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**New Concepts in Tele-Autonomous
Systems**

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NEW CONCEPTS IN TELE-AUTONOMOUS SYSTEMS*

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ABSTRACT

We have taken up the challenge of integrating telemanipulation technology and autonomous system technology. We are seeking methods for integration at a fundamental rather than an ad-hoc level. We believe that success in this effort can open up new space and defense applications now beyond reach of either technology alone.

In our presentation at this symposium, we introduce a series of concepts for "tele-autonomous" systems. The concepts involve new system architectures and associated new system interface controls including "time clutches", "position clutches" and "time brakes".

Taken together, the concepts enable effective, efficient intermingling of real-time cognition and manipulation tasks performed by either humans or machines. The concepts also yield simple mechanisms and protocols for handoffs of such tasks between multiple agents.

In this presentation we focus primarily on the tutorial introduction of the basic tele-automation concepts. We then briefly describe our environment for exploring this new technology and the results of our initial experiments. Further details concerning tele-autonomous system architecture and our initial experimental results can be found in an attached reference [CON87].

* This presentation is based on recent work described in a paper [CON87] to be published in the Proceedings of the IEEE International Conference on Robotics and Automation, March 30, 1987. A preprint of that paper is included with this AIAA/NASA/USAF Symposium preprint. Our presentation is further supplemented with a University of Michigan Robotics Research Laboratory video-report [CON87a].

INTRODUCTION

We are seeking simple, generic methods for intermingling and integrating telemanipulation and autonomous systems technology. Now, you might ask, why would we want to do that?

First, we wish to provide more effective systems for autonomous environmental manipulation. Consider an AI cognition system embedded within an overall perception-cognition-action system. Many tasks of interest will involve perception-cognition-action computing delays on the order of fractions of a second or seconds. How can we deal with such delays, when the basic behavioral acts to be done to complete a manipulation task themselves require only on the order of fractions of a second or seconds?

Presently we require substantial environmental knowledge and then piece together preprogrammed forms of interactions to cope with such delays. When that isn't possible, we fall back on a rather halting, stumbling form of perceive-think-act cycling, where the perception to action delays are contained in each basic behavioral act. Could we get around this somehow? After all, animals often perform manipulations with the aid of visualizations out just in front of their real time actions. Could we mechanize something like that?

The second challenge is to provide protocols for the interaction between multiple autonomous manipulation agents. Consider an ALV driving down a remote road. It suddenly encounters uncertain footing, and doesn't have sufficient exploratory behaviors and learning capabilities to get itself out of trouble. We know that AI will not soon be able to handle all the cognitive tasks and especially not all the manipulation tasks to get an ALV out of this kind of trouble. But how can we enable a human to easily "slip into the cockpit" and take over in mid-manuever

in such situations? How are they to perceive the local task goals and judge whether they are making progress towards them? And how are they to hand the task back to the machine?

This intriguing example illustrates the need to bridge the gap between direct human control and AI control of manipulation systems, and the need for handoff protocols between autonomous agents, whether human or machine. It is suggestive of the larger space of such examples, many of which are emerging in the machine intelligence research programs now underway under DARPA's Strategic Computing Initiative [DAR83], and emerging as a result of NASA space station automation activities.

The basic challenge in such examples is how to structure the actions and interactions of intelligent, goal-seeking systems when their activities are at least in part based on their physical manipulations of their environment rather than simply on symbolic communication. The challenge is how to mediate the interactions of cognitive agents that are embedded in perception-cognition-action systems.

Certainly there are a lot of ad-hoc, task-specific systems being built that do interact effectively in very narrow contexts. But such ad-hoc systems, while individually useful, do not readily generalize to provide a basis for others to build upon. Could we find some simple, general ways to think about the problem? Could there be some basic, generic protocols on top of which we could construct more uniform systems? We think the answer to these questions is yes.

BASIC TELE-AUTOMATION CONTROLS

We now present a sequence of interface control concepts that collectively enable efficient control of manipulation tasks and that enable simple protocols for exchange of such tasks between control agents. This paper focusses on tutorial development of the basic functional ideas. For details on architectures to mechanize these concepts, see [CON87].

We begin by looking via video link over the shoulder of a telerobotic manipulator, and controlling the manipulator via a joystick as shown in Figure 1. We are to perform the simple task of touching in sequence each of a series of boxes. This task's difficulty is some function of the ratio of the distance between consecutive boxes and the sizes of the boxes. The difficulty can be varied easily, and we can undertake various trials of performance as a function of system parameters. For example, we could do some simple trials to see if the time to complete the task is a logarithmic function of D/S, as in Fitt's Law [CAR83].

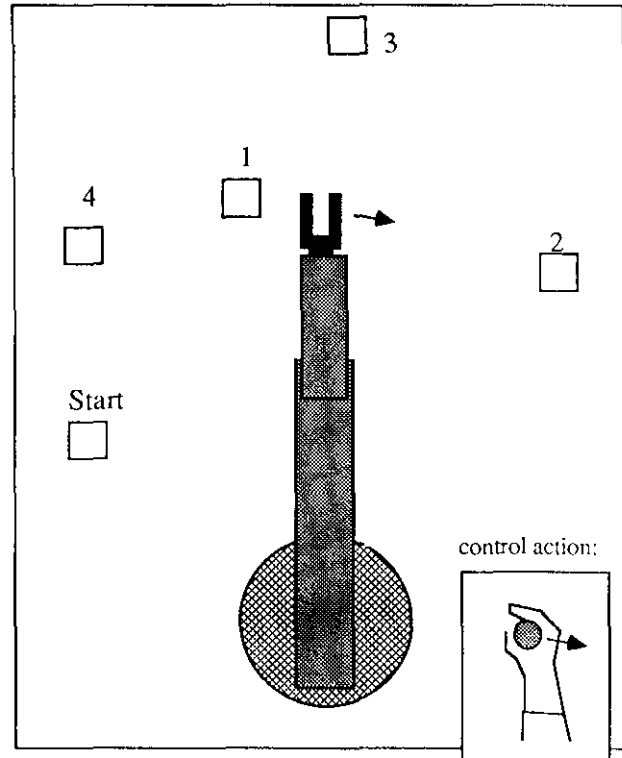


Figure 1. Visualizing a remote manipulation task

Coping with Time Delay

Because of our interest in remote space and defense systems, we visualize trying the same manipulation with a time delay inserted into the return video path. We find that the telerobot's motions then tend to be rather slow and jerky. The operator must move a little and then wait through the time delay to see what happened. As an illustration of this point, observe in the video-report the telerobot performing the manipulation task with no delay and then with a 2.0 second delay. The difficulties introduced by the time delay are quite noticeable. The time to complete the task is greatly extended. (Note that for convenience, we display a model of the telerobot using a Silicon Graphics IRIS workstation. The model is driven by the actual joint angles of the telerobot, and is thus equivalent to observing video of the real telerobot for our purposes here).

To overcome the time delay problem, Noyes and Sheridan [NOY84] have suggested that the operator control a local simulation of the telerobot, with the control signals then sent in parallel to the simulation and the remote telerobot. The simulation is then displayed superimposed over the return video. In this way the operator can "see" the effects of the control immediately without having to fully wait for the return signal from the telerobot. As a result, task time is reduced to nearly that of the no-delay case. (Noyes's and Sheridan's concept is further sketched in figures 2.1. and 2.2 in [CON87]).

Figure 2 presents a visualization of telerobotic manipulation using a forward simulation to cope with the time delay, as does the next segment in the video-report. The wire frame is the forward simulation that directly responds to operator control, and the solid frame represents the time delayed image of the real telerobot. Much faster and smoother control is achieved, as is evident in the videotape. This is a first step towards evolving machine manipulation visualization, since the visualization could help cope not only with communication delays, but also with computational delays within a self-contained autonomous agent.

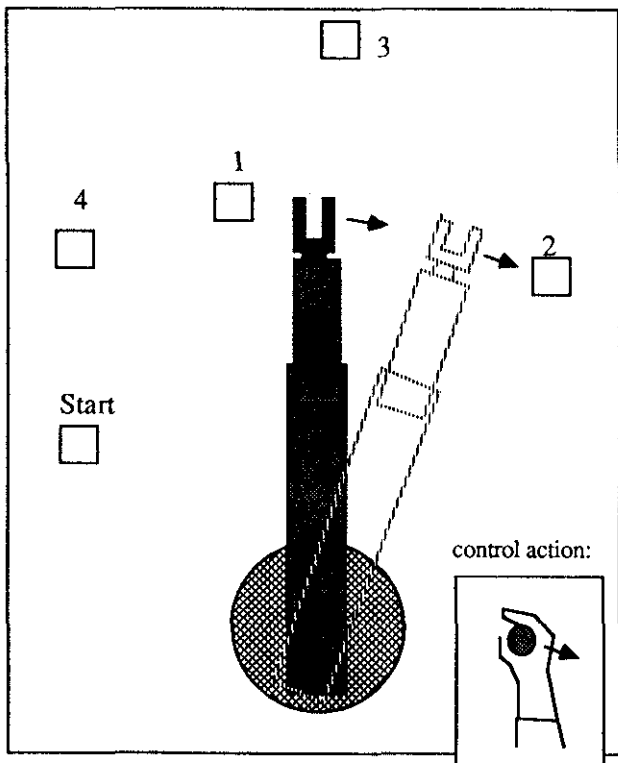


Figure 2. Visualizing manipulation through a time delay using forward simulation.

