TELEROBOTICS

Telerobotics is a functional combination of the automation technology of robotics with the sensing, cognitive, and dexterous capabilities of a human being to create synergistic systems for effective performance of physical tasks at a location remote to the human operator. It is necessary to examine the characteristics of robots, teleoperators, and humans to understand why this combination is advantageous for certain tasks.

A robot as defined by the Robotics Institute of America is "a reprogrammable, multifunctional manipulator designed to move material, parts, tools and specialized devices through variable programmed motions for the performance of a variety of tasks" (1). This strict definition limits the robot to devices that manipulate objects and is typified by a multijointed arm used on an assembly line. The science fiction definition of a robot is an anthropomorphic (humanlike) device that performs tasks normally performed by a human. An even broader definition is any device that performs physical action with some degree of autonomy such as a vehicle for ground, air, undersea, or space exploration. A common characteristic of each definition is that the robot can complete a task *autonomously* (i.e., with no human intervention) over some range of variation of environmental variables that it encounters.

In a structured environment in which the location of all things in a robot's environment is known to a relatively high degree of accuracy, such as an assembly line with palletized parts, the robot is able to take advantage of its high accuracy and repeatability to manipulate and assemble objects precisely. Another useful characteristic of the robot is that it is programmable and hence reprogrammable; that is, it can do many different tasks. However, if something unexpected occurs in any given application that the robot does not sense or has not been programmed to handle (e.g., something as simple as a misaligned part) it may be that the robot will have insufficient sensing and programming flexibility to accomplish the task. As the environment becomes more unstructured, the degree of sophistication of the robot necessary to accomplish the task becomes greater. Technology and cost will always place practical limitations on the level of autonomy that it is feasible to build into a robot system.

It is the ability of a human to recognize through an elaborate sensory and cognitive system and to react with highly dexterous appendages provides a distinct advantage for manipulation in an unstructured environment. A human is not

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

well suited to tasks that are repetitive or require a high degree of precision. When there is an option to choose either a human or a robot to perform a particular task directly (i.e., not remotely), such as on an assembly line, the considerations of this and the previous paragraph are used to make the selection. However, there are situations in which the human cannot or should not be permitted to perform the task directly, such as in the hostile environment of space or in a nuclear reactor. In such situations teleoperation is used to insert the human capability into a task remote to the operator.

A *teleoperator system* is a system in which one or more humans accomplish a remote task through intermittent or continuous commands to one or more actuation devices at the remote site. The device that interfaces to the human and issues commands is called the *master* and its location is called the *master site.* Display capability is also generally present at the master site to provide the operator with information about the state of the remote task. The device that affects the remote operation is called the *slave* and the location at which the work is being accomplished is called the *slave site.* Sensors are also present at the slave site to gather information for making autonomous (i.e., slave-site) decisions and for relay to the master site. If action by the slave occurs only in response to input from the human operator and stops whenever the operator's input discontinues and this is the only mode of operation, the teleoperator is said to be a *telemanipulator* and is said to operate in a *manual mode.*

The effectiveness of manual control is always reduced compared to that in direct (not remote) human control because feedback of knowledge of the state of the environment is necessarily limited by the bandwidth of the communication system. All sensory information presented to the operator must be sensed at the remote site by physical devices, sent via wire or radio transmission, and transformed into a virtual representation for the operator. One solution is to provide sufficient transmission bandwidth and sufficient virtual representation so that the requisite sensory data are presented to the operator. However, just as technology and cost place limitations the level of autonomy that can be built into a robot, technology and cost also place limitations on the level of sensory information that can be presented to an operator that is remote to the task.

Telerobotics is an alternative form of teleoperation in which one or more operators supervise (i.e., program) at least part of the task for at least part of the time, that supervised task part being performed by an automated device, that is, a robot. An operator's supervisory role is to monitor the task for unforeseen circumstances continuously and to restructure it when appropriate. The supervisory actions do not directly control the task; the autonomous controller at the slave site acts as an intermediary. Supervisory actions might consist of one or more of the following:

- Make plans to improve the next instance of the task.
- Teach the slave how to perform a task.
- Intermittently issue commands that alter the automated task algorithm of an operating slave.
- Intermittently issue commands that the slave autonomous controller recognizes as signal to initiate or alter a task action.
- Interrupt the autonomous mode by stopping the task or switching to manual control.

Table 1. Characteristics of Supervisory Actions in a Telerobotic Application

Action	Urgency
1. Plan task	Low
2. Teach task	Moderate
3. Alter task algorithm	Moderate
4. Initiate or alter task action	Moderate, high
5. Interrupt task action	High

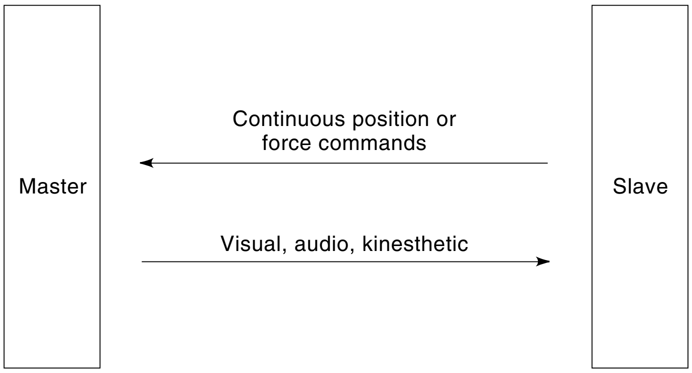
These programming actions can be considered hierarchical in the sense of urgency as indicated in Table 1. They can be accomplished *symbolically* by use, for example, of keyboard commands that the operator understands cognitively and that the autonomous controller associates with a task algorithm, or *analogically* by use of a master device that is isomorphic to the response observed by the operator, as, for example, forward motion of a master device that produces a corresponding forward motion of the slave. Supervisory actions that are more urgent require the intuitiveness of an analogic interface; those that are less urgent are generally accomplished symbolically.

A telerobotic system for which task control can be switched between the manual and supervised autonomous modes of operation is said to operate in the *traded-control* mode. A telerobotic system is said to operate in the *shared-control* mode if some aspects of a task are supervised and some are manually controlled. A telerobotic controller may also operate with a mix of traded and shared control. A computer is generally required to accomplish a task telerobotically. For telemanipulation a computer is not necessarily required.

Figure 1 compares the data flow of a telemanipulator and a telerobot. The most significant distinction is the capability of the telerobot to communicate programming information to the slave computer. For supervisory control, the primary communication to the slave is programming commands. Continuous position or force information might be necessary for teaching a task to the slave. For traded and shared control, continuous communication of position or force information plays a more significant role; for telemanipulation, that is the only data communicated to the slave.

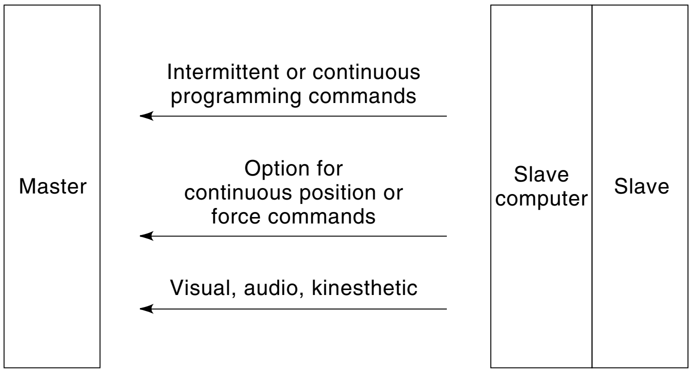
There are times during a telerobotically controlled task in which the control strategy conforms to the definition of manual control and other times when it conforms to the definition of autonomous robot control. Thus, the three basic methods of accomplishing a remote task, namely by telemanipulation, telerobotics, and robotics, are not entirely complementary, since a telemanipulator and an autonomous robot represent the extreme limits of functionality of a telerobot. Indeed, there is some tendency in the literature to use the terms teleoperation, telemanipulation, and telerobotics interchangeably with the increased use of computer-based automation viewed as a natural progression of the technology of remote control. In this article we shall maintain the distinction because it is a useful way to introduce and describe the topic.

And sometimes the task definition effects the distinction between a telemanipulator and telerobot. The confounding issue is "What is the task?" Even though the basic task might



Telemanipulator

(a)



Telerobot

(b)

Figure 1. Comparison of data flow in a telemanipulator and a telerobot.

be manipulation or motion, there are other things that must frequently be accomplished for the task to be successful. For example:

1. Gravity compensation of the slave device as mentioned previously
2. Collision avoidance of the slave device so as not to contact the object being manipulated or disturb the environment
3. Resolution of task space commands to slave joint space commands
4. Discrete event recognition such as contact with the environment
5. Vehicle disturbance rejection

Accomplishment of these "associated" tasks typically is accomplished autonomously, in which case the overall task could be declared telerobotic. In this article, we will not adopt this extended definition of a telerobot.

The device at the remote site can be a robot conforming to the strict or broad robot definitions given previously. Telerobots will be limited in this article to the control of remote devices for which motion control is required. Slave devices that fall into this category include manipulation devices, land-roving and guided vehicles, undersea exploration and recovery vehicles, unmanned spacecraft, and aerial vehicles, the latter sometimes referred to as aerobots. Excluded are remotely controlled processes (that do not directly control motion of a device) and manned vehicles and prosthetic devices (for which the operator is not remote). Even though the excluded applications have much technology in common with telerobotics, they have unique requirements that give them separate identities.

Classification of Teleoperators

In the preceding section, teleoperators were described as consisting of two classes: telemanipulators and telerobots. A second means for classifying teleoperators is by the kind of information transmitted between the master and slave. In early teleoperator systems, developed for handling nuclear fuel rods, the master and slave devices were connected by a mechanical linkage with the operator providing the source of power for actuation of the slave. Distance between the master and slave sites in a *mechanically coupled* teleoperator is limited, which generally makes possible direct viewing of the slave by the operator. The mechanical linkage also provides mechanical force feedback to give the operator a kinesthetic sense of the force and displacement applied by the slave to the environment with which it interacts. Examples of mechanically coupled teleoperators currently in use are the endoscopic and laproscopic instruments, used in minimal-invasive surgery.

