# 31. Telerobotics

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In this chapter we present an overview of the field of telerobotics with a focus on control aspects. Motivated by an historical prespective and some challenging applications of this research area a classification of control architectures is given, including an introduction to the different strategies. An emphasis is taken on bilateral control and force feedback, which is a vital research field today. Finally we suggest some literature for a closer engagement with the topic of telerobotics.



## 31.1 Overview

Telerobotics is perhaps one of the earliest aspects of robotics. Literally meaning robotics at a distance, it is generally understood to refer to robotics with a human operator in control or human-in-the-loop. Any high-level, planning, or cognitive decisions are made by the human user, while the robot is responsible for their mechanical implementation. In essence, the *brain* is removed or distant from the *body*.

Herein the term *tele*, which is derived from the Greek and means distant, is generalized to imply a barrier between the user and the environment. This barrier is overcome by remote-controlling a robot at the environment, as indicated in Fig. 31.1. Besides distance, barriers may be imposed by hazardous environments or scaling to very large or small environments. All barriers have in common that the user cannot (or will not) physically reach the environment.

While the physical separation may be very small, with the human operator and the robot sometimes occupying the same room, telerobotic systems are often at least conceptually split into two sites: the local site with the human operator and all elements necessary to support the system's connection with the user, which could be joysticks, monitors, keyboards, or other input/output devices, and the remote site, which contains the robot and supporting sensors and control elements.

To support this functionality, telerobotics integrates many areas of robotics. At the remote site, to operate the robot and execute the human's commands, the system may control the motion and/or forces of the robot. We refer to Chaps. 6 and 7 for detailed descriptions of these areas. Also, sensors are invaluable (Chap. 4), including force sensors (Chap. 19) and others (Part C). Meanwhile, at the local site information is often displayed haptically (Chap. 30).

A recent addition to telerobotics is the use of computer networks to transmit information between the two sites. This is the focus of Chap. 32 and opens up new possibilities in architectures. For example a single robot may be shared between multiple users or a single user may

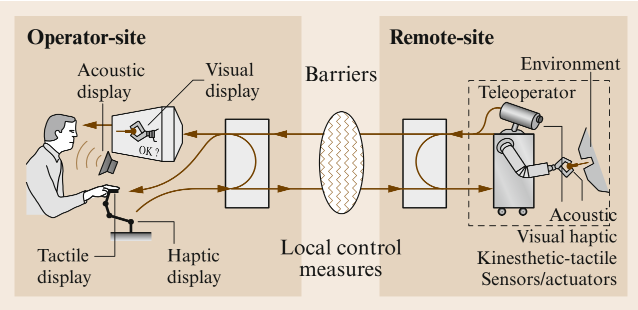


**Fig. 31.1** Overview of a telerobotic system (from [31.1], adapted from [31.2])

control multiple robots. Web interfaces are simplifying this process, allowing access from anywhere on demand. In this chapter, we focus on point-to-point architectures with continual communications and operation.

We should also point out the relation between telerobotics and human exoskeletons, as described in Chap. 33. Exoskeletons are also controlled by a human operator, leaving all planning and high-level challenges to the user, and their control systems share many aspects with telerobotics. However, the two sites may be combined in an exoskeleton as the user directly touches and interacts with the robot. In this chapter, we will disallow any such connection.

The inclusion of the human operator makes telerobotics very attractive to handle unknown and unstructured environments. Applications are plentiful (Part F) and range from space robotics (Chap. 45) to dealing with hazardous environments (Chap. 48), from search and rescue situations (Chap. 50), to medical systems (Chap. 52) and rehabilitation (Chap. 53).

Before proceeding, we first define some basic terminology. Indeed many other terms are used nearly synonymously with telerobotics, in particular *teleoperation* and *telemanipulation*. Telerobotics is the most common, emphasizing a human's (remote) control of a robot. Teleoperation stresses the task-level operations, while telemanipulation highlights object-level manipulation.

Within telerobotics, a spectrum of control architectures has been used. *Direct control* or *manual control* falls at one extreme, indicating that the user is controlling the motion of the robot directly and without any automated help. At the other extreme, *supervisory control* implies that user's commands and feedback occur at a very high level and the robot requires substantial intelligence and/or autonomy. Between the two extrema lie a variety of *shared control* architectures, where some degree of autonomy or automated help is available to assist the user.

In practice, many systems involve at least some level of direct control and include a joystick or similar device in the user interface, to accept the user's commands. As an instrumented mechanical device, this joystick can itself be viewed as a robot. The local and remote robots are called master and slave, respectively, while the system is referred to as a *master–slave system*. To provide direct control, the slave robot is programmed to follow the motions of the master robot, which is positioned by the user. It is not uncommon for the master robot (joystick) to be a kinematic replica of the slave, providing an intuitive interface.

Some master–slave systems provide force feedback, such that the master robot not only measures motions but also displays forces to the user. The user interface becomes fully bidirectional and such telerobotic systems are often called *bilateral*. The human–master interactions are a form of human–robot interaction (Chap. 57). The field of haptics (Chap. 30) also discusses bidirectional user interfaces, involving both motion and force, though more commonly to interface the user with virtual instead of remote environments. We should note that both motion and force may become the input or output to/from the user, depending on the system architecture.

Finally, *telepresence* is often discussed as an ultimate goal of master–slave systems and telerobotics in general. It promises to the user not only the ability to manipulate the remote environment, but also to perceive the environment as if encountered directly. The human operator is provided with enough feedback and sensations to feel present in the remote site. This combines the haptic modality with other modalities serving the human senses of vision, hearing or even smell and taste. We focus our descriptions on the haptic channel, which is created by the robotic hardware and its control systems. The master–slave system becomes the medium through which the user interacts with the remote environment and ideally they are fooled into forgetting about the medium itself. If this is achieved, we say that the master–slave system is transparent.

The chapter first examines telerobotic hardware and systems, before discussing various control architectures to operate these systems. A specific focus is placed on bilateral master–slave systems, which make the operator feel most connected to the remote environment and also present the largest stability and control problems.

## 31.2 Telerobotic Systems and Applications

Like mobile, industrial, and most areas of robotics, telerobotic systems are designed specifically with their tasks and requirements in mind. As such, many unique systems have evolved, of which we present an overview for different applications. We begin with a short historical perspective, then describe different applications with various robot designs and user interfaces.

### 31.2.1 Historical Perspective

Teleoperation enjoys a rich history and dates back to nuclear research by Raymond C. Goertz in the 1940s and 1950s. In particular, he created systems for humans to handle radioactive material from behind shielded walls. The first systems were electrical, controlled by an array of on–off switches to activate various motors and move various axes [31.3]. Without any feel, these manipulators were *slow and somewhat awkward to operate*, leading *Goertz* to build pairs of mechanically linked master–slave robots [31.3,4]. Connected by gears, linkages, and cables these systems allowed the operator to use natural hand motions and transmitted forces and vibrations through the connecting structure, yet they limited the distance between the operator and environment and required the use of kinematically identical devices, see Fig. 31.2. *Goertz* quickly recognized the value of electrically coupled manipulators and laid the foundations of modern telerobotics and bilateral force-reflecting positional servos [31.5].