The Time Clutch

But, this first exploitation of real-time forward simulation is only the beginning. Forward simulation can also be exploited even if we don't have a communications time delay. To do this, we introduce the concept of a "time clutch" to disengage synchrony between operator specification time and telerobot manipulation time during path specification. Our hypothesis is that operators can often think of and generate a path segment more quickly than the telerobot can follow it. Once generated, such a path

segment can then be followed more quickly by the robot than would be the case if the robot were time-synchronized to the specification process; with time synchrony disengaged, the robot can steadily proceed at nearly its maximum rate, subject of course to error limits and hard constraints.

An overall diagram of the basic system architecture including the time clutch is contained in figure 3.1 in [CON87]. Figure 3 in this presentation shows a path being generated well out in advance of the actual robot by an operator using forward simulation with time clutch disengaged. The associated video-report also demonstrates the effects of disengaging the time clutch; if you put a stop watch on the action, you will measure a significant speed up of the real telerobot's motion from that obtained using forward simulation alone.

This step in the evolution of machine manipulation visualization enables the cognitive agent to "look and think ahead" of the manipulation under control, with the look-ahead time being elastic, and not just a fixed internal or external system time delay. The implementation of this new capability requires only a simple mutation of the forward simulation previously used for coping with a time delay.

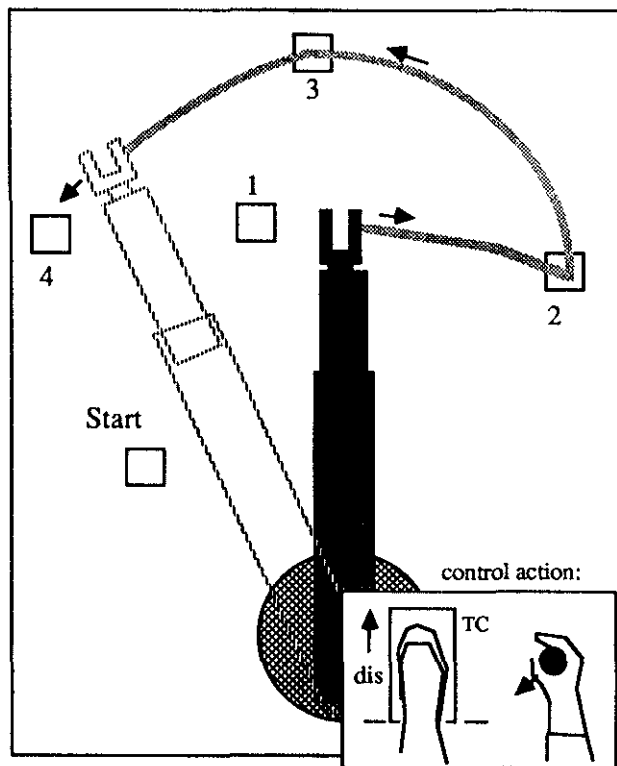


Figure 3. Rapid manipulation path generation using forward simulation with time clutch.

The Position Clutch

We next introduce the concept of a "position clutch" which enables a disengagement of position synchrony between simulator and manipulator path (see figure 3.1 in [CON87] for system diagram). We hypothesize that faster, shorter, cleaner paths can be generated on difficult tasks using this control. This idea is illustrated in Figure 4, which shows the use of the position clutch to disengage from path generation during a close approach to a difficult manipulation (in this case, touching a small object).

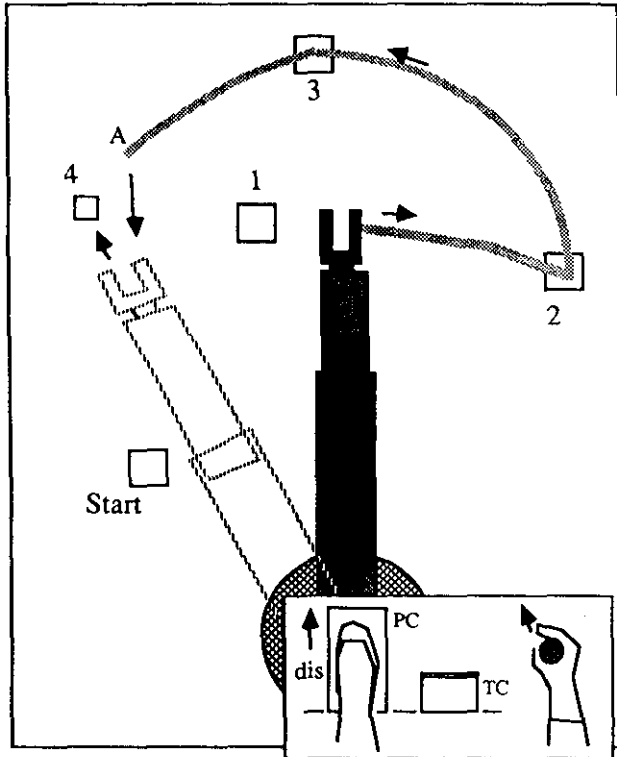


Figure 4. Using the position clutch to cope with a more difficult manipulation.

Suppose, for example, that the operator had arrived (in the simulation) at point A ahead of time by using the time clutch. The position clutch can then be disengaged, stopping the output from the operator control from going to the real telerobot - - it will only go to the simulation. When the forward simulator is in good position, the position clutch will be reengaged, causing a short, smooth path to be inserted that links to the earlier path. This avoids inclusion of jittery repositioning movements in the final path to be followed. Further, the time spent by the operator in achieving the proper position will not be incurred by the real telerobot since these motions were "clipped" out of the path sent to the telerobot.

The operator has thus used up some of the time saved through use of the time clutch, with the result that the overall task time of the telerobot is reduce still further. The next segment in the video-report illustrates this point. This level of manipulation visualization corresponds to quick "visualizations and visualized trials of multiple alternatives" prior to committment to action, and its implementation requires only another simple mutation of the basic forward simulation capability.

The Time Brake

To handle contingencies and errors we introduce the concept of a time brake. This control can be used to deal with situations such as something falling over a previously generated path, as illustrated by the "X" in Figure 5. In Figure 5 we see the time brake being applied and the forward-simulated manipulator backing down the path (in a race to get on the other side of the obstacle before the real system gets there). See figure 3.1 and the text in [CON87] for the associated system architectural concepts. The next segment of the video-report demonstrates the application of the time brake.

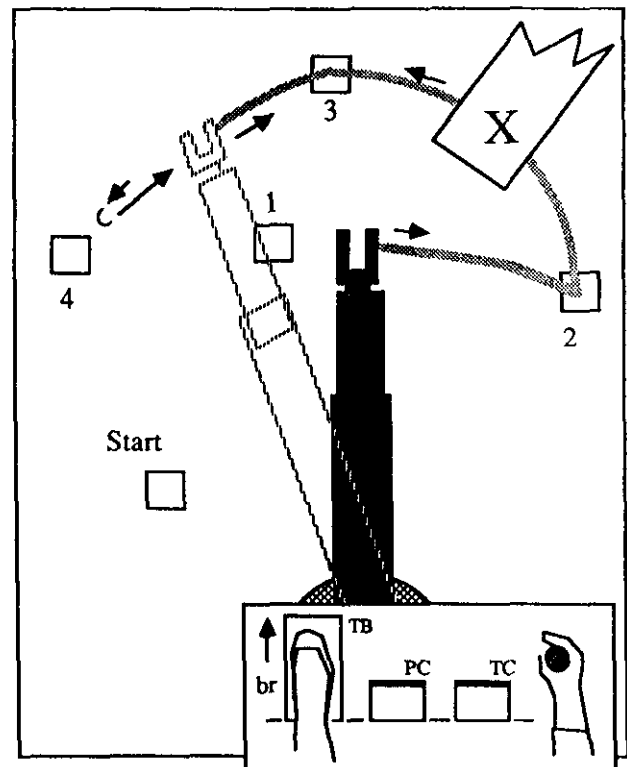


Figure 5. Using time brake to handle a contingency.

This aspect of visualization corresponds to seeing something about to happen that will interrupt an action previously visualized but not yet underway. If it had gotten underway, or is allowed to get underway, the system will have to deal with it through local reflex action or crash. But if visualized in time, the cognitive agent can withdraw the action using the time brake.

TASK HANDOFFS AND RENDEZVOUS

These basic tele-autonomous system interface controls enable us to greatly improve telemanipulation performances, as we'll see in the discussion of our initial experimental results. But the controls do more than that. They also provide the basis for a simple, elegant protocol for hand-offs and rendezvous of tasks between different control agents.

Imagine two operators, one in control of the telerobot and the other about to take over in relief of the first. Each operator would be in control of a simulation of the the telerobot, but only the controls signals of the first would be sent to the real telerobot. The relief operator would, with position clutch disengaged, guide his/her simulation as close to the first operator's as possible (or as close as required, as a function of the interpolation and smoothing methods to be used in the rendezvous). The first operator then disengages their position clutch, leaving the path "hanging". Figure 6 shows this moment in the interaction.

