Space Teleoperation Through Time Delay: Review and Prognosis

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***Abstract*—The paper reviews a 30-year history of research on dealing with the effects of time delay in the control loop on human teleoperation in space. Experiments on the effects of delay on human performance are discussed, along with demonstrations of predictive displays to help the human overcome the delay. Supervisory control is shown to offer a variety of options, from switching to local impedance control upon contact with the environment to higher-level local automation. Wave transformation techniques to ameliorate the effects of delay are also described. Space teleoperations have tended to deal with the problem of time delay by avoiding it and not attempting to teleoperate from the ground. The paper opines that our space effort might have gotten further ahead and at a lower cost had we committed more to space teleoperation from the ground through the delay. Predictive display works well for free positioning. Local impedance control is recommended for control in contact with the environment, possibly accompanied by wave transformation techniques. Higher level supervisory control is always an option for sufficiently predictable tasks, and will continue to improve with better sensors and task models.**

I. Introduction: The Problem of Time Delay in Space Teleoperation

CONTINUOUS TELEOPERATION in earth orbit or deep space by human operators on the earth's surface is seriously impeded by signal transmission delays imposed by limits on the speed of light (radio transmission) and computer processing at sending and receiving stations and satellite relay stations. For vehicles in low earth orbit, round-trip delays (the time from sending a discrete signal until any receipt of any feedback pertaining to the signal) are minimally 0.4 s; for vehicles on or near the moon these delays are typically 3 s. Usually the loop delays are much greater, approaching 6 s in the case of the earth-orbiting space shuttle because of multiple up-down links (earth to satellite or the reverse) and the signal buffering delays which occur at each device interface.

A similar problem is encountered with remote control in the deep ocean from the surface if acoustic telemetry is employed to avoid dragging miles of heavy cable. Because sound transmission is limited to around 1700 m/s in water, communicating over a 1700 m distance poses a 2-s round-trip delay. Alternatively some underwater vehicles are steered by dragging them by means of a passive cable, causing time delays of ten minutes or more.

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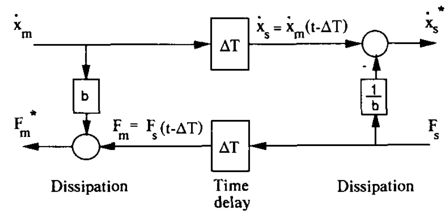

Fig. 1. Damping to stabilize a teleoperator communications process [1].

A. The Basic Instability Problem

Continuous closed-loop control over a time delay poses serious problems. Driving the controlled process to sufficiently null the difference between reference input and process output (negative feedback) normally requires a loop gain greater than unity in the frequency range of interest. However if the loop gain is greater than unity at such a frequency that half a cycle is equal to the time delay, this will result in positive feedback rather than negative. This means that energy at this frequency is continually added to the loop, and the amplitude of signal traversing the loop grows without bound, even though the reference input or disturbance inputs may be zero. Another way of stating the condition for stability is that the plot of the open-loop phasor with increasing frequency must never circle the (-1) point on the complex plane (the Nyquist criterion).

Such instability is normally avoided because frequencies in which good tracking is needed are lower than those at which loop time delay equals one-half cycle, and the dynamics in the open-loop attenuate the loop gain to less than unity by the time the critical frequency (at which one-half cycle is short enough to equal the time delay) is reached.

Recent theories, to be discussed further below, have set more stringent standards, imposing passivity to guarantee stability, i.e., the input power flow must exceed the output power flow. This requirement can easily be contravened by the communication system itself. In the conventional case of position or rate command and force feedback (see Fig. 1) passivity requires that the force-velocity product at the master port minus the force-velocity product at the slave port must be positive. (Note that power flow is in the direction of the velocity vector.)

Niemeyer and Slotine [1] have shown that placing energy dissipating (damping) elements (as shown in Fig. 1) guarantees this condition, in spite of the time delay, and independent of its time constant. (It is common experience that gripping a

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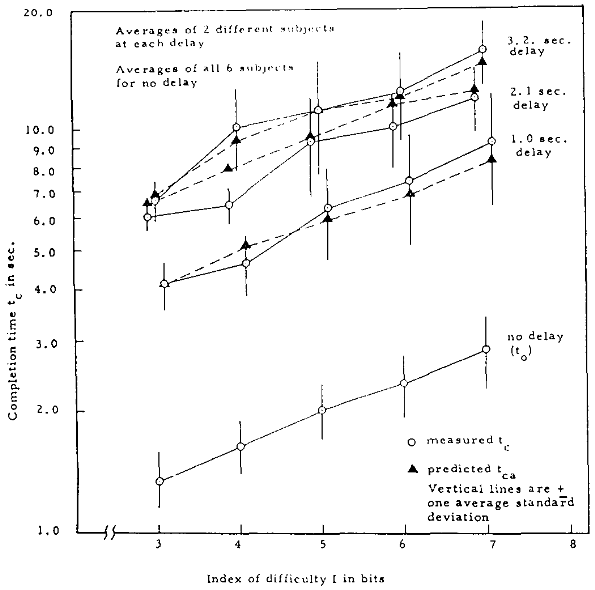


Fig. 2. Ferrell's experimental results for time-delayed telemanipulation in 2-DOF task. Predictions were based on counting the number of open loop moves for opening eyes momentarily before each move, but no actual time delay [5].

slightly unstable master arm tightly, or adding friction at the slave end makes the oscillations go away.) Use of the passivity idea is considered again later in the paper.

In the case of supervisory control, time delay in the supervisory loop normally would not cause instability. In this case commands are sent by the human operator through the time delay to a computer; the computer then implements the commands by closing a loop local to itself, reporting back to the supervisor through the time delay intermittently or when the task is completed. The computer's local loop normally has no or insignificant delay in it and therefore causes no instability.

B. Where the Delay is Located

Stability criteria do not care whether the delay elements within the loop consist of so-called pure delay elements, where output $y(t) = x(t - T)$, are arbitrary linear dynamic elements with poles and zeroes, or are nonlinear in a more general way. Stability criteria also do not care whether the delay elements are one or many, or whether (as in the case of telecommunications transmission delays from the ground to and back from spacecraft) the delay is in the forward loop or feedback loop or both.

Other considerations may matter very much, however, since it may be rather important whether some response action is taken in space as compared to when it is initiated on the ground. (Good control with no forward delay but with feedback delay nets simultaneous action, while good control with forward delay but no feedback delay imposes a delay between ground and space.

C. Surveyor and Later Unmanned Teleoperators

There have been many teleoperated spacecraft. In the early 1960s Surveyor first demonstrated a primitive manipulator for scooping up lunar soil. Each of its commands took about 25 min to complete, orders of magnitude more than the 3-s speed-of-light delay, in that case because of elaborate precautions taken to ensure the correctness of each discrete command. Essentially all of the unmanned spacecraft have had some capability for receiving (teleoperated) commands from earth, even Voyager, to which radio signal round trip delay when it was in the outer solar system was three hours.

II. Human Performance Experiments with Delayed Visual Feedback

Given finite delay in a continuous telemanipulation loop, many experiments have demonstrated how the time for a human operator to accomplish even simple manipulation is a significant function of the delay, the task complexity, and the manipulator control scheme.

A. Early Experiments

The problems of time delay in manual control from earth to space were recognized as early as 1962 [2]–[4]. Ferrell [5] first showed conclusively that the human operator, in order to avoid instability, can adapt what has come to be called a "move and wait strategy," wherein he makes a discrete control movement, then stops while waiting (the round-trip delay time) for confirmation that the control action has been followed by the remote hand or vehicle, then makes another discrete movement, and so on. This means that the operator can commit only to a small incremental position change "open loop," i.e., without feedback (which actually is as large a change as is reasonable without risking collision or other error) before waiting the delay period for the slave to "catch up".

Ferrell's experiments also showed clearly that teleoperation task performance is a predictable function of the delay, the ratio of movement distance to required accuracy, and other aspects of delayed feedback in teleoperation. Ferrell's results (see Fig. 2) are for simple two-axis-plus-grasp manipulations on a table.

