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The teleprogramming paradigm has been proposed as a means to efficiently perform teleoperation in the subsea environment via an acoustical link. In such a system the effects of both limited bandwidth channels and delayed communications are overcome by transmitting not Cartesian or joint level information but rather symbolic, error-tolerant, program instructions to the remote site. The operator interacts with a virtual reality of the remote site which provides immediate visual and kinesthetic feedback. The uncertainty in this model can be reduced based on information received from the slave manipulator's tactile contact with the environment. It is suggested that the current state of the model be made available to the operator via a graphical display which shows not only the position of objects at the remote site but also, through the use of color clues, the uncertainty associated with those positions. The provision of uncertainty information is important since it allows the operator to compromise between speed and accuracy. An additional operator aid, which we term synthetic fixturing, is proposed. Synthetic fixtures provide the operator of the teleprogramming system with the teleoperation equivalent of the "snap" commands common in computer aided design programs. By guiding the position and/or orientation of the master manipulator toward specific points, lines or planes the system is able to increase both the speed and precision with which the operator can control the slave arm without requiring sophisticated hardware.
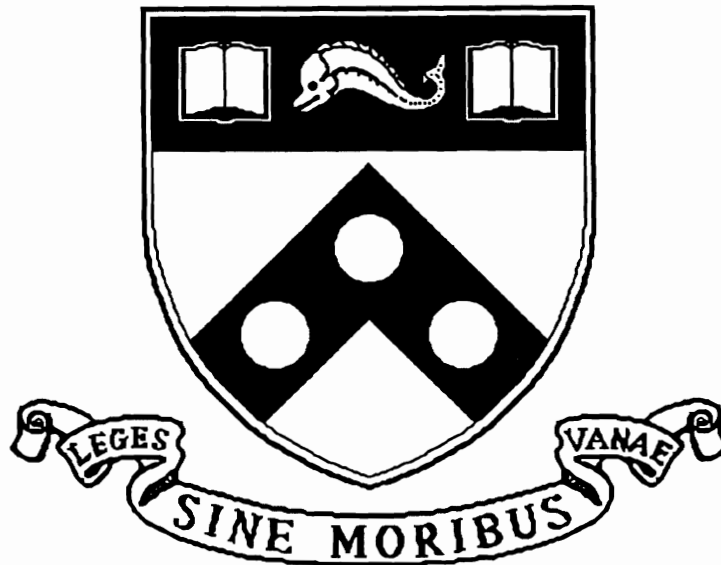
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Abstract

The teleprogramming paradigm has been proposed as a means to efficiently perform teleoperation in the subsea environment via an acoustical link. In such a system the effects of both limited bandwidth channels and delayed communications are overcome by transmitting not Cartesian or joint level information but rather symbolic, error-tolerant, program instructions to the remote site. The operator interacts with a virtual reality of the remote site which provides immediate visual and kinesthetic feedback. The uncertainty in this model can be reduced based on information received from the slave manipulator's tactile contact with the environment. It is suggested that the current state of the model be made available to the operator via a graphical display which shows not only the position of objects at the remote site but also, through the use of color clues, the uncertainty associated with those positions. The provision of uncertainty information is important since it allows the operator to compromise between speed and accuracy. An additional operator aid, which we term synthetic fixturing, is proposed. Synthetic fixtures provide the operator of the teleprogramming system with the teleoperation equivalent of the "snap" commands common in computer aided design programs. By guiding the position and/or orientation of the master manipulator toward specific points, lines or planes the system is able to increase both the speed and precision with which the operator can control the slave arm without requiring sophisticated hardware.

1 Introduction

Teleoperation is the performance of work at a distance [25] and involves an operator controlling the force or displacement of a slave manipulator while receiving both visual and kinesthetic feedback. We wish to be able to perform subsea teleoperation tasks by having a human operator, located either on a boat or ashore, control a manipulator located on an unmanned untethered submersible. Unfortunately, the only suitable long-range underwater communications systems are low-bandwidth, delayed, acoustical links [8]. The problem therefore is to perform a teleoperation task successfully despite the fact that communication delays on the order of seconds exist between the operator and slave sites and bandwidth requirements limit the amount of data which may be transferred between sites to less than 10Kbit/s. The teleprogramming concept, developed by Paul, Funda, and Lindsay, provides a way to overcome these limitations [11, 18, 12].

In such a system it is assumed that sufficient sensor data has been received from the slave site so as to enable the construction of a model of the remote environment. By using this model at the master station we can create a simulation of remote environment with which the operator can interact both visually and kinesthetically. The operator's actions are transformed, in real time, into a sequence of robot program instructions which, when executed by the remote manipulator, seek to mimic the operator's actions.