To achieve remote operation at any distance, motorized teleoperators are used in which the slave device is powered by electrical or hydraulic actuators. This allows commands to be sent from the master to the slave as electric signals via wire or electromagnetic waves. Feedback of video data to the master site is usually necessary for any remote teleoperator system. To provide a remote operator with a kinesthetic sense of the force and displacement applied by the slave, signals can be transmitted back to the master site and used to drive an actuated master. A motorized teleoperator is said to be *bilateral* if the master device is driven by signals from the slave. It is said to be *unilateral* if it is not actuated. Bilateral operation is also referred to as *force reflection* and *kinesthetic feedback*. The advantage of bilateral operation is the additional intuitive knowledge gained kinesthetically by the operator of the state of the task being performed remotely. Timing of the force feedback is critical. It must be synchronized with the visual display presented to the operator to prevent information conflict and operator sickness. Furthermore, and probably more important, any delay between commands issued by the operator and the kinesthetic feedback to him or her that is transmission delay can induce instability in the teleoperator (similar to pilot-induced oscillation in aircraft) unless an appropriate form of control is used. When properly implemented, the addition of force feedback has been shown to be helpful in the accomplishment of contact and tracking tasks (2). For telerobotic operation, the need for bilateral operation is somewhat diminished since the task may be amenable to accomplishment in the supervisory mode (3).

Visual feedback typically includes one or more camera views of the slave interface with the environment. It may also include visual presentation of data that aids in understanding the state of the manipulator system. For example, motor torque is useful information for a unilateral teleoperator. While visual and kinesthetic feedback is generally considered the most crucial information for the operator to have, feedback of other information can also be helpful. The feedback of other sensory information, such as tactile sensation (some researchers use the term *haptics*) and audible sounds such as motor vibration and noise that results when contact occurs also give the operator a better sense of how the task is proceeding. Audio signal proportional to force has also been investigated as an alternative to kinesthetic feedback of force (4). The goal is to give the operator the feeling that he or she is present and performing the task directly at the slave site. *Transparency* is a term that implies the operator of a remote device fails to recognize that there is a master and slave intervening between the operator and the task the operator is performing. *Telepresence* and *situational awareness* are terms frequently used to describe the feeling of the operator that he or she is present at the slave site.

A third means for classifying teleoperators is by the manner in which the operator interfaces to the master device and displays. When a single interface is used to impart multiple position or force commands for the operator, the master is characterized as an *integrated controller.* The hand-held stick in a helicopter is an example of an integrated controller that commands motion forward, sideways, and vertically. The master is characterized as an *analytical controller* if each command is issued with a different interface. This is the type of control used for a backhoe in which each joint is operated with a separate lever. It can also be used to impart analogic supervisory commands. A keyboard is used to impart symbolic commands as indicated before. References 5 and 6 provide useful surveys of master devices used to command position and force.

One specialized form of integrated teleoperator is the *anthropomorphic teleoperator* in which the slave resembles some portion of the human anatomy. The operator interface for an anthropomorphic slave is typically an exoskeleton that is interfaced to the corresponding part of the operator's anatomy. By duplicating the human form at the slave site, the operator is provided with an interface that will (it is believed) result in more heuristic control and thereby result in more effective and efficient accomplishment of the task with less training. Furthermore, joint motion of the slave is typically mapped directly to the joint motion of the operator, which makes the command simpler. This may also give the operator a better sense of how the slave will move in performing a task, thereby reducing the risk of collision with the environment. *Teleproprioception* refers to the operator's sense of position of the slave relative to the slave environment.

The three methods of classification are not unrelated. If a task is to be accomplished telerobotically with a high degree of supervision, the predominant data transmitted would be that required to enhance situational awareness of the operator. This might entail multicamera views, sound, etc. The master interface might be a mix of analytic and integrated interfaces. If the task is to be accomplished with a high degree of manual control, the predominant data transmitted would be that required to enhance the transparency of the teleoperator system. This might entail kinesthetic feedback and the interface might be integrated.

The reader is referred to the extensive treatment of teleoperation by Vertut and Coiffet (5) and by Sheridan (7) for a more thorough discussion of teleoperators and their classification.

TELEOPERATOR BACKGROUND

Telerobotics is an amalgamation of the more mature technologies of robotics and telemanipulation. A brief description of the origins of telemanipulation is given in this section followed by a description of representative applications of telemanipulation and telerobotics. The last section of this article contains a discussion of the potential applications and challenges of telerobotics. Robotic technology is reviewed in another article.

Origins of Telemanipulation

The early development of teleoperators evolved from the need to handle radioactive materials during the early years of the Cold War. The first master-slave manipulator developed in 1948 by Raymond Goertz at the Argonne National Laboratory was bilateral since it was mechanically coupled; all forces felt at the slave side were transmitted back to the master and the operator. Additional development by Goertz continued with the demonstration of an electric servo-controlled telemanipulator in 1954 [Goertz and Thompson (8)]. The nuclear industry has continued to refine bilateral control technology, one of the principle researchers in teleoperation being J. Vertut at the French nuclear agency, Commissariat a L'Energie Atomique (CEA) (5). Additional development has occurred at the U.S. Department of Energy's Sandia National Laboratory (9) and Oak Ridge National Laboratory (10) in both electromechanical and hydraulic systems.

Another area that created impetus for teleoperations came from the need to perform deep-water salvage and recovery operations by means that were less costly and less risky to human life. The U.S. Naval Ocean Systems Center developed the CURV (cable-controlled underwater research vehicle), which has a cable-controlled manipulator (11). The CURV was used in 1966 to recover a nuclear bomb that was accidently dropped from an aircraft. Additional applications have emerged in the commercial area of oil extraction and the scientific area of undersea exploration.

A third application that was an early driver for teleoperators was unmanned space exploration. In 1967, NASA's Surveyor III equipped with manipulator arms landed on the moon and took soil samples (11). The Soviet Union followed with a direct unilateral teleoperator system called the Lunakod (5). This was the first display of the drawbacks in using a teleoperator with significant time delays in information transfer between the master and the slave. As a result, the Draper Laboratory of the Massachusetts Institute of Technology, working under NASA direction, began investigating manual teleoperation assisted by computer control (a predecessor of shared control). The current NASA telerobotic effort is directed by the Space Telerobotics Program in the Office of Space Science.

Needs of these "unstructured" applications continue to advance the technology of telerobotics along with more recently identified applications in unmanned aircraft and telesurgery.

Recent Teleoperator Applications

Space Shuttle Remote Manipulator. The US Space Shuttle's Remote Manipulator System, built by Spar Space Systems, is a six degree-of-freedom *unilateral telemanipulator.* The motorized (electric) slave is a 20 m arm mounted in the service bay of the shuttle and controlled from the cabin of the shuttle. The operator views operation either on a monitor or directly through a window into the shuttle bay. He or she applies commands to the manipulator using two three-degree-of-freedom joysticks, one for translation of the end-effector and one for its rotation. The commands are converted to joint commands using resolved rate motion control as described in a section that follows (12).

Sarcos Dexterous Teleoperation System. An example of an *anthropomorphic bilateral telemanipulator* is the Sarcos Dexterous Teleoperation System. It is a research tool that consists of an exoskeleton arm worn by the operator and a slave arm identical in size and kinematic structure. It has bilateral control with both joint torque and position signals passed between each pair of master and slave joints so that various forms of coupling can be implemented. A computer in the communication link permits gravity compensation commands to be calculated and applied so that the operator does not feel the weight of the device. The Sarcos Dexterous Arm System can also be configured as a two-arm system (13).

Next Generation Munitions Handler. Another recent application of telemanipulation is the Next Generation Munitions Handler developed as an advanced technology demonstrator for the Air Force and Navy by Oak Ridge National Laboratory to load munitions and fuel pods on aircraft. This is a *bilateral shared control* device in which the operator commands position of the munition and the robot superimposes a corrective action sometimes referred to as *active compliance,* to prevent wedging and jamming of the insertion objects. The handler is a seven degree-of-freedom force-amplifying hydraulic manipulator mounted on an omnidirectional platform. It is therefore *kinematically redundant,* meaning that is has more joint degrees of freedom than are required to accomplish the task. The additional degrees of freedom give the arm the capability to avoid obstacles while simultaneously accomplishing the operator's command (14).

Predator Uncrewed Aerial Vehicle. An uncrewed aerial vehicle with an autopilot is an example of a telerobot in which the "pilot" can function in any of the three control modes: *supervisory, traded, or shared.* An autopilot, in full implementation, is a nested series of control loops that, from the inside out, provides (1) improved vehicle stabilization, (2) trajectory determination, and (3) navigation (15). The operator observes the aircraft flight condition on a monitor that presents an "out-the-window" view and cockpit instrumentation data from an onboard camera and onboard sensors, respectively. He or she issues symbolic commands with a keyboard and manual commands with a joystick and throttle lever. The operator is able to engage the autopilot and have hands off the stick; turn the autopilot off and control the vehicle manually with the stick); or operate in a shared mode in which the operator provides commands to supplement the autopilot. The Predator is an unmanned aerial vehicle currently used for surveillance by the US Air Force that operates in a manner similar to this (16).

Sojourner. The Sojourner rover is a battery-powered, six-wheeled vehicle that explored the Mars surface for four weeks in 1997. It operated in a *supervisory control* mode with the operator providing task commands in the form of a sequence of way points according to which the vehicle was to navigate. An onboard computer gave the rover autonomous capability to follow the path defined by the way points and make adjustments for hazard avoidance (17).

