# Virtual Fixtures:
# Perceptual Tools for Telerobotic Manipulation

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## INTRODUCTION

The fundamental purpose of a telepresence system is to extend an operator's sensory-motor facilities and problem solving abilities to a remote environment. [10]. Telepresence is achieved by projecting the operator's manipulatory dexterity to a remote site while reflecting sensory feedback from that site so realistically that the operator actually feels present in the remote location [1]. In order to enhance operator performance and understanding within remote environments, most research and development of telepresence systems has been directed towards improving the *fidelity* of the link between operator and environment [2,3,4,6,7]. Although higher fidelity interfaces are important to the advancement of telepresence system, the work described in this paper actually looks at the benificial effects of corrupting the link between operator and remote environment by introducing abstract perceptual information into the interface called *virtual fixures*.

### Perceptual Overlays:

When asked to draw a straight line in the real world, human performance can be greatly enhanced by using a simple tool such as a ruler. The use of a ruler reduces the mental processing required to perform the task, speeds an operators line drawing ability, and most of all allows an operator to draw a significantly better line than if no ruler had been used at all. Without a ruler, line drawing is a manual task that requires constant visual supervision and hand-eye coordination. With a ruler, line drawing is not only faster and straighter, but the dependence upon visual feedback is reduced, freeing up that modality for other uses. What is more, a ruler is often used as a barrier to protect against dangerous or destructive failures, protecting the work-piece from the slip of a pencil or knife. Such guidance and protection allows the operator to relax mental criteria for task success and failure, reducing the level of concentration devoted to the task. Although a simple tool by any standard, a common ruler is a powerful performance aid in manual line drawing tasks.

We can think of ruler use as an act of *overlaying* abstract sensory information on top of a workspace. A ruler is essentially a "perceptual overlay" designed to enhance line drawing performance. The overlaid sensory information represents a single rigid surface to be perceived hapticly and visually by the user. By overlaying this sensory information on top of the workspace, the user has reduced the mental and physical demands of the straight line drawing task and has thus enhances task performance. If a simple ruler-like perceptual overlay can enhance performance of real world manipulatory tasks like straight line drawing, it seems that computer generated perceptual overlays could be developed within virtual environments to enhance the performance of tele-manipulation tasks within remote worksites. Just as a ruler can be overlaid on top of a real workspace, virtual overlays could be laid on top of the sensory feedback from a remote workspace.

### The Virtual Fixture Metaphor

Because the abstract notion of overlaid sensory information is as difficult to conceptualize as it is to talk about, the *virtual fixture metaphor* was introduced as a means of describing such computer generated sensations as concrete physical structures [12,13]. It must be stressed that the point of this metaphor is to facilitate the understanding of, and interaction with perceptual overlays and should not be taken so literally as to limit the scope of the perceptual overlay concept. *Virtual Fixtures* are thus defined as abstract sensory information overlaid on top of reflected sensory feedback from a remote environment.

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Like a ruler guiding a pencil in the real world, virtual fixtures are intended to reduce mental processing required to perform remote tasks, reduce the work load of certain sensory modalities, and most of all allow precision and performance to exceed natural human abilities. Although virtual fixtures could be functionally equivalent to fixtures in the real world, there are many advantages inherent to virtual fixtures because they are computer simulations rather than real physical hardware. When overlaid on to a workspace, the fixtures only interact with the user and not with the workspace. Thus fixtures can occupy the same physical space as objects in the workspace. This means that the workspace geometry imposes no constraints upon the placement or configuration of virtual fixtures. What is more, virtual fixturing has no mass, no physical or mechanical constraints, requires no machining time or maintenance, can be easily prototyped and modified.

If we explore the concept of virtual fixtures, the first elements to consider might be rigid planar surfaces. Such fixtures would be composed of haptic sensations generated by reflecting simulated forces to the operator through a force-reflecting master. As the operator interacts with the modeled surfaces, the reaction forces would be computed and reflected appropriately. Of course, such fixtures are by no means limited to rigid surfaces. Abstracting the fixturing concept we might consider modeling compliant surfaces, damped surfaces, frictional contacts, even attractive or repulsive fields. Although fixtures composed of haptic sensations offer endless possibilities, the fixturing concept is not limited to that modality. Abstract fixtures could be composed of visual, auditory, even tactile sensations used alone or in cross-modal combinations.