**Fig. 31.2** Raymond C. Goertz used electrical and mechanical teleoperators in the early 1950s to handle radioactive material. (Courtesy Argonne National Labs)

At the beginning of the 1960s the effects of time delay on teleoperation started to become a topic of research [31.6, 7]. To cope with this problem the concept of supervisory control was introduced [31.2] and inspired the next years of development. In the late 1980s and early 1990s theoretical control came into play with Lyapunov-based analysis and network theory [31.8–13]. Using these new methods bilateral control of telerobotic systems became the vital research area it is today see Sect. 31.4. The growth of the Internet and its use as a communication medium fueled further this trend, adding the challenges of nondeterministic time delay.

On the hardware side, the Central Research Laboratory model M2 of 1982 was the first telerobotic system which realized force feedback while separating master and slave electronics. It was developed together with the Oak Ridge National Laboratory and was used for some time for a wide range of demonstration tasks including military, space or nuclear applications. The National Aeronautics and Space Administration (NASA) tested

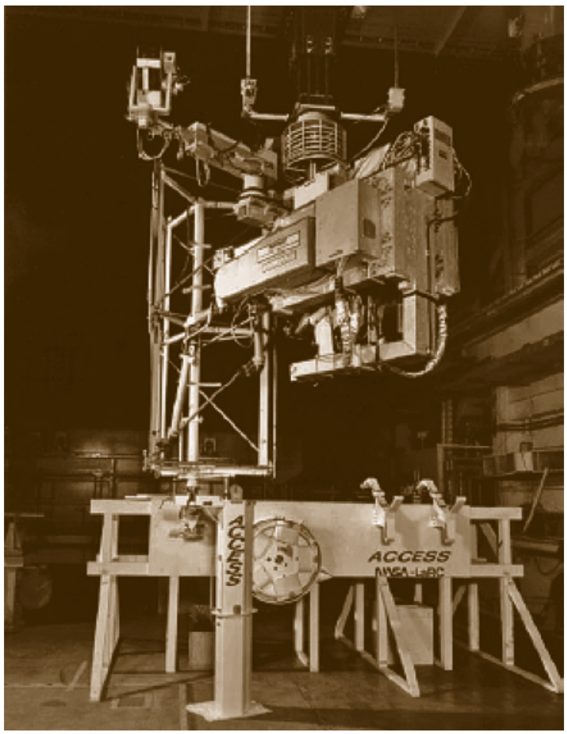


**Fig. 31.3** The telerobotic system CRL Model M2 is used to verify the assembly of space truss structures (1982). (Courtesy of the Oak Ridge National Laboratory)

the M2 system to simulate the ACCESS space truss assembly with excellent results (Fig. 31.3). The advanced servomanipulator (ASM) was developed from the M2 to improve the remote maintainability of manipulators and intended as a foundation for telerobotic systems [31.14].

Also driven by the nuclear application, bilateral servomanipulators for teleoperation were developed in France in the Commission de Energie Atomique (CEA) by *Vertut* and his colleagues [31.15]. With the MA 23 they demonstrated telerobotic operation including computer-assisted functionalities to improve the operator's performance [31.16]. The assistance included software jigs and fixtures or virtual walls and restrictions [31.17], see also Sect. 31.3.2.

For space applications a dual-arm force reflecting telerobotic system was developed by *Bejczy* et al. at the Jet Propulsion Laboratory (JPL) [31.18]. In this approach for the first time kinematically and dynamically different master and slave systems were used, requiring control in Cartesian space coordinates. Figure 31.4 shows the master control station with its two back-drivable hand controllers. This system was used for simulating teleoperation in space.

In the 1980s and 1990s, as nuclear power activities began to decline, interest shifted to other areas such as space, medicine or undersea. Efforts were accelerated by the availability of increasing computer power as well as the introduction of novel hand controllers, e.g., the PHANToM device [31.19], popularized by haptic applications in virtual reality (see Chap. 30).

**Fig. 31.4** JPL ATOP control station (early 1980s). (JPL no. 19902Ac, courtesy of NASA/JPL-CALTECH)

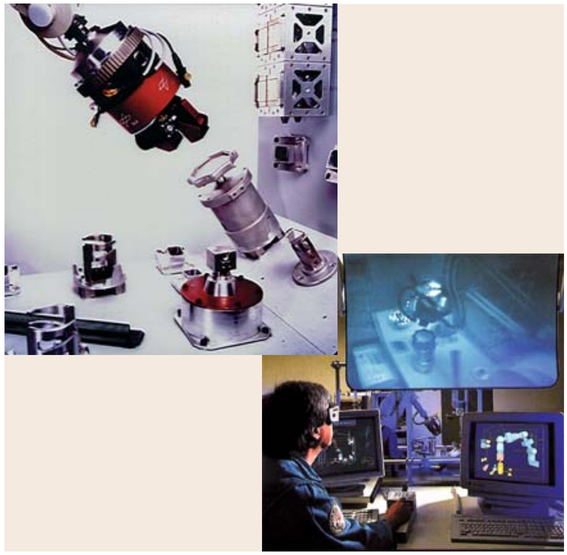

**Fig. 31.5** ROTEX, the first remotely controlled robot in space (1993). Telerobot in space and ground operator station. (Courtesy of the German Aerospace Center, DLR)

In 1993 the first telerobotic system was flown in space with the German Spacelab Mission D2 on board the Space Shuttle Columbia. The robot technology experiment (ROTEX) demonstrated remote control of a space robot by means of local sensory feedback, predictive displays, and teleoperation [31.20]. In this experiment the round trip delay was 6–7 s, such that it was not feasible to include force feedback into the control loop.

With the first transatlantic telesurgery demonstration in 2001, Computer Motion demonstrated the feasibility of telerobotic systems even in the delicate field of surgery [31.21]. A surgeon in New York (USA) used a ZEUS system to perform a laparoscopic cholecystectomy on a patient located in Strasbourg (France), as depicted in Fig. 31.6. The system did not include force feedback, so the surgeon had to rely on visual feedback only.

In this perspective we gave only reference to the systems, that are seen to be milestones within the history of telerobotics. Several different systems have been developed and added value to the research field, which could not be mentioned here.