It is recognized that the initial sensor data will be inaccurate. Small discrepancies between the model and actual world can be accommodated by allowing compliant motions which are within some pre-specified tolerance of the simulated motion. Larger discrepancies can be detected by including force and velocity limits along with the robot program commands for execution by the slave.

In this paper we consider how large discrepancies between the real and simulated worlds might be reduced by making use of information gained from the slave manipulator's kinesthetic interaction with the environment. By making use of a flexible compliant wrist, standard end-effector tools could

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be used as probes to gather data. However, merely updating the model is not sufficient because the operator also needs some indication of the positional uncertainty of objects. It is proposed that color clues be employed to aid the operator in compromising between the fast, but risky, approach of directly manipulating objects whose position is uncertain and the slow, but safe, method of feeling out the position of each object before attempting to work with it.

We also consider the problem of increasing the precision with which the slave manipulator is operated while simultaneously increasing the speed with which the operator can control it. To solve this apparent contradiction we propose employing "synthetic fixtures" where the system actively guides the motion of the master arm along one, or more, degrees of freedom such that it conforms to pre-defined and task-dependent geometric primitives.

2   Teleprogramming

The problems introduced by a significant communications delay are solved by decoupling the master and slave systems (see Figure 1). The operator interacts, not with the remote manipulator, but instead with a virtual reality of the robot and its task. When the operator moves the master manipulator the graphical image of the slave moves immediately within the virtual environment. Thus the operator has the impression that he or she is controlling a robot without any time delay.

When a collision is detected in the virtual world the operator's commanded motions are filtered so as to prevent further motion in the negative direction of the contact normal. In this way kinesthetic feedback is provided to the operator as the master arm will no longer move to penetrate the surface. The arm may be slid over a contact surface by simply maintaining a force on the master arm in the negative normal direction of that surface. If the arm, or object it is carrying, then comes into contact with other surfaces additional constraints are imposed on operator inputs. Using such a system

MASTER STATION   SLAVE STATION

Graphical Simulation of Remote Environment

Sensors

Human Operator

Command Generation and Error Recovery

Command Interpretation and Error Detection
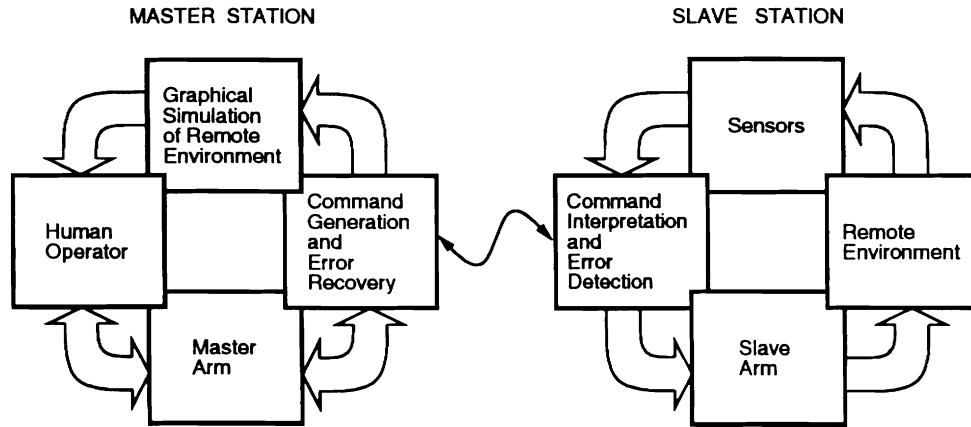
Remote Environment

Master Arm

Slave Arm

Figure 1: The teleprogramming system - high bandwidth local feedback loops exist at both the master and slave stations

it is relatively simple to perform tasks such as exploring the inside of a box entirely by feel.