If the description of virtual fixtures thus far seems too abstract, a simple example may drive the concept home. Imagine a situation where a teleoperating surgeon performs a delicate procedure on a patient. Now imagine that a virtual fixture is being used by the doctor to enhance his abilities in this procedure. The fixture might appear like a flat plane of glass with a grooved guide for the scalpel. The glass-like virtual fixture might actually pass directly through a patient's body, preventing the scalpel from penetrating below a particular depth but not obscuring vision of the tissue below. By sliding the scalpel along the edge of a groove in the virtual fixture, the surgeon could make a precise incision; the slightest deviation from the target trajectory might be reported by an audio or tactile signal. Such a fixture could pass directly through a patient's body, it could be put in place at the touch of a button, removed at the touch of another button, or easily altered as conditions change.

## HUMAN PERFORMANCE TESTING

To quantify teleoperator performance in a remote manual task, a Fitts' Law paradigm was chosen because of its general acceptance as a robust measure of human performance [5]. Through an extensive review of human psychomotor, perceptual, and cognitive test batteries, the Naval Oceans Systems Center developed a peg-in-hole performance task specifically representative of teleoperator manipulative activities [11,15]. The test battery requires subjects to move pegs of various diameter between holes of varied spacing. Movement times for peg motions are recorded and correlated with task difficulty. As defined by Fitts, the binary *Index of Difficulty*, ID, for the one dimensional peg transfer task was computed. Operator performance was computed in terms of the *Index of Performance* Ip, that quantifies performance in terms of the information processing capacity required of the operator to perform tasks of particular difficulty [5].

The overall system was divided into two physically separate parts as shown in figure 1: The *remote environment* and the *operator space*. The remote environment contained the peg task board, the slave robot-manipulator, and a video camera pointed at the task board. The camera was positioned so that the incident perspective was similar to what a human operator would see if standing in front of the task board and performing the peg insertions in person. The operator space contained the test subject, the upper body exoskeleton, the vision system, and the virtual fixture board. Once inside the exoskeleton and vision system, subjects were presented with a projection from the camera in remote worksite. The subjects were given the illusion that the task board was situated directly before them, within reaching distance of the exoskeleton . In reality the task board was on the opposite side of the laboratory, behind the subjects and completely out of view. A fixture table was placed in front of the subjects in such a way that it could not be seen when looking through the vision system but felt as though it occupied the same space as the projection of the remote task board. Thus virtual fixtures implemented on the fixture board felt as though they were overlaid on top of the remote environment. It should be noted that while wearing the vision system, subjects could not view thier own own arm but rather viewed the video image of the remote robot manipulator's arm in the location where thier arm kinesthetically seemed to be. This coupling between the operators kinesthetic sence of limb position and visual feedback from the remote worksite resulted in a strong illusion of presence.