Telesurgery. A medical application of *supervisory* telerobotics was the surgery performed on a pig in Los Angeles by a doctor in Milan, Italy in 1993. The operation consisted of locating a cyst and performing a biopsy by penetrating the cyst with a needle. This operation was performed unilaterally, with commands issued by keyboard entry and a two-dimensional mouse that pointed to locations on images projected onto a monitor at the master site from inside the abdomen. Graphical presentation of contact forces was also provided on a monitor to the doctor. Time delay between command and receipt of video acknowledgment was 1.9 (18).

ROBOT AND TELEOPERATOR CONTROL ARCHITECTURES

This section presents some of the fundamental control architectures appropriate for telerobotic systems. The section includes a description of the relevant control technology for robotics and telemanipulation, followed by discussion of supervisory control architectures used for telerobotics. The reader is referred to other articles on robots, intelligent control, and virtual reality for additional details on other aspects of telerobot technology.

There are three basic control architectures for a slave that must be able to function autonomously in a telerobotic systems:

- Joint control
- Task-resolved control
- Object-resolved control

Joint- and task-resolved control is generally associated with control of a single manipulator such that its end effector moves or applies force in a prescribed manner to accomplish a task. Object-based control is generally associated with a task in which two or more slave manipulators (fingers) grasp and manipulate an object. Figure 2 illustrates these two types of manipulation tasks. Task- and object-based control can also be applied to vehicle motion control.

Joint control is most applicable when the master and slave are identical and hence is typically associated with an anthropomorphic teleoperator system. Control data flowing between the master and slave are joint commands. Because the master

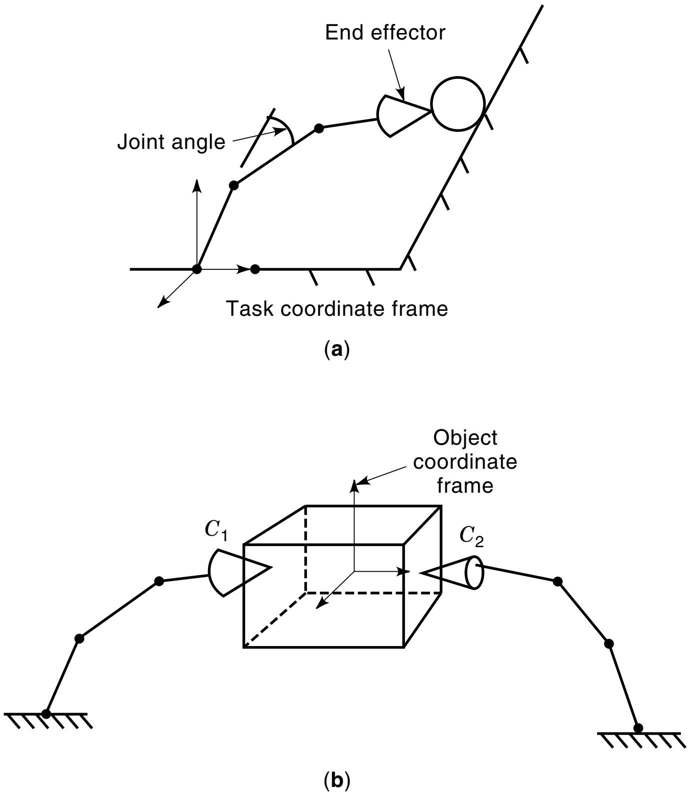


Figure 2. Two types of tasks: (a) single-arm manipulation; (b) grasp and manipulation.

and slave are similar, master-generated joint commands can be transmitted to the slave and used without further processing and hence can be accomplished with minimal computational capability at the slave site. For bilateral operation, this computational advantage also exists at the master site. Joint control, which is simpler but less prevalent, is not addressed in this article.

Task-resolved control is generally associated with a hand-held master device and a slave that need be neither anthropomorphic nor even configured similar to the master. To control the joints of the slave of such a system, commands generated by the hand-held device are telecommunicated as task frame components and must be transformed into joint commands when received at the master or slave site. Controllers that perform this transformation task are called *task-resolved controllers or work-space controllers* (19). For (autonomous) robots, task-resolved control is preferred simply because it is the most convenient frame for issuing commands. Because the manual and autonomous control commands must be traded or shared in telerobotic applications, task-resolved control is a particularly appropriate choice.

Task control will be introduced and applied to a telerobotic system before further introduction of object-resolved control.

Robot Task-Resolved Control

In the following two sections, we describe two basic task-space control architectures that are useful in telerobotics: (1) Cartesian position control for tasks in which the task involves unobstructed motion of the end effector and (2) Cartesian compliant control for tasks in which the end effector makes forceful contact with the environment. The controller for the former uses feedback of position measurements, whereas the latter also may use feedback of force measurement. To be fully functional and take advantage of the human's capability to handle unstructured tasks, a telerobotic system should be able to perform both noncontact and contact tasks and the transition between them.

Cartesian Position Control. The nonlinear forward kinematic relation between manipulator joint variables and position of the end effector in task space can be written

$$r = g(q) \tag{1}$$

where r is a six-component vector that describes the position and orientation of the end effector (hereinafter referred to only as position), g is a nonlinear function, and q is the vector of joint variables. Then, a Jacobian defined by $J = \partial g/\partial q$ can be determined that relates task-space velocities $\dot{r}$ to joint-space velocities $\dot{q}$ [full development of the Jacobian equations can be found in most robotics texts, (1, 20)]:

$$\dot{r} = J\dot{q} \tag{2}$$

In general, the dimension of J is $6 \times n$ where n is the number of joints in the manipulator. In general $n \neq 6$ so that in order to solve for $\dot{q}$ it is necessary to use the pseudoinverse

$$\dot{q} = J^{\#}\dot{r} \tag{3}$$

where $J^{\#}$ is the Moore–Penrose generalized inverse, more frequently called the pseudoinverse (21).

Cartesian position control, developed by Whitney and called resolved motion rate control (22), is based on the control law

$$u \doteq \dot{r}^{\mathrm{c}} = \dot{r}^{\mathrm{d}} + G(r^{\mathrm{d}} - r) \tag{4}$$

where G is a gain matrix associated with position error, and superscripts c and d denote the commanded and desired values of that variable, respectively.

When Eq. (4) is inserted into Eq. (3), we obtain

$$\dot{q}^{\mathrm{c}} = J^{\#}(\dot{r}^{\mathrm{d}} + G(\Delta r)) \tag{5}$$

where $\Delta r = r^{\mathrm{d}} - r$ and the superscript c has been added to the joint velocity to indicate that this is a command. Figure 3 depicts how this control law is implemented.

The block labeled "Manipulator" in Fig. 3 is the device under control. The input to the manipulator block is commanded torque τ^{c}, which is made proportional to $\dot{q}^{\mathrm{c}}$ by the gain matrix, K_{p}. The output shown in Fig. 3 is joint position q and velocity $\dot{q}$. The output is obtained from the endcoders on each joint, which are necessary for control of the manipulator.

The controller input is the desired position and velocity in task space. Task-resolved response that is fed back must be calculated from the measured joint output by using the forward kinematic equation (1). Alternatively, a camera fixed in the task frame could provide r directly but with less accuracy.

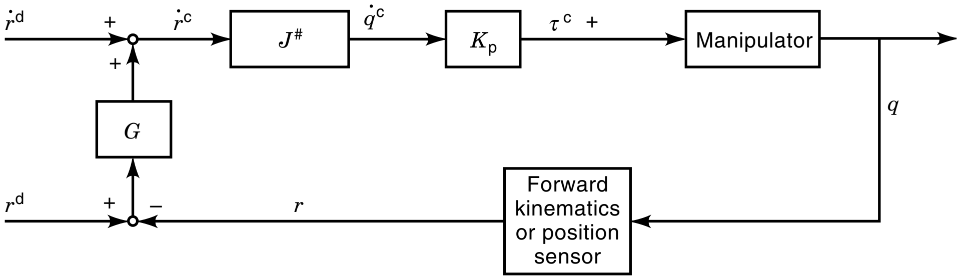


Figure 3. Block diagram illustration of resolved-motion rate control.

Joint commands for the manipulator are obtained by transforming the task-space commands with the pseudoinverse matrix $J^\#$. There are arm configurations for which the Jacobian becomes singular, which means physically that there are directions in which the end effector cannot be moved. If these configurations are within the workspace of the manipulator, the pseudoinverse and the singularity robust inverse are mathematical algorithms that can reduce the control difficulties by issuing only physically realizable commands. The pseudoinverse also is useful for formulating realtime strategy for use of redundancy in a manipulator with more joint degrees of freedom than the degrees of freedom in the task ($n > m$) (23). The comments of this paragraph also apply to each of the task-space-compliant control architectures that follow and are a concern when they are applied to teleoperation where the orientation of the manipulator may not be as easily monitored.

The gain matrix G_r is located such that the controller can be tuned in task space where the relative size of the elements can be selected more intuitively. Also note that the task-space velocity can be omitted from Eq. (4) without serious degradation in performance of the controller.

The degree of computation required to implement the controller of Fig. 3 generally necessitates the use of a microprocessor or computer. In the view of some, the use of a computer constitutes intelligent control.

Cartesian Compliant Control. The resolved-motion rate control technique described in the previous section has application in control of end-point motion. When the end point must contact the environment or oppose another end point in squeezing an object, these control techniques are not adequate. Figure 4 is a block diagram that illustrates a manipulator in contact with the environment that is controlled by resolved-motion rate control described in the previous section. The stiffness of the environment is denoted by a linear spring with stiffness K_e that is undeflected when r is at or less than equilibrium position r_e. When $r > r_e$, the end point is in contact with the environment and a reactive force $f_e = K_e\,(r - r_e)$ is produced. The equivalent reactive torque applied to the joints of the manipulator is obtained by multiplying f_e by J^T, the transpose of Jacobian J. Depending on the relative levels of environment stiffness K_e and device stiffness, the latter determined by gain G_r, a device will either perform satisfactorily or unsatisfactorily. However, the gain will need to be reduced considerably to attain stability when in contact and hence position error will be greater during noncontact operation.

