REVIEW OF TELEOPERATOR RESEARCH

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This is a progress report of four current projects, all dealing with teleoperator control.

1. A NOVEL PREDICTOR DISPLAY FOR TELEMANIPULATION THROUGH A TIME DELAY

Remote operation of manipulators, vehicles or other devices 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 typically 0.4 seconds and for vehicles on or near the moon this is typically three seconds. It has been shown that the time to accomplish even simple manipulation tasks can increase by many fold, depending upon the time delay and the complexity of the task. This is because the human operator, in order to avoid instability (which is quite predictable from simple control theory) must adapt what has come to be called a "move and wait strategy", wherein he commits to a small incremental motion of the remote hand or vehicle, stops while waiting (the round trip delay time) for feedback, then commits to another small motion, and so on. To control continuously is literally not possible.

Because of this problem, requirements for control by human operators has required astronauts to do such controlling from nearby locations in orbit themselves, i.e., where signal transmission delays are very small. However, as more and more devices are put in space the requirement will increase for humans to perform remote manipulation and control, and if this can be done entirely from earth there will be great savings in not having to send humans into space. Thus the problem is how to make such remote control more efficient.

A similar problem is encountered with remote operation of manipulators and vehicles in the deep ocean from the surface if acoustic telemetry is employed, where sound transmission is limited to around 5000 ft/second in water. Except for the time delays and energy dissipation such acoustic telemetry is an attractive alternative to dragging many miles of wire cable through the water.

"Predictor displays" have been implemented where cursors or other indications are driven by a computer which extrapolates forward in time, based upon current state and time derivatives (Taylor series extrapolation). These have been employed in gun sights and "head-up" optical landing aids for aircraft pilots. Such techniques are adequate for continuous control of vehicles, but not for "move-and-wait" control through finite time delays. Further, in the case of telemanipulation, it may be necessary to predict the position of a number of parts, i.e., a whole configuration of a device, relative to the environment, beyond a simple cursor.

The system we have conceived, constructed and tested is designed explicitly for control of a manipulator or other multi-degree-of-freedom device through finite time delay. The technique is made possible by new commercially available computer technology for video display which we have used for superposing artificially generated graphics on to a regular video picture (Figure 1).

The video picture is a (necessarily) time-delayed picture from the remote location, generated as a coherent frame (snapshot) so that all picture elements in a single scan are delayed the same. (Otherwise the lower part of the screen would be delayed more than the upper part). The computer-generated graphics is a line drawing of the present configuration of the manipulator arm, vehicle or other device. The latter is generated by using the same control signals which are sent to the remote manipulator (device) to drive a computer model of it. The computer model is drawn on the video display in exactly the same location as where it will actually be after a one-way time delay and where it will be seen to be on the video after one round-trip time delay. Since the graphics are generated in perspective and scaled relative to the video picture, if one waits at least one round-trip delay without moving, both the graphics model and the video picture of the manipulator (device) are seen to coincide. Using such a display operators can "lead" the actual feedback and take larger steps with confidence.

Experiments were performed with trained human subjects performing various telemanipulation tasks using both continuously updated video and buffered video (to intermittently generate and hold each video frame). The predictor technique proved to work well and has been shown for time delays in the 1-3 second range to reduce completion times for a variety of manipulation tasks by 50-150 percent reliably. It is still to be evaluated for longer time delays.

2. IMPEDANCE CONTROL

The common servomechanism provides position control: an actuator is forced in proportion to and to reduce a position error. When measured position corresponds to desired or reference position, the position error goes to zero and forcing stops.

Servomechanisms can also provide force control. Applied force is adjusted until the measured force matches the reference force.

Impedance control generalizes the relation between measured and actual to make the force-position relation (position being referenced to any fixed point in the environment) conform to whatever relation is desired. It may be desired that the relation between teleoperator hand and a fixed point environment be like a soft spring. It may be desired that it be like a