The second operator then engages their position clutch, rendezvousing with the path and taking control of future path generation. When the actual manipulator passes over this path segment, it will do so smoothly and will not notice that a change of control agent has occurred in mid-maneuver. We can again find interesting biological analogies to this visualization situation. For example, consider the interactions among basketball players as they previsualize fast-paced multiplayer interactions.

We believe that this simple protocol can be built upon to mechanize quite a wide range of manipulation interactions between autonomous agents. See for example the discussions in [CON87] concerning the various scenarios of "student pilot and instructor pilot", where we consider handoffs of manipulation and cognition tasks among humans, between humans and machines, and among machines.

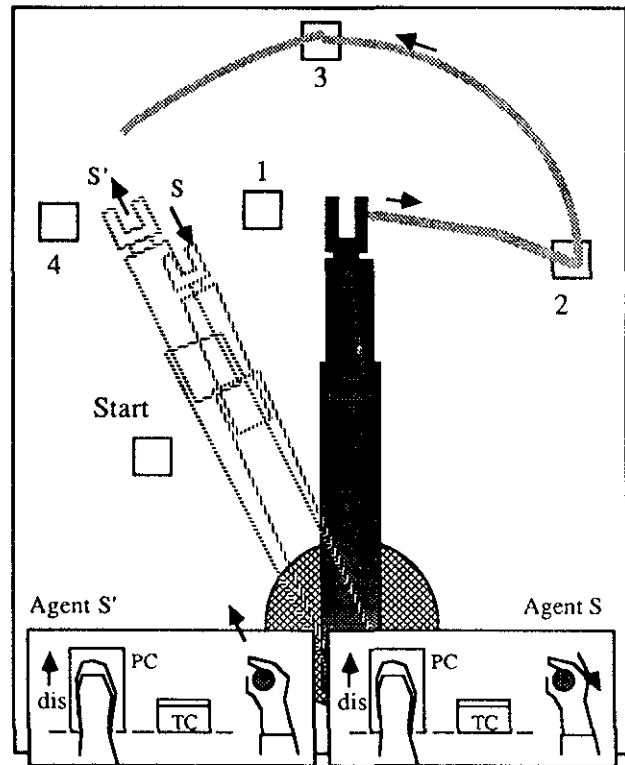


Figure 6. Using time and position clutches to handoff task to another forward simulation agent.

INITIAL EXPERIMENTS AND RESULTS

The manipulation tasks in our initial experimental trials consisted of having the telerobot touch a series of boxes of size S , each separated by a distance D . By varying D and S we produced tasks over a range of difficulties. Our goals were to test our hypotheses that the time and position clutches can improve the overall manipulation performance, and also to study the detailed functional relationship of task time vs task difficulty over a range of system parameter values. Analyses of such relationships may lead to principles for the design of future tele-autonomous manipulator systems.

We can take a closer look at our experimental setup in the video-report. You'll notice the solid robot image on the Silicon Graphics IRIS display corresponds to the real robot. To simulate the effects of communication delays, we insert a time delay in transmissions of information between the user control and the real telerobot. The user controls the telerobot through a joystick. The time and position

clutches and the brake are foot pedals on the floor. While either of the clutches is depressed, the corresponding synchrony is disengaged, and while the brake is depressed, the simulation backs up in time toward the real telerobot's position.

Each square block to be touched is placed a fixed distance D from its predecessor, but at a randomly determined angle. The tests were performed across a number of subjects, each performing each test a number of times with different random placements of the blocks. Results were first obtained with and without time delays for direct tele-manipulation (with no forward simulation), providing baselines for the remaining trials of the different modes of operation over a range of system parameters. The principle system parameters varied during these trials were:

- (i) Difficulty ratio D/S ,
- (ii) Manipulation size scale D ,
- (iii) Communication delay time,
- (iv) Mode of operation (with/wo clutches),
- (v) Robot joint angular velocity limits.

The resulting data on operator task specification times and robotic manipulation times are summarized graphically in figures 5.2 and 5.3 in [CON87]. In those figures we see that the times for manipulation in presence of delays are substantially reduced by forward simulation and then again substantially reduced by use of the new tele-automation controls. (Substantially means a time improvement of at least a factor of two). For some parameter values the use of the time clutch enabled operators to move out far ahead of the following telerobot. The use of the position clutch enabled operators to produce shorter manipulation path lengths on complex tasks. Demonstrations of these trials and also of handoffs using the position clutch are shown in the video-report. Refer to [CON87] for a detailed presentation and analysis of our experimental results.

RESEARCH PLANS AND ISSUES

We are augmenting our experimental environment to enable trials using additional forms of telerobotic manipulators and manipulation interface controls. We are further analyzing the sensory-cognitive-motor dynamics of the human-machine combination in efforts to generate additional testable hypotheses regarding factors affecting performance. We are also planning trials of simple autonomous activity, with the manipulations and handoffs being done under the control of AI planning programs.

This early tele-automation work suggests many opportunities for new interdisciplinary interactions

among those interested in human-computer interaction, robotics, and artificial intelligence. There are also challenges and opportunities concerning provision of appropriate experimental environments for such work in the larger research community. The provision of shared access to remote telemanipulation facilities might enable more researchers to collaborate on the evolution of such new technologies [CON87].

SUMMARY

We have begun to explore the integration of telemanipulation and autonomous system technology. We have created new concepts that enable substantial telemanipulation task performance improvements. These improvements are applicable to manipulations controlled by humans or by machines. Our initial hypotheses concerning performance improvements are well supported by our initial experiments. We have also demonstrated that the new concepts also enable simple, elegant protocols for handoffs of manipulation tasks between autonomous agents. We believe that a number of useful new space and defense applications can be based upon these concepts.

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TELE-AUTONOMOUS SYSTEMS: METHODS AND ARCHITECTURES FOR INTERMINGLING AUTONOMOUS AND TELEROBOTIC TECHNOLOGY

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ABSTRACT

As a result of recent advances in artificial intelligence, human cognitive modelling, autonomous systems and telerobotics, there is an opportunity to broaden our concepts of technology for projecting action at a distance. We draw on these advances to develop a conceptual and architectural framework that enables efficient projection in time and space of intermingled manipulation and cognition tasks.

Where AI-based autonomous systems have previously been concerned with human supervisory intervention primarily at a cognitive level, we add methods for rendezvous, capture and rehandoff of embedded manipulation tasks. Where telerobotics has been concerned with the projection of sensory-motor manipulation, we add the projection of cognitive processing. Thus extended, the two technologies mirror one another and merge into one of "tele-autonomous systems".

We introduce notions of how the sensory, cognitive and motor functions of tele-autonomous systems can be factored and transferred back and forth between human and machine. We illustrate how the times to complete tele-autonomous tasks can be reduced through time and space constraint relaxations effected through simple controls: We employ the concepts of forward simulation and predictor display, augmented by "time and position clutches", "time ratio controls" and "time brakes", to control the resulting manipulation paths and event transitions. We sketch some generic architectural and human interface implications of these methods. Finally, we describe our environment for exploring these methods and the results of some recent experiments.

1. INTRODUCTION

In this paper we draw on recent research advances in autonomous systems and telerobotics, and develop a framework for an integrated technology that enables efficient projection in time and space of intermingled manipulative and cognitive tasks. The technology builds a bridge between telerobotics and intelligent autonomous systems by providing methods for controlling real-time transitions between human and machine control of remote events.

In this introductory section we reflect on the paradigms of the telerobotics and autonomous systems research communities. We illustrate gaps in the two paradigms, and opportunities for technology integration, by describing practical tasks humans can do that would be hard to implement with either technology alone.

In the later sections of the paper we introduce functional concepts and terminology for "tele-autonomous" or "tele-automation" technology. We present architectural and control methods for implementing these concepts, discuss our experimental environment for exploring these concepts, and finally present the results of some recent experiments.

1.1. Paradigms of Telerobotics

Up till now the concerns of the telerobotics community have been primarily those of the roboticist and control theorist, dealing with sensing the physical environment, measuring positions, forces, and accelerations, and responding with movements and forces to directly manipulate the physical environment. The human provides the cognitive power of the system, with the human's sensory-motor processing intermediated and projected at a distance by the machine.

The coin of the telerobotics realm is manipulation. Support for telerobotics has come primarily from DOE for projection of manipulation capability into hazardous environments. Support has also come from NASA for projection of manipulation into the space environment, and from DoD for undersea applications. When teleroboticians discuss the projection of "autonomous intelligence" to remote mechanisms, the projected capabilities are usually envisioned as programs that can be invoked to independently carry out physical manipulation tasks while the human remains in contact and control at a supervisory level [SHE86].

A common goal of telerobotics research is the production of as realistic a sense of remote telepresence and telecontrol for the human operator as possible, given physical constraints such as communication delay times [NOY84, SHE86]. The goal is to enable operators to do as nearly as well at manipulation tasks as they could do if physically present at the remote location.

