suitable for use in teleoperation systems.

In order to improve the performance of teleoperation systems, quality of service (QoS)-based schemes have been used to provide priorities on the communication channel. The main drawback of today's best-effort Internet service is due to network congestion. The use of high-speed networks with recently created protocols, such as the Internet protocol version 6 (IPv6), improves the performance of the whole teleoperation system [27.19].

Besides QoS, IPv6 presents other important improvements. The current 32 bit address space of IPv4 is not able to satisfy the increasing number of internet users. IPv6 quadruples this address space to 128 bits, which provides more than enough globally unique IP addresses for every network device on the planet. See Fig. 27.7 for a comparison of these protocols.

When using packet-switched networks for real-time teleoperation systems, besides bandwidth, three effects can result in decreased performance of the communication channel: packet loss, variable time delay, and in some cases, loss of order in packet arrival.

27.3.3 Sensory Interaction and Immersion

Human beings are able to perceive information from the real world in order to interact with it. However, sometimes, for engineering purposes, there is a need to interact with systems that are difficult to build in reality or that, due to their physical behavior, present unknown features or limitations. Hence, in order to allow better human interaction with such systems, as well as their evaluation and understanding, the concepts of *virtual reality* and *augmented reality* have been researched and applied to improve development cycles in engineering.

In virtual reality a nonexistent world can be simulated with a compelling sense of realism for a specific environment. So, the real world is replaced by a computer-generated world that uses input devices to interact with and obtain information from the user and capture data from the real world (e.g., using trackers and transducers), and uses output displays that represent the responses of the virtual world by means of visual, touch, aural or taste displays [e.g., haptic devices, head-mounted displays (HMD), and headphones] in order to be perceived by any of the human senses. In this context,

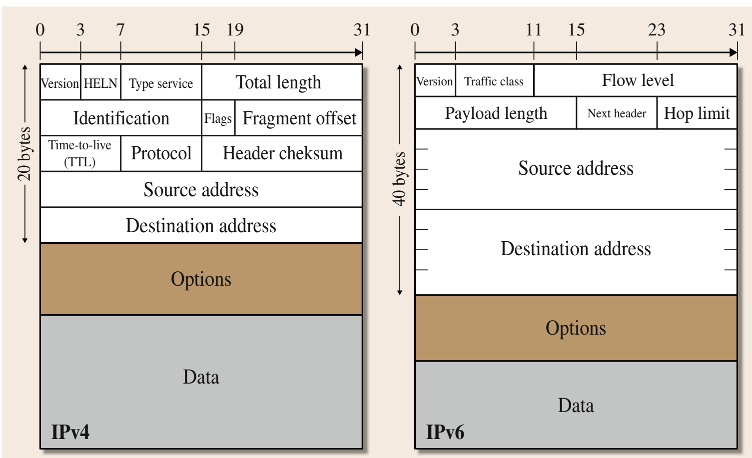

Fig. 27.7 Comparison of IPv4 and IPv6 protocols

immersion is the sensation of being in an environment that actually does not exist and that can be a purely mental state or can be accomplished through physical elements [27.20].

Augmented reality is a form of human–computer interaction (HCI) that superimposes information created by computers over a real environment. Augmented reality enriches the surrounding environment instead of replacing it as in the case of virtual reality, and it can also be applied to any of the human senses. Although some authors put attention on hearing and touch [27.21], the main augmentation route is through visual data addition. Furthermore augmented reality can remove real objects or change their appearance [27.22], operations known as diminished or mediated reality. In this case, the information that is shown and superposed depends on the context, i. e., on the observed objects.

Augmented reality can improve task performance by increasing the degree of reliability and speed of the operator due to the addition or reduction of specific information. Reality augmentation can be of two types: *modal* or *multimodal*. In the modal type, augmentation is referred to the enrichment of a particular sense (normally sight), whereas in the multimodal type augmentation includes several senses. Research done to date has focused mainly on modal systems [27.21, 23].