This controller senses and feeds back position. It does not sense force. Hence, it cannot be said to be explicitly controlling force while in contact. On the other hand, the response to a change in desired input position is not a proportional change in output position. It is said to be controlling stiffness. Hence, this response is also known as *stiffness control* (1) and *implicit force control* (24).

Control techniques specifically designed to accomplish endpoint contact are classified as *compliant control techniques.*

Force Control. Following the preceding process for the implicit controller, a diagram as shown in Fig. 5 results. As with stiffness control, there is a feedback of the reactive force f_e to the plant as a result of contact with the environment. A sensor in the load path measures this force for feedback to the summing node of the controller. If contact is lost while in explicit force control, the force feedback signal as well as the reactive force feedback is lost and the system responds to input commands in open loop fashion. Thus, while explicit force

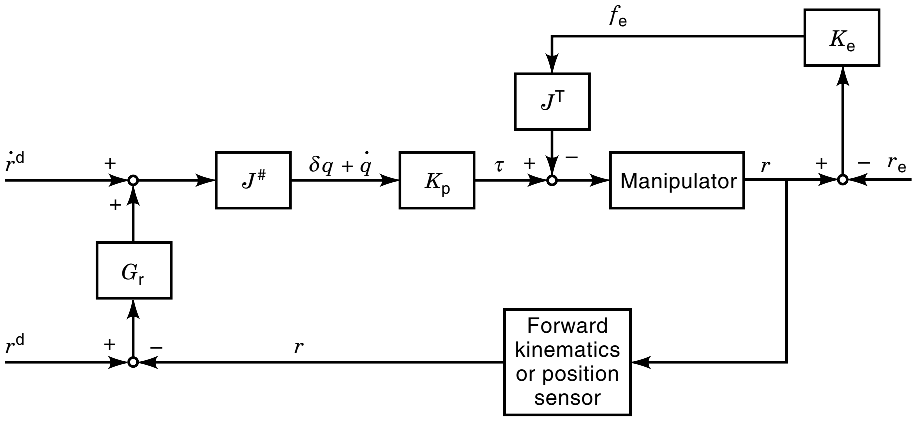


Figure 4. Block diagram illustration of contact with the environment under resolved-motion rate control.

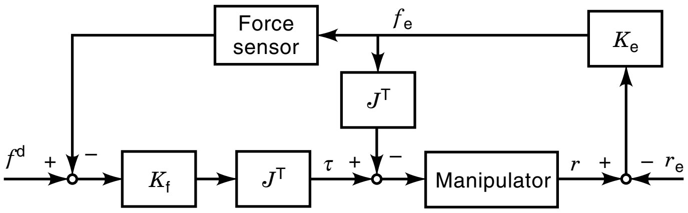


Figure 5. Block diagram illustration of force control (after Ref. 24).

control provides better control of force than does stiffness control, it is undesirable for tasks with intermittent contact.

Impedance Control. Impedance control is defined in the seminal writings of Hogan (25–27), which describe control of the relationship between force and velocity. It is a blend of position and force control and requires measurement of both position and force as indicated in Fig. 6. Note that force is measured and is fed back because it is part of the control law. Impedance control has the virtue of transitioning well from free-space motion to environmental contact with little control difficulty. Just as it is possible to find an acceptable set of gains for a position controller to operate well over a broad range of free-space speeds, it is possible to find a single set of gains (impedance level) that will permit an impedance controller to operate over a wide range of free-space motions and contact conditions (approach speeds, levels of environmental stiffnesses, etc.). The stiffness controller, which does not measure contact force, would have far less a range of stable operation at a single gain setting. The drawback of an impedance controller is that neither force or position is being explicitly controlled during contact, and gain settings G will be low compared with the gain settings of Cartesian position control so that precision in following desired position commands in free space is low. And in contact, the force level will not be directly proportional to the desired input signal, but rather proportional to the impedance setting.

Hybrid Control. Hybrid control is a combination of Cartesian position and compliant controllers applied to a single manipulator to control orthogonal subspaces of task space (28). Figure 7 shows a hybrid controller that consists of a resolved-motion rate controller and a force controller. The parallel paths to the summing junction that creates the error signal are made to operate on orthogonal subspaces by the diagonal matrices S and I-S, where the elements of S are a set of bipolar switches (0 or 1) whose setting can be altered in real time and I is an identity matrix. Usage in robot control is for such tasks as erasing a board where the task subspace parallel to the board is best controlled in position and the subspace normal to the board is best controlled in force. The hybrid controller could also be configured with either or both of the two orthogonal subspaces controlled by other architectures discussed before.

Telemanipulator Control

In this section, we present some of the Cartesian control architectures that have been used to implement unilateral and bilateral telemanipulation (plus one bilateral joint control architecture) and define transparency for bilateral operation. For ease of presentation, assume that the master in all examples in this section is a handle (hand interface) attached to the last link of an articulated arm with 6 degrees of freedom (3 orthogonal rectilinear and 3 orthogonal rotation motions) such as the PerForce (PerForce is a trademark of Cybernet Systems Corporation, Ann Arbor, MI) master (29), which can be operated either unilaterally or bilaterally. Assume that sensors measure joint position and that these can be issued as commands to the slave site or used to calculate task-space commands (rectilinear position and angular orientation of the handle) using the forward kinematics of the arm. Furthermore, assume there is a vision system in place at the slave site that is inertially fixed for manipulators and attached to the slave end effector if it is a vehicle.

Unilateral Control.

Cartesian unilateral telemanipulators are implemented in a straightforward fashion by simply sending the vector of master signals to the input of any of position or compliant robot controllers identified in the previous section, excluding the hybrid controller.

Position Control. If a master command is sent to the desired position input of Fig. 3 with no desired rate input, then the slave responds with a proportional master displacement, the proportionality constant being a function of the gain

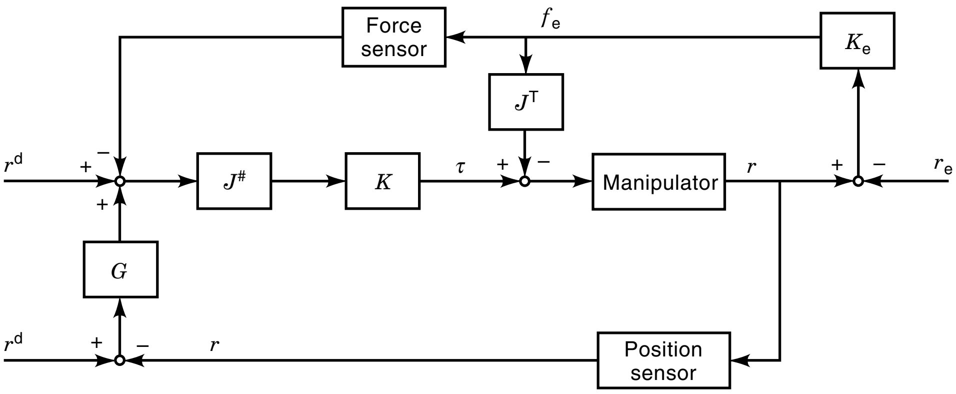


Figure 6. Block diagram illustration of impedance control.

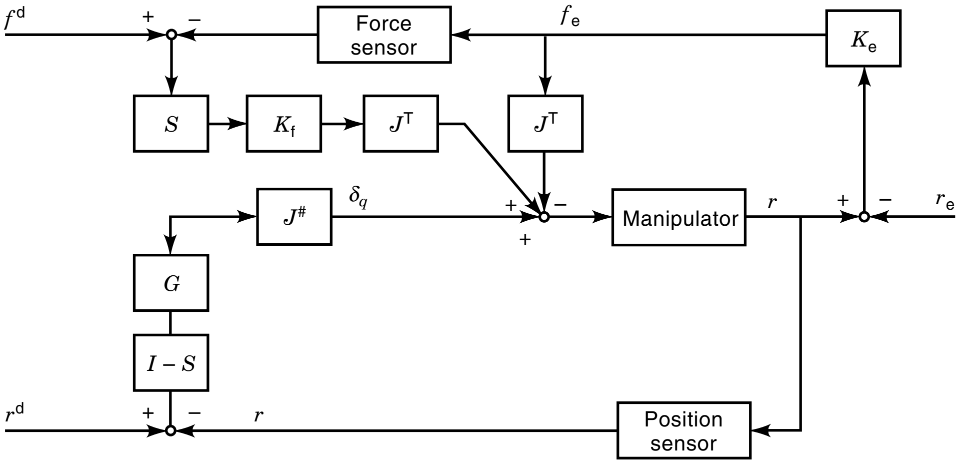


Figure 7. Block diagram illustration of hybrid control (after Ref. 24).

placed on the command signal. This architecture is suitable for tasks in which the slave movement is free (i.e., no environmental contact). The shuttle remote manipulator is controlled in this manner by two three-axis joysticks, one for position and one for orientation.

Rate Control. If Fig. 3 is altered such that r^d becomes $\dot{r}^d$, r becomes $\dot{r}$, and $\dot{r}^d$ is omitted (i.e., velocity is measured and fed back so that the control loop creates an error in velocity), then the slave responds with a speed proportional to master displacement. When the master is held at a constant displacement away from neutral, the output is constant speed. When the master returns to the neutral position, the slave stops. This architecture is suitable for vehicle control.

Force and Impedance Control. If the master command is sent to the desired force input of the force control of Fig. 5 and the slave is in contact with the environment, then the slave force will be proportional to master displacement. If it is sent to the desired position input of Fig. 4 or 6 (with the slave in contact with the environment), it will produce a slave force but not proportional to master displacement (see the discussion in the section entitled "Impedance Control").

Each of these three controllers can also be implemented with a master that has displacement limited to material strain such as the SpaceBall (SpaceBall is a trademark of CIS Graphics, Westford, MA) (30). The operator would then relate force applied to the master to slave response.

