July 1993

Wide Bandwidth, Distributed, Digital Teleoperation

Desikachar Venkatesh
University of Pennsylvania

Matthew Stein
University of Pennsylvania

Richard P. Paul
University of Pennsylvania

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Wide Bandwidth, Distributed, Digital Teleoperation

Abstract

Teleoperation means to perform a task at a distance. The task is performed by a manipulator located at a remote site, controlled by the master manipulator located in the control room. The loop between the master and the slave manipulator is closed by the human operator. The dexterity and manipulability of the overall system has to be high such that the actions can be easily carried out by the operator. A visual display provides the operator a view of the slave arm and the task environment, kinesthetic feedback provides a sense of physically performing the task. Kinesthetic feedback is direct feedback to the operator, while visual, audio, and other feedback are indirect in nature. The displays generated from the video data are very useful even when the quality of the image is degraded. Changes in the camera position and orientation can cause severe strain on the operator when interpreting the viewed image. The corrections are applied to the position and force transformations to reduce the strain on the operator. The position and force data are communicated over a communication channel from one station to the other. The use of communication channel basically not designed for real time processes can introduce significant delays leading to operator induced instability of the teleoperator system. In the presence of such delays the force reflection as a non-reactive feedback can help in maintaining the stability of the system. The forces encountered by the slave manipulator is transformed into audio range signals. The audio signal to the operator is a reflection of force in a non-reactive manner. Advances in high speed networks with increased bandwidth and decreased error rates provide an opportunity to implement teleoperator systems for long distance and distributed teleoperation. A single operator from a control station can interact physically with a system situated anywhere in the world and perform the tasks as though he or she was present at the remote site. A step by step implementation procedure of a direct teleoperator system with communication between master and slave stations through a computer network is described. The corrections to the transforms to nullify the effect of change in viewing parameters are discussed. The experimental results showing the effectiveness of the change in camera orientations and the comparison of active force reflection to the non-reactive force reflection in the form of auditory signal is presented.

Comments

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GRASP LAB 351

Venkatesh Desikachar
Matthew Stein
Richard Paul

University of Pennsylvania
School of Engineering and Applied Science
Computer and Information Science Department
Philadelphia, PA 19104-6389

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Venkatesh Desikachar Matthew Stein Richard Paul

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Abstract

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1 Introduction

Teleoperation means to perform a task at a distance. The task is performed by a manipulator located at a remote site, controlled by the master manipulator located in the control room. The loop between the master and the slave manipulator is closed by the human operator. The dexterity and manipulability of the overall system has to be high such that the actions can be easily carried out by the operator. These qualities can be improved by providing as much information as possible to the operator in the form of feedback. A visual display provides the operator a view of the slave arm and the task environment, kinesthetic feedback provides a sense of physically performing the task. Other feedback information such as audio, enhances the ability to perform the task. Kinesthetic feedback is direct feedback to the operator, while visual, audio, and other feedback are indirect in nature. Essentially, the master arm serves as a computer I/O device with a force reflection capability.

The operator performs the manipulations with the master arm. The operator should not feel the mass of the arm, gravity, and inertial forces of the arm and the end effector should appear weightless. The kinematic configuration, size, and strength of the slave arm can be different from that of the master. The master arm configuration should be friendly to the operator while that of the slave should be suited to perform the real task. Dissimilar configurations of the master and slave demands additional processing [1]. Very often, the need for controlled and scaled operation of displacements and forces arise in performing assembly operations and load carrying operations. As mentioned earlier, the displays generated from the video data are very useful even when the quality of the image is degraded. Changes in the camera position and orientation can cause severe strain on the operator when interpreting the viewed image. To improve the overall system performance, each of these factors are to be considered separately and corrections incorporated for each of them, this can be viewed as different modes of operation of the system. Digital control of the overall system allows various modes of master - slave interaction. Normally, it is not known apriori which mode of operation is best suited for a specific task at hand.

Advances in high speed networks with increased bandwidth and decreased error rates provide an opportunity to implement teleoperator systems for long distance and distributed teleoperation. A single operator from a control station can interact physically with,any system situated anywhere in the world and perform the tasks as though he or she was present at the remote site. The motivation for this work is to develop a teleoperator system utilizing a new Gigabit rate communication data network.

Issues of time delay in communication between master arm and slave arm present serious problems for teleoperation [2]. The work described in the report is implemented on a communication network not designed primarily for teleoperation. The complete system configuration is shown in Fig.1.

The report is organized in major sections describing the importance, concepts and the implementation of each of the above mentioned issues. The conclusion section highlights the limitations in the present setup and the possible further work in the area.