In teleoperation environments, augmented reality has been used to complement human sensorial perception in order to help the operator perform teleoperated tasks. In this context, augmented reality can reduce or eliminate the factors that break true perception of the remote station, such as time delays in the communication channel, poor visibility of the remote scene, and poor perception of the interaction with the remote environment.

Amongst the applications of augmented reality it is worthwhile to mention interaction between the operator and the remote site for better visualization [27.24, 25], better collaboration capacity [27.26], better path or motion planning for robots [27.27, 28], addition of specific virtual tools [27.29], and multisensorial perception enrichment [27.30].

27.3.4 Teleoperation Aids

Some of the problems arising in teleoperated systems, such as an unstructured environment, communication delays, human operator uncertainty, and safety at the remote site, amongst others, can be reduced using teleoperation aids.

Amongst the teleoperation aids aimed to diminish human operator uncertainty one can highlight virtual fixtures for guiding motion, which have recently been added in surgical teleoperation in order to improve the surgeon's repeatability and reduce his fatigue.

The trajectories to be described by a robot end-effector – either in free space or in contact with other objects – strongly depend on the task to be performed and on the topology of the environment with which it is interacting; for instance, peg-in-hole insertions require alignment between the peg and the hole, spray-painting tasks require maintenance of the nozzle at a fixed distance and orientation with respect to the surface to be painted, and assembly tasks often involve alignment or coincidence of faces, sides, and vertices of the parts to be assembled. For all these examples, virtual guides can be defined and can help the operator to perform the task.

Artificial fixtures or motion guidance can be divided into two groups, depending on how the motion constraints are created, either by software or by hardware. To the first group belong the methods that implement geometric constraints for the operator motions: points, lines, planes, spheres, and cylinders [27.2], which can usually be changed without stopping the teleoperation. An often-used method is to provide obstacles with a repulsive force field, avoiding in this way that the operator makes the robot collide with the obstacles. In the second group, specific hardware is used to guide the motion, for example, guide rails and sliders with circled rails. Figure 27.8 shows a teleoperated painting task restricted to a plane.

An example of a motion constraints generator is the PMF (positioning mobile with respect to fixed) solver [27.31]. PMF has been designed to assist execution of teleoperated tasks featuring precise or repetitive motions. By formulating an object positioning problem in terms of symbolic geometric constraints, the motion

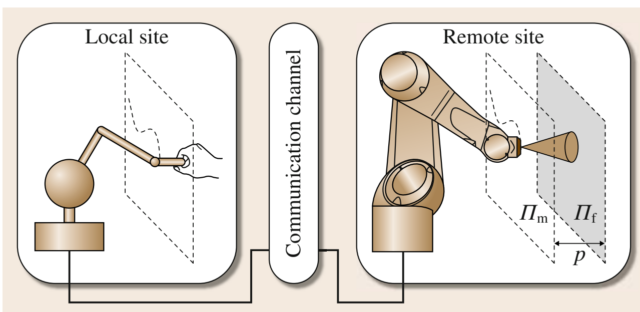

Fig. 27.8 A painting teleoperation task with a plane constraint on the local and the remote sites

of an object can be totally or partially restricted, independently of its initial configuration. PMF exploits the fact that, in geometric constraint sets, the rotational component can often be decoupled from the translational one and solved independently. Once the solution is obtained, the resulting restriction forces are fed to the operator via a haptic interface in order to guide its motions inside this subspace.

27.3.5 Dexterous Telemanipulation

A common action in robotics applications is grasping of an object, and teleoperated robotics is no exception. Grasping actions can often be found in telemanipulation tasks such as handling of dangerous material, rescue, assistance, and exploration, amongst others.

In planning a grasping action, two fundamental aspects must be considered:

1. *How to grasp the object*. This means the determination of the contact points of the grasping device on the object, or at a higher level, the determination of the relative position of the grasping device with respect to the object (e.g., [27.32–34]).
2. *The grasping forces*. This means the determination of the forces to be applied by the grasping device actuators in order to properly constrain the object (e.g., [27.35]).

These two aspects can be very simple or extremely complex depending on the type of object to be grasped, the type of grasping device, and the requirements of the task. In a teleoperated grasping system, besides the general problems associated with a teleoperation system mentioned in the previous sections, the following particular topics must be considered.