### 31.2.2 Applications

Telerobotic systems have been motivated by issues of human safety in hazardous environments (e.g., nuclear

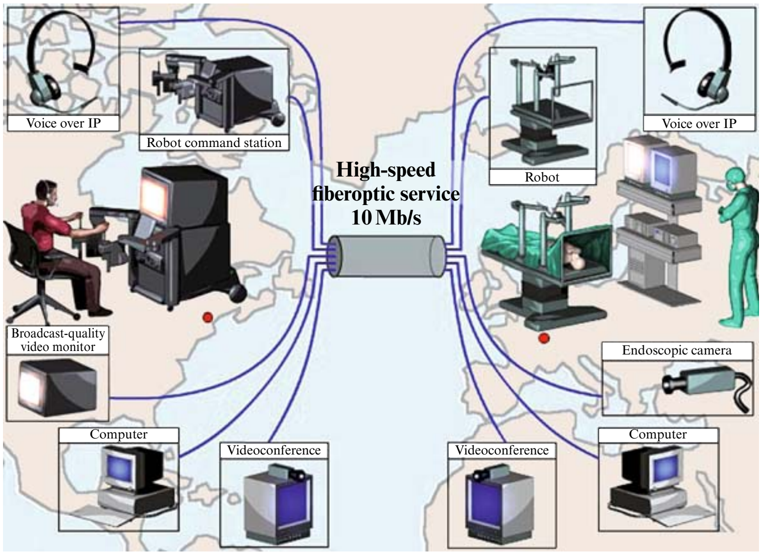


**Fig. 31.6** Operation Lindberg. The first transcontinental telerobotic surgery (2001). (Courtesy M. Ghodoussi)

or chemical plants), the high cost of reaching remote environments (e.g., space), scale (e.g., power amplification or position scaling in micromanipulation or minimally invasive surgery), and many others. Not surprisingly, after their beginning in nuclear research, telerobotic systems have evolved to many fields of application. Nearly everywhere a robot is used, telerobotic systems can be found. The following are some of the more exciting uses.

In minimally invasive surgery telerobots allow procedures to be performed through small incisions, reducing the trauma to the patient compared to traditional surgery [31.22]. The da Vinci system, made by Intuitive Surgical Inc. [31.23] and shown in Fig. 31.7, is the only commercially available device at present. Other efforts, however, include Computer Motion [31.24] and endoVia Medical [31.25] on the commercial side, as well as the University of Washington [31.26], Johns Hopkins University [31.27], the German Aerospace Center [31.28], and many others.

**Fig. 31.7** Intuitive Surgical Inc. makes the da Vinci telerobotic system, which is used in minimally invasive surgery. (Courtesy ©2008 Intuitive Surgical, Inc.)

**Fig. 31.8** tEODor, A telerobotic system for disarming of explosives. (Courtesy telerob Gesellschaft für Fernhantierungstechnik mbH, Ostfildern, Germany)

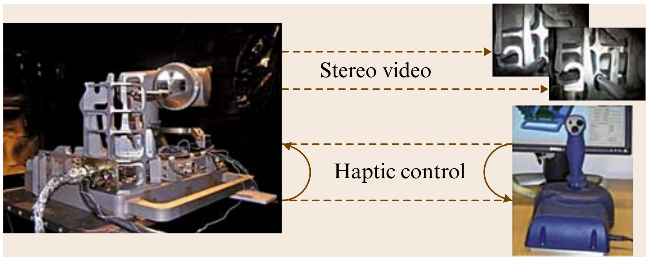


**Fig. 31.9** ROKVISS, a telerobotic system providing stereo vision and haptic feedback to the ground operator. (Courtesy of the German Aerospace Center, DLR)

Protecting the operator from having to reach into a hazardous environment, telerobotic systems are widely used in nuclear or chemical industry. Some systems have been developed for the maintenance of high-voltage electrical power lines, which can be safely repaired without service interruption by a human operator using a telerobotic system. Disarming of explosives is another important task. Many systems like the telerob explosive ordnance disposal and observation robot (tEODor) shown in Fig. 31.8 or PackBot, made by iRobot [31.29], are used by police and military to disarm mines and other explosives. Similar vehicles are remote controlled for search and rescue in disaster zones [31.30].

Space robotics is a classic application, in which distance is the dominating barrier, as discussed in Chap. 45. The NASA rovers on Mars are a famous example. Due to the time delay of several minutes, the rovers are commanded using supervisory control, in which the human operator is defining the goal of a movement and the rover achieves the goal by local autonomy using sensory feedback directly [31.31].

In orbital robotics the German technology experiment ROKVISS (robot component verification on ISS) is the most advanced telerobotic system [31.32]. Launched in 2004, it is installed outside the Russian module of the international space station. In this experiment advanced robot components of a slave system, including torque sensors and stereo video cameras, are validated in real space conditions. Due to a direct communication link between the space station and the operator station at DLR (German Aerospace Center), the time delay was reduced to about 20 ms allowing a bilateral control architecture with high-fidelity force feedback to the operator [31.33] (Fig. 31.9). This technology is leading toward robotic service satellites, called Robonauts, which can be remotely controlled from the ground to help real astronauts during extravehicular activity (EVA) or to perform repair and maintenance tasks [31.34].

## 31.3 Control Architectures

Compared to plain robotic systems, in which a robot executes a motion or other program without further consultation of a user or operator, telerobotic systems provide information to and require commands from the user. Their control architectures can be described by the style and level of this connection, as shown in Fig. 31.10. Organized in a spectrum, the three main categories are

- direct control
- shared control
- supervisory control

In practice, however, control architectures often include parts of all strategies.

Direct control implies no intelligence or autonomy in the system, so that all slave motion is directly controlled by the user via the master interface. If task execution is shared between direct control and local sensory feedback and autonomy, or if user feedback is augmented from virtual reality or other automatic aids, the architecture is denoted as shared control. In supervisory control the user and slave are connected loosely with strong local autonomy, i. e., the operator is giving high-level commands, which are refined and executed by the telerobot. The following explains the architectures in reverse order, followed by a detailed treatment of direct and bilateral control in Sect. 31.3.3, which introduces the basic ideas for Sect. 31.4.

### 31.3.1 Supervisory Control

Supervisory control, introduced by *Ferell* and *Sheridan* in 1967 [31.2], is derived from the analog of supervising a human subordinate staff member. The supervisor gives high-level directives to and receives summary information from, in this case, the robot. *Sheridan* describes this approach in comparison with manual and automatic robot control [31.35]: "Human operators are intermittently programming and continually receiving information from a computer that itself closes an au-

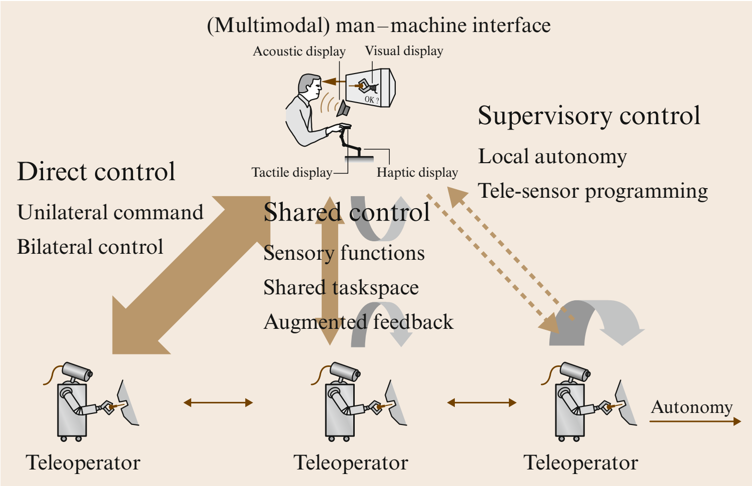


**Fig. 31.10** Different concepts for telerobotic control architectures

tonomous control loop through artificial effectors and sensors."