1.2 Paradigms of Autonomous Systems

Within the past few years, the U. S. Department of Defense has been supporting a rapidly growing autonomous systems research community [DAR83, DAV85]. This community's concerns are those of computer scientists and artificial intelligence researchers working to produce self contained, mobile platforms, such as the Autonomous Land Vehicle (ALV) [MAR86] and various autonomous undersea vehicles, that can maneuver around and employ machine cognition to seek high-level goals in their environments. The focus is on mechanization of sufficient cognitive power to achieve interesting goals, such as complex route planning and replanning to effect reconnaissance or force projection missions,

and on providing sufficient perception and maneuvering capability to do things like follow roads, avoid obstacles, and find things in the environment [DAR83, MAR86].

Given present limitations and computational complexity of self-contained machine perception (such as machine vision), the sensory-motor aspects of autonomous systems technology are currently rather crude when compared to telerobotics, which can exploit human perception. The community thus tends to focus on widening the exploitation of machine cognition on tasks that are feasible given the envelope of available perception technology, conducting a parallel effort on incremental enhancement of perception technology performance [MAR86]. The coin of this realm is cognition, and cognitive interaction with the environment at a symbolic level.

A common goal of autonomous systems research is the mechanization of cognition and the associated task-dependent knowledge systems so that the remote machine is as smart, robust, knowledgeable and persistent as a human might be in attempting to carry out its mission. Since the focus of the work is on autonomy, human supervision or interaction is seldom stressed. When the notion of supervisory control appears in autonomous systems, it usually is concerned with having the human intervene if the system is "not smart enough" to cognitively handle a given situation [MAR86].

1.3. Illustrative task examples.

The following task examples shed light on our problem space, and suggest opportunities and methods for blending telerobotics and autonomous systems. Consider text editing on a workstation. A human operator can often envision and generate the command sequence to achieve a local goal much faster than the workstation can effect the screen manipulation. Thus the human may quickly "type or mouse ahead" (assuming the control stream can be buffered), then shift their cognitive or manipulation attention to the task to be done when the machine catches up [CAR83]. In contrast, in teleoperation systems the operator is often "slaved in real-time" to the local and remote sensory-motor apparatus. Can we imagine a telerobotic analogy to type-ahead?

An extension of "type ahead" occurs when the operator has constructed their own, perhaps intelligent, high-level commands such as "sort this list", or "send a message to X to get the address of Y". The operator may then type ahead at a rather high level, with each command in the sequence performing not just physical manipulations but also elaborate symbolic manipulations of the environment to eventually produce the text. Again, can we imagine a telerobotic analogy?

Or, imagine that you are learning to fly in aircraft that has dual controls. On a given flight your cognition may be just fine, but you suddenly fail to manage a manipulation task, and the instructor takes over. By analogy, an autonomous system might be doing fine in its cognitive tasks, but might need occasional human help in its "lower-level" manipulation tasks. For example, an ALV might run off the road and get stuck, and require a skilled "teledriver" to free it; this is quite a different form of intervention than the "mental" supervisory intervention usually envisioned by ALV'ers.

Intervention into an ongoing autonomous manipulation task may not be easy, since taking over in mid-maneuver may involve smoothly effecting a multidimensional control rendezvous. You can study a simple form of this situation by interacting with the cruise control of your automobile.

The dual-controlled aircraft story yields several scenarios that have interesting autonomous system analogues. The instructor can coach the student on various sensory-motor manipulation tasks, and on various cognitive tasks such as interpreting instrument readings. Visualize the piloting coach as a human supervisor, and the student as a remote autonomous system: The coach can take over either cognition (correcting an instrumentation interpretation) or take over lower-level manipulation (prevent an unwanted stall). There is a matrix of possible division of responsibilities. Sensing, thinking, and acting can be separately assigned and reassigned at any moment to either the supervisor or the system.

But what are the embedded protocols that make such human practices feasible? What shared knowledge is involved? How are the transitions performed? How do both student and coach know who's doing what at any moment? To make the picture even more interesting, consider the fact that the overall system has full duality: the role of coach and student is reversible under some situations. Could such insights have architectural implications for general autonomous systems?

1.4. Merging the augmented paradigms

Can we somehow build a solid bridge between these two technologies so as to merge them? We believe the answer is yes, as discussed in following sections. We also suggest that qualitatively new kinds of functions and new opportunities for performance improvement appear as a result.

2. BASIC TELE-AUTONOMOUS SYSTEM CONCEPTS

Consider either a teleoperator or a supervised autonomous system consisting of (i) a human, and (ii) a machine that is partly local to the human and partly at the remote site of intended projected activity. Among the concerns of architects of such systems are: In specific situations, what is the human best at? Worst at? What is the machine best at? Worst at? How can we shift control between human and machine to exploit these capabilities? Are there generic architectural principles to draw on? What are the constraints on ultimate performance? What traditional constraints can we find ways around? In this section we will explore these questions to develop step-by-step some basic functional concepts for tele-autonomous systems.

2.1. Expanding the functions of telerobotics

Let's first reexamine some of the architect's questions from the "tele-autonomous" point of view. One important constraint on performance in certain key applications is the time delay for communications between the local and remote system. Noyes and Sheridan [NOY84] have innovated and demonstrated a very novel way to cope with such a delay, by using a locally situated forward-in-time telerobot simulator, and a graphical "predictor display" overlay of the forward simulation onto the fixed-delay return video of remote teleoperation (Fig. 2.1). Such forward simulation enables an operator to move the controls and immediately visualize the effect of control action without waiting for the return video. Their experiments show that the time to perform manipulation tasks in the presence of communication delays can be reduced by exploiting such predictor displays (Fig. 2.2).

But instead of just finding ways to better cope with constraints, can we also find ways to relax some constraints? Suppose we had a forward simulator and predictor display, but were not operating through a large time delay. Although we needn't enter commands prior to the observed time of their remote execution, we still might want to do so, and we could

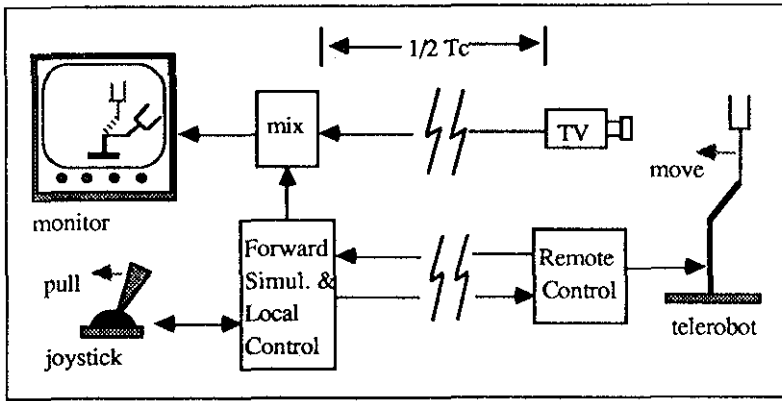


Figure 2.1 Using forward simulation and predictor display to cope with time delay (after Noyes and Sheridan).

use a modified version of forward simulation to do so. For example, we might be able to enter commands a lot faster than the telerobot could carry them out, as in "type ahead". Graphical overlay of accelerated forward simulation enables us to do this, and to then manage the cognitive limitations of short term memory when commanding in advance of observed effects. Such simulation can be augmented by including kinematic and/or dynamic forward simulation of portions of the environment. The result is a sort of coordinated "faster than real-time recording, and then real-time playback" form of manipulation control.

There appear to be a number of ways that displays of simulation overlain onto telerobot video can relax telerobotic time-synchrony constraints, yielding possibilities for improvements in manipulation time performance. We also hypothesize that freeing the operator from the "time-slaving" and attention constraining aspects of time-synchronized control may make a qualitative difference in the subjective "feel of the controls" of such systems, making them more like the controlling of one's own limbs. This hypothesis may eventually be made testable by defining new measurements of performance and fatigue in new forms of telerobotic situations.

We can also visualize telerobotic manipulation as analogous to text editing, in that it is a series of sensory-motor limited tasks intermixed with cognitively-limited tasks. Thus in some situations we may be able to project intelligent cognitive functions into the manipulation world (analogous to the "go find the address" command during text editing) while continuing direct editing manipulations. Methods that relax the constraint of command-to-manipulation time-synchrony might enable operators to better intermix such tasks.

2.2. Expanding the functions of autonomous systems

The transfer of cognitive tasks between supervising human and remote machine is already a part of the autonomous systems paradigm, being based on past artificial intelligence work on human machine cooperation in areas like diagnostics, design, advising and coaching [HAY83]. Shifts between machine and human manipulation while the machine retains cognitive control have not usually been considered. However, these can now be seen as just a mirror image, role-reversed version of the augmented telerobotics described above. Any forward simulation, time manipulation and control methods that work there will apply here also. In both cases we must deal with control and human interfacing of rendezvous, capture and rehandoff of manipulation tasks between human and machine.

