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# TELEOPERATION, TELEROBOTICS AND TELEPRESENCE: A PROGRESS REPORT

**T.B. Sheridan**

*Man-Machine Systems Laboratory, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

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**Abstract:** This paper briefly surveys and reports progress in the field of *teleoperation*, meaning human control of remote sensors and actuators. Included is the subclass of teleoperation called *telerobotics*, which means human *supervisory* control of remote semiautomatic systems, and the phenomenon of *telepresence*, in which special sensing and display technology enables the human to feel present at the remote location even though not really there. Current and new applications are reviewed. Techniques for human-computer cooperation in planning, commanding, and sensing are described. The telerobot is considered as a paradigm for any complex vehicle or process having many separate automatic control loops all of which are supervised by a human; some current examples are presented. Finally, opinions are given as to the current status of the field.

**Keywords:** man-machine systems, telerobotics, robotics, manipulation, human factors, computer interfaces, artificial intelligence.

## 1. INTRODUCTION: DEFINITIONS AND TAXONOMY

A review of telerobotics by the author appeared in *Automatica* five years ago (Sheridan, 1989). The present paper is a short report of progress in the field since then, with the emphasis on man-machine interaction rather than hardware or software. The reader interested in a fuller account is referred to (Sheridan, 1992a).

A *teleoperator* is a machine enabling a human operator to move about, sense and mechanically manipulate objects at a distance. It usually has artificial sensors and effectors for manipulation and/or mobility, plus a means for the human to communicate with both. Most generally, any tool which extends a person's mechanical action beyond his reach is a teleoperator.

A *robot* is a machine which senses and acts upon its environment autonomously (which means it also has a computer), and, according to most dictionaries, behaves with what appears to be human intelligence. A *telerobot* is a subclass of teleoperator in which the machine acts as a robot for short periods, but is monitored by a human supervisor and reprogrammed from time to time. (The latter is called *supervisory control.*) Non-telerobot teleoperators are fully manual, like a master-slave manipulator, or a joystick (rate-controlled) manipulator.

Teleoperators may look like "robots", i.e., be anthropomorphic, with serial-link arms mounted on a mobile platform, and video-camera eyes mounted above on a moveable "head". Or they may be non-anthropomorphic, i.e., not have human-like form. Thus any semiautomatic machine which has artificial sensors, actuators, and a computer, and is controlled in supervisory fashion, may be called a telerobot. Later in the paper modern aircraft, automobiles and power plants will be discussed as non-anthropomorphic telerobots.

Figure 1 diagrams the author's current model of the supervisor's task in controlling a telerobot. The generic telerobot may have multiple degrees of freedom (DOF) and act upon multiple task components, as shown in the bottom half of the diagram. A microcomputer may be locally attached to most task elements, such as task 3 in Figure 1; some may still have to be controlled manually to effect transient control or regulation relative to a set point. At the top of the diagram are shown the steps the supervisor must go through, in many cases aided by a computer. The blocks can represent mental activities or computer activities or a combination. The supervisor functions are:

(1) plan, which includes the sub-activities of (a) modeling the physical system, (b) trading off objectives to decide what is satisfactory ("satisficing"), and (c) formulating a strategy.

(2) teach, including the distinctly different activities of (a) deciding what to have the telerobot do, and (b) deciding how to tell the telerobot to do it.

(3) monitor, which includes (a) deciding how to allocate attention among all the various signals that can be observed, (b) estimating current system state or "situation", and (c) detecting /diagnosing any abnormality in what is currently happening.

(4) intervene, which in the case of abnormality means (a) deciding on and effecting minor adjustments if they will suffice, or (b) complete manual takeover, or (c) system shutdown; or (d) if the programmed action has come to a normal conclusion, it means reverting back to step (2).

(5) learn from experience to improve future planning.

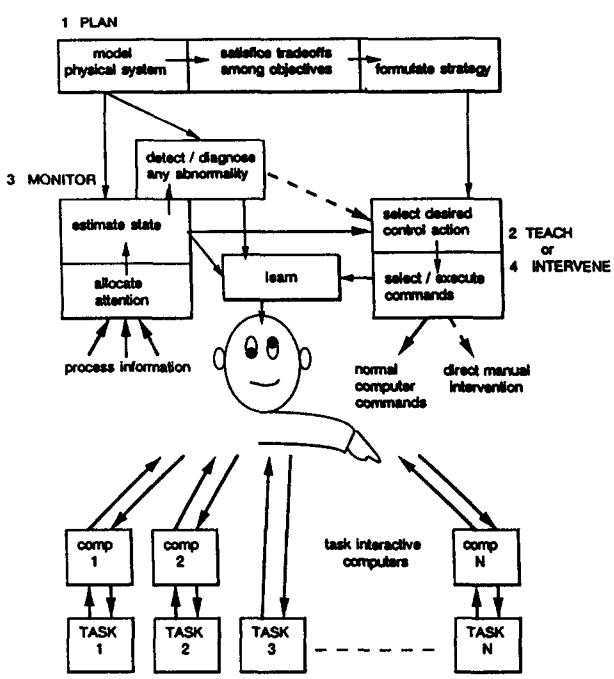


Fig. 1. Supervisory functions in control of a telerobot.