As the operator performs the task at the master station (see Figure 2) his or her task interactions are monitored and translated into robot instructions which are sent to the manipulator at the remote site for execution. These instructions take the form of "execution environments" which specify:

1. A task frame

2. Displacement control and force control

3. Pre-load forces for force control directions

4. Guard forces and velocities

5. The compliance state to assume upon successful completion

Since these commands are at a relatively high level they are well suited to transmission over a low-bandwidth acoustical link. The slave manipulator, by executing these instructions, attempts to mimic the actions of the operator. The instructions which involve contact interaction with the task
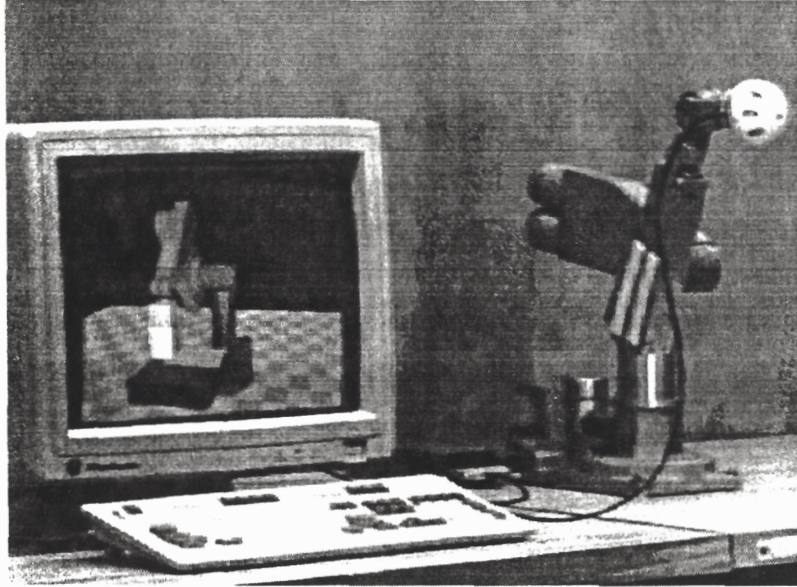
3

Figure 2: Photo of the master station

are "guarded moves" [17] in which motion or force exertion are terminated by either a reaction force or resulting motion. By continuously comparing its motion with these prescribed tolerances the slave is able to detect cases where its motion significantly differs from that predicted by the master station. When such an error occurs the slave pauses execution and advises the master system which can then reset the graphical view presented to the operator to correspond to the actual position of the slave.

Because operators interact with a virtual reality of the remote world they are, to a large extent, insulated from the effects of the significant communications delay between the master and slave sites. However, when an error is detected at the remote site the slave must transmit a message to the master and then wait until new instructions are received — this will take a minimum of one whole round-trip communications delay. Thus, if we are to perform tasks efficiently it is important that the number of such errors be minimized. This can be achieved using two complimentary approaches. The first is to continuously update the master's model of the slave site as new in-

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formation becomes available (thus minimizing the discrepancy between the real and virtual worlds). The second method is to make the operator aware of cases where errors are likely to occur by providing a visual indication of uncertainty.

3   Interacting with the World Model

It is generally recognized that the efficient performance of teleoperative tasks in a delayed environment requires the use of some form of predictive or preview display [2, 5, 14]. In the teleprogramming system this is accomplished by maintaining a model of the remote environment at the master station and displaying a graphical representation of that model to the operator.

It is assumed that an initial, imprecise, world model could be constructed prior to the initiation of a teleprogramming session using sensor data collected from the remote site. The uncertainty in this model can then be reduced during the teleprogramming session using information gained from the slave manipulator's kinesthetic interaction with the environment. The emphasis on kinesthetic, rather than other sensors, is motivated by the necessity of operating in real-time over a low bandwidth acoustical link as well as by the relative immunity of physical contact-based sensing to "the vagaries of seawater composition" [13]. Rather than using a specialized touch sensor [21] the intention is that the current end-effector tool be used as a probe [24]. By equipping the slave robot with a flexible compliant wrist [19] it is possible to detect contact between the tool and the environment.

Since data from the remote site will itself be uncertain we can never know exactly the position of any object. Instead the system must combine *a priori* knowledge with available information from the remote world to generate a "best estimate" as to the current state of the environment. Given multiple contacts with an object we can, using a least squares type of approach, generate an updated estimate of its position

For example, consider the simplest case - a single plane. Define the plane

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by the set of all points, q, which satisfy:

$$\mathbf{q} \cdot \mathbf{v} - k = 0$$

where $\mathbf{v}$ is a unit normal to the plane and k is the distance from the origin to the closest point on the plane. Now, let $\mathbf{c}_1, \mathbf{c}_2, \ldots, \mathbf{c}_N$ be the points at which the plane has been contacted. The distance from each contact point to the plane is then:

$$\mathbf{c}_i \cdot \mathbf{v} - k$$

Thus an improved estimate of the plane's position may be determined by finding $\mathbf{v}$ and k which minimize:

$$\sum_{i=1}^{N} (\mathbf{c}_i \cdot \mathbf{v} - k)^2$$

subject to the constraint that $\mathbf{v}$ is a unit vector.

