Switching Among the Four Modes of a Teleoperator System: Teleoperation, Simulation, Replay and Robot

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Abstract

A teleoperation system can function as a simulator (by replacing the telerobot end of the system with a simulation algorithm), or as an autonomous robot (by replacing the human operator's end of the system with a robot algorithm). It is also possible to use a teleoperator system to record sequences of events, and later replay them. It is feasible and useful to integrate these four functions -- Teleoperation, Replay, Simulation and Robot modes -- into a single teleoperation system. These four system modes can be viewed as enhancements of native human capabilities -- Action, Memory, Imagination and Reflex -- and the fact that humans switch rapidly, continuously, and fluidly among these native capabilities indicates that fast and easy switching among the four system modes might help the human operator do his or her job more effectively. The realization of these four modes are discussed for a specific micro-teleoperation system, the UNC nanoManipulator.

Key words: Teleoperation, Simulation, Robotics, Microscopy, nanoManipulator

1. Introduction

One research direction for making teleoperation systems more effective has been to use simulation and computer graphics to predict the future behavior of the systems. Predictive displays typically predict the future positions (for example, 0.5 seconds into the future) of user-controlled parts of the system, such as a telerobot arm, based on current velocities and control parameters; this is important where time delays exist in the control loop [KIM96]. Simulations have also been used for planning with teleoperators [TACHI91][MACHIDA90].

Another research direction has been to develop methods of supervisory control in which the human operator defines high-level tasks, observes the system's behavior, but gives up direct control of the telerobot to an algorithm (while retaining the option to intervene if problems occur) [SHERIDAN92][CANNON97].

A third approach is to use data gathered at a earlier times to aid in perceiving the situation and to guide decisions made while teleoperating. For example, in [OYAMA93] a dynamic model of a real environment was constructed in advance, and then this real-time model was updated to match the real environment while teleoperation occurred there; the real environment had poor visibility conditions (it was filled with smoke) and therefore the model could be used to provide a computer-generated view to augment the poor quality images acquired by the telerobot's cameras.

It is argued in this paper that these three techniques -- simulation, autonomous behavior, and using models of earlier environments or events -- are all complementary to teleoperation, and in fact offer synergies when all of them are available in a single teleoperation system. Thus, we distinguish four modes of a teleoperation system: Teleoperation mode, Simulation mode, Robot mode, and Replay mode.

In this paper, we first observe that many teleoperation systems have all the hardware resources needed to implement all four of these modes. This indicates it would be feasible to integrate these functions into many existing teleoperation systems without hardware modifications. Next, we consider the human behavior pattern of switching fluidly between action, memory, imagination, and reflex. Each mode of a teleoperator system can be viewed as augmenting one of the native human capabilities: Replay of earlier scenes or events enhances human memory; Simulation of what may occur later enhances human imagination; autonomous (Robot) response controlled by algorithms enhances human reflex; Teleoperation itself enhances human action. Thus, integrating the four modes into a teleoperation system should allow the operator to switch fluidly from one to another, mirroring the normal switching people do between Action, Memory, Imagination and Reflex. Lastly, we consider an example teleoperation system -- the UNC nanoManipulator -- and examine the feasibility and usefulness of the four modes on that system.

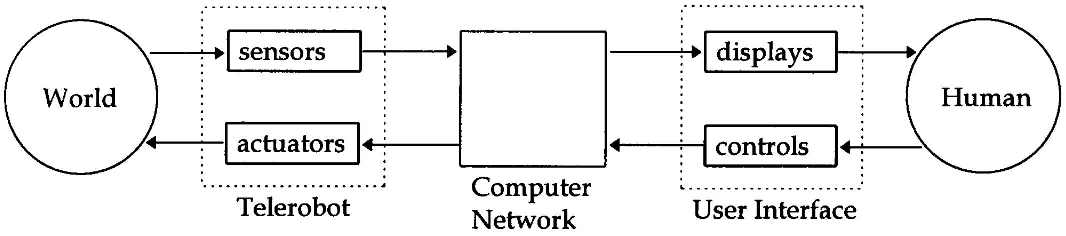


Figure 1. Teleoperator System Diagram.