## 2. APPLICATIONS AND CONFIGURATIONS

### 2.1 Space

This is the application that most frequently comes to mind when teleoperation is mentioned. In fact, most of the deep space probes have been telerobots, relatively simple ones with respect to their control, having low-bandwidth capability to receive pictures and other sensory data, and ability to be reprogrammed in space. The Viking's tour of the outer solar system is the most striking example, from which signals have been received and updates sent from over a billion miles distance.

In 1993 the German space agency DLR successfully demonstrated the first space telerobot, the "Rotex" experiment, on the NASA Space Shuttle (Hirzinger, *et al.* 1993). By being relatively small and operating wholly inside a container, it wisely precluded concerns about safety of the astronauts. This experiment demonstrated the ability of a computer to control a telerobot in space, and also showed that space telemanipulation can be controlled from earth through a time delay.

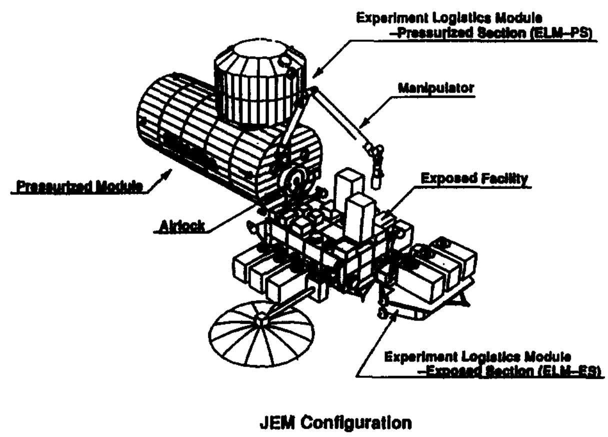


Fig. 2. Teleoperator on Japanese Experimental Module for Space Station Freedom.

Currently Japan might be said to be the leader in space teleoperator developments (Whittaker *et al.*, 1991). The Japanese Experimental Module (JEM) is an integral part of Space Station Freedom. JEM includes a long teleoperator operating from a "porch" (Fig. 2). In its initial phases this teleoperator will be controlled manually from ground and later be telerobotic. A 6-DOF "small fine arm" is to be added later to the end of the long teleoperator. The Japanese also plan a "free flyer" vehicle with a telerobot arm, scheduled for flight in 1997 aboard Japan's own H2 rocket.

Canada, who supplied the remote manipulator system for the NASA Space Shuttle back in 1981, is now developing a similar (55 foot long, seven degree-of-freedom) manipulator for the Space Station. They are also supplying a smaller dual-arm dexterous manipulator to go on the end of the long arm or be used independently. All of these devices are controlled by human teleoperation using two three-degree-of-freedom hand controllers, one for translation and one for rotation.

Regrettably, the large U.S. NASA effort in space teleoperation, the three-limbed and rather ambitious Flight Telerobotic Servicer, which was well along in its development, was cancelled in 1991, allegedly to save money. A truncated version, called the Dextrous Orbiter Servicing System, is planned for a 1996 flight.

Another telerobot, NASA's Ranger, developed at the University of Maryland, is designed to demonstrate what a relatively low-cost system made from standard components can do in automatic rendezvous and docking, coordination of two arms, satellite servicing, and replacement of modules.

Planetary surface telerobots are also being planned. Following from the American Surveyor mission in 1967, the Russian Lunakhods in 1969 and 1980, and the American Viking missions to Mars in 1976, recent developments have shifted to much smaller vehicles. Since 1992 the French space agency CNES has been developing a telerobotic roving vehicle for a Mars mission; for reliability reasons considerable emphasis has been placed on automatic vision-based path generation. A NASA 5 Kg. Mars Environmental Survey (MESUR) vehicle will be a telerobot controlled from earth combining predefined behavior elements with control based on sensory input. Russia has plans for a six-wheeled 100Kg. telerobot in a Mars mission planned for 1996. A Virginia-based (U.S.) company named Luna Corp. has announced a 1998 lunar rover project motivated not by science but for entertainment. It incorporates a telepresence interface and a predictive display to compensate for the expected 4-8 second round trip time delay (Lavery, 1994).

*2.2 Undersea*

Current undersea applications include offshore oil exploration, inspection and maintenance on drillheads, oil platforms and pipelines, marine biology experiments, geological surveys, archeological search and recovery, and classified navy tasks. The French, British, Norwegians, Japanese and Americans have led in this research.

The Argo-Jason project of Woods Hole Oceanographic Institution, named after Jason and his Argonauts of Greek mythology, has been the premier test-bed for deep ocean teleoperation in recent years. Argo is a heavy passive assembly of high-energy sonar and photographic equipment suspended by up to 6000 m of cable from its support ship, while the telerobot Jason maneuvers on a flexible cable within easy return range from Argo, all controlled from the surface. Jason is pictured in Figure 3. It was Jason's prototype, Jason Junior, which swam inside the Titanic, but was later lost at sea. Jason is programmed with a variety of supervisory control modes, and also makes use of some sophisticated techniques such as sliding-control to compensate for unmodeled dynamics (e.g., for the mass of water being pushed along in front of Jason as it maneuvers).