Bilateral Control. Three bilateral control strategies will be discussed in this section:

1. Position difference
2. Forward flow
3. Bilateral impedance control

The first is appropriate for joint-to-joint control. The last two are applicable for hand-held masters that issue task-space commands.

Position-Difference Control. To describe position-difference control, consider Fig. 8 as presented by Handlykken and Turner (31). Input from the operator is the master hand force f_m. The output is the slave position X_s. The slave reaction force f_s is measured and transmitted from the slave to the master. $H_m(s)/s$ is the model of the master and $H_s(s)/s$ is the model of the slave. The predominate feature is that master and slave velocities V_m and V_s and position X_m and X_s, respectively, are subtracted from each other and those signals become error terms that the master and slave control loops attempt to drive to zero. The loops are identical when the master and slave are identical so they are "slaved" to have identical motion.

This is a simple single-axis model that ignores any cross coupling between axes and only considers the mass properties of the devices. Omitted are the computations necessary to

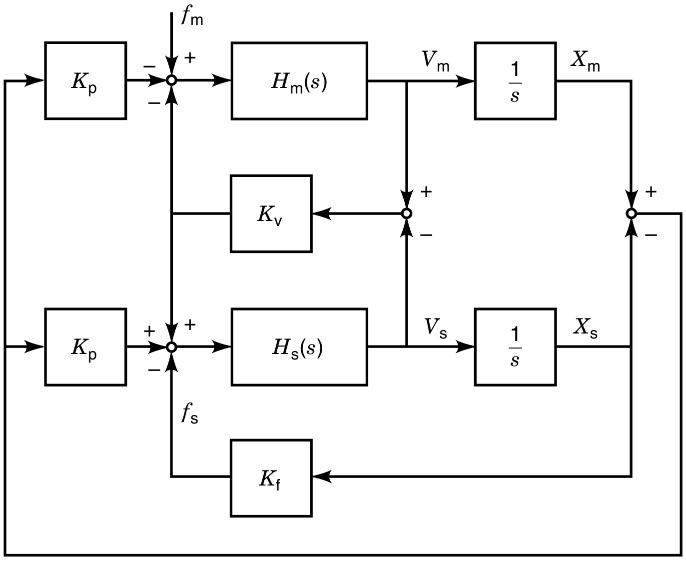


Figure 8. Block diagram illustration of a single-axis position-difference control (after Ref. 31).

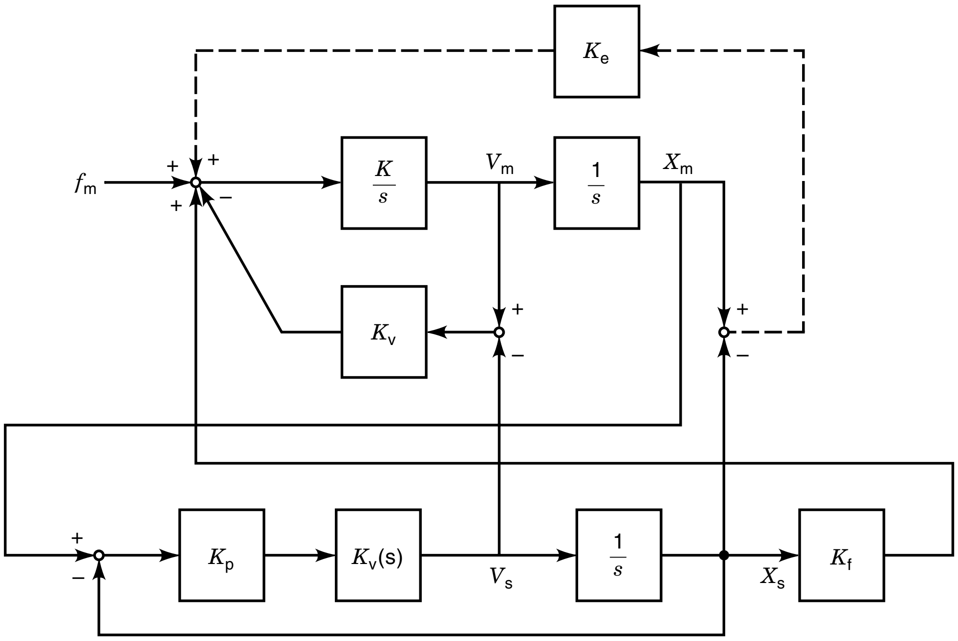


Figure 9. Block diagram illustration of single-axis forward flow control (after Ref. 31).

convert task-space commands to joint-space commands. All K symbols signify gains. These comments apply, as well, to Figs. 9 and 11, which follow.

Forward Flow Control. Figure 9 shows a version of forward flow referred to by Handlykken and Turner (31) as the single-axis force reflecting hand controller (FRHC). The master is configured as in the position-difference system, and there is velocity-difference feedback as in the position-difference system. The predominant difference is that the master feeds its position (not the position difference) forward to the slave and the slave feeds force back to the master. There may also be position difference fed back to the master but this is optional. The advantage of this form of signal communication is that the master and slave need not be identical.

Figure 10 shows the FRHC for six-axis control. There are three feedback loops to the master as for the single-axis case: velocity, position error, and force. Note these are in task-frame components and must be converted to joint values, the FRHC and the slave. Kinematic and instantaneous kinematic relations for the master and slave devices given by Equations (1) and (2), respectively, and their inverses are used to accomplish this conversion. This is what permits the master and slave to differ kinematically.

Bilateral Impedance Control. Figure 11 shows a bilateral impedance control architecture developed by Moore and Kazerooni (32). This block diagram includes models of the human and the environment that were not included in the previous two architectures and are not described further herein. The human applies a force f_m to the master, which the master converts to a signal command. Likewise, the environment applies a force f_s (the reactionary force f_e of previous block diagrams). The distinctive feature of this architecture is that these signals go to an admittance matrix H, which produces position outputs for the slave and master.

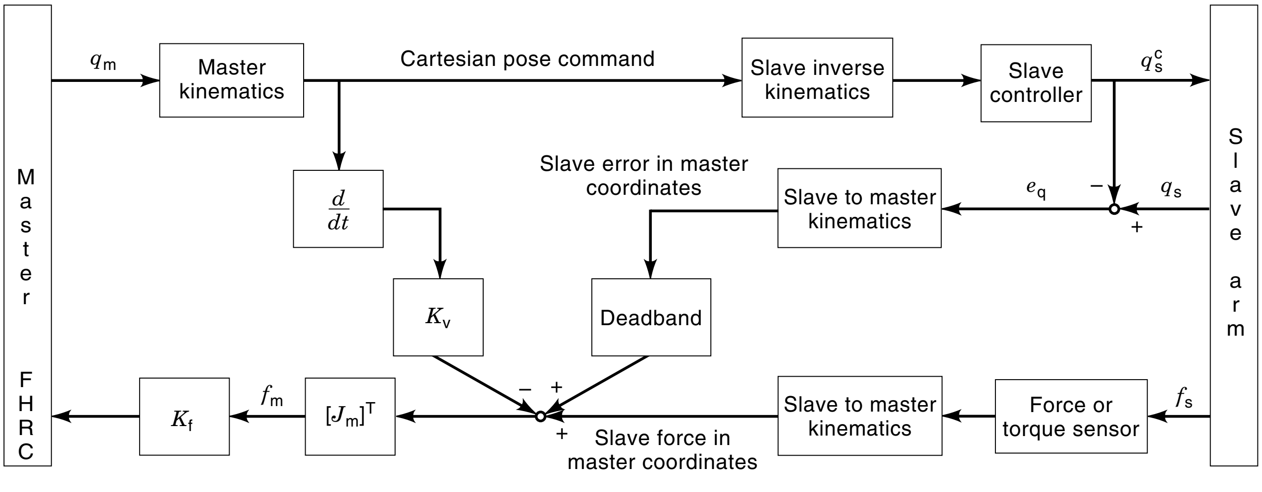


Figure 10. Block diagram illustration of six-axis forward flow control (after Ref. 31).

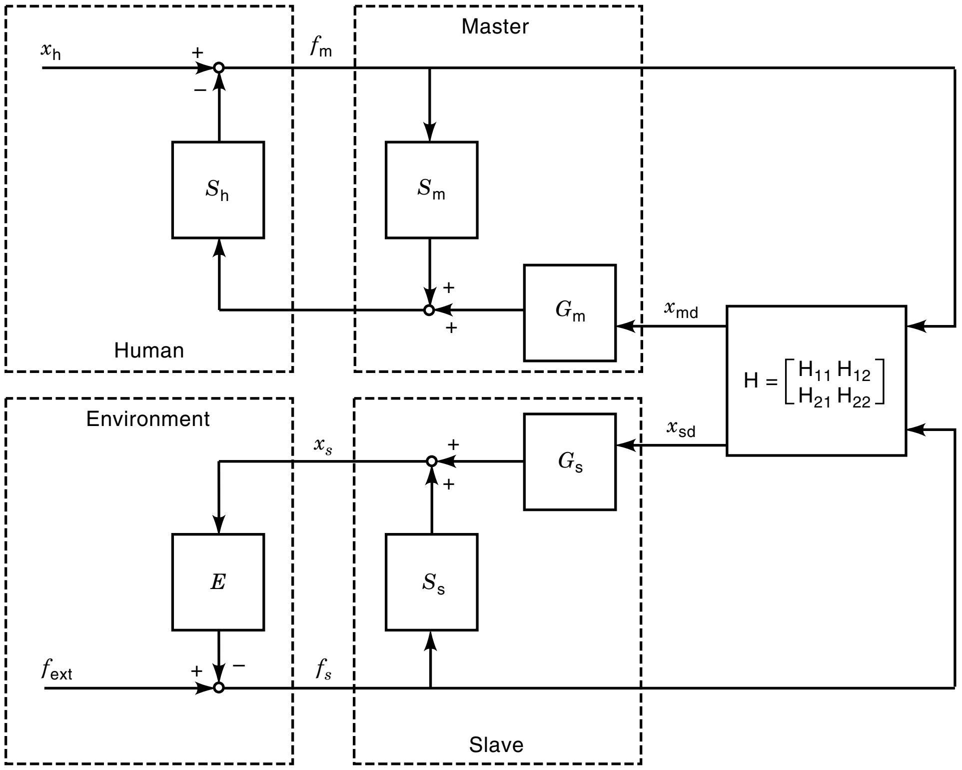


Figure 11. Block diagram illustration of bilateral impedance control (after Ref. 32).