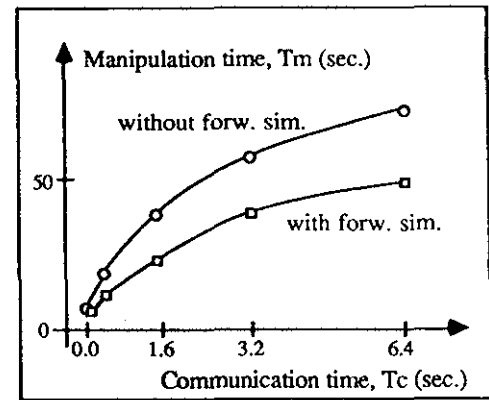


Figure 2.2: Manipulation time as a function of time delay, Tc. [HAS86, NOY84, SHE86]

As we discover control and human interface methods for such manipulation task transfers, perhaps we can also gain insights into how to better structure the methods for cognitive task transfer between human supervisor and autonomous system. Those methods are presently rather ad-hoc, being based on diverse applications experiences in AI. Finally, there is the human interface challenge of presenting "who has control, of what, and at what time and position?" The human may set goals into the autonomous system, and then later be called on to enter tasks to help the system reach either cognitive or manipulation subgoals. Can we use some sort of task lattice or tree, to represent and interface the distributed tasks underway towards goals and subgoals? New human computer interaction knowledge and technology must be developed to support these new possibilities for autonomous systems.

2.3. Integration of tele-autonomous function.

The distinctions between telerobotics and autonomous systems blur when the technologies are each expanded as discussed above. But we don't just get the sum of the two technologies. We get a technology with some new dimensions for enabling action at a distance. This leads us to wonder if we should revise the goal of telerobotics. Could it be possible to project manipulation capabilities to a distance that are better in time performance than those of the unaided human? Considerable research will be required to generate and test hypotheses to determine feasible performance improvements and limits of such an extended tele-manipulation technology. In addition to examining new aspects of robotics and control methods, this research will also enter previously unexplored areas in the psychology of human-computer interfacing.

3. TELE-AUTONOMOUS SYSTEM ARCHITECTURE AND CONTROL METHODS.

In this section we describe methods for relaxing the operator to manipulator time-synchrony constraints usually found in telerobotics. The first key idea is the use of a "time-clutch" to enable disengagement of time synchrony during path planning. We extend this idea by adding a "position clutch" that allows forward simulation manipulation and positioning trials without generating path plans. We include a "time-ratio control", to enable variations in the ratio of simulation time to real time. We introduce the concept of a "time brake" to allow the forward simulation to be "braked" back in time to avoid unforeseen contingencies. We then

provide scenarios of how these new controls might enable operators of the augmented systems to achieve considerable time improvements in certain manipulation tasks. We also suggest how the augmented architectures enable easy transitions of control of cognition and manipulation tasks between human and machine, thus enabling integrations and mirrorings of telerobotic and intelligent autonomous functions.

3.1. Disengaging time-control synchrony using a Time-Clutch

We build upon the forward simulation and predictor display concept of Noyes and Sheridan as follows. Suppose we are using a telerobotic system as in Fig. 2.1. We augment the system with a control that we call a "Time Clutch". This control enables us to disengage the "direct gearing" or time-rate (but not absolute time) synchrony of simulated time and real-time, and move the forward simulator ahead as fast as skill and judgement will allow. The predictor display presents a forward path as a goal, that is as a sequence of point positions to be followed by the system as fast as is feasible. Note that the path could be generated subject to some settable mean error parameter, for example as a "tube" of given radius [SUH87].

The time clutch enables an operator to disengage from real-time, and manipulate ahead of the displayed video of the real manipulator by working the overlay wire-frame figure of the manipulator on the predictor display. Example situations where this would have benefit would be during slow movements of large space structures and in slow undersea vehicle manipulations. The operator can thus do the telerobotic equivalent of "type-ahead" and then perhaps slow down and carefully position for some tricky maneuver. We hypothesize that in many manipulation task sequences such time saving accumulations and later exploitations will be possible, thus reducing overall manipulation task times and also the fraction of the task time that requires operator involvement.

How can we implement the time clutch control? How is the system to determine the path as a function of time when the clutch is disengaged? The time clutch can be thought of as a simple switch used to make or break the connections within the kinematic/dynamic robot simulation that would normally constrain the rate at which the forward simulator could be

slewed around in space. When the clutch is engaged, the position (or rate) joystick control of the simulator is sampled and directly controls the movements of a simulator model which is constrained in its movement rates and accelerations as if it were a real robot. A buffer is inserted between the simulator and the telerobotic manipulator, to hold the stream of sampled position increments as incremental "move to" commands (see Fig. 3.1).

With the time clutch is engaged, the command buffer presents a stream of position points at a fixed sample rate, and the telerobot can simply increment its position accordingly. But when the time clutch is disengaged, the distance between successive path positions may be greater than the telerobot can move in a time sample, and an interpolator is used to generate intermediate points along the path. This interpolator can always be active, with the only difference in function upon disengaging the time clutch being the breaking of simulator constraints on simulator velocities and accelerations. In sophisticated systems where telemanipulator touch sensing and force-sensing during interactions with the environment are reflected back to the manipulator operator, disengagement of the time-clutch must also disengage these reflected forces and substitute simulated forces generated by the simulator.

3.2 Disengaging position synchrony using a Position Clutch

In some cases, we may want to move the forward simulator in space without actually sampling the path, for example to pre-position for a complex manipulation. Thus we may wish to disengage the simulator from recording any positioning commands. To do this we disengage a "Position-Clutch" that allows forward simulation without path planning. This provides a positioning-synchrony constraint relaxation analogous to the earlier time-synchrony relaxation. In this case no position information is entered into the command buffer until the position clutch is reengaged, at which time the reengagement position is entered into the control buffer, and later used by the actual robot in path interpolation from the previous path position. If the real system catches up with a position-clutch disengagement point, it hits an "empty mark" in the command buffer and must wait for further path data to enter the buffer (see Fig. 3.1).

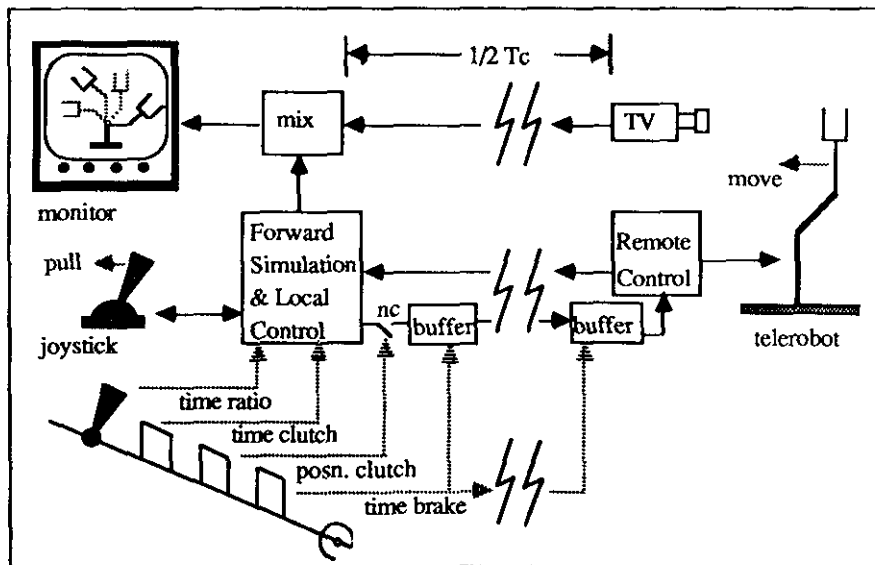


Figure 3.1: Using time and position clutches, time ratio and time brake to control forward simulation path planning in a tele-autonomous system.

Note that the time-clutch can be disengaged while the position clutch is engaged. But disengaging the position clutch overrides any actions of the time clutch. Reengaging the time-clutch after an interval of time-saving places the forward simulator and predictor display in much the same relationship to the remote unit as when operating through a time delay, with the operator directly generating a synchronized time and position trajectory in advance of the return video. In all these cases, use of time and position clutches can be superimposed over time delays in the communications between the local and remote machines (assuming adequate buffer capacity).

The command buffer can be constructed to hold more complex commands (in parallel) than just simple moves, enabling the operator to mark certain path positions as places where an embedded task is to be done. For example, suppose a switch must be pushed at some point along a path, and that the manipulation program for switch pushing resides in the remote controller. The operator might just mark the spot on the path when the forward simulator reached the switch (momentarily disengaging the time and position clutches and manipulating a screen menu entry signifying switch pushing). The telerobot manipulator (or remote vehicle, etc.) would then execute the task when it arrived at that point on the real path, i.e., when that path information emerged from the command buffer.

3.3. Scenario showing use of the Time and Position Clutches

A short scenario for using the two clutches follows: 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 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 be at the right place 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 display the new interpolated path segment) and wait for the remote system to catch up. We then begin the maneuver. In this way we (i) save some time, (ii) use the time saved to later reposition for another action, (iii) avoid taking the actual remote system through complex, manipulatively unnecessary repositioning movements, and (iv) do this all in a natural way through simple controls.

Note that the following of paths generated during time-clutch disengagements can be done by crude methods such as simple interpolations while keeping movements slow enough to avoid robot rate limits. Or it could be done by sophisticated methods that take into account the full dynamics of the situation and drive the remote telerobot at nearly its maximum feasible rate along the path, given specific actuator limits and desired mean-error limits. This defines a large tradeoff space in the computational complexity of trajectory generation vs the time-performance and robustness of the resulting manipulation.