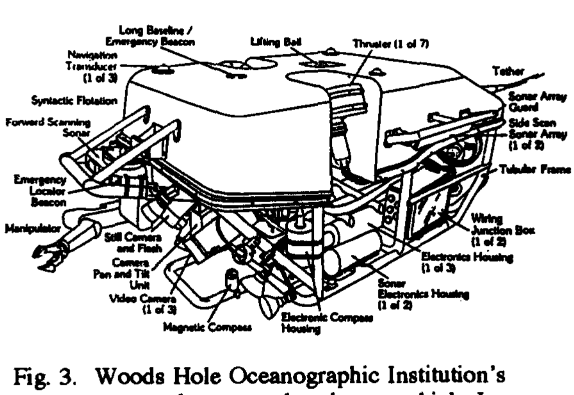


Fig. 3. Woods Hole Oceanographic Institution's remotely operated undersea vehicle Jason.

Jacobson *et al.* (1989) have developed for the Naval Ocean Systems Center what is surely the highest fidelity (bandwidth) master-slave teleoperator with force feedback. Master and slave are isomorphic, having seven DOF in the arm. The hand and fingers of both master and slave have three DOF. The system, shown in Figure 4, is electrohydraulic.

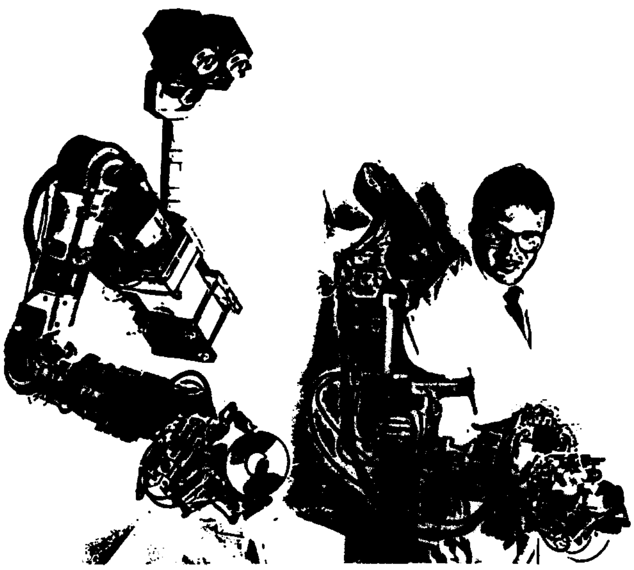

Fig. 4. University of Utah – Naval Ocean Systems Center electrohydraulic master-slave teleoperator.

*2.3 Toxic waste cleanup*

The U.S. Department of Energy (DOE), the U.S. manufacturer of nuclear weapons for several decades, has not been subjected to the same regulations as are the commercial nuclear power plants for storage and disposal of radioactive and chemically toxic wastes. Over the years DOE stored high-level wastes in large tanks in desert areas, and low-level wastes in ordinary 55 gallon steel drums. After several decades these tanks and drums corroded and leaked their toxic contents into surrounding groundwater. The U.S. government now feels an obligation to recover the wastes and transfer them to more secure containers. The hazards to human health are such that the job must be done by teleoperation. The task is mammoth, the number of tanks and containers being quite large, and no one quite knows exactly how it will be done or where the waste will be stored permanently.

*2.4 Telediagnosis and telesurgery*

There is new interest in telerobotics and teleoperation in medicine. CAT and MRI imaging is now being used to guide robotic devices to machine the heads of femurs and other bone structures for much tighter and surer fitting of prosthetic joint implants than was possible with manual drilling. Teleoperators are also serving to guide laparoscopes (coherent fiber-optic bundles or miniature video cameras) into the abdomen so the surgeon can see to perform diagnosis and surgery (e.g., gall-bladder removal) through cannulas (small sealed tubes from outside to inside the patient's body). Similar techniques are now used for arthroscopic surgery in the knee and shoulder joints and neurosurgery in the brain. The U.S. Advanced Research Projects Agency of the Department of Defense is supporting development of telesurgical tools whereby a soldier attended only by paramedics in a forward area of battle, or any person located remote from a hospital, can undergo telerobotic surgery by a surgeon at the hospital. (The telerobot would have to be carried to the remote site or air dropped.)

### 2.5 Other applications

In recent years developmental telerobots and manual teleoperators have moved into mines, are being commercially sold as night sentries for factory security, and are delivering mail and sweeping floors in factories — many of the applications promised but not realized only three years ago. Applications such as fire fighting and fire rescue are still not realized, but are believed by the writer to be compelling candidates for telerobotic development.

As teleoperators find their way into more and different applications, they become accepted as the normal and mundane way of doing tasks, not particularly "robotic" or otherwise glamorous.