Sensing information in the local station. In telemanipulation using complex dexterous grasping devices, such as mechanical anthropomorphic hands directly commanded by the hand of the human operator, the following approaches have been used in order to capture the pose information of the operator hand:

- *Sensorized gloves*. The operator wears a glove with sensors (usually strain gauges) that identify the position of the fingers and the flexion of the palm [27.36]. These gloves allow the performance of tasks in a natural manner, but they are delicate devices and it is difficult to achieve good calibration.
- *Exoskeletons*. The operator wears over the hand an exoskeleton equipped with encoders that identify the position of the fingers [27.37]. Exoskeletons are more robust in terms of noise, but they are rather uncomfortable and reduce the accessibility of the hand in certain tasks.
- *Vision systems*. Computer vision is used to identify hand motions [27.38]. The operator does not need to wear any particular device and is therefore completely free, but some parts of the hand may easily fall outside of the field of vision of the system and recognition of hand pose from images is a difficult task.

Capturing the forces applied by the operator is a much more complex task, and only some tests using pressure sensors at the fingertips have been proposed [27.39].

Feedback information from the remote station. This can be basically of two types:

- *Visual information*. This kind of information can help the operator to realize how good (robust or stable) the remote grasp is, but only in a very simple grasp can the operator conclude if it is actually a successful grasp.
- *Haptic information*. Haptic devices allow the operator to feel the contact constraints during the grasp in the remote station. Current approaches include gloves with vibratory systems that provides a kind of tactile feeling [27.40], and exoskeletons that attached to the hand and fingers and generate constraints to their motion and provide the feeling of a contact force [27.37]. Nevertheless, these devices have limited performance and the development of more efficient haptic devices with the required num-

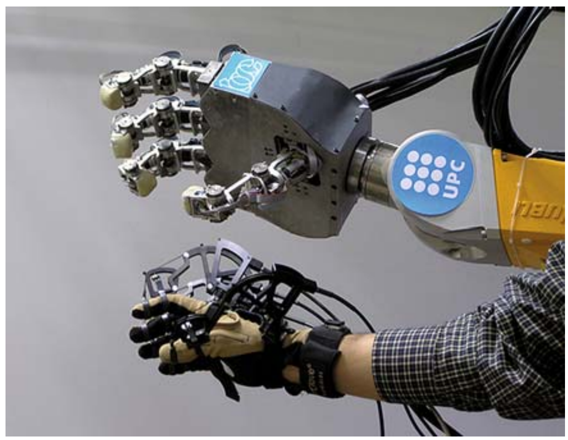

Fig. 27.9 Operator hand wearing a sensorized glove and an exoskeleton, and the anthropomorphic mechanical hand MA-I (courtesy of IOC-UPC)

ber of degrees of freedom and the configuration of the human hand is still an open problem.

Need for kinematics mapping. In real situations, the mechanical gripper or hand in the remote station will not have the same kinematics as the operator hand, even when an anthropomorphic mechanical hand is used. This means that in general the motions of the operator cannot be directly replicated by the remote grasping device, and they have to be interpreted and then adapted from one kinematics to the other, which may be computationally expensive [27.41].

Use of assistance tools. The tools developed with the aim of performing grasps in an autonomous way can be used as assistance tools in telemanipulation; for instance, grasp planners used to determine optimal grasping points automatically on different types of objects can be run considering the object to be telemanipulated and then, using augmented reality, highlight the grasping points on the object so the operator can move the fingers directly to those points. Of still greater assistance in this regard is the computation and display of independent grasping regions on the object surface [27.42] such that placing a finger on any point within each of these regions will achieve a grasp with a controlled quality [27.43].

Figure 27.9 shows an example where the operator is wearing a commercial sensorized glove and an exoskeleton in order to interact with the anthropomorphic mechanical hand MA-I [27.44].

27.4 Application Fields

The following subsections present several application fields where teleoperation plays a significant role, describing their main particular aspects and some relevant works.