3.4 Time-Ratio Control.

So far we have implied a 1:1 ratio of forward simulation time to real time when a tele-autonomous system is operated in time-synchronized mode (time clutch engaged). This needn't be the case. For example, we might be able to operate the simulator much faster than the telerobot can follow, and wish

to plan the path sequence in a synchronized, but scaled, time. So instead of using the time-clutch to disengage time synchrony, we might want to establish a low time-ratio between simulated and real time. But there also might be tasks that the telerobot can do far more rapidly than we could prescribe with the simulator. In those situations, if we had "saved up" some time, we could establish a high time-ratio of simulated time to real time and slowly perform a maneuver to be later done very rapidly by the telerobot (when it catches up to that section of the path).

These "time-ratio" scalings relating real-time to simulated time can be easily implemented and then controlled by allowing a change of time-ratio while the time-clutch is disengaged (analogous to changing the gear-ratio of a vehicle while the clutch is disengaged). The time-ratio then holds its new value until changed again during a later time-clutch disengagement. Time-ratio scaling should not be confused with operating while the time clutch is disengaged (where no fixed relationship is specified between simulator time to generate a path and telerobot time to follow the path).

3.5. Handling of contingencies by using Time Brakes

What are we to do if we are forward simulating way out in front of the telemanipulator and suddenly see (in return video) something intrude into the planned path of the manipulator? To handle such simple contingencies, we introduce a mechanism we call a "Time Brake". Depression of the time brake disengages the clutches and "decelerates simulated time" by incrementally extracting (LIFO) previously generated position commands from the command buffer. The forward simulator is correspondingly moved in reverse back down the path. This allows the operator to move (as quickly as desired) back in time along the forward simulation path until located in space on the earlier side of the obstacle. We also provide an "emergency brake" that "immediately" empties the command buffer and halts the telemanipulator (subject, of course, to overshoots due to manipulator compliance and/or dynamic constraint management, and to races against $1/2 T_c$).

3.6. Manipulation and cognition control-transitions and their mirrorings in telerobotic and supervised autonomous systems

The control methods described in this paper enable simple and smooth handoffs from local human teleoperation control to and from remote machine manipulation control (using downloaded manipulation commands). But they also provide a base-level protocol that enables easy mechanizations of the other types of transitions from local-control by human or machine of cognition-or-manipulation, to local-or-remote machine control of manipulation-or-cognition. Seen this way, the augmented teleoperation and autonomous systems mirror into one another to become tele-autonomous systems. Human or machine agents on "either side of the mirror" can exploit similar forward simulation and control handoff methods.

We hypothesize that human operators of this technology can learn to accomplish graceful and efficient hand-offs, rendezvous and recaptures of real-time thinking and manipulation tasks, and that human-or-machine cognition-or-manipulation operators can also exploit the forward simulation constraint relaxations to improve performance in many situations. Humans could thus supervise, or be dynamically embedded into, complex human-machine task lattices, taking and releasing control of subtasks at appropriate times and places.

For example, the tele-autonomous technology provides a framework that enables us to mimic the aircraft student-instructor scenario, with either student or instructor being machine or human, each undertaking sequences of cognition and manipulation tasks. Consider for example the situation in Figure 3.2., where we see a telerobot, R, following a path specified by a forward simulation, S, that is proceeding with its time clutch disengaged. The operator of simulator S then disengages the position clutch and moves S down and to the right. S is now essentially disengaged from any connection with the telerobot. At the same time, some other operator (human or artificial) is maneuvering another simulator, S', down towards the forward planned path (S' is also operating with its position clutch disengaged). When S' gets "close enough" to the point where S left off path planning, S' can then engage its position clutch, and take over control of the telerobot (subject to acquisition intermediation by arbiter or collision detect mechanism at the telerobot). The interaction controls can be factored from the actual manipulations through a small, but important, time increment. The two "players" can formulate and interact using shared visualizations and rapid cueing methods, much as skilled sports players learn to do. This simple example is suggestive of a number of more elaborate protocols and scenarios that can be constructed on top of the low-level hand-off and rendezvous protocol.

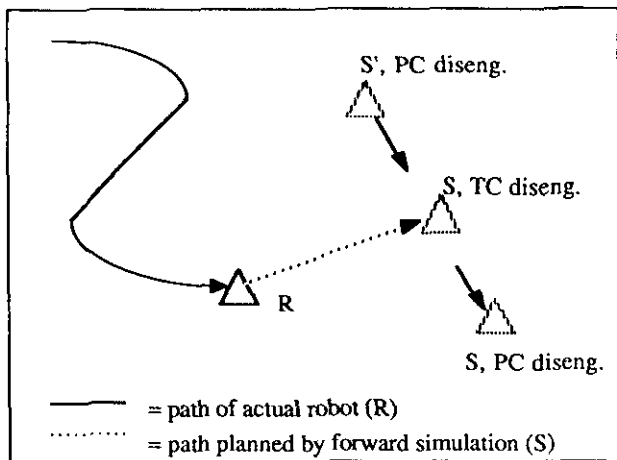


Figure 3.2: Using time and position clutches to "hand-off" and to "rendezvous" with a manipulation task.

4. INITIAL RESEARCH ISSUES AND HYPOTHESES

Our initial approach to tele-autonomous system research is to form hypotheses concerning the overall human-machine system much as current human-computer interaction work models unassisted human perceptual, cognitive, and motor systems. We then test these ideas by experiment. For example, Fitt's law [CAR83] predicts that the time for the eye-mind-hand task of touching an object of linear size S at a distance D is given by $T = K \log_2(D/S + 0.5)$, where $K \sim 100$ msec./bit. Therefore, simple tasks based on varying the relative sizes of objects, and the distances between objects, might produce meaningful trials of the various modes of tele-autonomous operation. Could performance operate under some sort of scaled Fitt's law in some modes? Or is it more complex than that? We could find out, and perhaps develop some insights and principles on how to best design such systems.

A simple 2-dimensional testbed can accommodate a wide range of such performance trials, such as the manipulation trial sketched in figure 4.1. In that figure, we see a number of "switches" of linear size "S" located in sequence at known positions in the manipulator workspace. Each switch is distance "D" from its predecessor in the sequence. The objective is to touch each switch in the sequence as rapidly as possible. Increasing the ratio D/S corresponds to increasing task manipulation complexity, possibly requiring more time for manipulation convergence, as abstracted in Fitt's law.

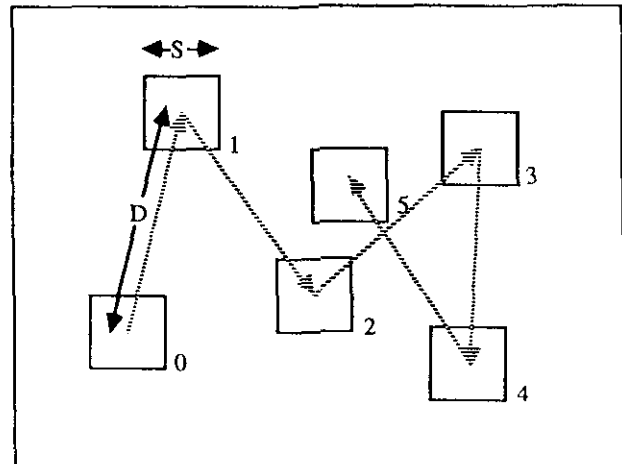


Figure 4.1: Simple testbed and example manipulation trial.

We can explore and answer many questions using this simple testbed. What is the functional form of the reduction in manipulation time, over direct teleoperation, that can be obtained when using the different augmentations of control? How are these functions and times affected in the presence of communications delays? How are the times affected by the difficulty of the manipulation targeting task (larger mean values of D/S). What are the effects of other system parameters, such as joystick force constants and robot velocity limits? What determines the percentage of the task execution time that the system operator needn't be in the control loop, so that they can be available for performing other functions?

The quantitative results of such trials can yield important early measures of the forms and dimensions of performance improvements possible with the tele-autonomous controls. The results can then help guide planning of further trials and the exploratory evolution of the technology.

5. EXPERIMENTAL ENVIRONMENT AND RESULTS

We are building a general experimental environment in which to create and evolve tele-autonomous technology. In this section we describe our initial facility and some early experiments with the different control methods. These early experiments are being done on transitions viewed from the telerobotic point of view, and provide the basis for planning later experiments in which we will study transitions from the various mixed telerobotic/autonomous systems points of view.

Our initial facility consists of a Unimation PUMA 560 used as a telerobot, controlled by either a DEC VAX 11/750 computer or an Apollo DSP90 computer (both modes are

available). A force and moment sensitive joystick is used as an input device to provide a rate input for the telerobot. To simulate a variety of real robots typical of those used in space or undersea operations, appropriate velocity limits are placed on each joint. To simulate remoteness of the telerobot from the operator, a variable delay can be inserted between a forward simulator generated control stream and the PUMA, using a buffer to hold the trajectory sample stream.