## 3. HUMAN-COMPUTER COOPERATION IN PLANNING, COMMAND AND CONTROL

Modern control theory is based on the use of a model of the controlled process to provide a best state estimation. Measurements of state are combined, using Bayesian updating, with the model's prediction of response to past control inputs to produce a best current "belief state". An optimal gain matrix then operates upon this best estimate of current state to produce the new control input. The discrepancy between measured state and estimated state (after modifying the latter by a model of the measurement delay/distortion) is used to modify the process model. Figure 5 diagrams this well documented idea as it can apply to control aids for man-machine systems. This idea is a powerful one, and is being used in various ways to aid the human operator of dynamic systems, as described below.

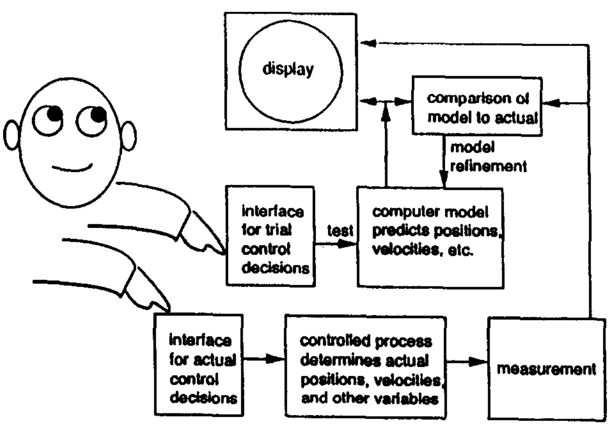


Fig. 5. Use of computer-model of process as aid to human operator for system control.

### 3.1 Predictor display

One of the more straight-forward applications of the computer model is where there are significant time delays in human control loops and the unaided operator therefore cannot provide stable control. A remedy is model-based prediction, in the form of what has come to be called a predictor display. Sheridan (1989) discussed development of such a predictor display (Noyes and Sheridan, 1984) for controlling a teleoperator over a several-second transmission delay. The operator's control commands are sent simultaneously to the controlled process and to a model. Since the model has no delay the operator sees immediately what the commands will do to the process. This lead provides compensation which enables him to stabilize control. A modified version of this predictor display was used in the 1993 German space telerobot experiment described earlier.

One interesting task for the Argo-Jason project described above is to maneuver the passive Argo along ocean canyons by control of the thrusters on the support ship. However the (up to 6000 m) umbilical poses a time delay of up to 10 minutes between ship movement and Argo response, and thus it has been virtually impossible to control Argo in other than very large radius curves. Thus it seemed that a predictor display might help. However the cable dynamics are quite nonlinear and complex, depending on ocean currents and many other factors. Cheng (1991) describes a predictor display technique which, even though representing the cable by an extremely simple adaptive model, nevertheless enables manual control to be quite stable and smooth.

Conway *et al.* (1987) developed a novel way to use the predictor display in which they "disengage control synchrony" in time and space by use of a "time clutch" and a "space clutch". The time clutch allows the operator to disengage from real time by making control inputs and getting back simulator responses more rapidly than the actual process would allow for easy maneuvers, and conversely slowing down the pace of human interaction where more samples are needed in higher bandwidth maneuvers. A computer buffers the commands and later feeds them to the actual process at the real-time pace, interpolating between samples as necessary. Disengaging the position clutch allows the user to move the simulator in space without later commitment of the commands to the actual process -- for the purpose of trying alternative commands to see what they will do -- in essence going into an off-line mode for short periods. An experimental evaluation of using this scheme in telemanipulation confirmed its efficacy.

### 3.2 Other recent applications of the internal model

The computer has been used in other ways to aid in the planning, command and control of teleoperators. Machida *et al.* (1988) demonstrated a system on which the supervisor could teach a computer-modeled telerobot and receive force feedback on the master hand if mechanical interference occurs between the modeled slave hand and its environment. The operator can edit the trajectory on any selected time-scale, with the sequence of actions selected to run in either forward or reverse. The latter proved useful, for example, if after some trial instructions the telerobot became hung up. In this case it could easily be returned to the last acceptable point and reprogrammed from there.

Park (1991) demonstrated a computer-aided technique for commanding a telerobot to move to a goal point while avoiding objects. The technique assumes a model of the geometry of the teleoperator, and all other objects (obstacles to motion) in the near environment. Additional obstacles can be inserted into the model when observed by television, after fixes are taken on their positions (from their edges).

In real telemanipulation television cameras can be panned and tilted but not otherwise moved, and hence there are unseen spaces (penumbra) behind the newly seen obstacles. In Park's technique these are regarded as *virtual obstacles* (Fig.6). At any time the computer can be called upon to display the updated field of obstacles (by using a trackball any viewpoint can be

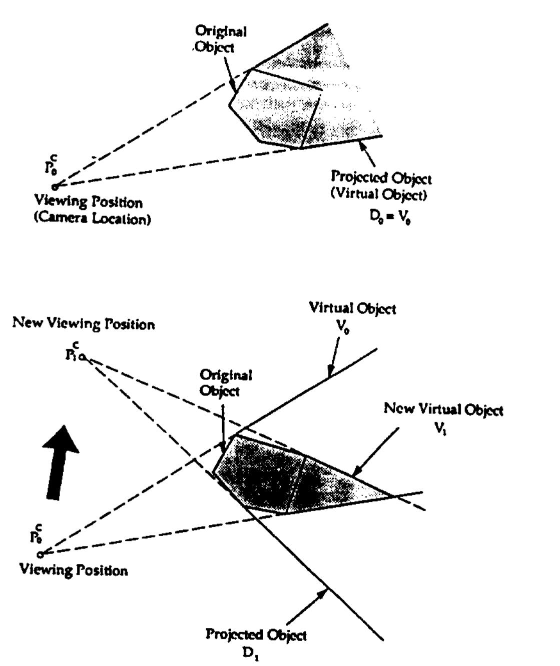


Fig. 6. Park's "virtual obstacles" in a computer-graphic model used for planning teleoperator moves.