2. Functional Modes and Data Paths in Teleoperator Systems

The earliest teleoperator systems used analog electronics to link sensors in the telerobot to displays in the operator's user-interface, and to link the operator's manual controls to the actuators in the telerobot. However, with the advent of computers and digital electronics, a more common block diagram for a teleoperator system is that shown in Figure 1, in which a computer network is used to route data, rather than having the connections hard-wired.

In such a system, data can be routed from sensors to displays and from controls to actuators to enable teleoperation (see Fig 2a), but there are also some other data paths that are possible, due to the flexible routing provided by the computer[ROBINETT92]. The telerobot end of the system can be replaced by a simulated telerobot, with the simulation algorithm running either on the routing computer or on another computer accessible through the network (see Fig 2b). In this mode, the sensors, actuators, and the external world are completely ignored, and the system is used as a simulator. The computer doing the routing is assumed to be powerful enough to, in real time, generate the required display data, and to perform an update calculation to maintain a simulated world, while the human operator interacts with it. The basic idea here is that, given enough computer power, either at the local computer or accessible through the network, we have all the hardware we need (namely, the operator's console) to treat the teleoperator system as a teleoperator simulator, and ignore that it is connected to an actual telerobot that can interact with the real world.

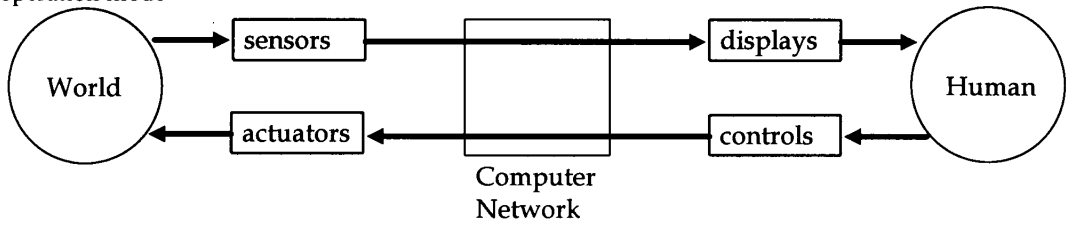
Alternatively, the human operator's end of the system can also be replaced by a robot algorithm, which can guide autonomous behavior of the real telerobot as it interacts with the real world (see Fig 2c). In this mode, the display, controls, and the human operator are completely ignored, and the system is used as a robot; a computer program is given control of the behavior of the telerobot, and it initiates actions based on its internally defined goals, its internal model of the world, and the sensor inputs received by the program.

Figure 2d shows recording of the sensed state of the world, which can be going on while teleoperation is in progress. Figure 2e shows replaying a recorded sequence of events at a later time. The basic idea here is that the state of the world as displayed to the human operator can be spooled into storage while normal teleoperation is in progress. Then, at a later time, the earlier sequence of events can be replayed. The replay of events is not interactive -- it is simply a linear sequence of world states. It is probably best thought of as a videotape -- the sequence of events on the tape is fixed, but all the normal VCR functions applying to viewing the replay: Play, Fast Forward, Slow Motion, Freeze Frame, Reverse, and Rewind. Although the recorded world state data is fixed during replay, it is often possible to look at that data from new viewpoints or with new viewing parameters during replay.