A high-performance Silicon Graphics IRIS workstation is used to generate and mix the display of the forward simulator and the telerobot, with the telerobot seen either in return video or as a graphics model (the latter can be useful since it is both easier to obtain correspondence between the overlay and the simulation and easier to modify the viewpoint of the system).

Simple time and position clutches have been implemented in the system. The logical operation of the clutches is portrayed as a state diagram in Figure 5.1., which shows the allowable combinations of time and/or position synchrony and the transitions between them. There are three allowable control states from the teleoperation point of view: 1) TSyn & PSyn -- time and position synchrony, 2) PSyn -- position synchronism only, and 3) NoSyn -- both time and position synchrony disengaged. Changes between these states are controlled by switches that operators push with their feet -- similar to the clutch in an automobile. The joystick moves the simulator in all three states, but the state determines the effect of simulator movement on path planning and path buffer encoding.

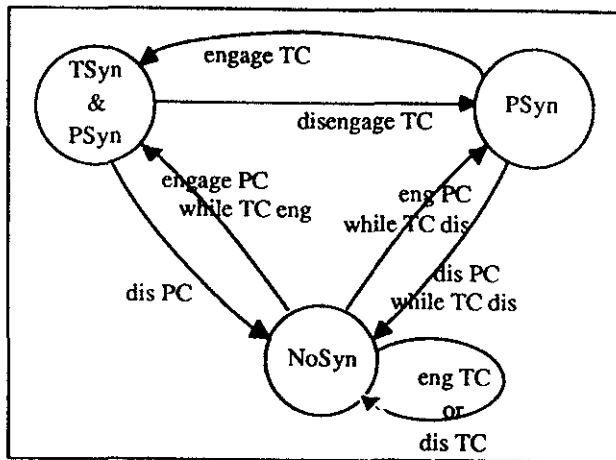


Figure 5.1: Diagram of forward simulator states and the transitions caused by time and position clutches.

A foot operated time brake is implemented which when pressed (i) disengages both clutches, causing an overriding transition to NoSyn, and (ii) begins deleting entries in the command buffer (LIFO), thus running the forward simulator back down the previously generated path.

In the time and position synchronized state (TSyn & PSyn), the force and moment outputs of the joystick are sampled at the input rate required by the PUMA. The forces and moments obtained are treated as vectors of desired velocities in Cartesian space. These are integrated to obtain position samples, and these samples are placed in the command buffer. While in time synchronized mode the buffer is emptied at the same rate it is filled, and the values obtained from the buffer are input to the PUMA system, which treats each sample

as a goal to reach in its sample period, by slewing any or all of its six joints. When we wish to simulate situations where the actions can be visualized and simulated much faster than they can be manipulated, such as when moving large structures in space [NAS81] or underwater, we place a selected angular velocity limit $W_j(i) < W_{jmax}(i)$ on each axis, i , of the PUMA

When the time clutch is disengaged, and the position synchronized (PSyn) state is entered, the robot-model physical constraints on simulation distance covered per time-sample are removed, and the usual joystick force and torque constants are multiplied by a gain constant, G_s , enabling the operator to rapidly slew the simulator. Path samples may be generated at varying wider path intervals than is possible when control is synchronized in time. Values removed from the buffer may thus request incremental moves larger than can be accomplished in one PUMA sample period, given selected constraints on the angular velocities of the PUMA joints. When this occurs, the commanded move is interpolated and spread across more than one PUMA sampling interval, with the actual PUMA rate of motion constrained as above by the selected joint angular velocity constraints. Thus, the simulated telerobot can be moved out along a path well ahead of the real telerobot, and we can "save up some time". In addition, the real robot follows this path at nearly its maximum rate, for a given set of values of $W_{jmax}(i)$. Thus we predict that the overall manipulation time, T_m , will usually be smaller using this mode than if there were a fixed ratio between simulation time and real-time (as for example in time-ratio control).

If a transition is made from PSyn to the unsynchronized (NoSyn) state, the operator becomes free to move the simulated telerobot without values being placed in the command buffer. Then, when a transition is made back to PSyn, the current position of the simulated telerobot is placed in the buffer. When this value is extracted from the buffer, the telerobot makes interpolated incremental moves directly towards that desired position, without going through all of the motions the operator had to use to get to that position. This enables "saved up" time to be used to "edit" out some real time and path motions used, for example, for complex repositioning.

5.1. Experimental Parameters, Trials and Results

In our first trials we used simple, random, 2-dimensional, 5-switch testbeds similar to that in Figure 4.2. We conducted a series of trials varying the following parameters:

- (i) Three different subjects (X, Y, Z) each performed a series of manipulation tasks using the testbed. Two times were recorded for each trial: The subject's time to specify the manipulation, (T_s), and the system's time to complete the manipulation, (T_m). We also recorded the actual manipulation path length, L_m . The ratio of L_m to the minimum path ($\sim 5D$) provides a measure of one dimension of operator skill).
- (ii) The series of switch-touching tasks varied from simple to difficult by ranging from low values of D/S to high values of D/S ($D = 500$ mm.; $S = 25, 50, 75, 100$ mm.).
- (iii) Communication delays, T_c , of 0, 2 and 4 sec. were used.
- (iv) Tasks over the range of difficulty and the range of communication delays were performed by each subject using: (a) direct teleoperation (TOP), (b) teleoperation assisted by forward simulation (TOP+FS), and (c) teleoperation assisted by forward simulation and time clutching (TOP+FS+TC).

During these first trials, other key system parameters were held constant as follows:

- (i) Workspace to monitor-screen length-ratio = 8:1.
- (ii) Joystick sample period = 0.017 sec.
- (iii) Joystick force constant = 0.01 mm per oz per sample period = 0.6 mm per sec. per oz.
- (iv) Joystick torque constant = 0.0012 rad. per oz-in per sec.
- (v) Joystick gain constant, G_s , in (TOP+FS+TC) = 4.0.
- (vi) Angular velocities of all 6 PUMA joints were limited to $W_j < W_{jmax} = 0.5$ radians per sec. (but see also below).

Other comments on our methods: The chosen constant values yield moderately responsive controls when moderate joystick forces and torques are applied. The angular velocity limits yield a moderately fast robot (slower than the PUMA can go at its fastest, but very, very much faster than a scaled shuttle arm). All subjects engaged in preliminary learning trials. All used the joystick "one-handed". Trials began after a period of preliminary learning. Comparable power-law of practice performance levels [CAR83] were recorded for each mode.

Results of some of these initial trials for one subject are plotted in Figures 5.2, which shows the specification time (T_s) and manipulation times (T_m) for tasks over the range of D/S difficulty holding $D = 500$ mm. Included are results for communication delays, T_c , of 0.0, 2.0 and 4.0 seconds. The results are displayed for the three relevant modalities of control, (a) TOP, (b) (TOP+FS), and (c) (TOP+FS+TC).

We note that a comparison of TOP and (TOP+FS) repeats experiments of Sheridan, et. al. [HAS86, SHE86], confirming the results of that work. We see that (TOP+FS) gives a significant gain in both T_s and T_m over TOP alone. Then we notice that (TOP+FS+TC) gives another significant gain in T_s

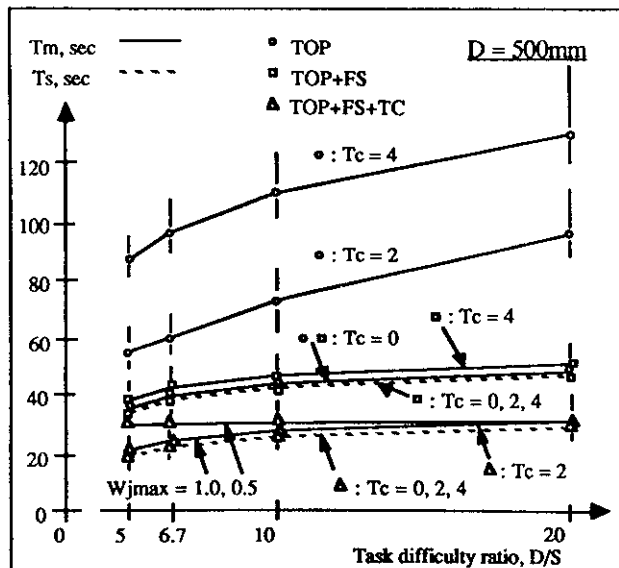


Figure 5.2: Initial trial results, showing T_s , T_m as functions of system and task parameters for three modes of control.

over (TOP+FS). In the initial trials, we found that $W_{jmax} = 1.0$ rad./sec. was high enough for the robot's T_m time to keep up with even the shortest (TOP+FS+TC) T_s times (see Fig. 5.2). We then found that $W_{jmax} = 0.5$ rad./sec. constrained T_m so that subjects could easily outpace the robot and save up time (see Fig. 5.2). Many of the initially hypothesized forms of results were demonstrated using these parameter ranges.

We then noticed that T_s and T_m grew less rapidly in D/S than anticipated. We hypothesized that $D = 500$ mm was large enough, given the joystick constants and W_j values, to produce dynamic constraints related to D and not just D/S. So we repeated scaled versions of these trials at smaller values of D .