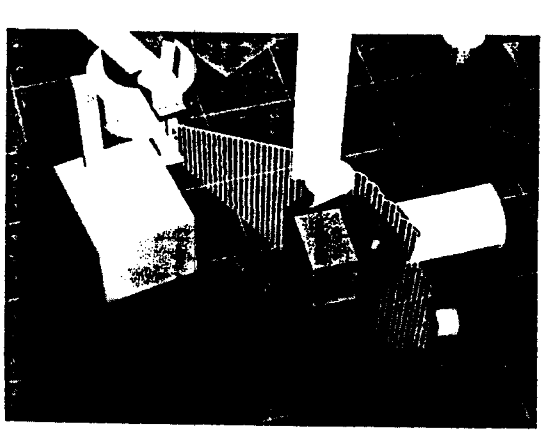

Fig. 7. Planned trajectory displayed in Park's computer model.

set in) and the human operator can suggest a trajectory of the vehicle and/or manipulator through the obstacles which is drawn on the computer screen (Fig. 7). There are also some simple AI trajectory search heuristics which may be used. Then the computer immediately displays whether the trajectory is feasible, and if so how close it comes to collision (how tight is the path). The human may iterate with other trial paths. Once a satisfactory path is selected, the computer can automatically guide the teleoperator for part or all of the trajectory, stopping if it finds itself in trouble. In simulated tasks Park found this technique to prevent errors and speed up teleoperation considerably.

Funda *et al.* (1992) extended the work of Machida *et al.* and the earlier supervisory programming ideas. Again the operator programs by kinesthetic as well as visual interactions with a (virtual) computer simulation. A key feature of their work is that the instructions to be communicated to the telerobot are generated automatically in a more compact form than record and playback of analog signals. Several free-space motions and several contact, sliding and pivoting motions, which constitute the terms of the language, are generated by automatic parsing and interpreting of kinesthetic command strings relative to the model. These are then sent on as instruction packets to the remote slave.

The Funda *et al.* technique also provides for error handling. When errors in execution are detected at the slave site (e.g., because of operator error, discrepancies between the model and real situation and/or the coarseness of command reticulation), information is sent back to help update the simulation. This is to represent the error condition to the operator and allow him to more easily see and feel what to do to correct the situation. With a time delay, of course, some additional actions may have been taken in the meantime. In this situation a predictor display could be useful to help the operator explore on the simulation different alternatives for how best to recover from the error. The authors' current research is considering a system which can automatically take back control when a safe situation is recognized.

Van de Vegte *et al.* (1990) were concerned with modeling the supervisory operator of teleoperator in a time-delay situation. They extended the Kleinman, Baron and Levison (1970) optimal control model (OCM) of the human operator (which assumes a perfect representation of process dynamics) to allow for an imperfect internal model of the system being controlled. They also relaxed the requirement that the human internalize a prediction to compensate for his own time delay (delays significantly less than one second being significant in the aviation applications for which the OCM was developed). Instead they assume the human to take predictor display information (typically used for loop delays of several seconds) as though it truly represents current process state. They tested their revised model on a simulated undersea teleoperator and found it to work well.

## 4. OTHER ASPECTS OF SENSORY FEEDBACK: MORE ROLES FOR THE COMPUTER

### *4.1 Visual aids to sense depth*

Several graphical techniques have become common to enhance visual sense of depth, which can be very difficult to obtain from a video picture. Stereoptical video (two cameras) accompanied by stereo display is the most promising. The latter may be accomplished in several ways. One is to feed two separate images to the two eyes, say by miniature video monitors A second is to alternate video images from the two cameras onto a single monitor (e.g., each successive interlace from a different camera) and have the viewer wear liquid crystal spectacles which alternately block one eye or the other, synchronized to the interlace. Computer stereopsis is now available commercially in computer-graphic workstations, requiring the user to wear liquid crystal glasses which are gated through infrared communication to a sensor and circuitry built into the glasses.

A non-stereopsis technique is to superpose onto the video picture a computer-graphic image with a drawn-in-perspective rectangular grid comprising a "floor". Each of many objects in the visual field has a vertical line "attached" at one end, the other end of the line being projected to the artificial floor at the corresponding (known) distance.

### *4.2 Force feedback*

Force feedback in a master-slave teleoperator means that the net force vector imposed by the slave on the environment is reflected back and imposed by the master on the operator's hand. Many of the earliest teleoperator systems were force-reflecting.