When the master sensitivity of position to force, S_m, is small, there is not much motion out of the master; that is, the operator finds it difficult to move the master. By adding the component $H_{11}f_m$, the impedance of the master is reduced so that the operator can more easily move it. One can also say the sensitivity of the master is increased. Likewise, H_{22} supplements S_s to increase the sensitivity of the slave to the reactionary force. The off-diagonal terms of H couple the master and slave: H_{12} provides force reflection to the master; H_{21} provides force to drive the slave. This is called bilateral impedance control (BIC) because it establishes a relation between position and force at each end of the telerobotic system.

A feature of BIC is that one can readily adapt the teleoperator system to various kinds of requirements. The most quoted desire is to have the system be "transparent," that is, to feel as if the operator is directly manipulating the slave with no master present. Sometimes it may be desirable to have the master not feel a vibration that is coming from the slave if, for example, the slave is a jackhammer. Or it may be desirable to have the master be insensitive to the inertia effects of a massive slave that is being used for a precise tracking task. And there is sometimes the need to scale force and/or velocity (or position). All of these are readily accomplished with BIC.

Two-Port Model of Bilateral Telemanipulator Systems. Two-port modeling techniques (33) can be used to represent bilateral telemanipulator systems. Figure 12 shows the basic structure of the two-port network model in which, for illustration, the human and the environment are each modeled as a velocity source (V_H and V_E, respectively) in series with an impedance (Z_H and Z_E, respectively). The block labeled "Teleoperator system" can include models of the master, communications link, and slave, either lumped into one block or as individual blocks connected serially. The variables that connect blocks are variously known as flow and effort variables, whose product is power exerted if the connection represented is mechanical, or power proportionate variables if the connection represented is signal variables. This two-port model can be used to quantify the level of fidelity that a bilateral system possesses and to examine the effects of time delay on stability and performance.

Transparency. An ideal teleoperator can be defined as one that will transmit the desired velocity commands of the operator to the environment and the forces felt at the environment to the operator in a manner that duplicates direct control. Consider a two-port hybrid model that has the master velocity command and the environmental force sensed at the slave. The dependent variables are the force fed back to the human (kinesthetic feedback) and the velocity command to the slave. The two-port equations can be written using the hybrid parameter set $h_{i,j}$ as (34)

$$\begin{Bmatrix} v_s \\ f_m \end{Bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{Bmatrix} f_s \\ v_m \end{Bmatrix} \tag{6}$$

where v_s and f_s are the velocity and force at the slave interface, and v_m and f_m are the velocity and force at the master interface. The hybrid matrix elements represent

$$H = \begin{bmatrix} Z_{\text{in}} & \textit{Reverse force scaling} \\ \textit{Velocity scaling} & 1/Z_{\text{out}} \end{bmatrix} \tag{7}$$

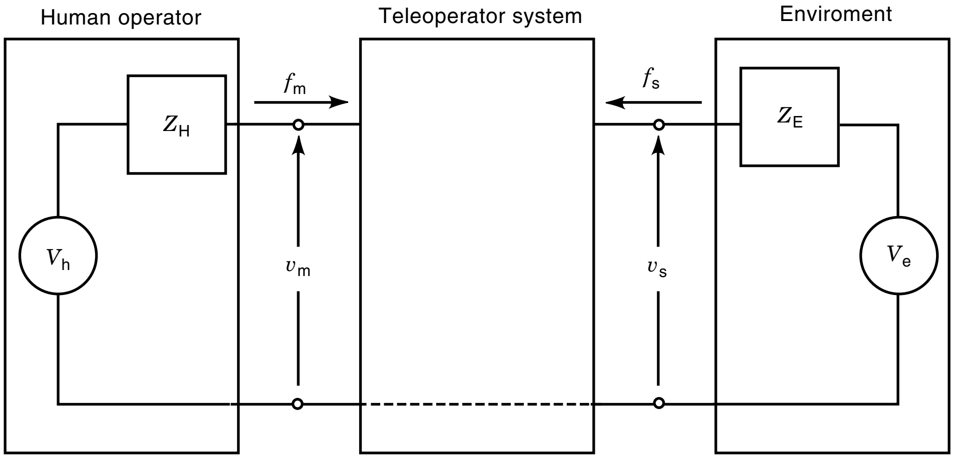


Figure 12. Two-port network model of a single-axis telemanipulator system (after Ref. 34).

where Z_{in} is the impedance looking into the master side of teleoperator system with no force applied by the slave and Z_{out} is the impedance looking into the slave side of the teleoperator system with no motion of the master. Using this notation, the ideal teleoperator would have zero impedance looking into the master, infinite impedance looking into the slave, and unity scaling for force and velocity. In other words,

$$H = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \tag{8}$$

Ref. 34 also contains a two-port representation of the 6 degree-of-freedom FHRC of Fig. 10.

Since the hybrid elements are affected by the dynamics of the master and slave, it is not possible to select the hybrid parameters of Eq. (6) arbitrarily. Lawrence (35) has shown that it is necessary to have both force and velocity pass in both directions in order to realize transparency practically, making a four-port connection as indicated in Fig. 13. The Sarcos Dextrous Teleoperation System has this form of master–slave communication for each joint pair.

Time Delay. When there is time delay in the transmission line, teleoperator hardware that is otherwise stable, can exhibit instability. This was demonstrated by Anderson and Spong (36) using two-port theory. They showed that the norm of a scattering matrix S, defined in terms of the hybrid matrix H,

$$S(s) = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} [H(s) - I][H(s) + I]^{-1} \tag{9}$$

could be used to predict stability, where I is the identity matrix. If the norm of the scattering matrix S is less than (or equal to) one, then the system exhibits passivity, that is, it dissipates (or conserves) energy, and it is well known that a passive system is stable. For a bilateral teleoperator system that exhibits stability for no time delay and instability when time delay was present, Anderson and Spong developed an alternative control strategy that ensures stability for the time-delayed case.

Telerobot Control

Note in each of the unilateral and bilateral architectures, the slave stops when the human operator stops giving commands. This is a characteristic of telemanipulators. In the next section we discuss telerobotic control architectures for which slave motion can proceed with operator supervision.

The control architectures that have been applied to telerobots have not at all matured. Presented below are illustrative architectures for the three telerobotic architectures: traded control, shared control and supervised control.

Traded Control. A slave controller that

1. Applies task-resolved control as described in the previous section on robotic controllers
2. Applies one of the telemanipulator architectures described before in the section on telemanipulator control
3. Can be *switched* to accept input from either an operator or a command generator at the slave site

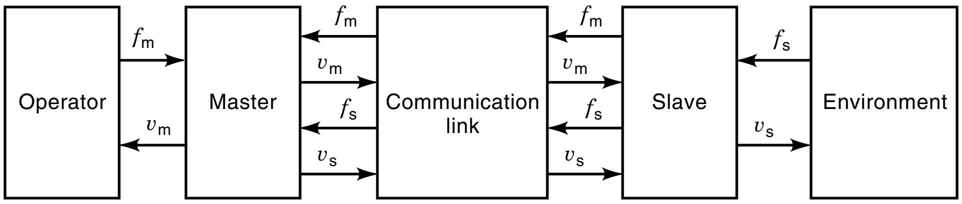


Figure 13. Block diagram of a general teleoperator control architecture (single axis).

qualifies as a traded controller when the most general definition of telerobotics above is applied. The slave controller can be given increased levels of autonomy beyond task-resolved control, as will be discussed in the next section.

Shared Control. The three basic methods of accomplishing a remote task, namely by telemanipulation, telerobotics, and robotics, are not entirely complementary, since a telemanipulator and an autonomous robot represent the extreme limits of functionality of a telerobot. A shared control architecture was developed by Hayati and Venkataraman (37) that weights the input of the human and computer based on the task requirements, such as whether there is contact or free motion. The architecture includes the capability to have a telerobot behave both as a telemanipulator and as an autonomous robot, that is, it can exhibit traded control capability as well. A similar form of shared control, called *functional* shared control by Tarn et al. (38), attempts to parse the task or tasks on a functional basis using event-based planning. They have demonstrated application in hybrid force–position tasks, coordinated motion, and obstacle avoidance.

Grasp and Manipulation. The grasp and manipulation task can be divided on a basis other than orthogonality of task subspaces. Figure 2(b) depicts a block held by two three-jointed fingers or arms. Consider the object to be a single rigid body whose motion or force of interaction with the environment is to be controlled. The equations of motion are

$$I_0\ddot{\phi} + Q_0 = WF + F_{\text{ext}} \tag{10}$$

where I_0 is the inertia tensor of the object, $\ddot{\phi}$ is the linear and angular acceleration of the object with respect to the absolute coordinates, Q_0 is a force and moment vector that includes gravity and the nonlinear Euler equation inertia effects of centripetal and Coriolis acceleration, W is a grasp matrix that premultiplies to transform the contact forces and moments into equivalent forces and moments at the object center of mass, F is the vector of forces and moments applied to the object by each manipulation device or actuation device, and F_{ext} is the resultant force and moment applied at the object center of mass as a result of object contact with the environment. The mathematics of the grasp problem is well developed in the texts of Nakamura (23) and Murray, Li, and Sastry (19).