Figure 5.3 shows the results for $D = 250$ mm and $S = 50$, 37.5, 25 and 12.5 mm. (with work to screen scale = 16:1, and $W_{jmax} = 0.5$). It also includes results using $D = 125$ mm and $S = 25$, 18.7, 12.5 and 6.2 mm (with work to screen scale = 32:1, and $W_{jmax} = 0.5$). These results are interesting, because for all three modes the data per mode at $D = 250$ mm and $D = 125$ mm essentially fall on top of one another. The 250mm and 125mm curves for each mode lie well below those for $D = 500$ mm. Refer Fig. 5.2 for the time-clutch mode data for $D = 500$ mm (it would partly overlay the Fig. 5.3 time-clutch data).

At this scale the system operates in a "Fitt's law-like" region, with T_s and T_m being functions of D/S (but not D), with the values in most cases at $D/S = 20$ about twice those at $D/S = 5$. For $W_{jmax} = 0.5$, the robot's T_m at this scale could stay up with the subjects T_s . We varied W_{jmax} and found values of 0.35 (for $D = 250$) and 0.25 (for $D = 125$) that yielded demos of significant time differences between T_m and T_s for (TOP+FS+TC) mode on the easier tasks (see Fig. 5.3).

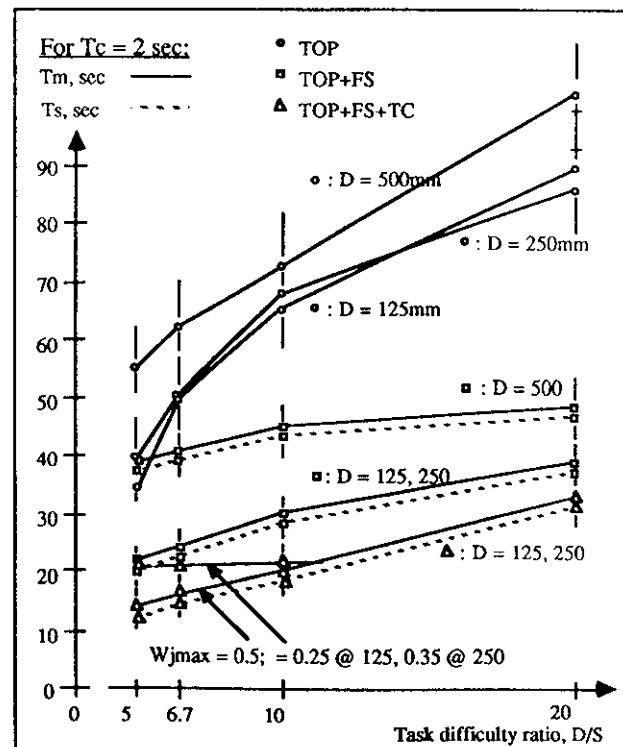


Figure 5.3: Trials showing T_s , T_m as functions of system and task parameters, for several values of task size scale D .

On further scaling-down of D, the system enters its "Heisenberg" region on the harder tasks ($S < 2$ to 3mm). Position sample-sizes, interpolator discretization and operator jitters cause large increases and variances in T_m and T_s (like trying to poke at things with a needle under a microscope).

Throughout the trials, subjects noticed striking difference in the "feel" of the different control modes, and developed special tactics for coping with each mode. Most treated TOP in the presence of delays like hitting a series of "successively shorter golf shots", trying to get closer each time. Subjects controlled (TOP+FS) aggressively, firmly driving the simulator to each switch. The (TOP+FS+TC) mode was usually handled with finesse, so as to drive it fast, but not so fast as to yield a wild path and thus large T_m and large $L_m/5D$.

In addition to these preliminary quantitative results, we have demonstrated the use of the position clutch to enable graceful handoffs of control by one agent and rendezvous of control by another agent. This is done by simply having two human operators swap use of the controls following disengagement of the position clutch once the forward simulation is out well ahead of the telerobot. We have compiled a video report showing the above experiments, demonstrations and control effects [CON87].

5.2. Plans for further experiments and concept demonstrations

We are continuing the above series of trials, varying additional system parameters. We are also preparing additional types of experiments and demos. The time brake and position clutch will be used to determine their effects on specification and manipulation times, and manipulation path lengths. (Skilled operators can use the time brake to "erase" poor path sections, and the position clutch to make and "jump across" gaps during overshoots). The time brake will be tested in contingencies (example: an obstacle falls across the planned path behind the forward simulator). Transitions involving cognitive/manipulative task-nesting will be explored. We will add the command buffer and interpolator modifications, and HCI controls, to implement and demonstrate time-ratio control during time-synchronized forward simulation.

We also plan to attempt demos of simple forms of role-reversal by having the tele-automaton do the path planning, and letting the human rendezvous to telemanipulate along selected portions of the projected path. In the role reversal demo a route planner uses AI techniques to plan a path through a maze. The planner then places the path into the forward simulator and, when necessary, calls upon the human to take over and manipulate through certain path segments. The human then just drives the manipulator along the displayed path segment. This mimics a human taking over the driving of an ALV while the ALV remains under machine cognitive control. This environment will also enable demos of human intervention in cognitive tasks, for example to assist in planning the route if the machine gets stuck in that high-level planning task.

We found basic principles such as Fitt's law very useful in thinking about forms of testbeds and hypotheses for our early trials. We need to consider additional system parameters, and also the dynamics of the human/machine combination, generate further hypotheses regarding factors affecting performance, and then design experiments to test these ideas. Such work may eventually produce principles and design rules for tele-autonomous manipulation systems.

6. FUTURE RESEARCH CHALLENGES

This initial tele-automation work suggests opportunities for coordination of research in several specialized fields. It also raises issues concerning research equipment infrastructure.

Tele-autonomous technology presents new challenges in human computer interaction. We have proposed a set of interface controls that are conceptually simple and easy to mechanize. The controls are generic ones that may be applicable in many different specialized situations. They are also cognitively and manipulatively accessible to the uninitiated by analogy. But many other new human interface aspects haven't been pinned down at all. How is the operator to visualize where they are, who has control of what, and who they give control to next as they enter or leave some subtask within a complex task lattice? What measures can we provide concerning operator performance, and what feedback can we provide? And what about the analysis and design of cognitive and manipulation tasks themselves? Research can perhaps provide better measures of joint human-machine cognitive-manipulative performance. Analyses similar to those in [CAR83] may then lead us to design intermixings of human and machine activity that yield substantial improvements in overall performance.

Research challenges arise in robotics, such as the eventual need to perceive, model and forward simulate not only the remote tele-automaton, but also portions of the remote environment itself. Forward simulation will work fine when interacting with static objects, but what about interactions with moving objects? Even if we knew how to specify interactions with moving objects, such work would be severely constrained by the high computational complexity of present methods for representing and simulating mechanical systems. Further basic work, such as that of Hopcroft, on efficient representation and simulation of mechanical systems is required if we are to handle problems of really interesting complexity [HOP87].

More work is needed on methods for path-error specification and associated methods for the time optimization of path following, such as in [SUH87]. Additional work is also needed on autonomous "reflex" actions that the remote robot can perform when encountering uncertainties (particularly those involving contact) not modelled in the forward simulation. We also need augmented AI programming environments that interface in such a way with real-time programming environments as to easily enable rapid estimation of time available for short-term AI planning tasks (enabling us to select among AI methods as a function of available time).

We believe that fundamental work can be done in these areas with modest robotic laboratory equipment. AI techniques [WIN84] and expert system technology [HAY83] have matured so that roboticists can now mechanize knowledge-intensive cognitive functions well beyond their reach just a few years ago, and can run these systems on accessible workstations. Thus mixings of manipulation and cognition technologies are now ripe for research exploration.

However, some experiments will benefit from multi-dimensional teleoperators or high-tech automation or autonomous system technology. One way to gain access to such expensive equipment is to treat remoteness as a feature: For example, we are negotiating connection of our tele-autonomous control equipment via satellite links with

automation systems at several remote sites. As such efforts provide useful testbeds, others might exploit shared access to the same remote facilities. Shared access to capital equipment has obvious costs benefits, but in addition can stimulate standards, collaborations and healthy direct competitions among researchers. Shared access to silicon foundries greatly increased the productivity of the VLSI research community [CON81]; a remote tele-automation facility could play an analogous role in tele-autonomous systems research.

7. SUMMARY

We have introduced basic functional concepts for tele-autonomous technology and an architectural framework for implementing the technology, using controls over time and position synchrony that enable simple structuring of control transitions. We have proposed hypotheses concerning capabilities of the technology, described our environment for investigating these phenomena, and discussed the results of early tests of some of the hypotheses. The results indicate how telerobotics can be extended to include projection of cognitive activity and autonomous systems extended to accommodate smooth transitions of cognitive or manipulative responsibility between machine and human operator. Through such extensions, the two technologies merge into one of "tele-autonomous systems". Finally, we have also sketched some further lines of research suggested by this initial work.

We believe that tele-autonomous systems research can yield methods and systems for improved projection of intelligent, manipulative action at a distance in time and space. This interdisciplinary presents interesting new research opportunities to teams having expertise in robotics and automation, artificial intelligence, and the psychology of human-computer interaction. We envision many possible applications for the resulting technology, not only in space and defense systems, but also in design and production systems, and eventually in personal and recreational environments.

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