Force feedback in teleoperation has been studied in laboratory experiments for many years (Sheridan, 1992a). A study by Hannaford *et al.* (1989) compared both task completion time and level of force used for a variety of teleoperation tasks as well as a variety of control modes. The latter included (1) position control with visual but no force feedback, (2) regular visual feedback plus force feedback by means of visual display, (3) visual plus kinesthetic (conventional bilateral force) feedback, (4) what the authors call "shared control", and (5) bare-handed manual control. Shared control in this case means force feedback is imposed or suppressed as a computer-based function of object contact, recent past forces applied in all degrees of freedom, and other stability considerations (Hayati and Venkataraman, 1989). Some sample results from Hannaford *et al.* are shown in Figure 8 for a peg-in-hole task. Massimino and Sheridan (1989) showed how mean completion time in such tasks is significantly reduced by force feedback independently of visual parameters such as frame rate and spatial resolution of the image.

Force reflection has been accepted in remote handling of nuclear and toxic wastes, where master-slave position teleoperation is common. However in space and undersea applications force feedback is not generally accepted. This is because in space forces are to be avoided, so rate-control joysticks are used to control motions to very slow rates. It is also because of the added complexity and cost imposed, and because when there is a significant time delay in the control loop force feedback to the same hand as is operating the control produces a (thus far unavoidable) instability. Massimino (1992) showed that the latter problems can be overcome when vibrotactile or auditory displays are substituted for display of actual force.

When force feedback is used, it is important to avoid biasing forces caused by friction, damping and inertial properties of the intervening teleoperator mechanism. Therefore force is measured near to the slave hand and near to the operator's hand (e.g. using a multi-DOF force sensor at the wrist), and control gains are adjusted carefully to avoid instability while minimizing the discrepancy between the two (Raju *et al.*, 1989).

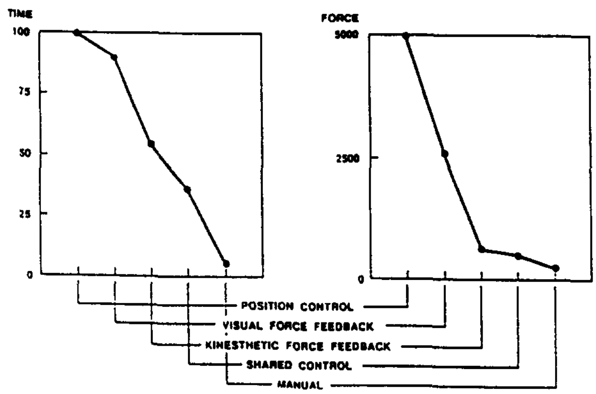


Fig. 8. Hannaford et al. results for task completion time and level of force used under a variety of teleoperator control modes.

### *4.3 Teletouch*

In contrast to feedback of the force resultant from the slave hand to the master hand, teletouch refers to feedback of the spatial distribution of forces imposed on the slave hand by contact with the environment. Electrical, optical and other types of touch sensors have been developed to measure patterns of forces and mechanical distortion on the gripping surface of the slave hand, and some of these are now available commercially at low cost. Unfortunately there is no available counterpart display of touch information to the skin, though it is relatively simple to devise computer-graphic visual display of the sensor's spatial force pattern.

### *4.4 Telepresence, virtual presence and the combination*

*Telepresence* is the sense of being at a real location other than where one actually is. *Virtual presence* is the sense of being at a location which does not actually exist, which instead is a compelling graphic or auditory illusion. New computer and display technology is driving much current activity in this field, which also goes by the terms *virtual reality* and *artificial reality* (neither term being acceptable to the author because the dictionary definitions of the terms are self-contradicting).

Currently *visual telepresence* is said to be experienced when a human operator wears a head-mounted video display, which, upon panning or tilting of the head, drives a slaved remote video camera in corresponding motions. Thus the observer sees the same moving images as would be seen were the eye placed at the remote camera's viewpoint. Stereo, high resolution, high frame-rate, good contrast and color rendition all enhance visual telepresence. Having tried a number of such telepresence systems, the writer believes the best to be that of Prof. S. Tachi of the University of Tokyo (Tachi et al, 1989).

Virtual presence may be achieved the same way, but with a computer-generated graphic images replacing the video. The software must be able to modify the images quickly to keep up with even modest head movements, which pushes today's graphic workstations to their limits. A most interesting demonstration of virtual presence can be seen at Matsushita Electric's kitchen show- room in Tokyo. A prospective customer can don a head-mounted display, also equipped with an auditory device to generate compelling sound "presence", and have the experience of walking into different kitchens, looking around, peering into closets, even knocking over glassware and hearing it smash in just the correct location – none of it real, all of it produced by software.

Some informal experiments in the writer's laboratory have revealed that even relatively poor visual telepresence and poor force feedback, when used together, are mutually enhancing. Though there are glove and exoskeletal devices to sense the relative poses of fingers and communicate these to a computer-graphic hand image, no one has yet produced satisfactory virtual teletouch. Patrick (1990) came close, by showing that vibrotactile sensors mounted on the fingertips, when activated by the fingers performing a grasping motion in space, do give the impression of grasping a tuning fork (Fig.9).