27.4.1 Industry and Construction

Teleoperation in industry-related applications covers a wide range of fields. One of them is mostly oriented towards inspection, repair, and maintenance operations in places with difficult or dangerous access, particularly in power plants [27.45], as well as to manage toxic wastes [27.46]. In the nuclear industry the main reason to avoid the exposure of human workers is the existence of a continuous radioactive environment, which results in international regulations to limit the number of hours that humans can work in these conditions. This application was actually the motivation for early real telemanipulation developments, as stated in Sect. 27.1. Some typical teleoperated actions in nuclear plants are the maintenance of nuclear reactors, decommissioning and dismantling of nuclear facilities, and emergency interventions. The challenges in these tasks include operation in confined areas with high radiation levels, risk of contamination, unforeseen accidents, and manipulation of materials that can be liquid, solid or have a muddy consistency.

Another kind of application is the maintenance of electrical power lines, which require operations such as replacement of ceramic insulators or opening and reclosing bridges, which are very risky for human operators due to the height of the lines and the possibility of electric shocks, specially under poor weather conditions [27.47]. That is why electric power companies are interested in the use of robotic teleoperated systems for live-line power maintenance. Examples of these robots are the TOMCAT [27.48] and the ROBTET (Fig. 27.10) [27.49].

Another interesting application field is construction, where teleoperation can improve productivity, reliability, and safety. Typical tasks in this field are earth-moving, compaction, road construction and maintenance, and trenchless technologies [27.50]. In general, applications in this field are based on direct visual feedback. One example is radio operation of construc-

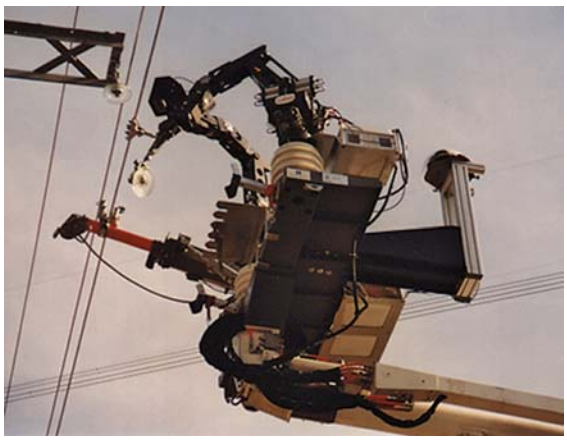

Fig. 27.10 Robot ROBTET for maintenance of electrical power lines (courtesy of DISAM, Technical University of Madrid – UPM)

tion machinery, such as bulldozers, hydraulic shovels, and crawler dump trucks, to build contention barriers against volcanic eruptions [27.51]. Another example is the use of an experimental robotized crane with a six-DOF parallel kinematic structure, to study techniques and technologies to reduce the time required to erect steel structures [27.52].

Since the tasks to be done are quite different in the different applications, the particular hardware and devices used in each case can vary a lot, ranging from a fixed remote station in the dangerous area of a nuclear plant, to a mobile remote station assembled on a truck that has to move along a electrical power line or a heavy vehicle in construction. See also Chap. 61 on *Construction Automation* and Chap. 62 on *Smart Buildings*.

27.4.2 Mining

Another interesting field of application for teleoperation is mining. The reason is quite clear: operation of a drill underground is very dangerous, and sometimes mines themselves are almost inaccessible. One of the first applications started in 1985, when the thin-seam continuous mining Jeffrey model 102HP was extensively modified by the US Bureau of Mines to be adapted for teleoperation. Communication was achieved using 0.6 inch wires, and the desired entry orientation was controlled using a laser beam [27.53]. Later, in 1991, a semiautomated haulage truck was used underground, and since then has hauled 1.5 million tons of ore without failure. The truck has an on-board personal computer (PC) and video cameras and the operator can stay on the surface and teleoperate the vehicle using an interface that simulates the dashboard of the truck [27.54]. The most common devices used for teleoperation in mining are load–haul–dump (LHD) machines, and thin-seam continuous mining (TSCM) machines, which can work in a semiautonomous and teleoperated way.