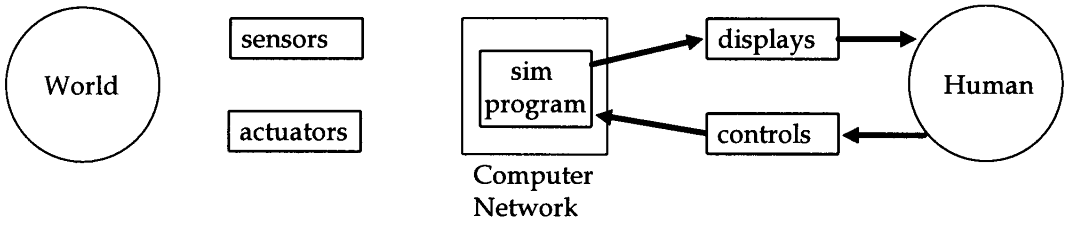
Thus, there are four main functional modes in which a teleoperator system can be used: Teleoperation, Simulation, Robot, and Replay. (Recording can take place during simulation or robot mode also, because in each case there is a sensed or simulated world state to record to storage.) There is nothing that should prevent the operator from rapidly switching among these different modes -- all that is needed is to route the incoming data to different programs. We assume that the programs that manage Teleoperation, Simulation, Robot, and Replay modes can all be loaded simultaneously and ready to run, so that switching modes can be done rapidly.

In connection with aircraft, all four of these modes are in use at the present time and known to be useful. The military uses remote-piloted aircraft for reconnaissance (Teleoperation mode). Flight simulators are widely used to train pilots (Simulation mode). Commercial jetliners and other planes have auto-pilots, capable of flying the plane and even landing (Robot mode).

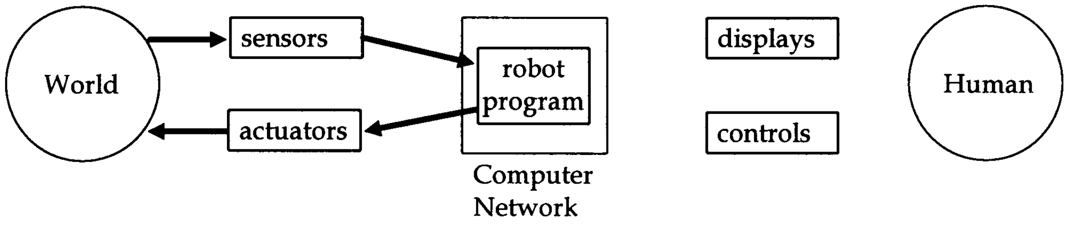
(a) Teleoperation mode



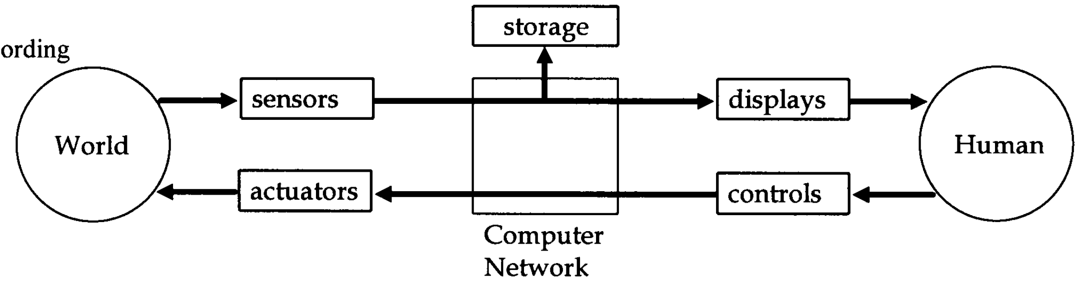
(b) Simulation mode



(c) Robot mode



(d) Recording



(e) Replay mode

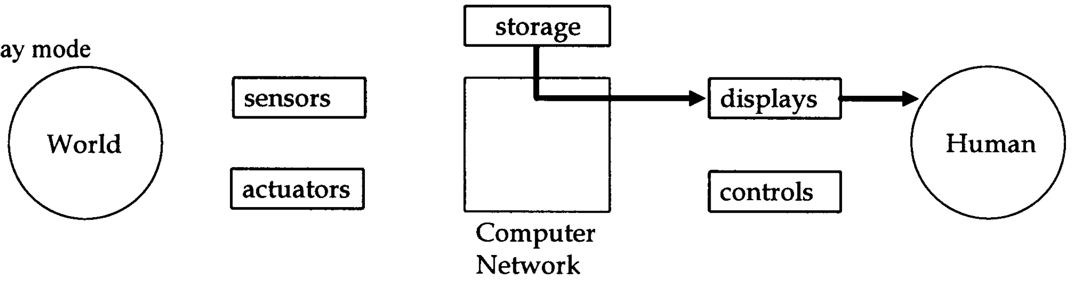


Figure 2. Data Flows for Teleoperation, Simulation, Robot, and Replay modes.