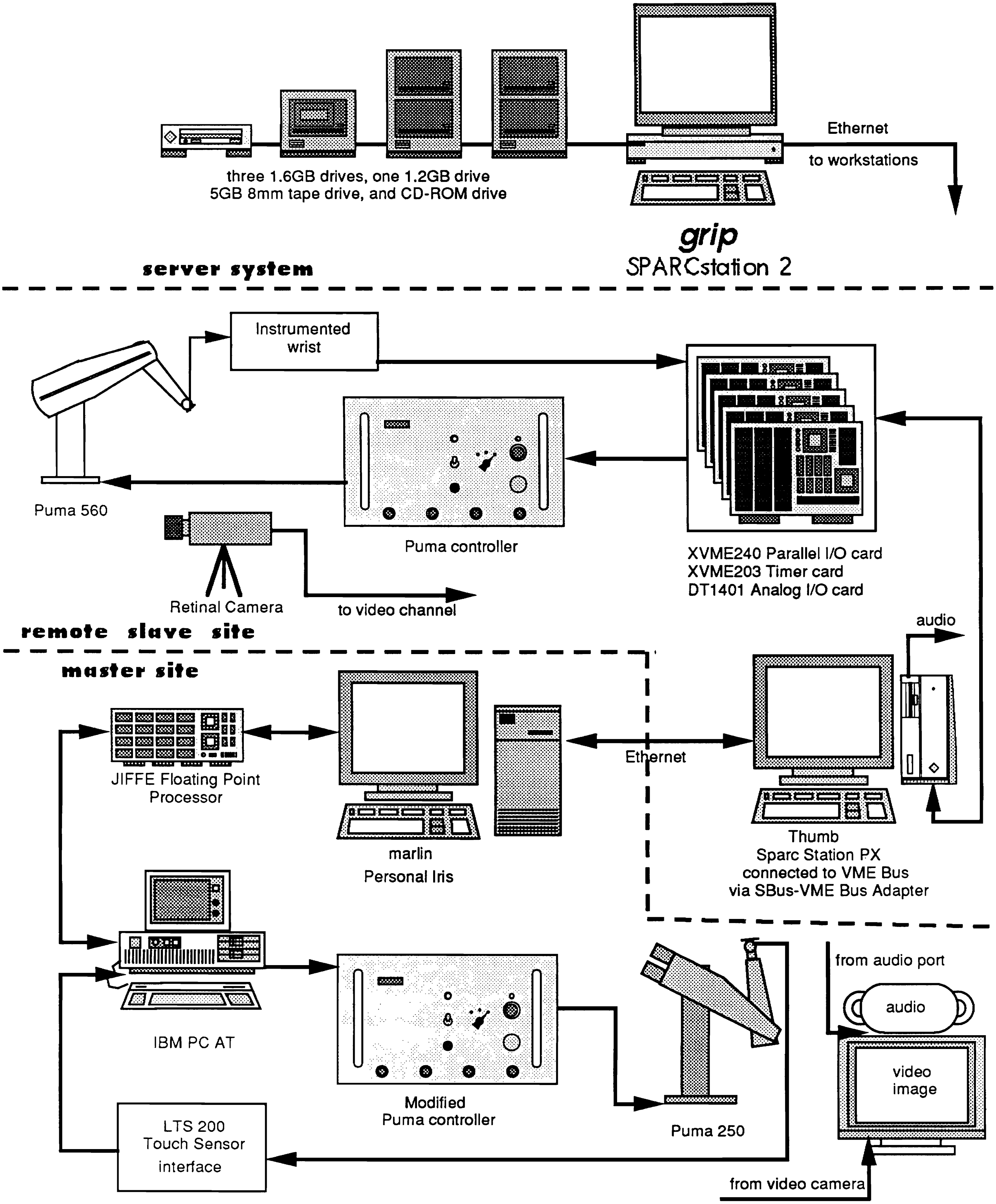

Fig.1. Teleoperator System setup.

2 Position and orientation information from Master to Slave

Teleoperation involves the manipulation of the end effector of the slave arm at the remote site by an operator effecting these manipulations on the end effector of the master arm at the control room. In order to achieve this goal, the position and orientation information of the master arm has to be transmitted to the remote site where the slave arm mimics the motion from this information. If the master arm and the slave arm are of similar kinematic configurations, then the joint space information of the master arm is sufficient for the slave to follow the master. The implementation in this case is straightforward. The drawbacks in such an implementation would be a limited workspace and possibly the awkward configurations of the master arm make it difficult for the operator to perform the task at ease. Effectively this affects the dexterity as well as manipulability of the overall system. A solution to this is in choosing the master and slave arms to be of different kinematic configurations, such that master is well suited as an operator interface and slave arm is well suited for the task to be performed. With such a choice the simplicity of joint space control is lost and one has to resort to Cartesian space control strategy. The following subsection deals with each aspect of Cartesian space control of master-slave arms.