This may then be solved as an eigenvalue problem [7, 3].

Since the initial graphical model is imperfect it is not sufficient to merely provide the operator with information about the position of objects in the environment. Consider, for example, the case where an operator is attempting to place a wrench over a bolt head. In such a situation the operator must make a choice between the direct approach of simply applying the wrench to the nut or, alternatively, the more conservative method of feeling around the object first to accurately locate the position of the nut before attempting to place the wrench over it.

To aid the operator in making such a decision we propose using color clues to discriminate between objects with differing levels of uncertainty. These clues could be based directly on the positional uncertainty of each object or alternatively, and perhaps more importantly, they could be based on the probability of successfully interacting with each object. For example, if the operator were to select a torque wrench the system could color bolt heads according to the probability that the wrench could be successfully placed over them.

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By continuously updating the world model and by displaying uncertainty information to the operator we can guide them in choosing where next to move the slave robot. However, merely helping the operator choose where to move next is not enough - we must assist the operator in actually moving to those chosen locations. Synthetic fixtures provide just such an operator aid.

4   Synthetic Fixtures

We are interested in designing a system which will allow an operator to control the slave manipulator in a very precise manner (as may be required, for example, when parts are to be mated together). One approach to this problem is to improve the visual information avaliable to the operator. This could be achieved by using stereo systems [9], by providing additional visual clues with the addition of shadows and textures [26] and by superimposing visual enhancements onto the viewed scene [16]. A second, complimentary, approach is to improve the "feel" of the master arm by using improved hardware [20]. The problem is that no matter how realistic the graphical simulation is and no matter how perfect we make the master arm we will still be limited by the accuracy of the human operator.

Consider, by way of example, the situation where an operator wishes to move the slave robot along a straight line in Cartesian space - as may be required during the task of mating two parts. The problem is that its very difficult for the operator to move the master arm in a perfectly straight line - even if the problem is reduced to only two dimensions it is still very hard - consider trying to draw a straight line without using a ruler. One possible solution is to have the operator define starting and ending points and then have the system generate commands for motion between them. This could be accomplished with the "position clutch" described by Conway et al [6]. However the operator must still correctly specify the starting and ending points.

This is, in some sense, analogous to the problem faced by computer aided design (CAD) programs where its very difficult, for example, for a user to draw a line which exactly meets another line. In CAD systems this is overcome by the use of a "pseudo pen location" [23] or "precision point assignment" [15] or, more recently, the "osnap" command [1]. These solutions to the precision problem all work by moving the cursor, not to exactly where the operator pointed, but rather to where the system thinks the operator intended.

What is needed for teleoperation is similar feature which provides kinesthetic as well as visual feedback.

We propose using a concept we term synthetic fixturing to bring these ideas to the telerobotics domain. In essence we suggest giving the operator a kind of virtual ruler - a device which allows the operator to feel, as well as see, the relationship between the current end-effector position and a number of pre-defined task-dependent geometric primitives. Since we are working in a computer-generated virtual environment we're not limited just to physically realisable rulers. For example we should be able to assist the operator in maintaining a spatial position and/or orientation within a particular plane, or along a specified line, or within a particular region. In many cases it is unnecessary for the operator to explicitly request that a synthetic fixture be activated since the system can infer which fixtures are appropriate based on the location and current state of the end effector. For example, when the operator moves a torque wrench near a bolt the system could activate a fixture to guide the wrench along a line normal to, and centered on, the top surface of the bolt.

Tactile feedback has been employed in a number of telerobotic systems, however these have typically focussed on providing the operator with forces derived from the physical interaction between objects. These forces were either attractive, as in the case of molecular docking [22] or repulsive, as in the case of collision avoidance [4]. Synthetic fixturing differs from these in that it presents the operator with task-dependant tactile clues which have no direct physical analogy.

It is important that the addition of the fixturing capability not impose undue restrictions on the operator. It should be possible, for example, for the operator to move a torque wrench past a bolt without being forced into a vertical position over it. Thus, we would like a system which compromises between providing as much aid as possible to the operator when its needed and yet is as unobtrusive as possible when not required.

Fixturing is accomplished by giving the manipulator a tendency to drift, in one or more degrees of freedom, toward a predetermined value. The trick is to make the force sufficiently large that an operator who wishes to make use of the fixture can just relax and let it pull their hand along and yet sufficiently small that an operator who wishes to move in a different direction can still get there - they just need to push a little harder.