Today the autonomous control loops may be closed on the remote site, with only the state and model information being transmitted to the operator site. The operator supervises the telerobotic system and decides how to act and what to do. A special implementation of supervisory control is the telesensor programming approach, which is presented hereafter.

### Telesensor Programming

The telesensor programming (TSP) approach is a shared autonomy concept that distributes intelligence between man and machine [31.36]. Presuming that sufficient information about the actual environment is available from the sensor systems, partial tasks can be executed independently on the machine level. Specifications and decisions on a high task planning level have to be done by human operators. Local sensory feedback loops are used by the robot system, while global task-level jobs have to be specified interactively by a human operator. This shared autonomy approach is the basis of the TSP paradigm, with which the robot can be teleprogrammed on a task directed level. The teaching of a robot system occurs not on the joint or cartesian manipulator level but on a higher language level, i. e., the operator plans activities at a level which can be performed by the robotic system independent of human intervention.

Figure 31.11 shows the structure of a TSP implementation, consisting of two control loops working in parallel. One loop controls the real (remote) system, which contains internal feedback for local autonomy. The other loop establishes a simulation environment which is structurally equivalent to the real system, with a few exceptions.

Most importantly, any signal delay which may result from communication to the remote system, e.g., in space applications, is not duplicated in the simulation. This makes the simulation predictive with respect to the real system. A second exception is the display of internal variables in the simulation, which cannot be observed (measured) in the real system. This gives the operator or task planner more insight into what is happening or may happen in the system in response to commands. Communication between the two loops occurs via a common model data base which delivers a priori knowledge for execution on the remote system and a posteriori knowledge for model updating in the simulated world. For such a telerobotic control system unique tools are necessary to implement the required functionality. First a sophisticated simulation system has to be provided to emulate the real robot system. This includes the simulation of sensory perception within the real environment. Beyond this sensor simulation, the shared autonomy concept has to provide an efficient operator interface to setup task descriptions, to configure the task control parameters, to decide what kind of sensors and control algorithms should be used, and to debug an entire job execution phase.

In the field of telerobotics with large time delays, e.g., in space and undersea applications, this sensor-based task-directed programming approach [31.36] has advantages. Under direct visual feedback with a time delay of a few seconds, is not feasible for the human operator to handle the robot's movements in a suitable way.

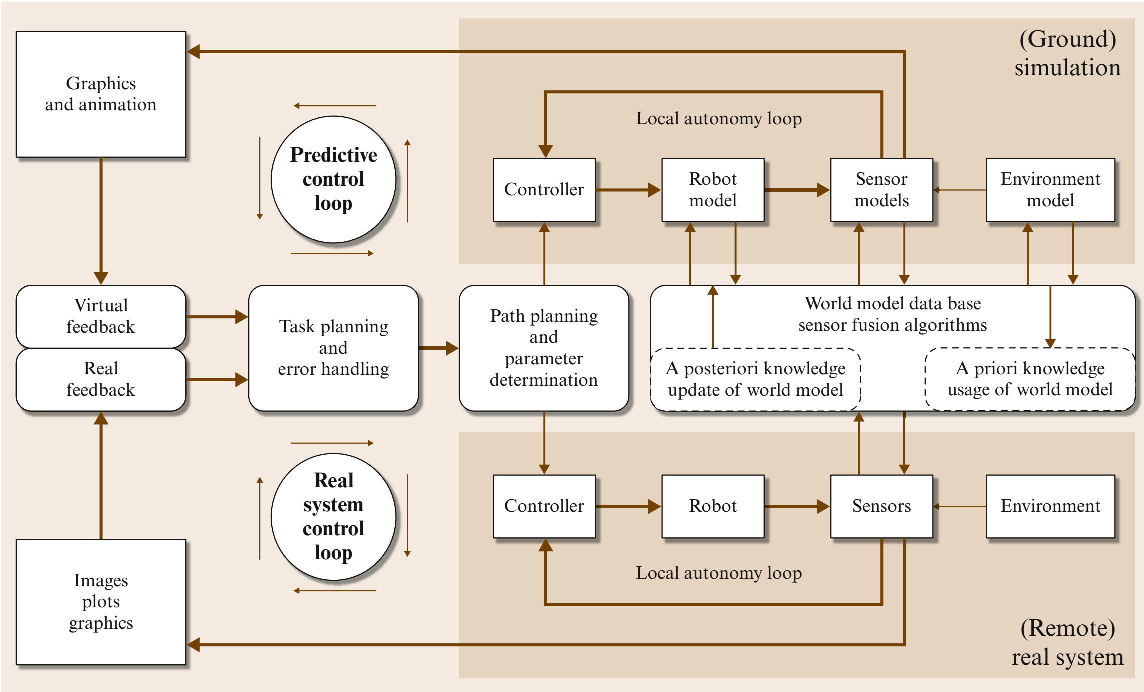


**Fig. 31.11** The concept of telesensor programming as demonstrated during the ROTEX mission

Predictive simulation allows the operator to telemanipulate the remote system [31.37]. In addition, the use of force reflecting hand controllers to feed back force signals in shared and teleoperated control modes [31.38] or from the simulated predicted world can improve the operator's performance. Finally, an interactive supervisory user interface makes it possible to configure the environmental and control parameters.

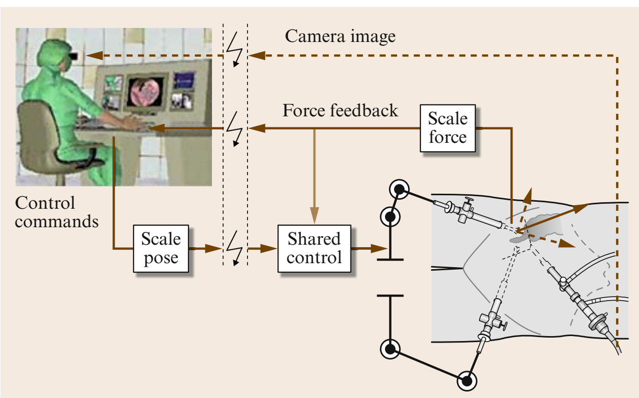


**Fig. 31.12** An example for the shared control concept in telerobotic surgery

The main feature of this telerobotic concept is to replace the time-delayed visual feedback with predictive stereo graphics including sensor simulation, providing a supervisory control technique that will allow a shift of more and more autonomy and intelligence to the robot system.