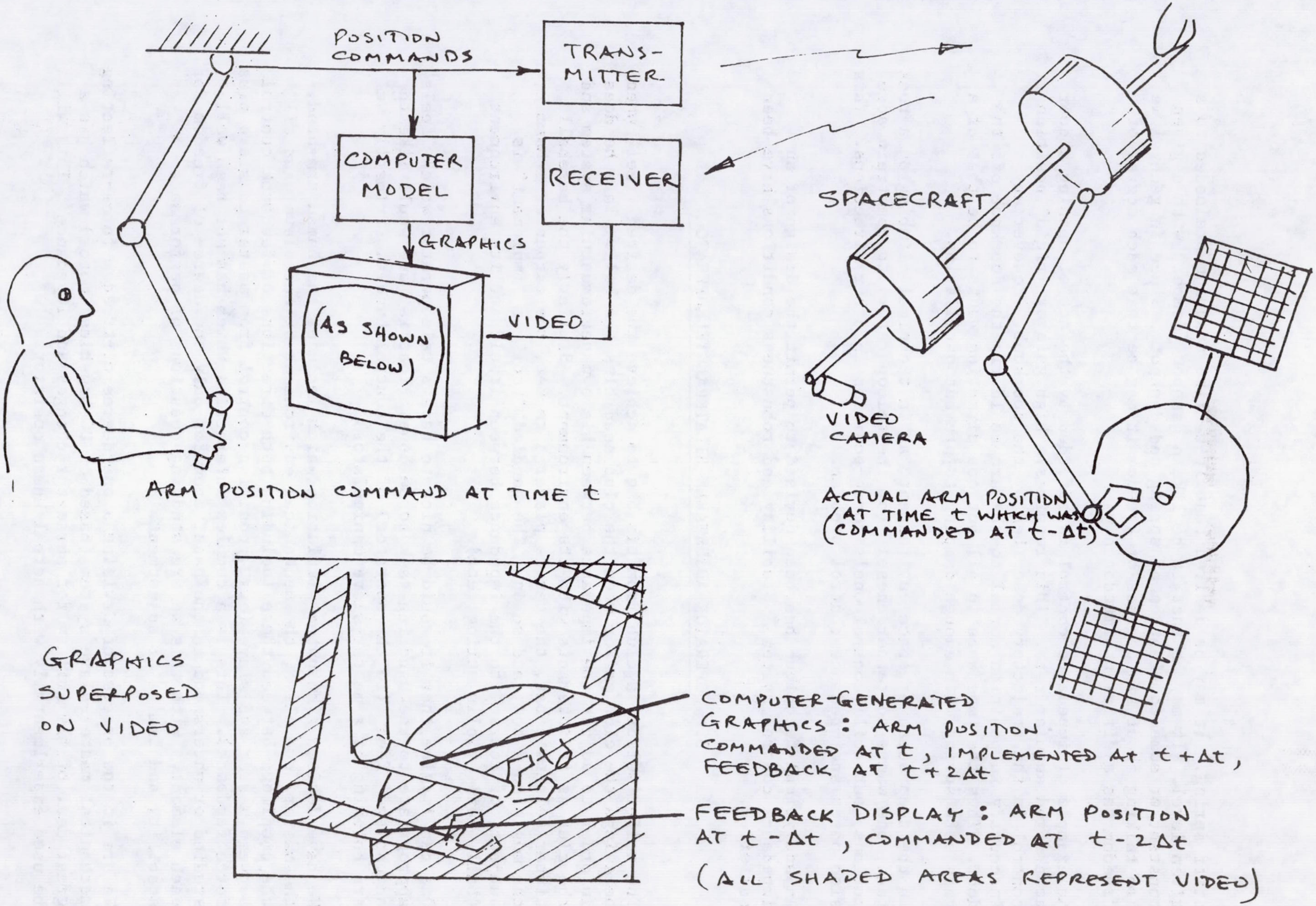

FIGURE 1. SYSTEM FOR REMOTE CONTROL THROUGH TIME DELAY

stiff spring. It may be desired that it be like a spring preloaded to a given level. It may be that it be like a dashpot (damper) with a given constant or some combination of spring and dashpot. Since in general we are talking about six degrees of freedom it may be that each degree of freedom has a different impedance.

An example of impedance control is afforded by the act of opening a door at a fixed angular rate. This requires a high gain or "rigid" position control in the trajectory described by the doorknob. However any inaccuracy in position normal to the arc could rip the doorknob off the door. Thus the impedance in all but one direction wants to be that of a very soft spring with enough damping to prevent oscillation.

In the deep ocean or space environment, as in technical climbing on a rock face, one wants to tether oneself (or the teleoperator) to constrain some motions, but still control one's force-position in other directions. This also poses an impedance control problem.

An analytical technique has been devised to permit the design of an impedance control system.[2] Stability and robustness conditions have been satisfied.

3. OPERATOR ADJUSTABLE BILATERAL TELEOPERATOR

The golfer selects a club from his bag to achieve the desired "feel" when he swings the club and/or when the club head hits the ball. This he does in order to adjust the impedance between his own neuromuscular system and the club as it interacts with its environment. Similarly the baseball hitter selects a bat, the tennis player a racket, the carpenter a hammer, the musician a bow, and so on. The handled "tool" or "implement" is subject, of course, to the impedance between itself and its environment (ball, nail, violin string, etc).

One can imagine that it would be nice to have a teleoperator which "feels" appropriate to the handling task to be done. That is, one would like to adjust the "feel" (to the operator) of the control handle. (Primarily we are thinking of a master-slave manipulator).

We have devised a computer simulation which includes the human arm-hand, the master, the slave, the mechanical environment of the slave, and all the couplings between these including both directions of feedback control between master and slave (e.g., position control from master to slave plus force feedback). This is a complex interaction which has not been well studied or understood in the past, even for only one degree of freedom for each element. With this we are studying questions of performance stability and limits of adjustment.

We are in the process of devising a one-degree-of-freedom force-reflecting mechanical master-slave system (based on DC brushless motor) which has a great deal of flexibility for parameter changes and impedance. This will be used experimentally with actual human operators.

4. SUPERVISORY CONTROLLED SUBMARINE-MANIPULATOR

An unmanned submarine is being constructed and is expected to undergo initial supervisory control trials this summer, first in a tank and then in the Atlantic Ocean.

The vehicle, which we call Sea Grant I, is actually a reconstruction of the Perry Oceanographic RECON 5. It is approximately 2 1/2 meters in length, weighs approximately 300 Kg, has five individually controlled hydraulic motor thrusters to allow control effectively in all degrees of freedom excepting pitch and roll, has on-board compass, inclinometer, sonar altimeter and a microcomputer.

A video camera can be controlled in pan and tilt. A novel parallel link six-degree-of-freedom manipulator is being designed for its front end. Both are controlled with hydraulic motors.

The onboard computer is connected through 1000 feet of tether to a second microcomputer on the surface, through which the human operator will give supervisory commands. The language structure will be based in large measure on the recently compiled supervisory control structure of Yoerger.[5]

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