Figure 10 suggests that virtual presence is a function of three independent components (Sheridan, 1992b). The first is the resolution of the sensory channel, including pixels per visual, auditory or tactile "frame", frames per second, and bits per pixel of grayscale or magnitude resolution – the product of which is bits per second. The second component is the observer's ability to move the sensor about in space, much as head motion with a visual sensor takes and compares images from different viewpoints (thus using parallax and other cues), or by active touch one samples multiple tactile "frames". The third component is the capability to actually modify the relative positions of objects in the environment. An ultimate sense of "being there" requires full use of all three components.

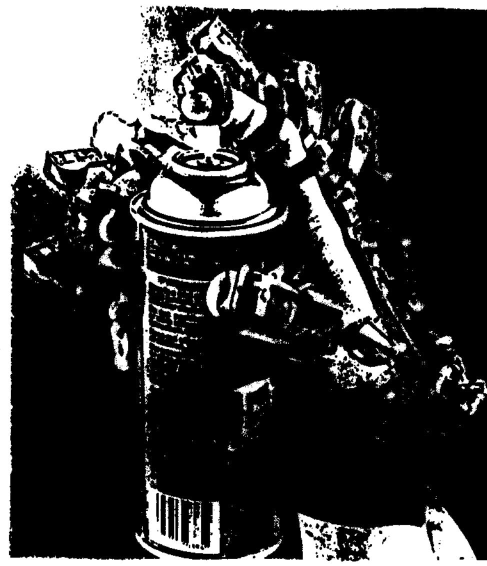

Fig. 9. Patrick's experimental setup: vibrotactile sensors mounted on the fingertips are activated when grasping position reaches a criterion corresponding to a computer (actual object pictured is not really there). This gives a virtual sensation of grasped object.

Currently there is no commonly accepted measure of "presence" of either the tele- or the virtual variety. Held and Durlach (1991) proposed using natural reponses such as "ducking" when an object in the virtual environment unexpectedly threatens to collide with the observer's head. Subjective scaling as a measure is an obvious approach tried by various investigators, though there has been no effort to standardize such scales, as has happened with mental workload.

Schloerb (1995) proposed that perfect telepresence or virtual presence occurs when the observer cannot discriminate virtual from actual. Therefore a ratio of the probability of judging that an environment is real given that it is actually virtual, normalized by the probability of judgment that it is real given that it is actually real, can serve as a quantitative measure of telepresence. (This assumes an experiment where both virtual and real are randomly intermixed in equal proportions). However, given no constraints on the observer's ability to test the environment, this ratio

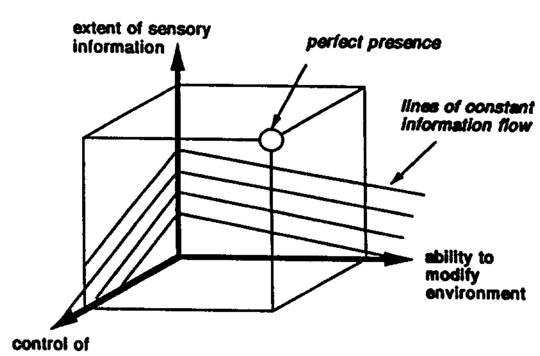


Fig. 10. Independent components of virtual presence.

would hardly be expected to exceed zero by very much. Therefore, it could be useful to add noise to make the discrimination more difficult. Then, another measure of presence would be the amount of noise which must be added to the virtual environment before the observer cannot tell the difference between virtual and real.

## 5. NON-ANTHROPOMORPHIC TELEROBOTS: AIRPLANES, AUTOMOBILES, TRAINS AND POWER PLANTS

A *non-anthropomorphic teleoperator* is a teleoperator which does not have human form – arms or legs or scanning eyes or creature-like motions. It may still be a vehicle which moves through its environment such as an aircraft or an automobile, or it may be a chemical or power generation or manufacturing plant in which the manipulated environment (in this case the product) moves through the teleoperator, while the teleoperator itself is stationary in space. The latter still involves human control of sensors and actuators which are remote, functionally if not physically (i.e., the human operator is located in a centralized control room, far from the machines that process the product). Just as with the anthropomorphic kind, as such teleoperators become semiautomated and the human becomes a supervisor, the devices are called *non-anthropomorphic telerobots*. Below are descriptions of what is happening in four such applications. The parallels with space, undersea, and toxic environment teleoperation are striking.

### *5.1 Aircraft*

The newer aircraft, both commercial and military, are largely controlled in supervisory fashion through computers. The human pilot is called the *flight manager*, and he or she more and more controls the aircraft through a multi-purpose interactive computer called a *flight management system (FMS)*. By means of the FMS he can program the autopilot in one of several modes, or examine electronic check lists which remind him to take certain actions and call his attention if he misses some. He can also do routine maintenance or fault diagnosis by calling up different synoptic displays of electrical or hydraulic diagrams, indicating the quantitative values of voltages, currents, temperatures, pressures, etc. at the key component locations, as well as showing by color, or flash-rate whether a variable is in an abnormal state (Billings, 1992).