Black [6] performed similar experiments with a conventional six-axis-plus-grasp master-slave manipulator. He parsed the task into four separate components and determined times for these components (see Fig. 3).

Thompson [7] showed how task-completion time was affected not only by time delay but also by degrees of constraint. Fig. 4(a) shows the progressively more constrained peg-in-hole task used by Thompson, along with some of his results (see Fig. 4(b)).

Held *et al.* [8], showed that sensory-motor adaptation is essentially impossible for delays as small as 0.3 s, and that experimental subjects dissociate the teleoperator hand movements from those of their own hand at these delays [9].

By 1980 there was abundant experimental evidence that time delay was a serious problem for teleoperation, at least one which could not be ignored.

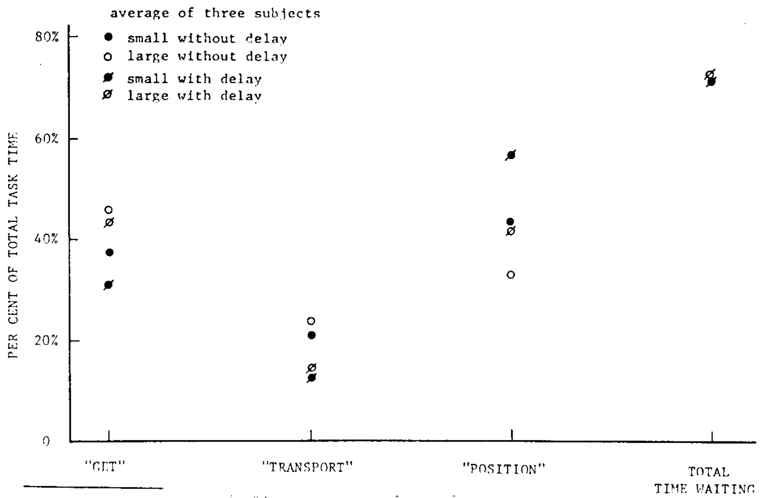


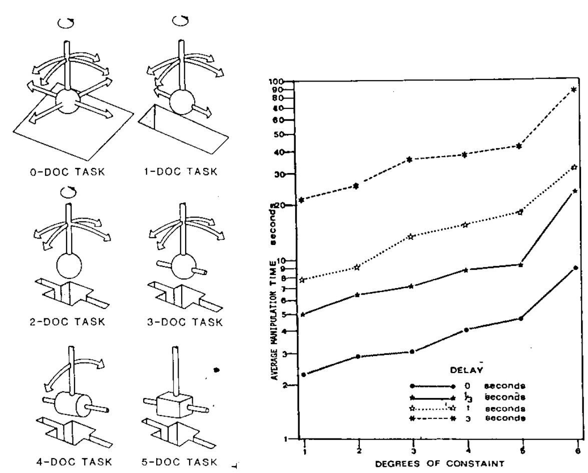
Fig. 3. Black's experimental results for time-delayed telemanipulation in 6-DOF peg-in-hole task. Task times were separately measured for four task components shown [6].

III. Direct Control by Use of Predictive Aiding

A. The Basic Idea of a Predictor Display

In a "predictor display," a cursor or other visual indication of the motion is generated by a computer and extrapolated forward in time. This aids the operator by predicting "this is what will happen, given the current initial conditions of the vehicle or teleoperator, and possibly also given the current control input." Predictor displays are of two types. A first is simply a Taylor-series extrapolation upon current state and time derivatives. The second, initiated by Ziebolz and Paynter [10], see also Kelley [11], involves inputing current state and time derivatives, as well as expected near-future control signals, into a model; the model is then run many times faster (i.e., with shorter time constants for the modeled process) than the actual process (see Fig. 5). The first approach is satisfactory for short predictions and utilizes only the state initial conditions. The second approach accounts for the properties of the process that may cause nonlinear dynamic properties such as saturation.

Predictor displays have been employed in gunsights, on large ships and submarines, in air traffic control displays, and as "head-up" optical landing aids for aircraft pilots. When there is significant delay (say more than 0.5 s) and operator movements are relatively slow, say mostly below 1 Hz, a predictor display can be very useful.



(a) (b)

Fig. 4. (a) Thompson's degrees of constraint. (b) Thompson's experimental results [7].

B. Early Computer-Graphic Predictor for Space Vehicle Control

Sheridan and Verplank [12] implemented an experimental predictor of the second type for a simulated planetary rover. A computer model of the vehicle was repetitively set to the present state of the actual system, including the present control input, then allowed to run at roughly 100 times real time for a few seconds before it was updated with new initial conditions. During each fast-time run, its response was traced out in a display as a prediction of what would happen over the next time interval (say several minutes) "if I keep doing what I'm doing now." A random terrain was generated and displayed in perspective, and was updated every 8 s (see Fig. 6). A predictor symbol appeared on the terrain,

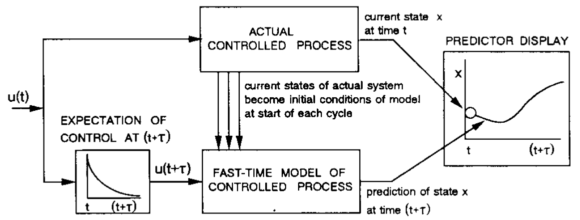
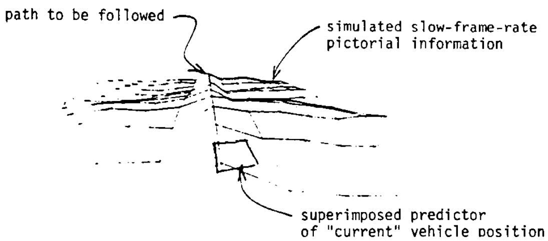
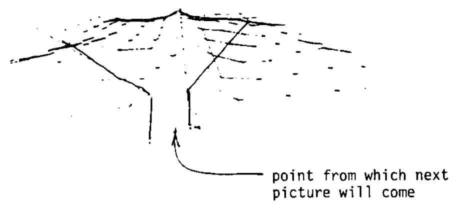


Fig. 5. Ziebolz and Paynter predictor technique. Current control input $u(t)$ is gradually discounted over prediction interval $(t+\tau)$. A new prediction trace is displayed over each new fast-time modeling interval.

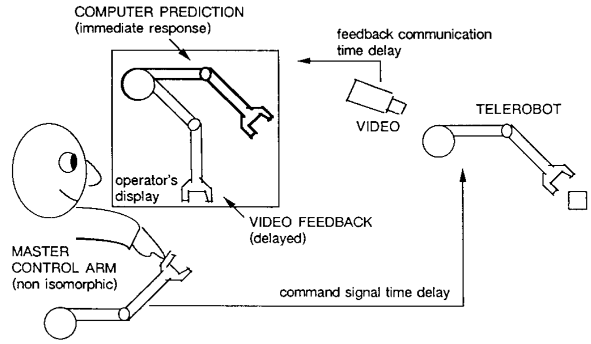


(a)



(b)

Fig. 6. Verplank predictor for lunar roving vehicle. Slow-frame-rate pictures (8 s per frame) were simulated by a computer-generated terrain. The path to be followed was a ridge. A moving predictor symbol (perspective square) was superposed on the static picture of the terrain. The point from which the next picture was to be taken and the corresponding next field of view were also indicated [12].