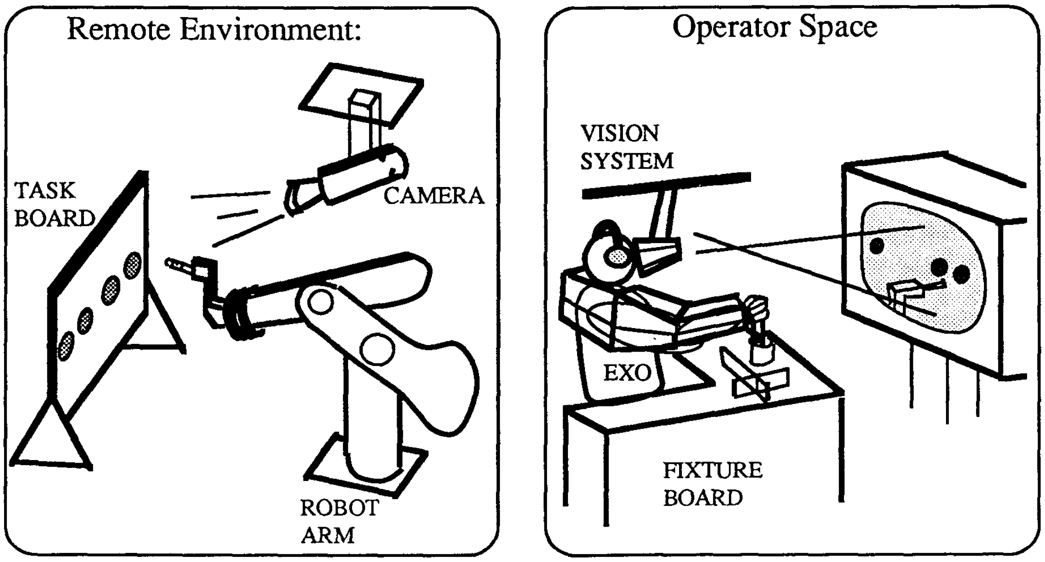


Figure 1: Experimental Setup for Telepresence Performace Assessment showing operator and workspace.

## EXPERIMENTAL DESIGN

Subjects were required to telemanipulate pegs on a task board from a designated start hole to a designated target hole with and without the aid of virtual fixtures. Movement times were recorded and index of performance was computed as defined by Fitts' Law [5]. Eight simple virtual fixtures were developed for comparison to a no-fixture control case. Six of the test fixtures were purely haptic sensations while two fixtures introduced both haptic and auditory information. As shown in Figure 2, the eight fixtures tested are composed of simple combinations of planar surfaces overlaid on top of the reflection of the remote task board. Fixture 1 is simply a rigid horizontal surface oriented like a table top in the workspace and positioned so that contact with the virtual surface will result in vertical alignment of the operators hand with the holes in the task board. Fixture 2 is like fixture 1 but it includes a second surface which is parallel to the plane of the task board located three inches back from the board. When using this fixture, subjects operate in the space between the vertical plane and the task board. Fixture 3 is similar to fixture 2 except the vertical plane is angled so as to guide hand motion toward the task board as the target hole is approached. Fixture 4 is like fixture 3 except a third plane is added which is intended to stop operator hand motion when in front of the target hole. Fixture 6 is similar to fixture 3 except two funnel-like surfaces are added in front of the target hole to guide hand motion into the hole.

Fixture 5 is very different from those presented thus far in both its geometry and implementation. This fixture was *not* interacted with by the subjects' right hand (the hand that performed the peg insertion task), but rather was designed for interaction only with the *unused* left hand. Fixture 5 is a rigid impedance plane parallel to the task board located approximately 0.5" in front of the board. A subject would place his or her left hand upon the planar surface while performing the task with the right hand. The intent of this fixture was to isolate the effect of localization on performance. It was hypothesized that virtual fixtures provide some localizing information to the user which enhance their understanding of the geometry of the workspace and allowed them to better correlate their kinesthetic sense of hand position to the remote site. Thus fixture 5 was designed to interact only with the operators unused hand and therefor only influence performance by providing purely localizing cues.

Virtual fixtures 7 an 8 implement both haptic and auditory information. Fixture 7 is identical to Fixture 1 but also introduces a texture-like field of auditory information. The auditory field is represented as a series of surfaces perpendicular to the task board as shown with black lines in Figure 1. Operator interaction with these surfaces result in the production of an audible tone whose pitch increases from left to right across the task board. Fixture 8 is identical to fixture 6 but it introduces an abstract auditory percept in front of the target hole as shown in black in Figure 1. This percept is modeled as an "auditory compliant surface" with a linear stiffness such that interaction with this surface produces a tone whose pitch is proportional to compression of the surface.

### Experimental Protocol:

A series of tests was run to evaluate subject performance using each fixture configuration. Operator performance was recorded during test periods which included 12 practice and 36 timed peg insertion trials for each fixture studied. A single trial consisted of moving a peg from a designated start-hole to a designated target-hole. Two different peg motions were studied in these tests: a 16 cm motion and a 4 cm motion. The 36 trial period was divided into three groups of 12 trials. Each of these groups required the subject to perform the insertion task using a different peg size. The use of two motion amplitudes (4 cm and 16 cm) and three peg sizes (0.75 cm, 0.98 cm, 1.50 cm diameter pegs) allowed for the testing of insertion trials with six different task difficulties.