A variety of commands and other information, which in the past would have been sent by verbal communication from ground controllers, are now being sent directly to the FMS by digital data links, and then interpreted by computer for display to the pilot. In this mode the FMS has the capability to provide navigation maps showing dynamic changes in weather (the same information that comes to TV weathermen), horizontal and vertical views of other traffic in the area (the same information as is now provided to air traffic control), approach plate information on different scales or with some detail suppressed, or advisories or instructions on operation or maintenance of various systems more detailed than what would normally be carried onboard.

### *5.2 Automobiles*

In the past the automobile driver controlled the vehicle entirely manually. That is now changing, with the European Community PROMETHEUS and DRIVE projects, the Japanese AMTICS and RACS projects, and the American IVHS, for intelligent vehicle highway systems (more recently renamed ITS, for intelligent transportation systems) (IVHS America, 1992). In ongoing field trials, in-vehicle computers now receive navigational and accident-alert data from infrared, radar, or ultrasonic sensors mounted either in the vehicle or by the roadside, or get messages via satellite from an advanced traffic management center in urban areas. Tiny antennas mounted on the test vehicles get latitude and longitude fixes from GPS (global positioning system) satellites to within 30 feet, and this together with an on-board gyrocompass provides continuous route information relative to programmed starting point and destination.

Display of route information is presented visually by computer-graphic map, graphic symbols indicating lane to be in or upcoming left or right turn, or name of the street to turn onto. Simultaneously information is given by computer-generated speech, relieving the operator from having to look down at displays except for confirmation. Such messages also contain alerts about accidents and congestion. Such systems can also be queried to determine nearest fuel stations, or medical/police services, or restaurants. The new technology also allows for automatic braking or steering in the event the driver is not responding to obstacles that are measured to be too close, and there are interesting questions here about whether control should be seized from the driver suddenly or applied gradually so that for a time both driver and computer are working in parallel, and indeed when and under what circumstances to give control back to the driver.

As with many of the other applications of telerobotics and supervisory control, the "hard" technology is mostly in hand. What is lacking is a base of human machine research (Sheridan, 1991) and an understanding of the legal and socioeconomic implications.

### *5.3 Trains*

The modern high-speed passenger train is a good candidate for telerobotic control. The track geometry is known and the train dynamics are known. The speed limits based on track maintenance or obstacles ahead can be relayed in real time to a computer which "sees" ahead better than can the engineer by looking out the window. The computer can give advice on the optimal action to take at every moment, and indeed could control the train automatically. Is an on-board driver really necessary?

*5.4 Process Control Plants*

Many chemical plants, oil refineries, and nuclear and fossil power generating stations have been re-engineered in recent years to move the human operator away from being a direct controller manipulating valves and switches out in the plant to being more of a supervisor of computer-based semi-automation, operating from a centralized control room which may be physically remote from many parts of the plant. This configuration appears least like a telerobot (is most non-anthropomorphic), but still, from the human operator's viewpoint, poses the very same requirements as diagrammed in Figure 1.

There may be conventional anthropomorphic teleoperators within it, for example, for the remote handling of nuclear fuel elements during refueling operations or repairing of radioactive steam generators in nuclear plants, or remote handling operations on highly toxic substances in chemical plants. However, "teleoperation" in process control plants is also characterized by giving commands to a central computer in the control room which in turn sends set points to hundreds or thousands of simple computer-regulators out in the plant, and getting back information from sensors, which the central computer translates into integrated graphical information.

## 6. CONCLUSIONS

Telerobotics is alive and well, especially in Japan. The field could certainly be healthier in Europe and the US, but distrust of technology and demand for quick profits have discouraged investment in telerobotics research and development. In the aviation and automotive fields, non-anthropomorphic telerobots are being developed actively, most commonly under the rubric of *human-centered automation.*

Telerobots of various forms have been touted as answers to problems of safety, productivity, transportation and military security. Thus far little fear has been manifest that they will destroy people or take meaningful jobs away. But, as with the seemingly benign automobile and refrigerator, which by quietly generating greenhouse gases or releasing chlorofluorocarbons that destroy the ozone, the telerobot can easily be put to tasks which are unnecessary or in some cases harmful, all the while wasting valuable resources. The socioeconomic impacts have yet to be taken seriously by more than a small number of people.

In systems of the type discussed above, the human is called upon to perform those "higher-level" functions of pattern recognition, association, evaluation of objectives, and creativity which programmers do not yet know how to make computers do. At the same time, computers are called upon to give advice or to control systems cooperatively with the human. In these circumstances there remain serious questions about how to study the human operator, what intelligence can be attributed to him or her vis-a-vis the computer, and how far one can go in modeling such complex human-machine systems.

For the same reason that engineers lack knowledge of how to program computers to do these functions, they also do not know how to model them. Almost by definition of a system being complex enough to require a human supervisor, such a model and explicit objective function are not available. However, in order to rigorously evaluate a computer aid or a cooperative control system, a relatively complete process model and objective function must be used as a norm. But, if the latter were available, why would the human be necessary? The system engineering discipline has only begun to face these compelling challenges of human-machine interaction.

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