In our implementation the master manipulator is position controlled. When fixturing is not active the arm is servoed by reading the force of the operator (using a six-axis wrist-mounted force/torque sensor) and computing a new Cartesian set point for the arm motion based on those readings. Fixturing is implemented by computing the distance from the end-effector to the fixture and then altering the set point based on that distance. For example, consider the case of a planar fixture where orientation is not controlled.

The fixture plane is defined by the set of all points $\mathbf{q}$ which satisfy:

$$(\mathbf{q} - \mathbf{p}) \cdot \mathbf{v} = 0$$

where $\mathbf{p}$ is some point on the plane and $\mathbf{v}$ is a unit normal to the plane. In this case the displacement, $\mathbf{h}$, from the calculated set-point, $\mathbf{e}$, to the plane is just:

$$\mathbf{h} = ((\mathbf{e} - \mathbf{p}) \cdot \mathbf{v}) \mathbf{v}$$

A modified set point is then calculated (see Figure 3) with the simple function:

$$\mathbf{e}' = \mathbf{e} - \mathbf{h} \frac{a}{a + \mathbf{h} \cdot \mathbf{h}}$$

The actual choice of fixturing function is somewhat arbitrary but the above equation provides stable operation with the desirable property that the ap-
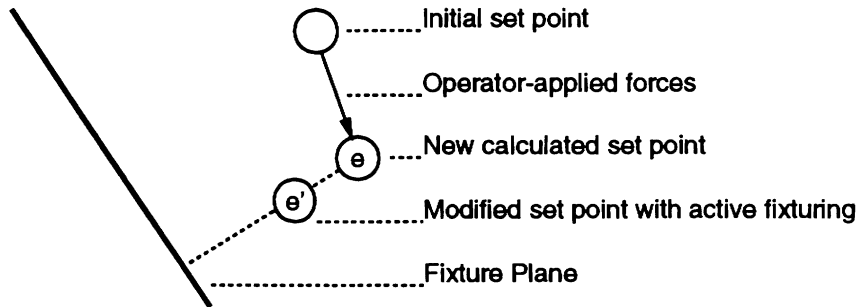
Figure 3: A planar synthetic fixture

parent force felt by the operator increases as the end effector moves closer to the fixturing plane.

It seems intuitively clear that the speed with which an operator can move will increase as the required accuracy decreases and indeed this has been found to be the case. The time taken for an average human to perform a motion is approximately proportional to $\log(d/W)$, where d is the distance to be moved and W is a measure of the desired accuracy [10]. Thus, in the teleprogramming system, we can increase the rate at which an operator can work by decreasing the accuracy with which they must move. The use of synthetic fixtures allows us to do this without compromising the positional accuracy of the slave.

Synthetic fixturing has an additional, more subtle benefit. As the system observes the operator's actions it must interpret the operator's input and transform that into a command sequence for execution at the remote site. Now, if the operator complies with, for example, a line fixture then motion of the master will be along a straight line and its obvious to the system that this motion was what the operator desired. In the case where the operator chooses to deviate from the fixture path this will also be obvious and the system can act accordingly. Without fixturing the system must guess whether any deviation from a straight line is deliberate or merely accidental.

5 Conclusions

The teleprogramming paradigm has been suggested as a means to efficiently perform teleoperative tasks in the uncertain subsea environment. It is assumed that an imprecise model of the remote site is known before the teleprogramming session is initiated. That model can them be improved by using information gained from the remote manipulator's kinesthetic interaction with the environment. By making use of an instrumented compliant wrist it is possible to obtain simple contact information using standard end-effector tools.

The use of color clues to provide the operator with a visual measure of uncertainty has been proposed. Providing users with information about both the position and positional uncertainty of objects should enable them to compromise between the fast, but risky, approach of directly manipulating objects whose position is uncertain and the slow, but safe, method of feeling out the position of each object before attempting to work with it.

Improvements to the master station for teleoperation systems have generally focussed on improving operator performance by providing more sophisticated master arms or improved visual displays. We propose synthetic fixturing, where the master system actively guides the operator's motions in one or more degrees of freedom, as a means of increasing precision and speed without the need for sophisticated and expensive hardware.

The advantages of providing a synthetic fixturing capability for the master station seem quite clear - it aids the operator when needed and yet is relatively unobtrusive when not required. By observing operator motions the system can activate appropriate fixtures automatically and thus there should be little need for additional operator intervention. The advantages of adding color clues are, however, considerably more difficult to quantify and much more testing is required to evaluate the merits of this operator aid.

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