The finger actuation must be controlled in such a way as to accomplish (1) regulation of the force applied by the fingers such that the fingertip contact with the object maintains the desired kinematic structure (i.e., the object is not dropped), and (2) manipulation of the object in a desired fashion. Figure 14 presents a telerobotic control architecture that can accomplish these objectives based on the object control architecture proposed by Nakamura (23).

This architecture permits separate control laws to be formulated for the object and each device that manipulates the object. The manipulation aspect of the task is assigned to the operator and the grasp stabilization task is assigned to the autonomous controller at the slave site. In the architecture illustrated here, the only variable necessary to communicate to the remote site is the desired positional state of the object. Inferred from the block diagram is feedback control based on error between desired and measured position of the object, $\phi^d - \phi$, where ϕ is defined in Eq. (10). The block labeled "Object control laws" issues commands $Q = WF$ required to move the object so as to accomplish the task. In turn, the block labeled "Contact force distribution" converts the object force Q into fingertip commands to accomplish grasp stabilization and manipulation. The stabilization task is generally regarded as too difficult and time critical to accomplish remotely. It is necessary for the fingers to create opposing forces (called internal forces) that are dependent on both time and task geometry (23). Algorithms that can compute in real time the forces required for both grasp stability and the commanded object motion have been developed (39,40). The blocks labeled "Task Resolution" perform a task comparable to the resolved motion control discussed before but has the added complication of determining force and velocity relations across the contacts between the object and each finger (19).

An application of object-resolved control that is suited to both shared and supervised teleoperation has been developed by Schneider and Cannon (41). An object-based control architecture that uses coarse and fine actuators in series has been postulated in Ref. (42).

Supervisory Control. One of the "more autonomous" systems in wide use is the commercial and military aircraft under the control of a navigation and guidance system (15,43). The autonomous system in its most general form consists of three nested feedback control systems, the automatic flight control system, the guidance system, and the navigation system, with functional capabilities as follows:

Automated Flight Control System. A flight computer and autopilot issue commands to the aerodynamic control surfaces and throttle of the aircraft based on input of steering commands from the guidance system, set-point values, and aerodynamic disturbances.

Stability Augmentation. Feedback control loops alter the stability derivatives of an aircraft to improve aircraft flying qualities. Pitch, yaw, and roll rate dampers increase the effective damping of the aircraft to disturbances from wind gust, crosswinds, and wind shear.

Control Augmentation. Feedback control loops assist the pilot so as to reduce his workload including attitude and altitude hold, speed control, heading control, sideslip suppression, and coordinated turn.

Structural Mode Control. Feedback control loops limit or redistribute aerodynamic load on the aircraft that results from a maneuver command; used on some military aircraft.

Guidance System. Algorithms convert navigation commands into automatic flight control commands.

Great Circle Steering. Open or closed control loop determines the instantaneous trajectory commands to cause an aircraft to follow a great circle path.

Navigation System. A computer and inertial measuring unit plus navigational aids that determine the position, velocity, and attitude of the aircraft and location of the destination relative to a reference coordinate system.

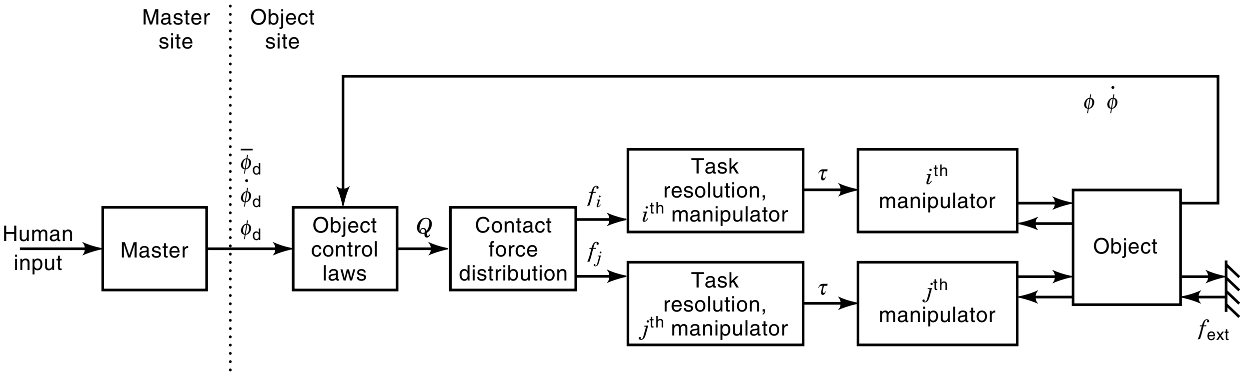


Figure 14. Adaptation of object control for shared manipulation.

En-route Navigation. Latitude and longitude of geographic way points are provided along the trajectory to the destination to which the aircraft is commanded to fly.

Terminal Navigation. Relative position is provided for guidance to a selected touchdown point.

In autonomous en-route operation, the navigation system is programmed with a series of way points that the aircraft is to fly over. At the way points new direction, speed, and altitude commands can be issued. This en-route navigation algorithm, in conjunction with automated terminal navigation, which will not be described further here, provides capability for an airborne aircraft to fly to any appropriately instrumented airfield in the world and land without pilot intervention. The capability is not typically provided to permit autonomous takeoff.

The pilot of a crewed aircraft performs many vehicle control-related actions during a typical flight including manual flight control during the transition between autopilot modes and for flight maneuvers for which no autopilot mode exists. The pilot also monitors the autopilot when it is activated and can intervene if any contingencies arise. The pilot has the option of turning the autopilot off (traded control) or sharing control such as leaving the stability augmentation on but turning off or supplementing a control augmentation capability.

In the section that follows, we describe two possible control architectures for an unmanned aerial vehicle as an illustration of a supervised telerobot whose autonomy is accomplished with current man-on-board autopilot technology. The supervised operation and operator backup (traded control) modes are described.

Uncrewed Aerial Vehicle. Not all of the autonomous capabilities listed previously for a crewed aircraft are necessarily appropriate for remote manual control due to reduced situational awareness resulting from (1) reduced visual information, (2) loss of "seat-of-the-pants" feel of vehicle dynamic response, and (3) time delay in obtaining flight data. Those that should probably remain autonomous are those of the inner loop, the automatic flight control system. For example, a coordinated turn would not be easily accomplished without feel of direction of the aircraft g vector. This also eliminates the need to duplicate the foot pedals for yaw control in the master. Most guidance and navigation functions are less time critical and are candidates for remote manual control. That the sum of all these modes provides enough functionality to fly an uncrewed aerial vehicle (UAV) autonomously has been demonstrated by the Predator vehicle described previously and by the Dark Star vehicle, which has flown fully autonomously, including autonomous takeoff.

One UAV control configuration is duplication, to the extent practical, of the conventional aircraft cockpit. This might include a stick and throttle interface; a flight manager, which consists of a keyboard for data entry and a display for readout of flight and vehicle characteristics; and an out-the-window view, obtained from a camera onboard the vehicle. The data flow as indicated in Fig. 1(b) would be present. In the supervisory mode, navigation commands as listed previously (i.e., way-point locations, speed altitude) would be issued by the operator through the flight manager keyboard and would be received by the autopilot and converted into commands to the vehicle's aerodynamic control surfaces and throttle.

All of the control, guidance, and navigation capabilities listed before must be achieved through control of the aerodynamic surfaces and throttle of the vehicle. Equation of motion (10) applies and a teleoperator control architecture of Fig. 15 can be applied to teleoperate the UAV, where the master input would be toggled between supervised and shared control. The engine and lifting surfaces replace the manipulators as the means of controlling motion. Using this representation, the ϕ variables that would be controlled are the vehicle forward velocity and the roll and pitch angles. The autopilot, whose role is comparable to the role of the manipulator controller in Fig. 14, is conventional in this configuration. Velocity and the roll and pitch angles would also be the variables communicated to the master site for shared control. In the shared mode, manual override would be used in which the operator uses the stick and throttle to issue commands that supplement those of the autopilot.

An alternative telerobotic configuration might include operator control of aircraft (x, y, z) position in the sense of next navigational way point instead of speed and attitude, both in the supervisory and shared modes. Figure 15 also applies to this configuration. However, the ϕ variables that would be communicated to the master site are the three components of

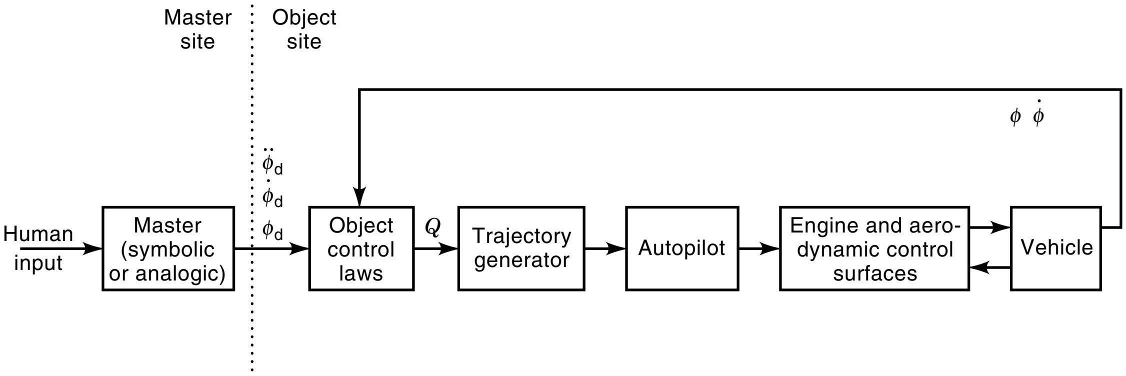


Figure 15. Adaptation of object control for the unmanned aerial vehicle application.

rectilinear position. From a flight control viewpoint, a new guidance algorithm is required to convert the position command into a realizable autopilot command. From the telerobotic viewpoint, the guidance or autopilot role is similar to that of the Jacobian pseudoinverse computation for resolved motion in Fig. 3. Namely, it must convert task-space position commands into aircraft actuation commands in a way that is realizable within the performance capabilities and constraints of the aircraft.