Commercial jetliners record operating data into “black boxes,” whose data tapes can be recovered after crashes and used to reconstruct what happened in the crashes (Recording and Replay mode). This aircraft example shows that each of these modes is useful in its own right. For aircraft, they are not normally integrated into a single system.

We will argue in this paper that it is useful to be able to switch frequently between these modes. As the preceding discussion shows, many teleoperation systems contain all the hardware resources needed to perform all four of the modes described. This indicates that a fluid switching among Teleoperation, Simulation, Robot and Replay modes may feasible for many teleoperation systems that were designed only for teleoperation. But why would we want to switch frequently among these system modes?

3. Human Rhythms of Thought and Action

The predominant mode of human behavior is to perform actions that affect some part of the world, guided by the conscious mind and its perceptions of the current state of the world. However, we do stop sometimes to remember past events, or to imagine the consequences of a contemplated action. Also, we sometimes perform habitual or reflex actions without conscious decision or control. These four modes of human thought -- action, memory, imagination, and reflex -- can succeed and interact with one another rapidly in normal human behavior.

For example, here is a description of an activity requiring thought and action:

> *Our house was being painted, and the painters asked me to open a particular window that was locked from the inside. I began to open it (this was action), but then jumped back when I saw there was a wasp's nest between the inner and outer glass (this was reflex). I remembered I had left a previous wasp's nest in such a place undisturbed, and treated it as a sort of terrarium for my son, since the wasps could not get through the inner glass (this was memory). But this time the painters needed to get to all surfaces, so the wasps had to go (comparing memory and the current situation). I thought about whether I could open the window further without riling up the wasps (this was imagination). Finally I decided to let the painters remove the wasp's nest (making a decision after consulting memory and imagination).*

It is normal human behavior to fluidly switch between action, memory, imagination, and reflex.

The operator in a teleoperator system will of course use his or her own native memory, imagination, and reflexes in doing the work. But human memory, imagination and reflexes have limitations. We can do better by providing electronic supplements for these modes of thought in a system where switching between them is rapid and easy.

Table 1 shows the correspondences between human capabilities and the functional modes of a teleoperator system.

Human Capabilities	*System Modes*	*Advantages*
action	teleoperation	extend reach
memory	replay	perfect recall of events
imagination	simulation	more accurate details
reflex	robot	faster response

Table 1. Human capabilities and functional modes of a teleoperation system.

Human memory fades, but a technologically-enhanced memory can provide perfect recall of earlier events. Imagination lacks detail (and is sometimes completely wrong!), but a technologically-enhanced imagination can provide a highly detailed simulation of what might occur. Human reflexes respond in a fraction of a second, but technologically-enhanced reflexes can respond on time-scales of milliseconds or microseconds, can detect things human reflexes might miss, and can protect fragile human concentration from meaningless interruptions.

The purpose of switching between modes in a teleoperator system is to allow better control by the human operator. Augmenting native human capabilities while retaining human awareness, judgment, and control is sometimes called Intelligence Amplification [BROOKS88]. Allowing the human operator to set up machine-mediated reflexes, and allowing the operator to switch, as needed, from direct Teleoperation into Simulation or Replay can enhance the system's effectiveness, and is a form of Intelligence Amplification.

We now consider an example teleoperation system to examine the usefulness of these four modes.