### 31.3.2 Shared Control

To enable telepresence in long-distance or risky applications (e.g., space or surgery) a sufficient *shared control* concept [31.39, 40] for the control of the teleoperator can be preferable to guarantee the safety of the teleoperator and/or task. Herein, shared control is based on local sensory feedback loops [31.41] at the teleoperator site (Fig. 31.11), by which gross commands were refined autonomously providing the teleoperator with a modest kind of sensory intelligence. The human operator originates gross path commands e.g. by using a kinesthetic feedback device, which are *fine-tuned* by the teleoperator.

In applications with large time delays the *shared autonomy* concept distributes intelligence between the operator and the teleoperator in the sense of a task-directed approach [31.42]. Control of the task is distributed between the human operator and the (autonomous) telerobot, such that each controls a subtask. An example can be seen in Fig. 31.12, where the autonomous part of the system controls and compensates the patients movement, while the surgeon controls the operation itself on a virtual stabilized patient [31.43].

A special application of shared control is the use of *virtual fixtures* [31.44]. Virtual elements, such as virtual surfaces, guide tubes, or other appropriate objects, are superimposed into the visual and/or haptic scene for the user. These fixtures help the operator perform telerobotic or robot-assisted manipulation tasks by limiting movement into restricted regions and/or influencing movement along desired paths. Control is thus shared at the master site, taking advantage of preknowledge of the system or task to modify the user's commands and/or to combine them with autonomously generated signals.

Capitalizing on the accuracy of robotic systems, while sharing control with the operator, telerobotic systems with virtual fixtures can achieve safer and faster operation [31.45]. Abbott et al. describe the benefits by comparison to the common physical fixture of a ruler: "A straight line drawn by a human with the help of a ruler is drawn faster and straighter than a line drawn freehand. Similarly, a [master] robot can apply forces or positions to a human operator to help him or her draw a straight line." Based on the nature of the master robot and its controller, the virtual fixtures may indeed appear as impedance or admittance objects, i. e., providing corrective forces or positions to the user, respectively. In both cases, however, and in contrast to physical fixtures, the level and type of assistance can be programmed and varied.

### 31.3.3 Direct and Bilateral Teleoperation

To avoid difficulties in creating local autonomy, most telerobotic systems include some form of direct control: they allow the operator to specify the robot's motions. In the following we assume a master–slave system, i. e., the user is holding a joystick or master mechanism serving as an input device. We first describe unilateral operation, before focusing on bilateral control where the master also serves a display device.

#### Unilateral Acceleration or Rate Control

For underwater, airborne, or space applications, a slave robot may be a vehicle actuated by thrusters. Direct control thus requires the user to power the thrusters, which in turn accelerate the vehicle. For other applications, the user may be required to command the rate or velocity of the vehicle or slave robot. In both scenarios, the input device is commonly a joystick, often spring centered, where the commands are proportional to the joystick displacement. For six-degree-of-freedom (DOF) applications, i. e., when the slave needs to be controlled in translation and orientation, a 6D-Space Mouse or alternatively often two joysticks are used for translation and orientation respectively.

Acceleration and rate control can require considerable effort for the operator to reach and hold a given target location. As expected, users can more accurately position a system under rate control than under acceleration control [31.46]. Indeed acceleration control necessitates users to regulate a second-order system versus a first-order system for rate control. Assuming the slave has local position feedback available, a control system is often incorporated locally, such that the user may specify position commands and is relieved from the dynamic control problem.

#### Position Control and Kinematic Coupling

Assuming that the slave is under position control, we next consider the kinematic coupling between master and slave, i. e., the mapping between master and slave positions. In particular, we must remember that the master mechanism moves in the master workspace, while the slave robot moves in the slave workspace. These two spaces are nearly always somewhat different.

*Clutching and Offsets.* Before even discussing how the two robots are coupled, we must understand that they are not always coupled, for example, before the system is turned on, master and slave robots may, for whatever reason, be placed in some initial position/configuration. We have three options of how to engage the system: (1) first autonomously move one or both robots so they come to the same position, (2) wait until someone (the user) externally moves one robot to match the location of the other, or (3) connect the two robots with some offset.

Once connected, most systems also allow a temporary disconnection between the two sites. The reason is twofold: to allow the user to rest without affecting the slave state and to allow a shift between the two robots. The later is most important if the workspaces of both robots do not perfectly overlap. This is much like picking up your mouse off your mouse pad to reposition without moving the cursor.

In telerobotics the process is called *clutching* or sometimes also indexing. If clutching is allowed, or both robots are not constrained to start at the same location, the system must allow for offsets between the two robots.

*Kinematically Similar Mechanisms.* The simplest scenario involves a master and slave mechanism that are kinematically equivalent if not entirely identical. In this case, the two robots can be connected at a joint level. With $\boldsymbol{q}$ denoting joint values and subscripts 'm' referring to the master, 's' to the slave, 'offset' to a shared offset, and 'd' to a desired value, we can write

$$\begin{aligned}\boldsymbol{q}_{\mathrm{sd}} &= \boldsymbol{q}_{\mathrm{m}} + \boldsymbol{q}_{\mathrm{offset}} ,\\ \boldsymbol{q}_{\mathrm{md}} &= \boldsymbol{q}_{\mathrm{s}} - \boldsymbol{q}_{\mathrm{offset}} .\end{aligned} \tag{31.1}$$

At the instance the two robots are to be connected or reconnected, the offset is computed as

$$\boldsymbol{q}_{\mathrm{offset}} = \boldsymbol{q}_{\mathrm{s}} - \boldsymbol{q}_{\mathrm{m}} . \tag{31.2}$$

Most kinematically similar master–slave systems have the same workspace at both sites and do not allow clutching. By construction the offset is then always zero.

Depending on the controller architecture, the joint velocities may be similarly related, taking derivatives of (31.1). An offset in velocities is not necessary.

*Kinematically Dissimilar Mechanisms.* In many cases, the master and slave robots differ. Consider that the master is connected to the human user and thus should be designed accordingly. Meanwhile the slave works in some environment and may have a very different joint configuration and different number of joints. As a result, connecting the robots joint by joint may not be feasible or appropriate.

Instead kinematically dissimilar robots are connected at their tips. If $\boldsymbol{x}$ is a robot's tip position, we have

$$\begin{aligned}\boldsymbol{x}_{\mathrm{sd}} &= \boldsymbol{x}_{\mathrm{m}} + \boldsymbol{x}_{\mathrm{offset}} ,\\ \boldsymbol{x}_{\mathrm{md}} &= \boldsymbol{x}_{\mathrm{s}} - \boldsymbol{x}_{\mathrm{offset}} .\end{aligned} \tag{31.3}$$

If orientations are also connected, with $\boldsymbol{R}$ describing a rotation matrix, we have

$$\begin{aligned}\boldsymbol{R}_{\mathrm{sd}} &= \boldsymbol{R}_{\mathrm{m}} \boldsymbol{R}_{\mathrm{offset}} ,\\ \boldsymbol{R}_{\mathrm{md}} &= \boldsymbol{R}_{\mathrm{s}} \boldsymbol{R}_{\mathrm{offset}}^{\top} ,\end{aligned} \tag{31.4}$$

where the orientational offset is defined as slave relative to master

$$\boldsymbol{R}_{\mathrm{offset}} = \boldsymbol{R}_{\mathrm{m}}^{\top} \boldsymbol{R}_{\mathrm{s}} . \tag{31.5}$$

Again velocities and angular velocities may be connected if needed and do not require offsets.