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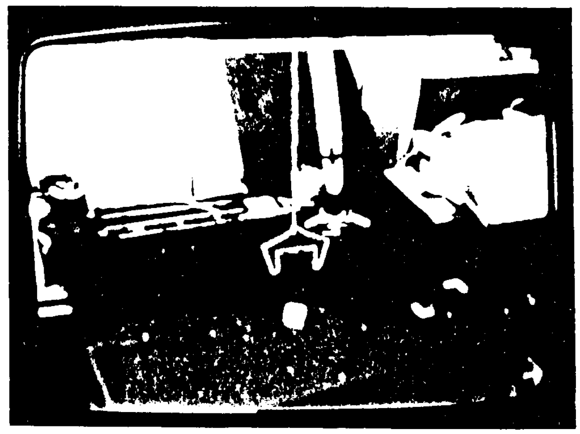


(b)

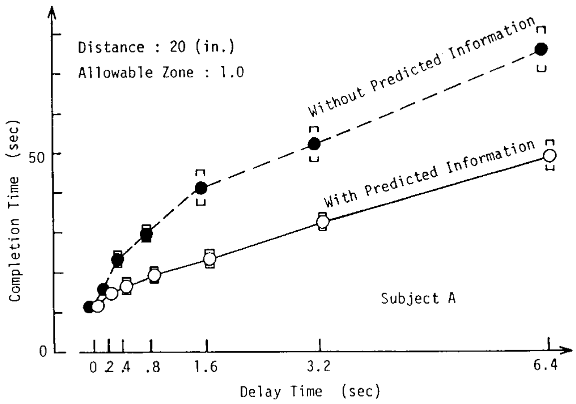
Fig. 7. Noyes' predictor technique for telemanipulator. (a) Diagram of experimental setup. (b) Photograph of stick-figure arm superposed on video screen [13].

continuously changing as the experimental subject controlled the motion of the vehicle, through a 1-s time delay. Front-back velocity control was accomplished through corresponding position adjustment of a joystick, and turn rate by the left-right position of the joystick. Also superposed on the static terrain picture was a prediction of the viewpoint for the next static picture, and an outline of its field of view. This reduced the otherwise considerable confusion about how the static picture changed from one frame to the next, and served as a guide for keeping the vehicle within the available field of view. By using both display symbols together, relative to the periodically updated static (but always out of date) terrain picture, subjects could maintain speed with essentially continuous control. By contrast, without the predictor they could move only very slowly without going unstable.

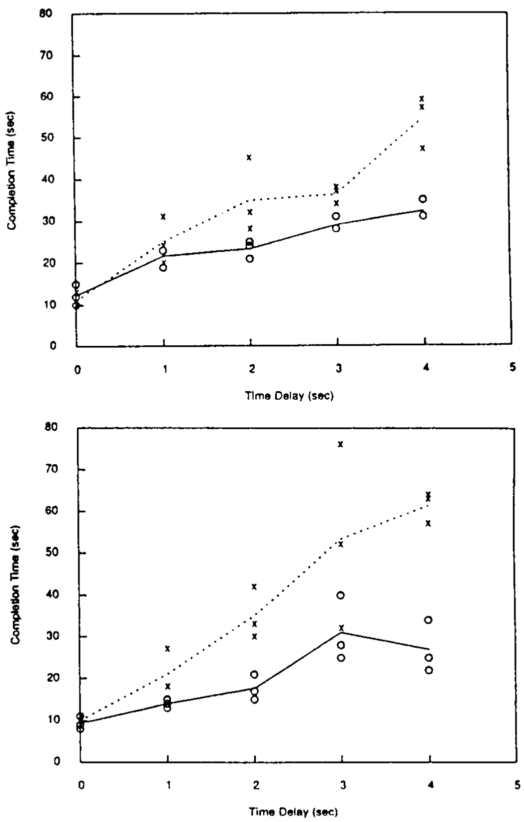
Such techniques are adequate for continuous control of single-entity or "rigid body" vehicles, but not for telemanipulation, where it is necessary to predict, relative to the environment, the simultaneous positions of a number of parts—i.e., a spatial configuration in multiple degrees of freedom, not just a single point.

C. Predictor Experiments for Telemanipulation

Noyes [13] built the first predictor display for telemanipulation, using newly commercially available computer technology for superposing artificially generated graphics on to a regular video picture. The video picture was a (necessarily simulated) time-delayed picture from the remote location, generated as a coherent frame (snapshot) so that all picture elements in a single scan were equally delayed. (Otherwise the part of the screen refreshed last would be delayed more than the part refreshed first.) As shown in Fig. 7, the predictor display was a "wire-frame" line drawing of the "present" configuration of the manipulator arm or vehicle or other device. The latter was generated by using the same control signals that were sent to the remote manipulator (device) to drive a kinematic model of it. The computer model was drawn on the video display in the same location where it would actually be after a one-way time delay and where it would be seen to be on the video after one round-trip time delay. Since the graphics were generated in perspective and scaled relative to the video picture, if one waited at least one round-trip delay without moving, both the graphics model and video picture of the manipulator (device) could be seen to coincide.



(a)



(b)

Fig. 8. Experimental results from use of predictor displays. (a) Hashimoto's averaged subjects' results using Noyes' predictor for task of repositioning a block 20 in to within a 1-in tolerance (from Hashimoto *et al.* 1986). (b) Bejczy and Kim results for two subjects in repeated peg-in-hole tapping task [14].

Bejczy and Kim [14] developed a similar predictor display using both a wire-frame display and a solid model display. The advantage of the wire frame is that it does not obliterate parts of the video picture that may be important.

The effectiveness of these techniques has been demonstrated for simple predictive models of the manipulator arm and simple tasks [13]–[18]. Figs. 8(a) and (b) from [17] show experimentally the advantage of prediction as used by different investigators for similar positioning tasks. With such a display, operators can "lead" the actual feedback and take larger steps with confidence, reducing task performance time by up to 50%.

Limitations of the predictor display, as thus far developed, are that: 1) it is only as good as the model of the arm or vehicle dynamics; 2) it must be carefully calibrated to the video in position, scale, and perspective; 3) it is not useful for movements in directions in and out of the video image plane, since even if additional depth cues are added to the computer-generated graphics, it is difficult to match predicted depth to that observed on the video; and 4) it does not accommodate manipulations which are fine relative to calibration errors (such as inserting a peg in a hole) or in which the video is blocked.

However, as demonstrated by Chiruvolu [19] if the model is good, the calibration error is small, and environmental objects are relatively fixed or themselves well modeled, computer-generated graphics can allow the operator to "see through" to any relation of hand to environment, without reference to actual video.

D. Addition of the Dynamics of the Uncontrolled Processes

When the motion of vehicles or other objects not under the operator's control can be predicted, e.g., by the operator's indicating on each of several successive frames where certain reference points are, these objects can be added to the predictor display. With any of these planning and prediction aids, the display can be presented from any point of view relative to the manipulator or vehicle—which is not possible with the actual video camera.

A prediction architecture proposed by Hirzinger *et al.* [20] includes this notion (see Fig. 9) as well as dynamic prediction. The stick-figure overlay on the delayed video is driven by a dynamic model (whereas Noyes *et al.* [15] used a kinematic model). In the figure this is constituted by the sum of the A and/or B feedback coefficients operating on correspondingly delayed commands. In the middle of the diagram is the implementation of the canonical first-order $x(k+1) = Ax(k) + Bu(k)$, where k corresponds to what is going on instantaneously with the space telerobot. The $x(k+1)$ estimate is corrected in the usual way by Kalman gain-multiplied discrepancy between estimated $y(k-nd)$ and the corresponding actual downlink signal. The delay line on the right side is required to estimate $y(k-nd)$. By estimating $x(k)$—i.e., what is happening in space—activities such as rendezvous and docking can be coordinated with clock-determined events which are not under the control of this human operator.