4. The Four Functional Modes on the NanoManipulator

The nanoManipulator is an experimental micro-teleoperation system built at the University of North Carolina at Chapel Hill. [TAYLOR93]. It combines an Atomic-Force Microscope (AFM) with a 3D computer graphics and haptic user interface to give its user a sense of presence on the surface of the sample within the microscope. The user can perceive the 3D topography of the sample surface using vision and touch, and can make certain types of modifications to the sample as it is being examined. Figure 3 shows a block diagram of the nanoManipulator system.

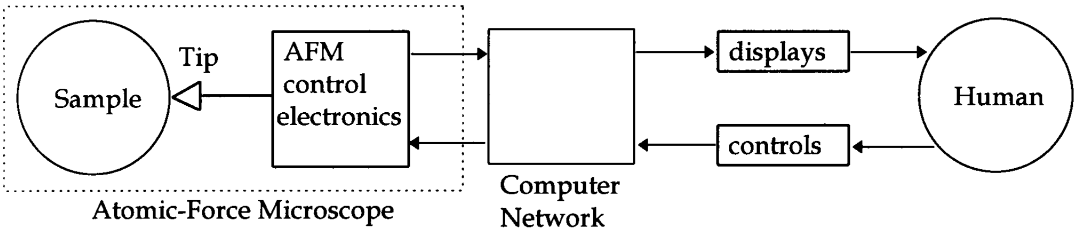


Figure 3. Block diagram of the nanoManipulator, a micro-teleoperation system.

An AFM uses a very sharp probe to collect surface shape data for a region of the sample within the microscope. Three independently-controllable piezoelectric crystals are used to move the probe in X, Y and Z with respect to sample, and a force of contact F is measured when the probe touches the sample. To collect an image, the probe (or "tip") is scanned in an X-Y raster pattern, and a feedback circuit adjusts the Z distance so as to keep the force F constant at a gently-touching force level that does not disturb the surface features being imaged. The Z height is sampled to produce a grid of measurements, which define an elevation map of the X-Y region of the sample being scanned. This 3D surface data can then be rendered as a continuous surface using standard 3D graphics techniques, and it can also be presented to the user through the haptic interface as a 3D surface that can be touched. The minimum feature size obtainable by imaging with the current AFM in the nanoManipulator is about 10 nm. The area being scanned is typically a few microns on a side.

The AFM's tip can also be used to make modifications to the sample. This is done by moving the tip to contact the surface at a starting position, increasing the applied force, and then moving the tip to dig a trench. The tip can also be used to move around material that is loosely attached to the surface. Thus, the AFM's tip can be used alternately as a sensor (for imaging the sample) and as an actuator (for modifying the sample).

4.1. Teleoperation

Teleoperation at a microscopic scale was the purpose for which the nanoManipulator was built. Through the mediation of the user interface of the nanoManipulator, the user can see and touch the sample, and make changes to it, with nanometer distances on the sample scaled up to meters for the human user. The nanoManipulator has been used to move large molecules, such as DNA and tobacco mosaic viruses, around on a sample surface [FALVO95], and to explore the mechanical properties of carbon nanotubes ("Bucky tubes") [FALVO97].

4.2. Replay

A second mode which has been implemented on the nanoManipulator is Recording and Replay [FINCH95][TAYLOR97]. The nanoManipulator has been used for experiments in nanofabrication. In the course of an experiment attempting to build a micro-structure, the AFM scans imaged the changing surface of the sample. It was convenient to record this data to a disk file as it came in, in parallel with the normal real-time displays and controls of the nanoManipulator. Then, at a later time, the recorded data could be replayed. The recorded data was time-stamped so that its time progression could be reconstructed during Replay. It also proved worthwhile to also record time-stamped user commands, so that these user actions could be displayed with their usual graphical indications during Replay.

During replay, the data coming from a file could be treated pretty much like fresh data coming in from the AFM, so that most of the nanoManipulator's functions were available for viewing the data. For example, the user could look at the changing 3D surface data from different viewpoints (flying through the landscape), at different orientations (tilting the surface), and at different scales (changing apparent size of the surface). Also, details of the lighting model, such as the direction of illumination, could be changed dynamically during replay.