Position measurement, needed for control, is not easy to obtain when the vehicle is beneath the surface, and interference can be a problem, depending on the mine material. Moreover, for the same reason, video feedback has very poor quality. In order to overcome these problems, the use of gyroscopes, magnetic electronic compasses, and radar to locate the position of vehicles while underground has been considered [27.55]. The problems with visual feedback could be solved by integrating, for instance, data from live video, computer-aided design (CAD) mine models, and process control parameters, and presenting the operator a view of the environment with augmented reality [27.56]. In this field, in addition to information directly related to the teleoperation, the operator has to know other measurements for safety reasons, for instance, the volatile gas (like methane) concentration, to avoid explosions produced due to sparks generated by the drilling action.

Teleoperated mining is not only considered on Earth. If it is too expensive and dangerous to have a man underground operating a mining system, it is much more so for the performance of mining tasks on the Moon. As stated in Sect. 27.4.4, for space applications, in addition to the particularities of mining, the long transmission delay between the local and remote stations is a significant problem. So, the degree of autonomy has to be increased to perform the simplest tasks locally while allowing a human teleoperator to perform the complex tasks at a higher level [27.57]. When the machines in the remote station are performing automated actions, the operator can teleoperate some other machinery, thus productivity can be improved by using a multiuser schema at the local station to operate multiple mining systems at the remote station [27.58]. See also Chap. 57 on *Automation in Mining and Mineral Processing*.

27.4.3 Underwater

Underwater teleoperation is motivated by the fact that the oceans are attractive due to the abundance of living and nonliving resources, combined with the difficulty for human beings to operate in this environment. The most common applications are related to rescue missions and underwater engineering works, among other scientific and military applications. Typical tasks are: pipeline welding, seafloor mapping, inspection and reparation of underwater structures, collection of underwater objects, ship hull inspection, laying of submarine cables, sample collection from the ocean bed, and study of marine creatures.

A pioneering application was the cable-controlled undersea recovery vehicle (CURV) used by the US Army in 1966 to recover, in the Mediterranean sea south of Spain, the bombs lost due to a bomber accident [27.59]. More recent relevant applications are related to the inspection and object collection from famous sunken vessels, such as the Titanic with the ARGO robot [27.60], and to ecological disasters, such as the sealing of crevices in the hull of the oil tanker Prestige, which sank in the Atlantic in 2002 [27.61].

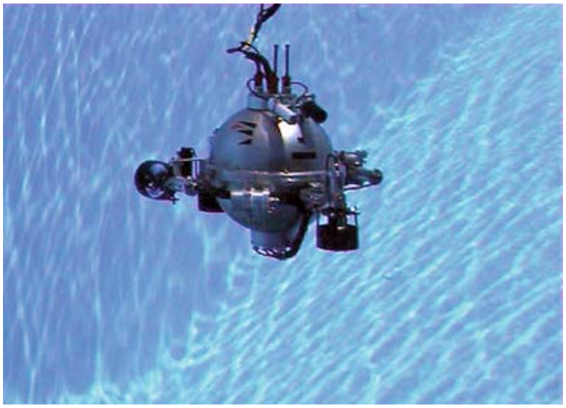

Fig. 27.11 Underwater robot Garbi III AUV (courtesy of University of Girona – UdG)

Specific problems in deep underwater environments are the high pressure, quite frequently poor visibility, and corrosion. Technological issues that must be considered include robust underwater communication, the power source, and sensors for navigation. A particular problem in several underwater applications is the position and force control of the remote actuator when it is floating without a fixed holding point.

Most common unmanned underwater robots are remotely operated vehicles (ROVs) (Fig. 27.11), which are typically commanded from a ship by an operator using joysticks. Communication between the local and remote stations is frequently achieved using an umbilical cable with coaxial cables or optic fiber, and also the power is supplied by cables. Most of these underwater vehicles carry a robotic arm manipulator (usually with hydraulic actuators), which may have negligible effects on a large vehicle, but that introduce significant perturbation on the system dynamics of a small one. Moreover, there are several sources of uncertainties, mainly due to buoyancy, inertial effects, hydrodynamic effects (of waves and currents), and drag forces [27.62], which has motivated the development of several specific control schemes to deal with these effects [27.63, 64]. The operational cost of these vehicles is very high, and their performance largely depends on the skills of the operator, because it is difficult to operate them accurately as they are always subject to undesired motion. In the oil industry, for instance, it is common to use two arms: one to provide stability by gripping a nearby structure and another to perform the assigned task.