Subjects were tested over 9 experimental sessions, each lasting 45 to 60 minutes. Each of the first two experimental sessions included two test periods of 36 trials. These initial 144 trials were treated only as practice during which the subjects familiarized themselves with the use of the exoskeleton, slave robot arm, vision system, and fixtures. It was found that by the end of the second practice session, all subjects had sufficiently learned the task that variability in movement times had fallen below 20% for each subjects with a mean variability 14% for all subjects. Once learning had stabilized, subjects were sequentially tested using each of the test fixtures.

## RESULTS

In order to quantify performance increase due to fixture use, percentage changes in Index of Performance (I.P.) were computed for each fixture with respect to the no fixture case. The following section addresses each test fixture separately, comparing performance to the no fixture case and discussing the implications to virtual fixture design.

### Haptic Fixtures (1 through 6):

Fixture 1 is a rigid surface oriented perpendicular to the plane of the task board. When interacting with this fixture, subjects' hand motion is restrained to move only in the plane It should be noted that the end effector of the slave robot was restricted by software to the same planar motion regardless of the operator's commands. Thus, the guidance provided by fixture 1 has no effect upon commands to the slave robot arm. The I.P was 21% greater when using fixure 1 than with no fixture. This comparison strongly suggests that a virtual fixture can enhance performance by altering the operators conceptualization of the task even though the task itself is unchanged. Without the fixture, subjects were free to move in all Cartesian directions even though they were well aware that the slave robots position was locked in the plane. With the fixture, the subjects were guided to move only in the plane. The improvement implies that even after the 144 trials of practice, the subjects were unable to completely ignore the irrelevant degree of freedom and wasted processing capacity on it. The use of this simple fixture was enough to alter the subjects understanding of the task and reduce the information processing required.

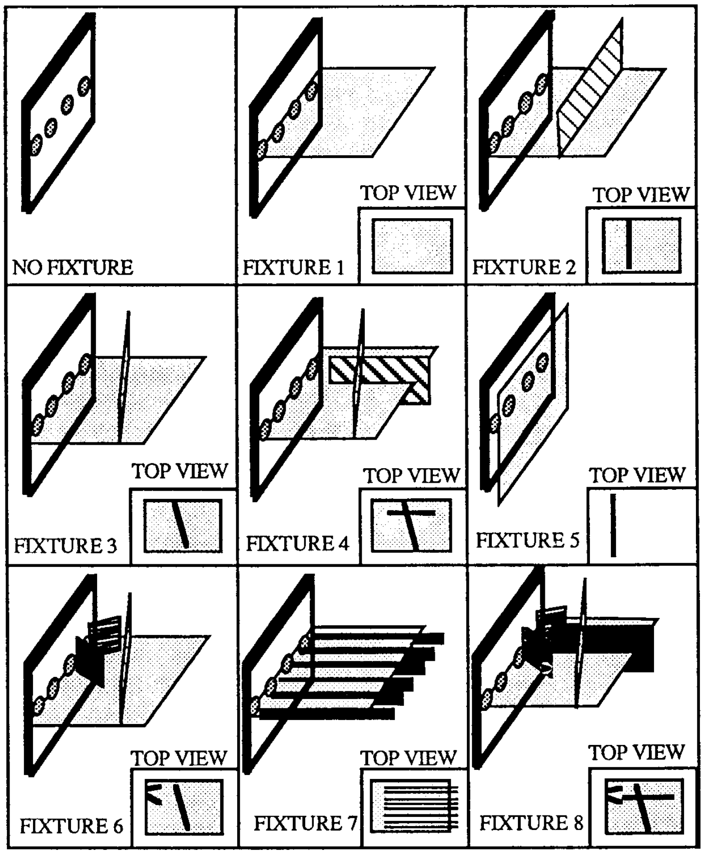


Figure 2: Virtual fixtures shown projected onto the task board as they are perceived by subjects. Also shown are top views, looking down from above the task board.

Fixture 2 is the same as Fixture1 except a second rigid surface is added parallel to the surface of the task board. The added surface restricts how far back from the board the operator can draw the peg. The I.P. was 34% greater than with no fixture. This comparison clearly shows that the use of fixture 2 significantly enhanced performance over the no fixture and fixture-1 trials. It is believed that the additional surface simplifies the operator's perception of the workspace because the distance from the task board is no longer a workspace parameter that the operator needs to be concerned with. Secondly, the added surface is believed to act as a kinesthetic localizing agent, giving the user a better sense of hand position in the remote workspace by providing a haptic indication of proximity from the task board. Thirdly, by providing depth information haptically, the fixture reduces the demand on the visual system to gage depth and frees up that modality for other uses such as tracking the target hole.