Finally note that most telerobotic systems use a video camera at the remote site and a monitor at the local site. To make the connection appear natural, the slave position and orientation should be measured relative to the camera, while the master position and orientation should be measured relative to the user's view.

*Scaling and Workspace Mapping.* Kinematically dissimilar master–slave robots are commonly also of different size. This means not only do they require clutching to fully map one workspace to another, but they often necessitate motion scaling. And so (31.3) becomes

$$\begin{aligned}\boldsymbol{x}_{\mathrm{sd}} &= \mu \boldsymbol{x}_{\mathrm{m}} + \boldsymbol{x}_{\mathrm{offset}} ,\\ \boldsymbol{x}_{\mathrm{md}} &= \frac{(\boldsymbol{x}_{\mathrm{s}} - \boldsymbol{x}_{\mathrm{offset}})}{\mu} .\end{aligned} \tag{31.6}$$

The orientation, however, should not be scaled. The scale $\mu$ may be set to either map the two workspaces as best possible, or to provide the most comfort to the user.

If force feedback, introduced below, is provided, an equivalent force scale may be desired. This will prevent distortion of the remote environmental conditions, such as stiffness or damping, by the scaling.

Beyond linear scaling, several research efforts have created nonlinear or time-varying mappings, which deform the workspaces. These may effectively change the scale in the proximity of objects [31.47] or drift the offset to best utilize the master workspace [31.48].

*Local Position Control.* By construction we are now assuming that the slave follows a position command. This necessitates a local slave controller to regulate its position. In particular for kinematically dissimilar mechanisms, this will be a Cartesian tip position controller with appropriate inverse kinematics. For details we refer to Chap. 6.

If the slave robot has redundancies, these may be controlled either automatically to optimize some criterion or manually with additional user commands. We refer here to Chap. 11 for appropriate techniques.

## 31.4 Bilateral Control and Force Feedback

In pursuit of telepresence and to increase task performance, many master–slave systems incorporate force feedback. That is, the slave robot doubles as a sensor and the master functions as a display device, so that the system provides both forward and feedback pathways from the user to the environment and back. Figure 31.13 depicts the common architecture viewed as a chain of elements from the user to the environment.

The bilateral nature of this setup makes the control architecture particularly challenging: multiple feedback loops form and even without environment contact or user intervention, the two robots form an internal closed loop. The communications between the two sites often inserts delays into the system and this loop, so that stability of the system can be a challenging issue [31.49].

To present force information without stability problems, it is possible to use alternate displays, such as audio or tactile devices [31.50]. Meanwhile, the combination of vibrotactile methods with explicit force feedback can increase high-frequency sensations and provide benefits to the user [31.51]. Tactile shape sensing and display also extends the force information presented to the user [31.52].

In the following we discuss explicit force feedback. We first examine the basic architectures before discussing stability and some advanced techniques.

### 31.4.1 Position/Force Control

Two basic architectures couple the master and slave robots: position–position and position–force. We assume that the robot tips are to be connected by the equations of Sect. 31.3.3, giving the control laws for translation. Control of orientation or joint motions follows equivalent patterns.

#### Position–Position Architecture

In the simplest case, both robots are instructed to track each other. Both sites implement a tracking controller, often a proportional-derivative (PD) controller, to fulfill these commands:

$$\begin{aligned} \boldsymbol{F}_\mathrm{m} &= -\boldsymbol{K}_\mathrm{m}(\boldsymbol{x}_\mathrm{m} - \boldsymbol{x}_\mathrm{md}) - \boldsymbol{B}_\mathrm{m}\left(\dot{\boldsymbol{x}}_\mathrm{m} - \dot{\boldsymbol{x}}_\mathrm{md}\right) , \\ \boldsymbol{F}_\mathrm{s} &= -\boldsymbol{K}_\mathrm{s}(\boldsymbol{x}_\mathrm{s} - \boldsymbol{x}_\mathrm{sd}) - \boldsymbol{B}_\mathrm{s}\left(\dot{\boldsymbol{x}}_\mathrm{s} - \dot{\boldsymbol{x}}_\mathrm{sd}\right) . \end{aligned} \tag{31.7}$$

If the position and velocity gains are the same ($\boldsymbol{K}_\mathrm{m} = \boldsymbol{K}_\mathrm{s} = \boldsymbol{K}$, $\boldsymbol{B}_\mathrm{m} = \boldsymbol{B}_\mathrm{s} = \boldsymbol{B}$), then the two forces are the same and the system effectively provides force feedback. This may also be interpreted as a spring and damper between the tips of each robot, as illustrated in Fig. 31.14. If the two robots are substantially different and require different position and velocity gains, the master–slave forces will be scaled and/or distorted.

Note we have assumed the slave is under impedance control and back-drivable. If the slave is admittance controlled, i. e., it accepts position commands directly, the second part of (31.7) is unnecessary.

Also note that by construction the user feels the slave's controller forces, which include forces associated with the spring–damper and slave inertia in addition to environment forces. Indeed while moving without contact, the user will feel the inertial and other dynamic forces needed to move the slave. Furthermore, if the slave is not back-drivable, i. e., does not easily move under environment forces, the environment force may be entirely hidden from the user. Naturally this defeats the purpose of force feedback. In these cases, a local force control system may be used to render the slave back-drivable. Alternatively, a position–force architecture may be selected.

#### Position–Force Architecture

In the position–position architecture, the user is presented with the slave's controller force. While this is very stable, it also means the user feels the friction and inertia in the slave robot, which the controller is actively driving to overcome. In many scenarios this is undesirable. To avoid the issue, position–force architectures place a force sensor at the tip of the slave robot and feedback the force from there. That is, the system is

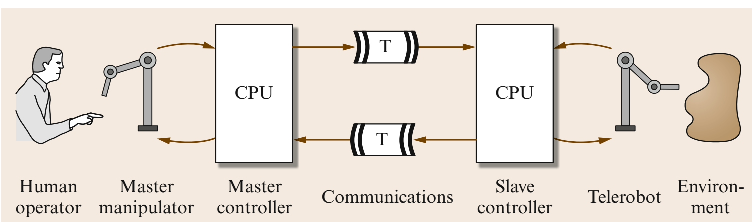


**Fig. 31.13** A typical bilateral teleoperator can be viewed as a chain of elements reaching from user to environment

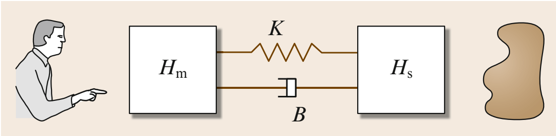


**Fig. 31.14** A position–position architecture effectively creates a spring and damper between the two robots

controlled by

$$\boldsymbol{F}_m = \boldsymbol{F}_{sensor} ,$$
$$\boldsymbol{F}_s = -\boldsymbol{K}_s(\boldsymbol{x}_s - \boldsymbol{x}_{sd}) - \boldsymbol{B}_s(\dot{\boldsymbol{x}}_s - \dot{\boldsymbol{x}}_{sd}) . \tag{31.8}$$

This allows the user to only feel the external forces acting between the slave and the environment and presents a more clear sense of the environment. However, this architecture is less stable: the control loop passes from master motion to slave motion to environment forces back to master forces. There may be some lag in the slave's motion tracking not to mention any delay in communications. Meanwhile the loop gain can be very high: a small motion command can turn into a large force if the slave is pressing against a stiff environment. In combination, stability may be compromised in stiff contact and many systems exhibit contact instability in these cases.