Fig. 27.12 Canadarm 2 (courtesy of NASA)

A new use of underwater robots is as a practice tool to prepare and test exploration robots for remote planets and moons [27.65].

27.4.4 Space

The main motivation for the development of space teleoperation is that, nowadays, sending a human into the space is difficult, risky, and quite expensive, while the interest in having some devices in space is continuously growing, from the practical (communications satellites) as well as the scientific point of view.

The first explorations of space were carried out by robotic spacecrafts, such as the Surveyor probes that landed on the lunar surface between 1966 and 1968. The probes transmitted to Earth images and analysis data of soil samples gathered with an extensible claw. Since then, several other ROVs have been used in space exploration, such as in the Voyager missions [27.66].

Various manipulation systems have been used in space missions. The remote manipulator system, named Canadarm after the country that built it, was installed aboard the space shuttle Columbia in 1981, and since then has been employed in a variety of tasks, mainly focused on the capture and redeployment of defective satellites, besides providing support for other crew activities. In 2001, the Canadarm 2 (Fig. 27.12) was added to the International Space Station (ISS), with more load capacity and maneuverability, to help in more sensitive tasks such as inspection and fault detection of the ISS structure itself. In 2009, the European Robotic Arm (ERA) is expected to be installed at the ISS, primarily to be used outside the ISS in service tasks requiring precise handling of components [27.67].

Control algorithms are among the main issues in this type of applications, basically due to the significant delay between the transmission of information from the local station on the Earth and the reception of the response from remote station in space (Sect. 27.3.1). A number of experimental ground-based platforms for telemanipulation such as the Ranger [27.68], the Robonaut [27.69], and the space experiment ROTEX [27.70] have demonstrated sufficient dexterity in a variety of operations such as plug/unplug tasks and tools manipulation. Another interesting experiment under development is the Autonomous Extravehicular Activity Robotic Camera Sprint (AERCam) [27.71], a teleoperated free-flying sphere to be used for remote inspection tasks. An experiment in bilateral teleoperation was developed by the National Space Development Agency of Japan (NASDA) [27.72] with the Engineering Test Satellite (ETS-VII), overcoming the significant time delay (up to 7 s was reported) in the communication channel between the robot and the ground-based control station.

Currently, most effort in planetary surface exploration is focused on Mars, and several remotely operated rovers have been sent to this planet [27.73]. In these experiments the long time delays in the control signals between Earth-based commands and Mars-based rovers is especially relevant. The aim is to avoid the effect of these delays by providing more autonomy to the rovers. So, only high-level control signals are provided by the controllers on Earth, while the rover solves low-level planning of the commanded tasks. Another possible scenario to minimize the effect of delays is teleoperation of the rovers with humans closer to them (perhaps in orbit around Mars) to guarantee a short time delay that will allow the operator to have real-time control of the rover, allowing more efficient exploration of the surface of the planet [27.74]. See also Chap. 69 on *Space and Exploration Automation* and Chap. 93 on *Collaborative Analytics for Astrophysics Explorations*.

27.4.5 Surgery

There are two reasons for using teleoperation in the surgical field. The first is the improvement or extension of the surgeon's abilities when his/her actions are mapped to the remote station, increasing, for instance, the range of position and motion of the surgical tool (motion scaling), or applying very precise small forces without oscillations; this has greatly contributed to the development of major advances in the field of microsurgery, as well as in the development of minimally invasive surgery (MIS) techniques. Using teleoperated systems, surgeries are quicker and patients suffer less than with the normal approach, also allowing faster recovery. The second reason is to exploit the expertise of very good surgeons around the world without requiring them to travel, which could waste time and fatigue these surgeons.