E. Adaptive Model Prediction

Another predictor instrument was developed by Cheng [21] as an aid to human operator control of the Woods Hole Oceanographic Institution's remotely operated submersible *Argo*. Essentially the latter is a heavy vehicle suspended and

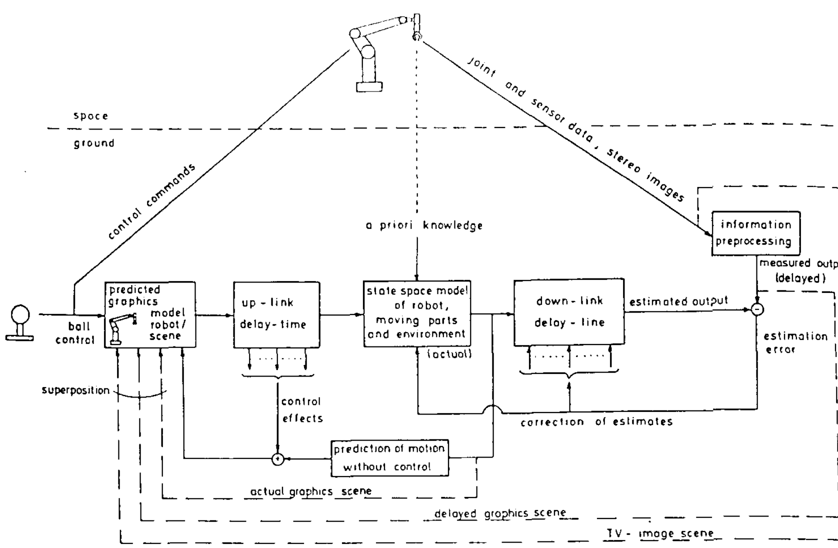


Fig. 9. Hirzinger predictor [20].

passively towed by a very long cable (up to 6000 m) from a support ship. The time constant for changes in control from the ship to become manifest in the position of the submersible is of the order of 10 min. To predict the submersible's trajectory in latitude and longitude from steering control actions performed on the ship, the model for the predictor must include the submersible, the cable, and the ship (all fairly nonlinear), and must account for both wind and water current disturbances. The cable was the most difficult to model, but it was found that a relatively simple linear model whose parameters are continuously updated (see Fig. 10) does a rather good job.

In simulation trials, use of such a model as a predictor instrument cut the error in following a given trajectory to about one third of the original, even at prediction spans which were shorter than the time constant of the cable. With the predictor display, human operator control actions were at significantly lower levels of thrust than without.

F. Modeling a Human Operator Who is Using a Predictor Display

Cheng [21] also performed a theoretical analysis of manual control with a predictor display. With the predictor, the effective time constant of the controlled process decreases equivalent to the prediction span, the gain of the human transfer function and the control action become smaller, and the damping of the closed loop system increases. This is consistent with the experimental result Cheng obtained.

Van de Vegte *et al.* [22] employed a modified version of the Kleinman *et al.* [23] optimal control model (OCM) in human control of a teleoperated submersible with a predictor. In essence, having an external predictor allowed them to eliminate in the human operator model the pure delay and the predictor which are internal to the OCM.

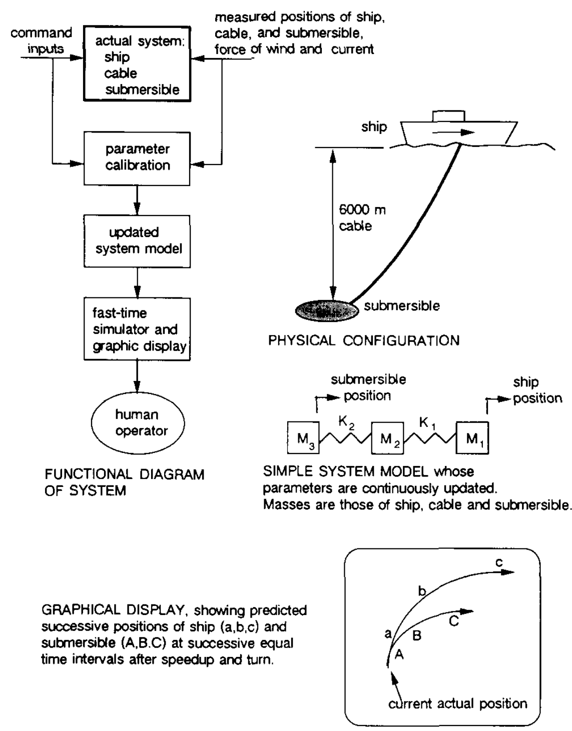


Fig. 10. Cheng's adaptive predictor technique.

Roseborough [24] called attention to a fundamental dilemma of validating the human operator's use of any decision aid, including the predictor display: 1) If the process can be perfectly modeled and the objective function explicitly stated, control can be automated. If not, the human operator is useful.

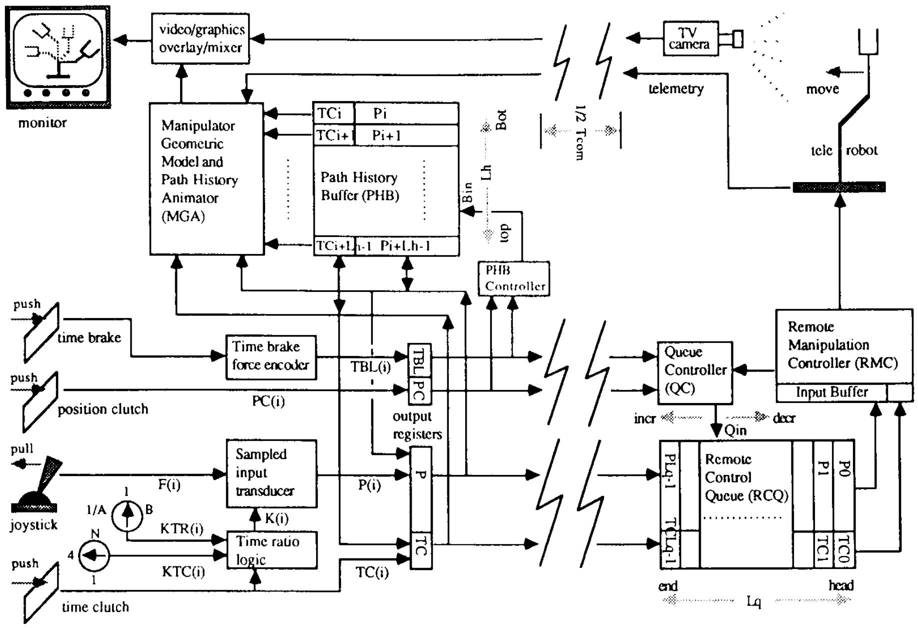


Fig. 11. Conway *et al.* [27] system architecture for time and position clutching and braking. (from Conway *et al.* 1987). TC = time clutch, PC = position clutch, TBL = time brake, KTR = timeration control, KTC = time clutch magnification rate.

2) The human is fallible and can be helped by a model-based predictor. 3) To evaluate the predictor a relatively complete model and objective function are necessary to serve as a norm. This condition conflicts with (a).

IV. Time and Space Desynchronization in Prediction/Planning Displays

The computer-simulated display need not be continuous or at a set pace. It can be desynchronized relative to the ongoing dynamic task. At one extreme of time desynchronization is recording a whole task on a simulator, then sending it to the telerobot for reproduction. This might be workable when one is confident that the simulation matches the reality of the telerobot and its environment, or when small differences would not matter (e.g., in programming telerobots for entertainment). Doing this would certainly make it possible to edit the robot's maneuvers until one was satisfied before committing them to the actual operation. The use of computer-based "internal" models for planning and control has been discussed in numerous contexts (See Sheridan [25] for a review).

A. Forward-Backward Editing

Machida *et al.* [26] demonstrated such a technique by which commands for a master-slave manipulator could be edited much as one edits material on a video tape recorder or a word processor. Once a continuous sequence of movements had been recorded, it could be played back either forward or in reverse at any time rate. It could be interrupted for overwrite or insert operations. Their experimental system also incorporated computer-based checks for mechanical interference between the robot arm and the environment.

B. Time and Position Clutching

Conway *et al.* [27] extended the predictor idea of Noyes and Sheridan [15] and combined it with a planning model in what they call "disengaging time-control synchrony using a time clutch" and "disengaging space control synchrony using a position clutch." In their scheme, the time clutch allows the operator to disengage synchrony with real time, to speed up making inputs and getting back simulator responses for easy maneuvers and to slow down the pace of such commands and simulator responses for hard maneuvers where more sample points are needed. The computer buffers the command samples and later feeds them to the actual control system at the real-time pace, interpolating between sampled points as necessary. (This is not unlike the "speeding up on the straightaways and slowing down on the curves" example often cited as an advantage of preview control, and in fact is what anyone would do in making best use of planning time.) The only requirement is that the progression of planned actions must keep ahead of what must be delivered "right now" for real-time control (and also take into account any time delay). The architecture of their system is shown in Fig. 11.