### 31.4.2 Passivity and Stability

The two basic architectures presented in Sect. 31.4.1 clearly illustrate one of the basic tradeoffs and challenges in force feedback: stability and performance. Stability issues arise because any models of the system depend on the environment as well as the user. Both these elements are difficult to capture and, if we assume we want to explore unknown environments, impossible to predict. This issue makes a stability analysis very difficult. A common tool that avoids some of this issue is the concept of passivity. Although passivity provides only a sufficient (not a necessary) condition for stability, it incorporates the environmental uncertainly very well.

Passivity is an intuitive tool that examines the energy flows in a system and makes stability assertions if energy is dissipated instead of generated. Three rules are of importance here. First, a system is passive if and only if it can not produce energy. That is the output energy from the system is limited by the initial and accumulated energy in the system. Second, two passive systems can be combined to form a new passive system. Third, the feedback connection of two passive systems is stable.

In the case of telerobotics, we generally assume that the slave robot will only interact with passive environments, that is, that the environments do not contain active motors or the like. Without the human operator, stability can therefore be assured if the system is also passive, without needing an explicit environment model.

On the master side the operator closes a loop and has to be considered in the stability analysis. In general, the master robot will be held by the user's hand and arm. A variety of models and parameters describe the human arm dynamics, mainly in the form of a mass–damper–spring system. In [31.53] we find a summary of model parameters used by different authors. For an impedance-controlled haptic interface, common to most systems, the worst-case scenario for stability is the situation when the operator is not holding the haptic device [31.54, 55]. Thus we may elect to ignore the human operator in the analysis, assuming the human force equals zero ($\boldsymbol{F}_{human} = 0$). A system then found to be stable will also be stable if the operator is interacting with the device.

To apply passivity, we take the system originally depicted in Fig. 31.13 and describe it as two-port elements in Fig. 31.15. We choose a sign convention, such that the power at every boundary is positive if flowing to the right. For example, at the first boundary, the positive power flow is the product of master velocity times applied (human) force

$$P_{left} = \dot{\boldsymbol{x}}_m^\top \boldsymbol{F}_{human} . \tag{31.9}$$

Meanwhile at the last boundary, the positive power flow is the product of the slave velocity times the environment force (which ultimately opposes the human force)

$$P_{right} = \dot{\boldsymbol{x}}_s^\top \boldsymbol{F}_{env} . \tag{31.10}$$

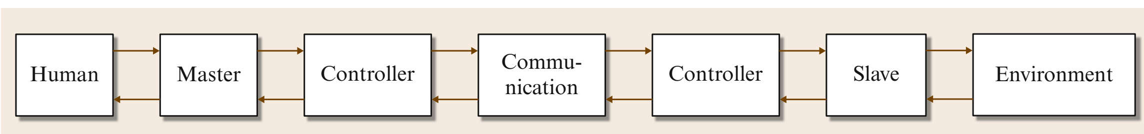


**Fig. 31.15** A teleoperator can be analyzed as a chain of-two port elements connecting the one-port operator to the one-port environment

Therefore the entire telerobotic system is passive if

$$\begin{aligned}\int_0^t P_{\text{input}}\,\mathrm{d}t &= \int_0^t (P_{\text{left}} - P_{\text{right}})\,\mathrm{d}t \\ &= \int_0^t \left(\dot{\boldsymbol{x}}_{\mathrm{m}}^{\top}\boldsymbol{F}_{\text{human}} - \dot{\boldsymbol{x}}_{\mathrm{s}}^{\top}\boldsymbol{F}_{\text{env}}\right)\mathrm{d}t \\ &> -E_{\text{store}}(0)\,. \end{aligned} \quad (31.11)$$

To simplify the analysis, we can examine the passivity of each two-port element and then deduce the overall passivity. The master and slave robots are mechanical elements and hence passive. The controllers of a position–position architecture mimic a spring and damper, which are also passive elements. So without delay, a position–position architecture is passive.

While powerful to handle uncertainty, passivity can be overly conservative. Many controllers are overdamped if every subsystem is passive. In contrast, the combination of an active and a passive subsystem may be passive and stable and show less dissipation. This is particularly true for the cascaded arrangement of two-port elements in the telerobotic system of Fig. 31.15. From network theory, the Llewellyn criterion specifies when a possibly active two-port connected with any passive one-port becomes passive. This two-port is then labeled unconditionally stable, as it will be stable in connection to any two passive one-ports. The Llewellyn criterion may hence be used as a more general stability test for telerobotic systems or components [31.56].

Passive controllers are also limited as they cannot hide the dynamics of the slave robot. In the above position–position architecture, the user will feel the forces associated with the slave inertia. In contrast the position–force architecture hides the slave inertia and friction from the user. As such, when the user inserts kinetic energy into the master without feeling any resistance, the system itself creates and injects the kinetic energy for the slave. This violates passivity and provides another insight as to why the architecture suffers from potential stability problems.

### 31.4.3 Transparency and Multichannel Feedback

Both basic architectures can be captured by the general teleoperator control system described by *Lawrence* [31.13], and later expanded by *Hashtrudi-Zaad* and *Salcudean* [31.56] and shown in Fig. 31.16. Knowing that ideally a teleoperator would have the master motion track the slave motion, as well as have the operator's force match the environment's force, both velocity (from which position may be integrated or vice versa) and force may be measured at both sites, for example, in this way the slave can start moving as soon as the user applies a force to the master, even before the master itself has moved.