However, while replaying earlier events, the user could not interact with or manipulate the world data being replayed. It was simply a linear sequence of raster-scan "frames" describing the changing shape of the surface during the original experiment. But like a linear video tape, the user could use VCR-like controls such as Play, Fast Forward, Slow Motion, Freeze Frame, Reverse, and Rewind. These functions are best thought of as giving flexible control of the time-rate during Replay. During actual Teleoperation, there is no way to make time run backwards or slow down, but this is easily done during Replay. In practice, Fast-

Forward replay has been extremely useful for quickly scanning through long experiments to find events of interest.

The data files from experiments have been useful in several ways. When treated as Recordings of the original experience of the experiments, it has been useful to re-experience the experiment while trying to understand why certain events occurred, while looking at the data from different viewpoints, scales, and time-rates. Replay has been useful to show interesting experiments to colleagues and visitors. Finally, the data files constitute the primary data records of the experiments, and can be analyzed numerically [TAYLOR97].

4.3. Robot

Certain kinds of autonomous behavior have been implemented on the nanoManipulator under software control. In addition, automatic behavior is present in the hardware of the nanoManipulator. The nanoManipulator is in Robot mode when there is an automatic mechanism for controlling the actuators of the system on the basis of input received from the sensors (See Figure 2c). As described in Table 1, Robot mode can be thought of, at least in some cases, as providing electronic reflexes for the human operator.

The feedback circuit which keeps the AFM's tip just lightly touching the sample surface during an imaging scan qualifies as operating in Robot mode. The feedback circuit adjusts the position of the tip in the Z-direction to maintain the sensed force F at a constant level while the tip is moved in a raster pattern in X and Y. It would be possible, though clearly impractical, to have the human in the loop to manually control the raster scan and to move the tip up and down in Z, also under manual control, based on sensed forces between the tip and sample being reflected back to the user's force-feedback controls. Obviously, to have this function performed automatically by a circuit or algorithm is much faster, more reliable, and less likely to cause tip crashes than to have it performed by the human operator in a completely manual way. The point is that this machine-mediated reflex is useful and improves the effectiveness of the entire system. Imaging would hardly be feasible at all with hand-scanning.

Another form of autonomous behavior in the nanoManipulator is called "virtual tips" [FALVO95]. Some virtual tips are Blunt Tip, Sweep, and Comb. For each of these virtual tips, the single physical tip is rapidly moved through a geometric pattern to give the effect of an actuator bigger than the physical tip which is, in effect, contacting the sample at many places at once. The virtual tips can be swept along straight-line paths by giving a user command which defines the two endpoints of the line. This has been used for carving away material in rectangular regions on the surface. During the time of the straight-line motion, the tip's motion is algorithmically controlled, and the system is therefore briefly in Robot mode.

Another possible application of the nanoManipulator would be to use controlled gouging of the AFM tip to carve away material to construct nanometer-scale circuits. One idea is to start with a non-conducting sample that had been coated with a very thin layer of conductor (say, a layer of gold a few nm thick), and then use the AFM tip as a scraper to remove unwanted material, leaving a very small circuit formed from the unremoved conductor. While it is desirable to directly control (teleoperate) the nanoManipulator while attempting to understand the behavior of the tip during scraping, after some understanding is gained, it might make sense for the human operator to step back into a supervisory control stance, letting the tip scrape certain regions automatically, perhaps until a certain depth was obtained. The operator could observe the progress of the construction activity as it progressed automatically, while retaining the option of intervening at any point and switching to direct manual control.

Note that scraping a defined region until a specified depth is obtained would be very well suited to Robot mode control. It would not be known in advance how many scraping passes would be needed to achieve the desired depth, and thus some variability in the scraping process could be tolerated through using a feedback loop from sensors to actuators. It might turn out that qualitatively different reliability could be achieved through thousands of passes of gentle scraping rather than a few passes with a large force applied. Thus, a goal-directed and algorithmically-controlled Robot mode might be able to enhance the system's capabilities.