Disengaging the *position clutch* allows one to move the simulator in space without committing to later playback, this for the purpose of trying alternative commands to see what they will do. Disengaging the position clutch necessarily disengages the time clutch and creates a gap in the buffer of command data. Reengaging the position clutch may require path interpolation from the previous position by the actual telerobot controller.

Conway *et al.* offer the following scenario as an example:

> "We perform a complex maneuver with clutches engaged. We then disengage the time clutch to quickly hop over a series of simple manipulation movements, such as pushing a series of switches. A faint "smoketrail" superimposes the forward simulation path over the return video display, helping us to visualize our progress along the chosen path. Having saved some time, we then disengage the position clutch, and by trial and error movements position our manipulator in simulation to begin a complex maneuver. During this phase, the simulation-generated manipulator image moves on the display, but leaves no "smoketrail" of a committed path. Upon reaching the correct position and orientation to begin the next maneuver, we reengage both clutches (the "smoketrail" will now be the new interpolated path segment) and wait for the remote system to catch up. We then begin the next maneuver. In this way we 1) save some time, 2) use the time saved to later preposition for another action, 3) avoid taking the actual system through complex, manipulatively unnecessary prepositioning movements, and 4) do this all in a natural way through simple controls."

Conway *et al.* tested these ideas experimentally using a Puma robot arm, a joystick hand controller, and a simple two-dimensional positioning task. They compared teleoperation under three conditions: without any predictor display, with predictor display, and with predictor display plus time clutch. Plots of task-completion time as a function of task difficulty ratio (distance moved divided by diameter of target) yielded results for the first two conditions which confirmed the Hashimoto *et al.* [17] results that the predictor by itself made significant improvement (they found up to 50% shorter completion times for some subjects). They also found that adding the time clutch could make further improvement (of up to 40%) if the slewing speed of the robot arm was constrained to be very slow and if the operators used finesse and were careful not to overdrive the system. Various other researchers have adopted versions of the "time clutch." These ideas deserve further development.

V. Time-Delayed Force Feedback

A. A Problem Different Than With Visual Feedback

All the discussion above dealt with time delay of visual feedback in teleoperator control. Force feedback with time delay is a different problem. Ferrell [28] showed that it is unacceptable to feed resolved force continuously back to the same hand that is operating the control. This is because the delayed feedback imposes an unexpected disturbance on the hand which the operator cannot ignore and which, in turn, forces an instability on the process. With visual delay the operator can ignore the disturbance and can avoid instability by a move-and-wait strategy [5] or by supervisory control.

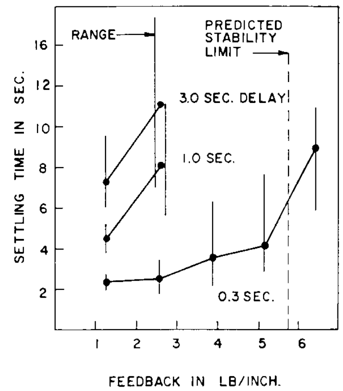


Fig. 12. Ferrell's results for settling time after imposed impulse disturbance with force feedback in time delay [28].

B. Early Experiment with Delay in Force Feedback

Fig. 12 from [28] illustrates the time it takes just to manually damp down a master-slave teleoperator system with delay in the loop after an impulse disturbance. Since Ferrell's experiments there have been various proposals, the simplest of which is to display force feedback in visual form on a computer display. Alternatively the force feedback can be to the hand that is not on the master hand or joystick. Another suggestion has been to feed back disturbances greater than a certain magnitude to the controlling hand for a brief period, at the same time cutting off or reducing the loop gain to below unity, and subsequently to reposition the master to where it was at the start of the event. Finally, there is the possibility of predicting the force feedback to compensate for the delay, and feeding the predicted force but not the real-time force back to the operator's hand.

C. Predictor Display for Force Feedback

Buzan [29], see also Buzan and Sheridan [30], evaluated the latter approach experimentally. He employed an open-loop model-based prediction to drive both a visual predicted-position display and a force exerted back on the operator through a master positioning arm. He did his experiments with a one-DOF teleoperator system, a 3-s time delay, and two challenging computer-simulated tasks. The first task was to extend the arm to make contact with (and unavoidably accelerate) a floating mass, then grasp it with a discrete action (an additional "half" DOF) before it "got away." The second task was to push an object into a "stiff slot" with enough force to get it in and have static friction hold it there, but not so much force that it goes right out the other side. Fig. 13 illustrates the two tasks.

Buzan tried three force-feedback-display techniques. In one, which he called *direct force feedback*, he simply presented the predicted force (but not the delayed "real" force) to the active hand, the hand commanding the teleoperator position. In a second method, which he called *dual force feedback*, he presented the delayed force to an inactive hand and the predicted force to the active hand. In the third display technique, which he called *complimentary force feedback*, he presented to the active hand

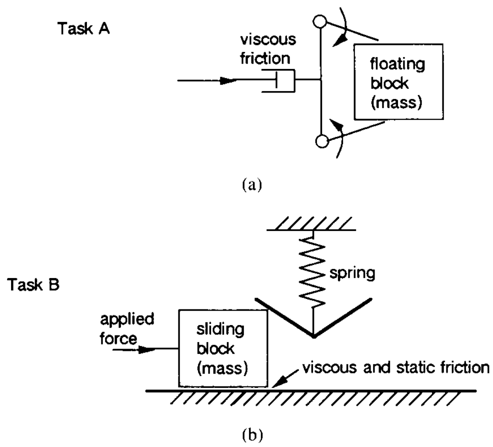


Fig. 13. Buzan's tasks for time-delayed force feedback experiments. In task A, human subject was to reach out andgrasp block (which was freely floating in space) without inadvertently accelerating it out of reach before grasp could be achieved. In task B, human was to push block to center ofspring-clamp until light static friction held it there and notlet it pop out the other side. Models used to generate predictor displays were simplifications of (simulated) real-timetasks (e.g., no static friction in task B) [30].

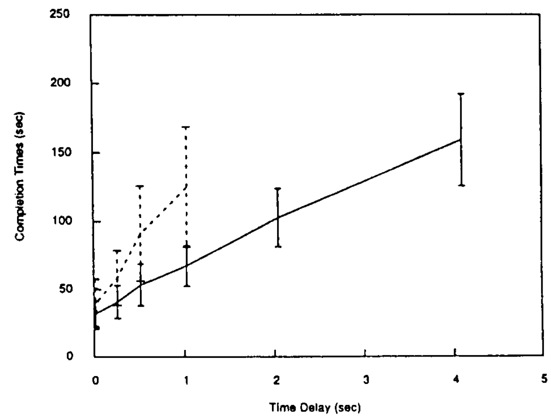


Fig. 14. Bejczy and Kim results comparing traditional delayed force feedback (dashed line) to shared compliance control (solid line) without force feedback to operator. Data are averaged task completion times for six operators performing peg-in-hole task (From Bejczy and Kim, 1990).

the sum of a low-pass-filtered delayed force feedback and a high-pass-filtered predicted force feedback.

Buzan's results showed, among other things, that end-point impedance made a big difference in these tasks. The contact-and-grasp task was easiest with a soft end point compliance, while the slot task favored a stiff end-point. Buzan also found that the complementary force feedback proved difficult to use. When the visual predictor was used and was perfect, the predicted force feedback had a negligible effect on performance. When telemanipulation was blind, both the direct and the dual force feedback worked quite well, enabling the operator to do the tasks where he otherwise could not.

D. Compliance Control at Slave Site

In a traditional master-slave telemanipulator the slave is stiffly position-servoed to the master. While positioning movements in free space are achieved satisfactorily, those in close proximity to hard environmental objects are not, since, unless environmental objects are approached very slowly, the slave can collide with the environment quite abruptly and build up very large force transients which may do serious damage. For this reason it may be useful to set the position error servo gains to low levels so that if the slave collides with a hard object the actuator will "give" (have a soft compliance, not suddenly build up a large force).