Following these concepts derived in [31.13], we can examine the relationships between velocity and force, in the form of impedances and admittances. Note we do this in a single degree of freedom, assuming that all degrees of freedom may be treated independently. The environment will exhibit some impedance $Z_{\mathrm{e}}(s)$ that is not known in advance and relates the environment force to the slave's velocity

$$\boldsymbol{F}_{\mathrm{e}}(s) = Z_{\mathrm{e}}(s)\boldsymbol{v}_{\mathrm{s}}(s)\,. \quad (31.12)$$

If we describe the teleoperator in whole as a two-port with a hybrid matrix formulation

$$\begin{pmatrix} F_{\mathrm{h}}(s) \\ \boldsymbol{v}_{\mathrm{m}}(s) \end{pmatrix} = \begin{pmatrix} H_{11}(s) & H_{12}(s) \\ H_{21}(s) & H_{22}(s) \end{pmatrix} \begin{pmatrix} \boldsymbol{v}_{\mathrm{s}}(s) \\ -F_{\mathrm{e}}(s) \end{pmatrix} \quad (31.13)$$

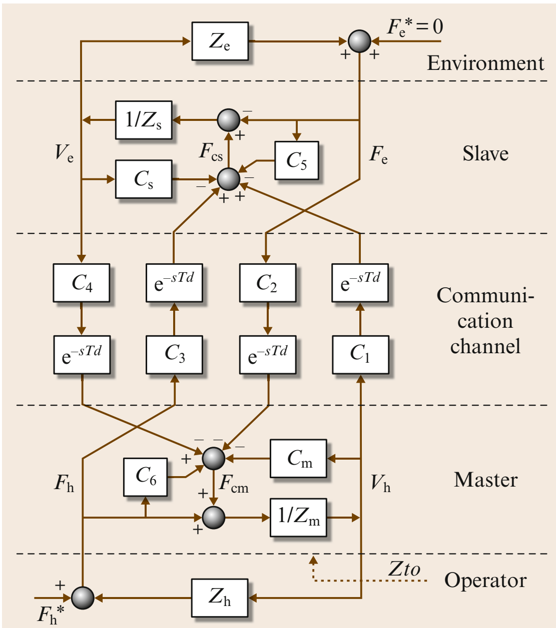


**Fig. 31.16** In general, a controller will use both position and force information from both master and slave robot (after [31.56], adapted from [31.13])

then the user will perceive the impedance

$$Z_{\mathrm{to}}(s) = \frac{\boldsymbol{F}_{\mathrm{h}}(s)}{\boldsymbol{v}_{\mathrm{m}}(s)} = (H_{11} - H_{12}Z_{\mathrm{e}})(H_{21} - H_{22}Z_{\mathrm{e}})^{-1} . \tag{31.14}$$

Transparency describes how close the user's perceived impedance comes to recreating the true environment impedance.

For a detailed treatment of passivity in telerobotics, impedance and admittance interpretations and designs, and transparency, we refer to some of the seminal works in [31.11–13, 56–59].

### 31.4.4 Time Delay and Scattering Theory

When delays occur in the communications between the local and remote site, even position–position architectures can suffer from serious instabilities [31.60, 61]. This can be traced to the communications block in Fig. 31.15, where the power entering the left side and exiting the right side do not add up. Rather energy may be generated inside the block, which feeds the instability [31.9].

Several approaches to operate under delay have been studied [31.62], in particular shared compliant control [31.63] and the addition of local force loops [31.64]. The use of the Internet for communication, adding variability to the delay, is also an area of interest [31.65, 66]. This further evokes issues of data reduction [31.67].

Here we note that natural wave phenomena are bilateral passive elements that tolerate delay. If the control system is described in the frequency domain and scattering matrices are used in place of impedance and admittance matrices, the system can tolerate delays [31.68]. Scattering matrices relate the sum of velocity and force to their difference, so that passivity becomes a condition on the system gain, which is unaffected by the delay. Alternatively, passivity may be explicitly observed and enforced to ensure stability [31.69–71].

### 31.4.5 Wave Variables

Building on the realization that delay communications can be active and that wave phenomena circumvent the issue, wave variables provide an encoding scheme that is tolerant of delay [31.72]. Consider the power flowing through the system and separate the power moving forward and returning.

$$P = \dot{\boldsymbol{x}}^{\mathrm{T}}\boldsymbol{F} = \frac{1}{2}\boldsymbol{u}^{\mathrm{T}}\boldsymbol{u} - \frac{1}{2}\boldsymbol{v}^{\mathrm{T}}\boldsymbol{v} = P_{\mathrm{forward}} - P_{\mathrm{return}} , \tag{31.15}$$

where the forward and returning power by construction have to be nonnegative. This leads to the definition of the wave variables

$$\boldsymbol{u} = \frac{b\dot{\boldsymbol{x}} + \boldsymbol{F}}{\sqrt{2b}} ,$$
$$\boldsymbol{v} = \frac{b\dot{\boldsymbol{x}} - \boldsymbol{F}}{\sqrt{2b}} , \tag{31.16}$$

where $\boldsymbol{u}$ is the forward-moving and $\boldsymbol{v}$ the returning wave.

If the normal signals are encoded into these wave variables, transmitted across the delay, and decomposed into regular variables, the system remains passive regardless of delay. In fact, in the wave domain, passivity corresponds to a wave gain of less than or equal to unity. No requirements are placed on phase and so lag does not destroy stability.

The wave impedance $b$ relates velocity to force and provides a tuning knob to the operator. Large $b$ values mean the system increases force feedback levels at the cost of feeling high inertial forces. Small values of $b$ lower any unwanted sensations, making it easy to move quickly, but also lower the desirable environment forces. Ideally the operator would lower $b$ when there is no risk of contact and raise $b$ when contact is imminent.

Recent developments are incorporating both position–position and position–force architectures within the wave frame work, so the resulting system is stable with any environment, stable with any delay, yet maintains the feedback of high-frequency forces that help the operator identify happenings at the remote site [31.73]. To improve performance and assist the operator, predictors may also be incorporated [31.74].

## 31.5 Conclusions and Further Reading

Despite its age, telerobotics remains an exciting and vibrant area of robotics. In many ways, it forms a platform which can utilize the advances in robotic technologies while simultaneously leveraging the proven skills and capabilities of human users. Compare this, for example, with the development of the automobile and its relation to the driver. As cars are gradually becoming more sophisticated with added electronic stability control and navigation systems, they are becoming safer and more useful to their operators, not replacing them. Similarly telerobotics serves as a pathway for gradual progress and, as such, is perhaps best suited to fulfill robotics long-held promise of improving human life. It is seeing use in the challenging area of search and rescue. And with the recent developments and commercializations in telerobotic surgery systems, it is indeed impacting on the lives of tens of thousands of patients in a profound fashion and extending the reach of robotics into our world.

For further reading in the area of supervisory control, we refer to *Sheridan* [31.35]. Though published in 1992, it remains the most complete discussion on the topic. Unfortunately few other books are devoted to or even fully discuss telerobotics. In [31.75] many recent advances, including methods, experiments, applications, and developments, are collected. Beyond this, in the areas of bilateral and shared control, as well as to understand the various applications, we can only refer to the citations provided. Finally, in addition to the standard robotics journals, we note in particular *Presence: Teleoperators and Virtual Environments*, published by the MIT Press. Combined with virtual-reality applications, it focuses on technologies with a human operator.

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