4.4. Simulation

The fourth mode, Simulation, is also feasible on the nanoManipulator, but has not been implemented yet. In simulation, the real microscope wired into the system would be ignored, and all operations would take place through a software-simulated AFM operating on a simulated sample. This is analogous to a flight simulator, where the cockpit and controls are the same as a real plane, but there are no wings or engine -- just a simulated plane flying through a realistic-looking virtual world. An AFM simulator would have to model the distribution of material in the sample and model how contact between the tip and sample, at various force levels and tip speeds, affected both the sample and the tip itself.

Using the nanofabrication example from above, a flat silicon substrate with a layer of gold a few nm thick might be fairly simple to model, because the flat layers of silicon and gold would mean that the surface material would be known from the Z-depth measurement at each point on the surface. Once a tentative understanding of the interaction of the tip scraping the surface was achieved, it would be a good test of the accuracy of that model to create a simulation of the trenching behavior of the tip as it scraped the surface. Thus a planned modification could be run in simulation, and then run on a real sample with the real AFM. Then the results of the simulation could be compared with what actually happened.

No simulation can predict the behavior of a physical system with perfect accuracy, but the accuracy with which a process can be simulated is a good indication of how well the process is understood. Given the existence of a Robot mode which could repeatably perform the same surface modification action (let's call it action A1) again and again, it would make sense to attempt action A1 in simulation and then A1 again on a real sample. Using Robot mode, rather than human Teleoperation, would guarantee that we were testing the accuracy of the simulation, and not the accuracy with which a human operator could repeat his or her actions.

To measure the accuracy of our simulation, we might define a metric giving a numerical measurement of how much two surfaces differed from one another -- let's say, first an alignment step, and then an RMS-type summation of the Z-differences between the two surfaces. (There are probably better metrics.) This numerical metric could be used to measure how repeatably a modification, say A1, could be performed on a surface, as well as measuring how well the simulation predicted the final surface shape resulting from using a real AFM and real surface.

In attempting a long and complicated construction, where a mistake might ruin the structure being built, it might be very useful to simulate a crucial step, and then see the predicted results, before committing to perform the step on the real sample. An overlay might be useful in displaying the two surfaces, with the current real surface shown with solid graphics, and the simulation result spatially superimposed using a semi-transparent surface.

5. Summary

Many teleoperation systems contains all the hardware resources needed to function either as a simulator for the teleoperation task (replacing the telerobot end of the system with an algorithm), or as an autonomous robot performing the task under algorithmic control (replacing the user-interface end of the system with an algorithm). In any of these modes -- Teleoperation, Simulation, or Robot -- the data describing the world can be streamed into storage for later playback. Thus Replay of earlier actions is a fourth mode in which a teleoperation system can be used.

In all of these modes, there is an interaction loop running between the human operator and the part of the world being operated upon. One way to think of Simulation and Robot modes is that it is sometimes useful to simulate either the World or the Human part of the system. Thus in Simulation mode, the interaction loop runs between a real human and a simulated world. In Robot mode, a simulated human (Robot program) interacts with the real world. We even found it might be useful in certain circumstances to have the Robot program interact with the simulated world. The interaction loop is present in Replay mode, as well, though the interaction is limited to controlling the playback of the recorded world data.

The four system modes -- Teleoperation, Replay , Simulation, and Robot -- can be viewed as augmentations of the normal human capabilities of Action, Memory, Imagination, and Reflex . Teleoperation extends human action to inaccessible or dangerous places. Recording and Replay extends human memory with perfect recall. Simulation extends human imagination with accurate and detailed predictions of the results of contemplated actions. Robot mode extends human reflexes to electronic speeds, and also allows the creation of algorithmically-mediated "habits," which normally proceed automatically under the watchful eye of the human operator, but can be interrupted when necessary.

Because humans normally switch fluidly between Action, Memory, Imagination, and Reflex in the course of doing their work, this suggests that providing fast and easy switching between the four system modes might help the human operator do his or her job better.

6. Acknowledgments

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