A basic initial step preceding teleoperation in surgical applications was telediagnostics, i. e., the motion of a device, acting as the remote station, to obtain information without working on the patient. A simple endoscope could be considered as a basic initial application in this regard, since the position of a camera is teleoperated to obtain an appropriate view inside the human body. A relevant application for telediagnostic is an endoscopic system with 3-D stereo viewing, force reflection, and aural feedback [27.75].

It is worth to highlight the first real remote telesurgery [27.76]. The scenario was as follows: the local station, i. e., the surgeon, was located in New York City, USA, and the remote station, i. e., the patient, was in Strasbourg, France. The performed surgery was a laparoscopic cholecystectomy done to a 68-year-old female, and it was called *operation Lindbergh*, based on the last name of the patient. This surgery was possible thanks to the availability of a very secure high-speed communication line, allowing a mean total time delay between the local and remote stations of 155 ms. The time needed to set up the robotic system, in this case the Zeus system [27.77], was 16 min, and the operation was done in 54 min without complications. The patient was discharged 48 h later without any particular postoperative problems.

A key problem in this application field is that someone's life is at risk, and this affects the way in which information is processed, how the system is designed, the amount of redundancy used, and any other factors that may increase safety. Also, the surgical tool design must integrate sensing and actuation on the millimeter scale.

Normally, the instruments used in MIS do not have more than four degrees of freedom, losing therefore the ability to orient the instrument tip arbitrarily, although specialized equipment such as the Da Vinci system [27.78] already incorporates a three-DOF wrist close to the instrument tip that makes the whole system benefit from seven degrees of freedom. In order to perform an operation, at least three surgical instruments are required (the usual number is four): one is an endoscope that provides the video feedback and the other two are grippers or scissors with electric scalpel functions, which should provide some tactile and/or force feedback (Fig. 27.13).

The trend now is to extend the application field of the current surgical devices so that they can be used in different types of surgical procedures, particularly including tactile feedback and virtual fixtures to minimize the effect of any imprecise motion of the surgeon [27.79]. So far, there are more than 25 surgical procedures in at least six medical fields that have been successfully performed with telerobotic techniques [27.80]. See Chap. 78 on *Medical Automation and Robotics*.

27.4.6 Assistance

The main motivation in this field is to give independence to disabled and elderly people in their daily domestic activities, increasing in this way quality of life. One of the first relevant applications in this line was seen in 1987, with the development of the Handy 1 [27.81], to enable an 11-year-old boy with cerebral palsy to gain independence at mealtimes. The main components of Handy 1 were a robotic arm, a microcomputer (used as a controller for the system), and an expanded keyboard for human–machine interface (HMI).

The most difficult part in developing assistance applications is the HMI, as it must be intuitive and appropriate for people that do not have full capabilities. In this regard different approaches are considered, such as tactile, voice recognition, joystick/haptic interfaces, buttons, and gesture recognition, among others [27.82]. Another very important issue, which is a significant difference with respect to most teleoperation scenarios, is that the local and the remote stations share the same space, i. e., the teleoperator is not isolated from the working area; on the contrary, actually he is part of it. This leads to consider the safety of the teleoperator as one of the main topics.

The remote station is quite frequently composed of a mobile platform and an arm installed on it, and the whole system should be adaptable to unstructured and/or unknown environments (different houses), as it is desirable to perform actions such as going up and down stairs, opening various kinds of doors, grasping and manipulating different kind of objects, and so on. Improvements of the HMI to include different and more friendly ways of use is one of the main current challenges: the interfaces must be even more intuitive and must achieve a higher level of abstraction in terms of user commands. A typical example is understanding of an order when a voice recognition system is used [27.83].

Various physical systems are considered for teleoperation in this field, for instance, fixed devices (the disabled person has to get into the device workspace), or devices based on wheelchairs or mobile robots [27.84]; the latest are the most flexible and versatile, and therefore the most used in recently developed assistance robots, such as RobChair [27.85], ARPH [27.86], Pearl NurseBot [27.87], and ASIBOT [27.82].