Bejczy and Kim [14] implemented such a system in which the slave compliance is like a spring with programmable adjustment of the stiffness parameter. A six-axis force-torque sensor served to measure forces imposed on the slave. They experimented with force feedback to the human operator (after appropriate coordinate transformations, as their master and slave kinematics were not isomorphic) through a first-order low-pass filter. This gave the impression of feeling the slave hand forces through a spring and dashpot in parallel. Without the damper the system felt like a spring but was unstable. Without the spring sustained forces caused position drift.

These authors also experimentally compared a conventional and fairly stiff force-feedback master-slave system with a similar system having active compliance control but no force feedback. The task was essentially a repeated peg-in-hole task. The subjects apparently could stabilize the pure force feedback system manually for delays up to 1 s (presumably with imposed damping much as was illustrated in Fig. 1), but not at longer delays. Fig. 14 shows the average results for six subjects, indicating the clear advantage of the active slave compliance control, even with no force feedback.

E. Sensory Substitution

Massimino [31] experimented with delayed force feedback by auditory tones and by tactile vibrations in various teleoperation tasks. For example, for a task of inserting a rectangular peg into a rectangular hole, to indicate force from contact at the left or right side of the hole the tone sounded in the left or right ear (the subject wore earphones). To indicate contact at the top or bottom the tone was at high or low pitch. To indicate contact in a corner corresponding binaural and pitch cues came on simultaneously. An alternative tactile display of contact consisted of vibrators located at four points on the hand corresponding to up or down and (possibly simultaneously) to left or right. Fig. 15 shows a summary of Massimino's results for this peg-in-hole task for both obstructed and unobstructed views. The significantly better performance with the auditory display over the tactile display in the obstructed view case was a surprise, and the reasons were not clear. The significant improvement when either sensory substitution display was added to vision was also a surprise.

VI. Ameliorating The Time Delay by Wave Transformation

Stable control under the condition of a pure time delay within the control loop was studied by Anderson and Spong

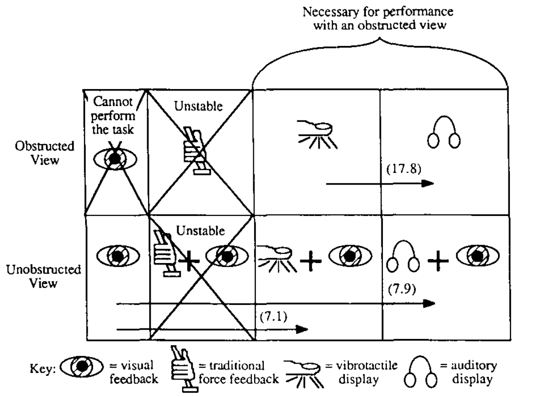


Fig. 15. Summary of Massimino's results [31] for sensory substitution for placement of peg in four-sided hole. Directional force feedback was received from contact with any side. Numbers on arrows indicate magnitude of improvement (seconds of mean time decrease) when changing in indicated direction.

[32]. They were able to validate a control law that compensates for time delay by wave propagation and energy scattering, much as an electrical transmission line remains passive in spite of pure time delay. Actually their scheme imitates wave variables as they might occur in positioning a mass from the other end of a rope which exhibits traveling waves. In effect the technique spreads the energy out in time so that the time delay no longer causes instability.

They showed that using such a scheme ensures asymptotic stability of manipulator joint velocities under the special circumstance of contacting arbitrary passive environments (thus coping with the problem of contact instability). Their result apparently accommodates nonlinearities in various DOF and allows for power to be gained between the human and the environment. In practice this suggests that force feedback in a teleoperator can be turned on automatically after contact is made, and that (apart from the problem of helping the human operator to achieve good closed-loop control) at least stability can be maintained.

Niemeyer and Slotine [1] further studied the problem in consideration of the Anderson and Spong results. They pointed out that using power dissipation to stabilize a teleoperator loop which includes a time delay, as illustrated in Fig. 1, requires continuous power input just to apply constant force to a remote environment or to receive constant force feedback. This will not allow master-slave position correspondence to be maintained and is not likely to be acceptable for other reasons. They propose ameliorating the effects of time delay by a direct transformation of velocity and effort variables to "wave variables" as shown in Fig. 16a. The output and input wave variables at the master are u_m and v_m, while those at the slave are u_s and v_s, respectively.

Niemeyer and Slotine [1] show that the desirable stability result has the concomitant undesirable effect that

$$\dot{x}_s(t) = \dot{x}_m(t-T) - 1/b[F_s(t) - F_m(t-T)]$$

and

$$F_m(t) = F_s(t-T) + b[\dot{x}_m(t) - \dot{x}_s(t-T)] \qquad (1)$$

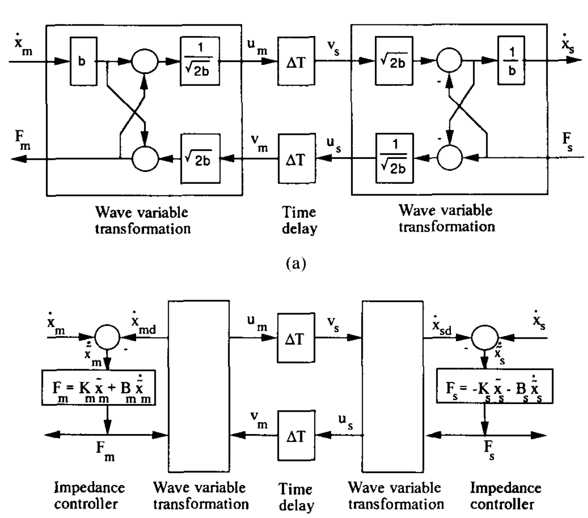


Fig. 16. (a) Time delayed transmission of wave variables. (b) Wave transmission providing velocity commands to both master and slave [1].

where $\dot{x}_m$ and $\dot{x}_s$ are velocities at master and slave, and F_m and F_s are forces at master and slave, respecively. In other words, the velocity tracking of the master by the slave is corrupted by forces at both ends, and the force feedback to the master is corrupted by the velocities at both ends. Velocity (position) tracking will be better if b is large, but force feedback will be worse.

These authors go on to deal with ways to attenuate the wave propagations and reflections at the master and slave terminals, which can cause undesirable vibrations. Impedance matching of the termination at each end to the impedance of the wave signals at the corresponding end provides the natural solution. This works if the required termination (as at the slave end of Fig. 16(a)) accepts a velocity command and produces a force response, such as is true of a viscous damper. Such a damper would be similar to the terminal damping shown in Fig. 1. This does, however, result in the slave having different momentum than the master.) However, the impedance-matching termination at the master end must accept a force command and produce a velocity response. This is shown by the authors to modify the original velocity command, which is normally unacceptable.

To rectify this problem Niemeyer and Slotine [1] propose that both master and slave ends be made to be velocity-control, i.e., have velocity inputs and force outputs. This is done by adding terminator impedances shown by the left-most and right-most blocks of Fig. 16(b), where the communications equations are defined by

$$\begin{aligned}
u_m &= 1/\sqrt{(2b)}[K_m(x_m - x_{md}) + B_m(\dot{x}_m - \dot{x}_{md}) + b\dot{x}_{md}]\\
u_s &= -1/\sqrt{(2b)}[K_s(x_s - x_{sd}) + B_s(\dot{x}_s - \dot{x}_{sd}) + b\dot{x}_{sd}]\\
\dot{x}_{md} &= [1/(b+B_m)][K_m(x_m - x_{md}) + B_m\dot{x}_m - \sqrt{(2b)}u_s(t-T)]\\
\dot{x}_{sd} &= [1/(b+B_s)][K_s(x_s - x_{sd}) + B_s\dot{x}_s + \sqrt{(2b)}u_m(t-T)].
\end{aligned} \qquad (2)$$

Here $\dot{x}_{md}$ and $\dot{x}_{sd}$ are outputs of the wave variable transformations. A position tracking experiment using this scheme showed the expected discrepancy between master and slave manipulator but otherwise was completely smooth and stable.