The relative merits of these two configurations will not be debated here. These two configurations are presented to illustrate that there are options and to be able to point out convincingly that selection between them and numerous other configurations would require evaluation of each system as a relatively complete prototype including the human-in-the-loop situation in order to make an informed selection. The most appropriate mix of manual and autonomous operation is an open issue for UAV control as it is for all telerobotic applications.

THE FUTURE OF TELEROBOTICS

Potential Applications

There are endless applications where telerobotic technologies could be utilized. Table 2 lists some of the potential applications in the fields that have been driving the development of technology. Industrial applications tend to have only cost as their principal payoff, which has caused that field not to be a significant contributor to or user of the technology. The primary driver is seen to be risk to human life and the most pervasive challenge is cost.

Telerobotic Challenges

There are many challenges to apply telerobotics effectively in the applications discussed previously. The most basic and significant issue is how to effectively parse responsibility between the operator and autonomous controller. Since both robotics and telemanipulation have evolved separately and each has focused on accomplishment of the entire task, there is little knowledge of how effective the combination of human and autonomous control can be (44). This is a very significant issue that will likely require significant time, effort, and funding. Furthermore, it is only possible to answer this question by exposing operators to the full range of configuration options in order to record their performance and preferences. While some human factor information can be obtained from tests with simulated manipulation hardware and partial systems, a controlled experiment can only be obtained with a telerobotic system configured with a range of autonomous capabilities.

Another crucial technology challenge is the level and form of transparency and situational awareness that is required for telerobotics to be most effective. One aspect is the degree of isomorphism that must exist between the master and slave stations. For teleoperation, the operator's internal model of the task is presumably formed in a coordinate frame at the slave site in which the camera that provides visual feedback is fixed. It would then seem appropriate from a human factor point of view that the frame in which master actuation is input by the operator be registered to the projection screen at the master site. This corresponds to the hypothetically perfect configuration posed by Sheridan (7) but is a human factor issue that has not been adequately addressed.

Another aspect of situational awareness that has not been evaluated is the form and fidelity of sensory feedback that is necessary for a given form of telerobotics. There have been studies that indicate that task success can be improved by enhancement of the visual representation presented to the operator (45). There have been studies that suggest kinesthetic feedback of force improves task performance if there is no time delay (34,46,47). There have been studies that suggest that time delay may degrade a task less if force reflection is provided via an audible representation rather than kinesthetically (4,7,48). Only recently has the capability to evaluate the full spectrum of feedback become practical by utilizing virtual reality as a research tool (49).

Another issue that needs to be addressed is the development and implementation of intelligent capability (i.e., increased autonomy) at the remote site. If this were not an issue, then it could be inferred that complete autonomy could be implemented and there would be no need for telerobotics. An underlying tenant of telerobotics is that it will hasten possible automation by not demanding full automation. There have been numerous demonstrations of "put that there," "go

Table 2. Payoff and Challenges for Potential Telerobotic Applications

Potential Application	Potential Payoff	Most Significant Challenges
	Medical	
Telemedicine	Greater medical availability; patient convenience; reduced health-care cost	Communication bandwidth; patient acceptance; video imaging technology
Remote surgery	Increased surgical precision	Patient acceptance; macro-micro manipulation technology; force reflection
Haptic-enhanced prosthetics and orthotics	Increased patient quality of life	Cost; bilateral capability
	Military	
Ordnance disposal	Reduced human risk	Cost; dexterity
Aircraft servicing	Reduced operating cost; reduced human exposure	Cost of maintenance
Base security	Increased vigilance; reduced human risk	Cost; threat susceptibility
Unmanned aerial vehicle	Reduced human risk; increased aircraft agility	Communication bandwidth; operator interface
	Space	
On-orbit servicing	Reduced EVA* (cost and risk reduction)	Mobility; reliability; manipulator base motion
Service payload robots	Reduced EVA (cost and risk reduction)	—
Exploration robotics	Reduced human risk; exploration beyond manned capability	Autonomy; communication bandwidth; power source; time delay
	Nuclear Power Plant	
Fuel rod replacement	Reduced human radiation exposure	Increased dexterity, reliability, and mobility
Accident cleanup	Reduced radiation exposure	Increased dexterity, reliability, mobility, and situational awareness
	Undersea	
Recovery and salvage	Reduced operating cost	Reliability; increased autonomy; improved communication; cost
Oil-well servicing	Reduced operating cost; reduced human risk	Reliability; cost; improved communication
Exploration	Reduced human risk	Dexterity; improved communication

*EVA = extravehicular activity.

there," and other forms of supervisory commands in which the slave device performs a nontrivial task upon command (41,50–54). A more significant hierarchy of intelligence in which the slave makes significant decisions about if and/or how to respond, such as the hierarchical grasp capability proposed in Ref. 19, has yet to be developed and demonstrated. In manipulation, the most significant limitation is the dexterity of the gripping device. This results from a lack of adequate sensing of the grasp forces and inability to build a mechanical device with the dexterity of the human hand. Even laboratory demonstrations of progress in this area have been limited, which is telling. The National Robotics Engineering Consortium, sponsored by NASA and administered by Carnegie-Mellon University, has been organized for the purpose of fostering commercial development of robotics and autonomous operations for unstructured applications (55).

While time delay in a bilateral system can be prevented from causing instability as discussed previously, it can still create a control problem for the operator. The simplest solution is "move and wait" but this directly affects the length of time required to complete the task. Time delay in any teleoperated system results from two principal sources: (1) transmission delays due to physical distance between the master and slave sites and (2) bandwidth capability of communication hardware. The latter is addressed by technology improvements that allow faster transmission rates and more data to be sent. There are alternative methods to increase transmission rates such as data compression and packaging. For communication links that require radio transmission, delay can be minimized by reducing the number of relays through which the signal must be sent. This is particularly significant for an application such as an unmanned aerial vehicle control, where relay of signals through a single satellite is preferable to transmission of the signal serially through multiple airborne and ground stations. Most telerobotic applications include feedback of imagery, which requires significant bandwidth. Video compression techniques and filtering techniques remove video data that the eye cannot see or filter. There is evidence that these video compression or data removal techniques can be utilized in telemedicine (56–58).

When transmission time delay is significant, a predictive model can be inserted into the coupling between the master and slave of a motorized teleoperator. Teleprogramming is a concept pioneered at the University of Pennsylvania (59), that predicts (at the master site) the consequence at the slave of a command issued by the operator the use of a predictive model of the slave at the master site to respond to the operator's inputs. Display data and kinesthetic feedback at the master site is the result of the interaction with the model, not the actual slave environment. Time delay during force interactions, which induces instability in the master–slave interaction, can be overcome with the teleprogramming method since force information is not transmitted between the master and the slave. The limitation of this approach is the ability to model the slave environment adequately. The challenge is to understand what data from the slave site is critical to the user of the predictive model. Critical data are likely to be task dependent.

One of the principal difficulties with obtaining improved bilateral control is time delay. When the vision and kinesthetic feedbacks are not synchronized, the operator's performance decreases significantly, even to the extent that it is less effective than unilateral operation. For telerobotics, to avoid time delay one can use autonomous control for task aspects that would require high bandwidth to be accomplished bilaterally by an operator (3). However, there may be tasks for which this option is not viable. Furthermore, kinesthetic feedback may prove useful as a means for maintaining situational awareness when the operator's visual and cognitive capabilities are occupied with other aspects of the task. One solution to this may be the use of audio representation of force feedback, which may prevent instability in systems with time delay and provide adequate situational awareness.

Finally, reduction in cost of telerobotic systems is perhaps the most needed accomplishment. For many of the potential applications cited in Table 2, cost is the most significant challenge. There has been some effort to standardize interfaces in telerobotics (60) and to modularize (9), both of which will promote cost reduction.

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CURTIS H. SPENNY
DEAN L. SCHNEIDER
The Air Force Institute of Technology
THOMAS E. DEETER
San Antonio-Air Logistics Center

TELETEXT

Teletext is a method of broadcasting data via a TV signal. In its most widespread form, it is a unidirectional system for transmitting textual information for display on the home TV receiver. The *pages* of text are selected by the viewer and displayed on the screen instead of the normal TV picture. Alternatively, text in *boxes* can be inserted into the TV picture for display as subtitles (captions). A wide range of information is available from most teletext services: news, weather, sports results, stock market prices, TV program schedules, program backup information, advertising, forthcoming events, travel information, leisure interests, etc. The service is free to the end user, being funded from revenue raised by carrying advertisements or directly by the TV broadcaster or other organization.

The teletext information provider, who may be part of the broadcasting organization or an independent company, collects together the information to prepare hundreds of teletext pages and assembles them into a database. After conversion to a suitable format for transmission, the data is added to unused lines in the TV signal and broadcast along with it. At the receiving end, the viewer has a TV set equipped with a teletext decoder. This decoder recovers the teletext signal, and according to the viewer's request entered via the remote control handset, stores the correct page and displays it on the screen.

Teletext transmissions are also used as a method of broadcasting commercial and professional data on a revenue earning basis. The information is acquired and subsequently processed by application–specific equipment.

Teletext was invented in the United Kingdom in the early 1970s. Later, other systems with different approaches were developed elsewhere (1). However, the original system, identified as system B in Ref. 1, has emerged as the dominant teletext standard. It is more generally known as *World System Teletext* (WST) and is referred to in this article simply as *teletext.* It has been very successful in some parts of the world, and well over 100 million teletext TV receivers are now in use. In Europe, teletext is a standard feature of most new TV sets, and almost all broadcasters provide a teletext service. Many variants have been produced to cater for different languages and alphabets such as Arabic, Greek, and Chinese. The most recent version of the European specification (2) defines enhancements for providing more colors and better graphics, backwards compatible with the existing teletext decoders.