Fixture 3 is the same as fixture 2 except the second rigid surface is not parallel to the surface of the task board but rather is diagonal so that it guides hand motion towards the board as the target hole is approached. The I.P. was 59% greater using fixture 3 than with no fixture. Like fixture 2, this fixture provides haptic depth cues and kinesthetic localization to the remote workspace. It is believed that this guidance in target convergence reduces the demand upon kinesthetic and visual feedback and thus reduces the information processing required for the task.

Fixture 4 is the same as fixture 3 except for the addition of a third rigid impedance surface which crosses the diagonal surface. This additional surface was placed such that the operator would contact this surface when the peg was directly in front of the target hole. Fixture 4 was intended to provide further trajectory shaping by halting hand motion when the peg was aligned with the hole. The I.P. was 53% greater than with no fixture . The results for fixture 4 are not significantly different from those for fixture 3, showing that the addition of the third surface did not enhance performance in these trials.

Fixture 5: Although all fixtures thus far described were designed for interaction with the operator's right hand (the hand that manipulates the peg), fixture 5 is designed for interaction only with the operator's unused hand. Subjects place the palm of their left hand upon the surface while they perform the task with their right hand. The purpose of testing this fixture was to isolate the effect of localization upon performance. This fixture can only influence performance by giving the operator a better sense of the physical relationship between kinesthetic output and workspace geometry. The I.P.was 20% greater than with no fixture. These results suggesting that localization to the remote site plays an important part in the effectiveness of virtual fixtures.

Fixture 6 is identical to fixture 3 with the addition of two angled surfaces which guide hand motion directly into the target hole. While fixture 3 guides gross hand motion by converging near the target hole, fixture 6 also guides fine motion by converging hand position directly into the center of the target hole. With fixture 6, the I.P. was 57% greater than with no fixture. These results are not statistically different from those for fixture 3 suggesting that the addition of the fine positioning surfaces did not enhance performance in these trials.

**Auditory / Haptic Fixtures (7 & 8):**

Fixture 7 is identical to fixture 1 with the addition of an auditory field such that traversing the field results in tones of varying frequency. Both the density of auditory pulses and the change in signal pitch provided rich position, velocity, and acceleration feedback to the operator. The I.P. for peg insertions performed with virtual fixture 7 was 23% greater than the fixture 1 case and 52% greater than with the no fixture case. The 23% improvement in performance when using fixture 7 over fixture 1 (which were identical except for the addition of auditory information) strongly suggests that the use of multiple sensory modalities is a powerful tool in fixture design. It further suggests that overlaying an auditory gradient field on top of the workspace to provide position, velocity, and acceleration cues is a simple means of enhancing operator performance.

Fixture 8 is identical to fixture 6 with the addition of an auditory compliant surface modeled such that compression of the surface corresponds to increasing pitch of the auditory feedback. The surface is positioned such that first contact occurs just before the peg should be inserted into the target hole. The I.P. when using virtual fixture 8 was 13% greater than the fixture 6 case and 70% greater than with no fixture. The 13% improvement in performance when using fixture 8 over fixture 6 suggests that the use of the additional modality was useful in increasing information processing capacity.

## CONCLUSIONS

The results confirm that overlaying abstract sensory information in the form of virtual fixtures on top of sensory feedback from a remote environment can greatly enhance teleoperator performance. Virtual fixtures composed of simple combinations of impedance surfaces and abstract auditory information increased operator performance by up to 70%. Analysis of some basic perceptual elements suggests that virtual fixtures enhance perfcrmance by simplifying the perception of the workspace, altering the conceptualization of the task, by providing localizing references to the remote worksite, and by reducing the demands on taxed sensory modalities by providing information through alternative sensory pathways. Post testing interviews revealed that the use of virtual fixtures caused subjects altered their conceptualization of the task such that a successful trial no longer just looked a certain way but also felt a certain way and sounded a certain way.

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