VII. Avoiding The Delay Problem by Supervisory Control

The notion of supervisory control first became apparent [33], [34] as part of research on coping with transmission time delay in planned space operations.

The human operator, instead of remaining within the control loop, can communicate a goal, and some instructions for getting there, over the delayed communication channel to the remote *telerobot* (a teleoperator with a computer capable of receiving, storing, and executing such commands automatically using its own artificial sensors and actuators). In this case, where the computer executing the operator's commands is colocated with the telemanipulator or remote vehicle, there is no delay in the closed control loop that implements the task and thus there is no instability.

In one sense this is just programming the computer. What makes it supervisory control is that the operator continually monitors and iteratively updates or modifies the program. Automation (loop closure through the computer, its sensors, and its actuators) is usually much faster than if the operator had to do the sensing, deciding, and controlling. Yet the human is still there observing and revising the instructions.

There necessarily remains, of course, a delay within the supervisory loop. This delay in the supervisor's confirmation of desired results is acceptable so long as 1) the delay is smaller than the time for task execution, 2) the subgoal is a conveniently large "bite" of the total task, 3) the unpredictable aspects of the remote environment are not changing too rapidly (i.e., the disturbance bandwidth is low), and 4) the subordinate automatic system is trustworthy.

As computers have become more capable both in hardware and in software, it has become evident that telemetry transmission delay is in no way a prerequisite to the usefulness of supervisory control. The incremental goal specified by the human operator need not be simply a new steady-state reference for a servomechanism in one or even several dimensions. Each new goal statement can be the specification of a whole trajectory of movements (as the performance of a dance or a symphony) together with programmed if-then-else branching conditions. It can be a specification in terms of the environmental objects to be moved and the goals to be met, rather than in terms of the teleoperator control signals or motions.

When supervisory control is defined to include *any* automatic loop closure at the site remote from the human operator, the parameters of which are resettable by the human supervisor, a number of relatively simple functions can be included. Coordinate transformations, sensor thresholds, and control gains are examples. When there is loop time delay, both predictor display and shared compliance control can be employed as decision-aiding enhancements to supervisory control, or can be used simply as decision aids for conventional manual teleoperator control to avoid instability and error.

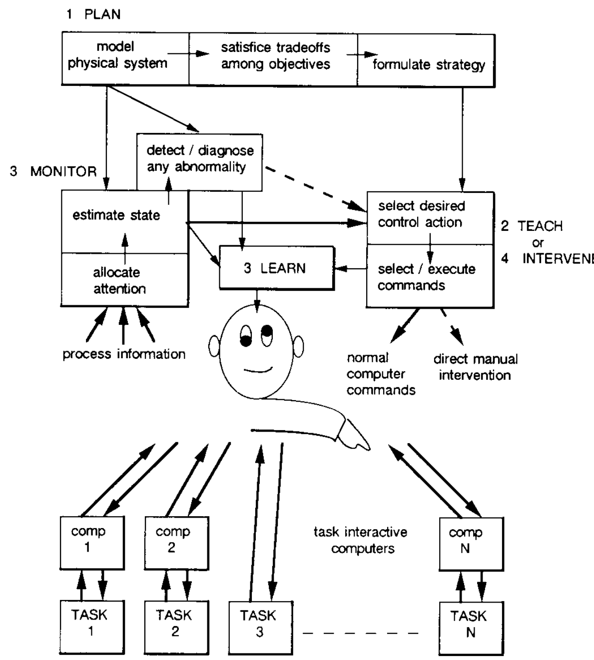
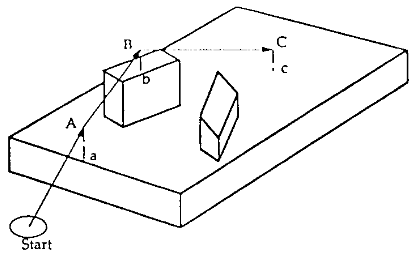


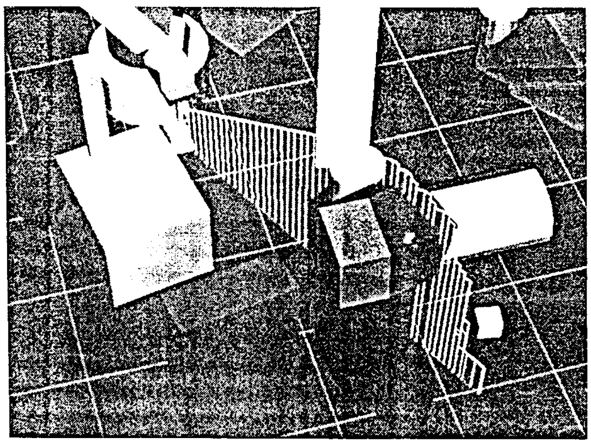
Fig. 17. Supervisory control paradigm.

A. More Robust Forms of Supervisory Control

There have been many demonstrations that supervisory control not only circumvents the time delay problem but also can speed up certain teleoperations beyond direct manual control even when there is no time delay (see, e.g, Brooks [35]). It is not the intention here to give an exposition on supervisory control. The reader is referred to [25] for a more complete exposition. However, Fig. 17 is provided to summarize the elements of supervisory control. It suggests that the human supervision of a telerobot, or indeed of any system having multiple control loops among which the operator must share attention, may be regarded as a sharing of human attention among many tasks (shown at the bottom of Fig. 17), each of which has its own local loop closure. The supervisory functions (at the top) are: 1) plan the supervisory actions (including acquiring an understanding of the physical system to be controlled, deciding on objectives, and working out a generic strategy that may include other exogenous factors; 2) instruct the subordinate computers of the plan (including both deciding on the action sequence and deciding how to program the computer to do same; 3) monitor the automatic execution of the programmed action (including deciding how to allocate attention, doing state estimation, and making sure there is no abnormality; 4) if there is an abnormality, intervene to correct the abnormality or abort to repair the problem; and finally 5) learn from experience.

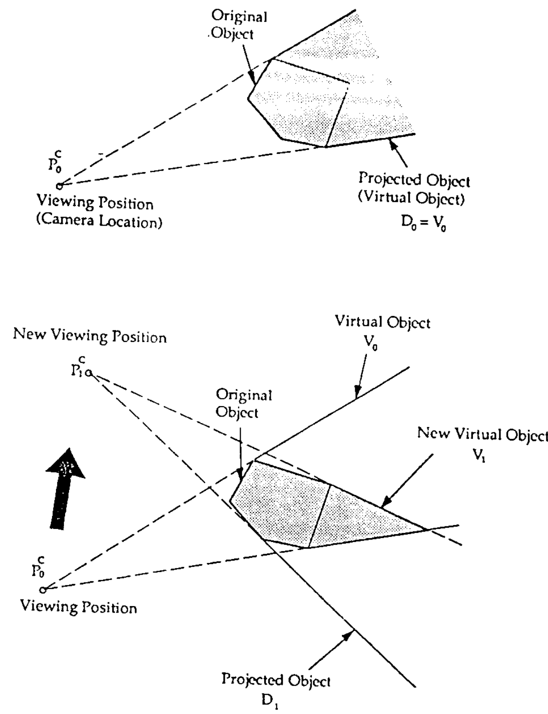


(a)



(b)

Fig. 18. Park's display of computer aid for obstacle avoidance. (a) Human specification of subgoal points on graphic model. (b) Computer display of composite planned trajectory with lines to floor to indicate heights. (c) Generation of virtual obstacles for single viewing position (above) and pair of viewing positions (below) [36].



(c)

Fig. 18. Continued.