27.4.7 Humanitarian Demining

This particular application is included in a separate subsection due to its relevance from the humanitarian point of view. Land mines are very easy to place but very hard to be removed. Specific robots have been developed to help in the removal of land mines, especially to reduce the high risk that exists when this task is performed by humans. Humanitarian demining differs from the mil-

Fig. 27.13 Robotics surgery at Dresden Hospital (with permission from Intuitive Surgical, Inc. 2007)

Fig. 27.14 SILO6: A six-legged robot for humanitarian demining tasks (courtesy of IAI, Spanish Council for Scientific Research – CSIC)

itary approach. In the latter it is only required to find a path through a minefield in the minimum time, while the aim in humanitarian demining is to cover the whole area to detect mines, mark them, and remove/destroy all of them. The time involved may affect the cost of the procedure, but should not affect its efficiency. One key aspect in the design of teleoperated devices for demining is that the remote station has to be robust enough to resist a mine explosion, or cheap enough to minimize the loss when the manipulation fails and the mine explodes.

The removal of a mine is quite a complex task, which is why demining tools include not only teleoperated robotic arms, but also teleoperated robotic hands [27.88]. Some proposals are based on walking machines, such as TITAN-IX [27.89] and SILO6 [27.90] (Fig. 27.14). A different method includes the use of machines to mechanically activate the mine, like the Mini Flail, Bozena 4, Tempest or Dervish, among others; many of these robotic systems have been tested and used in the removal of mines in countries such as Japan, Croatia, and Vietnam [27.91, 92].

27.4.8 Education

Recently, teleoperation has been introduced in education, and can be collated into two main types. In one of these, the professor uses teleoperation to illustrate the (theoretical) concepts to the students during the a lecture by means of the operation of a remote real plant, which obviously cannot be brought to the classroom and that would require a special visit, which would probably be expensive and time consuming. The second type of educational application is the availability of remote experimental plants where the students can carry out experiments and training, working at common facilities at the school or in their own homes at different times. In this regard, during the last 5 years, a number of remote laboratory projects have been developed to teach fundamental concepts of various engineering fields, thanks to remote operation and control of scientific facilities via the Internet. The development of e-Laboratory platforms, designed to enable distance training of students in real scenarios of robot programming, has proven useful in engineering training for mechatronic systems [27.93]. Experiments performed in these laboratories are very varied; they may go from a single user testing control algorithms in a remote real plant [27.94] to multiple users simulating and teleoperating multiple virtual and real robots in a whole production cell [27.95].

The main feature in this type of applications is the almost exclusive use of the Internet as the communication channel between the local and remote stations. Due to its ubiquitous characteristic these applications are becoming increasingly frequent.

27.5 Conclusion and Trends

Teleoperation is a highly topical subject with great potential for expansion in its scientific and technical development as well as in its applications.

The development of new wireless communication systems and the diffusion of global communication networks, such as the Internet, can tremendously facilitate the implementation of teleoperation systems. Nevertheless, at the same time, these developments give rise to new problems such as real-time requirements, delays in signal transmission, and loss of information. Research into new control algorithms that guarantee stability even with variable delays constitutes an answer to some of these problems. On the other hand, the creation of new networks, such as the Internet2, that can guarantee a quality of service can help considerably to solve the real-time necessities of teleoperated systems.

The information that the human operator receives about what is happening at the remote station is essential for good execution of teleoperated tasks. In this regard, new techniques and devices are necessary in order to facilitate immersion of the human operator in the task that he/she is carrying out. Virtual-reality, augmented-reality, haptics, and 3-D vision systems are key elements for this immersion.

The function of the human operator can also be greatly facilitated by aids to teleoperation. These aids, such as relational positioning, virtual guides, collision avoidance methods, and operation planning, can help the construction of efficient teleoperation systems.

An outstanding challenge is dexterous telemanipulation, which requires the coordination of multiple degrees of freedom and the availability of complete sensorial information.

The fields of application of teleoperation are multiple nowadays, and will become even more vast in the future, as research continues to outline new solutions to the aforementioned challenges.

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