B. Graphical Model Demonstrations for Trajectory Planning, Automatic Instruction and Error Handling

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 [36] these are regarded as *virtual obstacles*. At any time the computer can be called upon to display the updated field of obstacles (by using a trackball any viewpoint can be set in) and the human operator can suggest a trajectory of the vehicle and/or manipulator between the obstacles drawn on the computer screen (see Fig. 18). There are also some simple AI trajectory search heuristics which may be used. Then the computer immediately displays the tentative trajectory, shown with lines to the "floor" to provide a height cue. It is immediately evident 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 by the human, 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 prevented errors and sped up teleoperation considerably.

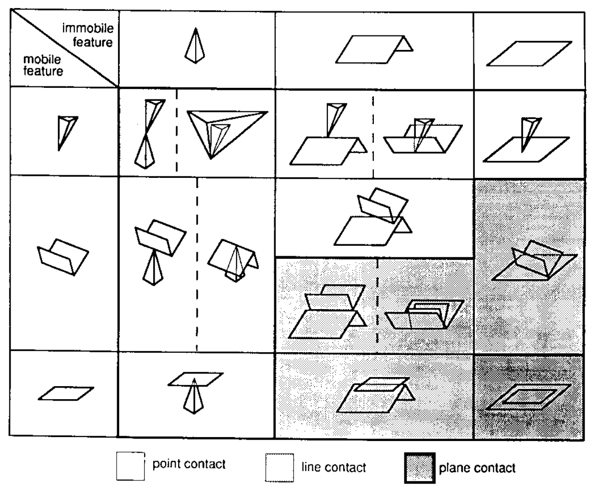


Fig. 19. Convex and concave polyhedral contact classes used by Funda *et al.* for automatic movement parsing and automatic command generation [37].

Funda *et al.* [37] extended the Machida *et al.* work [26] and the earlier supervisory programming ideas in what they call "teleprogramming." Again the operator programs by kinesthetic as well as visual interactions with a (virtual) computer simulation. That is, commands to the telerobot are generated by moving the teleoperator master while getting both force and visual feedback from a computer-based model slave.

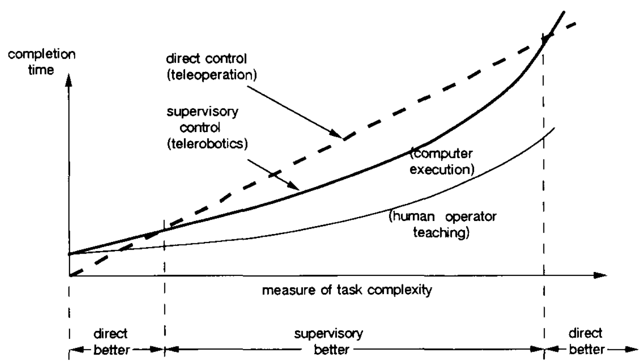


Fig. 20. Time allocation comparison of supervisory to direct control.

However, a key feature of their work is that instructions to be communicated to the telerobot are automatically determined and coded 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. Fig. 19 shows the classification scheme they used for parsing of movements.

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.

C. Needed Logistical Models

Any task performed under supervisory control requires time for the human to program (teach) the operation, and then time to monitor while the operation is being executed by the computer. Each of these components takes more time as the complexity of the task increases. There are many indices of task complexity. One might be the information content of movement selection plus the information content of move execution (see next section). Presumably, once the computer is programmed it can perform the task more quickly than the human could by doing it directly (or by teleoperation).

The human programming time and the machine (computer) execution times add to make up the supervisory control completion time (see Fig. 20, heavy line). This can be compared with the time for direct manual (teleoperated) control (broken line). For very simple tasks one might expect direct control to be quicker because instruction of a machine, as with that of another person, requires some minimum time. Common experience is that it is quicker to do some tasks yourself than to explain them to a helper. That means direct control beats supervisory control for the very simple tasks. As more complex tasks are encountered, there will be savings in going to supervisory control because the computer is faster at execution than the human (see, for example [35])—the broken line will cross the heavy solid line. However, when very complex tasks are encountered it is likely that the sheer difficulty of programming them and/or the complexity of computer execution will consume time at a greater rate than direct control, and the lines will cross back. This diagram, of course, is hypothetical, and curves surely would depend on many factors yet to be explored in a systematic way.

VIII. What NASA and Other Space Programs Should Do?

The obvious extension of task completion times caused by transmission time delay has discouraged control of space vehicles and systems from the ground. In relatively simple control tasks for unmanned space probes NASA has had no choice but to control from the ground. However, for performing more sophisticated manipulations for maintenance, for positioning of sensors, and for manning scientific experiments, they have been loathe to take advantage of what can be done by ground control in spite of the transmission delay.

However, as more and more devices are put in space, and as the needs for scientific experimentation and in-space maintenance increase, it becomes more and more desirable for humans to perform remote manipulation and control. If this can be done entirely from earth there are great savings in dollars and risk to life.

A. Mixing Techniques to Achieve Best Capability: A Growing Consensus

Mostly, operations in space need not be done in a hurry. Current space teleoperation on the Shuttle is very slow, even though the human operator views manipulations in the cargo bay from inside the Shuttle flight deck only a few meters away. Very gentle movements are performed mostly by joystick rate control without force feedback. Movements are carefully planned and rehearsed on the ground, and great care is taken before end-effector contact is made with environmental objects. Natural or haptic "feeling around" is not commonly done. For this kind of manipulation, visual time delay in the control loop does not cause significant instability or add much additional difficulty; it merely stretches the time, by a greater percentage as the movements become higher dimensional and involve contact. But considering the time it takes to get astronauts into space, and their limited working hours when there, urgency does not seem to be a major criterion.

For movements in free space, as noted above, predictor displays work well, and ameliorate the effects of time delay. For movements involving contact and assembly, predictor displays do not help much, but accommodation by soft compliance or impedance seems to be in order. This change from stiff position control for free positioning to soft compliance can be automatic upon close approach to contact, as suggested in several papers cited above, or it can be switched on manually as needed.

New techniques for transformation of control signals to wave variable propagation within the communications system offer interesting possibilities for preventing instability, but bring with them undesirable side effects of position mismatch and continuous drift. Amelioration is possible by adding termination impedances, but more research remains to be done in order to determine under what circumstances this is preferable to slow, damped movements, move-and-wait, or supervisory control.

Supervisory control in its various forms has been demonstrated in the laboratory, including coordinate transformations to effect resolved motion control (isomorphism between master and slave), automatic impedance changes, and predictor display. More robust supervisory control involving computer-graphic modeling, desynchronizing of commands from real-time process dynamics, and automatic command generation offer considerable possibilities for speeding up and improving control capability over what direct human control can do.

Thus, it seems, hybrid teleoperator (or, insofar as they are supervisory, telerobot) systems can be put into space with minimal additional cost and complexity over what telemanipulator hardware is now available.

B. Bandwidth, Reliability and Cost Considerations

For control of space telemanipulation from the ground, television from space to ground is the only significant consumer of bandwidth. Communication of control signals from ground to space is an insignificant addition. Space-hardened, high-resolution color television technology is now well developed and reliable.

Space teleoperator hardware is essentially the same whether control is from nearby or from a distance. Hence, were a communication channel made available specifically for teleoperation from the ground (such a channel was never designed into the Shuttle), there is no compelling reason why slow teleoperations cannot be achieved from the ground.

Continuing requirements are posed by the space science community for astronauts to tend experiments ("telescience"), usually making simple visual observations and performing simple manipulations. And there is discussion of a manned Mars mission, at a cost an order of magnitude greater than the space station. However, teleoperators and astronauts working together pose problems. The high costs of putting humans in space to perform inspection and manipulation tasks are exacerbated by having robots in the same workspace, since additional safety and reliability requirements must me met. Why not teleoperators which are caged when astronauts are nearby, but otherwise are fully utilized for construction, maintenance, and science tasks, and operated from the ground most of the time?

Even when operated in very slow motion, it seems that teleoperation has a tremendous cost advantage over astronauts for most tasks. There may be some tasks continuing to require astronauts in EVA, but for all the discussion, there remains little evidence demonstrating what teleoperators controlled from the ground cannot do, even over communication time delays.

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