2.1 Kinematic Configuration Information

In this subsection the processing of position and orientation information from master to slave is considered. Initially the master and slave arms are placed in a maximum manipulability configuration, though it is not absolutely necessary to do so. This configuration is referred to as home configuration for the respective arms. The idea is then to pass on the change

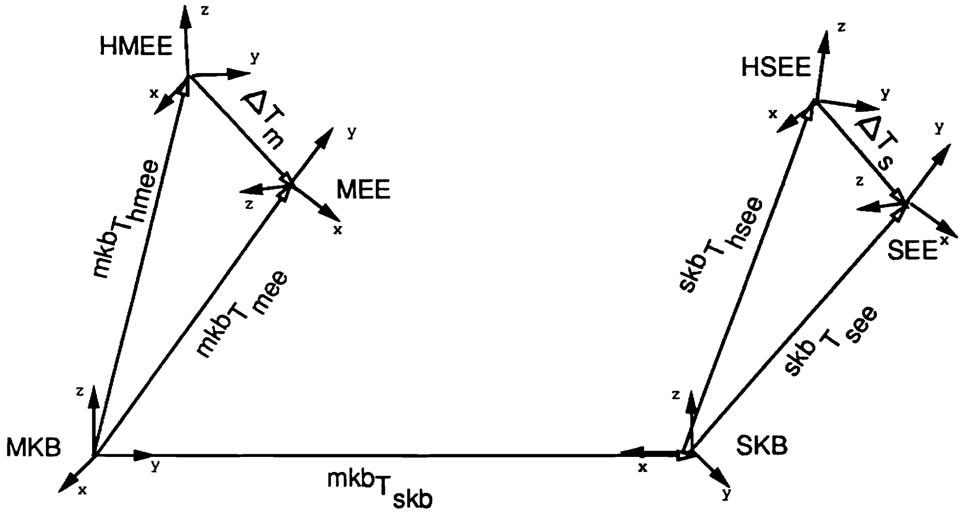

Fig.2.a Transform graph for the master arm and slave arm configurations

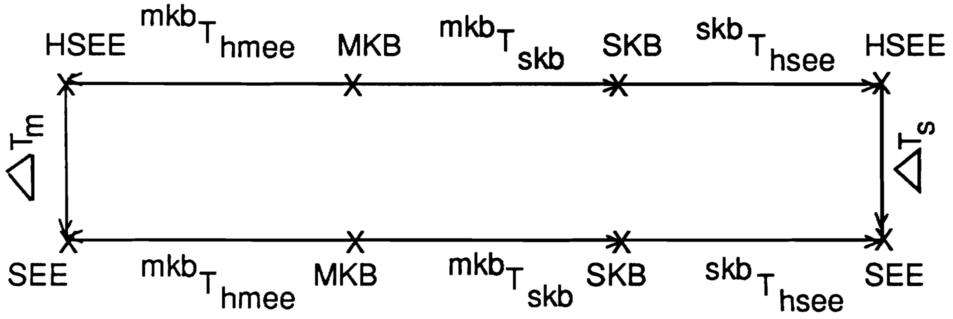

Fig.2. b. Differential Transform Graph for the master and slave arms

in master arm configuration with respect to its end effector to the slave site and make the slave arm configuration change to the same extent with respect to its end effector. This implies that the information transferred is relative to the current end effector frame of the master arm. A drawback in such a scheme, is either an erroneous transmission or a loss of transmission for even one servo cycle, would result in slave arm losing the kinematic correspondence with the master arm. Over a length of time, these errors would accumulate and the slave arm and the master arm would no longer be synchronized. Transmitting absolute position and orientation information from master to slave each cycle of the servo loop would circumvent this difficulty. The implementation discussed in this report is based on this hypothesis.

Fig.2.a, shows the transformation graph for the master arm and the slave arm coordinate frames and Fig.2.b, shows the differential transform graph for the master arm and the slave arm configurations.

From Fig.2.b, we can write the transform equation as follows

$$\Delta T_m {}^{mkb}T_{hmee}^{-1} {}^{mkb}T_{skb} {}^{skb}T_{hsee} = {}^{mkb}T_{hmee}^{-1} {}^{mkb}T_{skb} {}^{skb}T_{hsee} \Delta T_s \tag{1}$$

Let ${}^{mee}T_{see} = {}^{mkb}T_{hmee}^{-1} {}^{mkb}T_{skb} {}^{skb}T_{hsee}$,then from above equations;

$$\Delta T_s = {}^{mee}T_{see}^{-1} \Delta T_m {}^{mee}T_{see} \tag{2}$$

From Fig.2.a, we know that

$$\Delta T_m = {}^{mkb}T_{hmee}^{-1} {}^{mkb}T_{mee} \tag{3}$$

and

$${}^{skb}T_{see} = {}^{skb}T_{hsee} \Delta T_s \tag{4}$$

From equations 1 to 4 we have the final transformation equation as

$$^{skb}T_{see} = {}^{skb}T_{hsee}\,{}^{mee}T_{see}^{-1}\,{}^{mkb}T_{hmee}^{-1}\,{}^{mkb}T_{mee}\,{}^{mee}T_{see} \tag{5}$$

We can treat $^{mee}T_{see}$ as a correction transform, that takes care of the home configuration of both the arms and the relation between the master and the slave kinematic base frames. $^{mkb}T_{mee}$ represents the absolute position and orientation of the master arm with respect to its KB frame and is transmitted to the remote site. Although the processing of transformations can be performed at either end , in this implementation , the processing corresponding to the master arm is carried out at the master end and that of the slave arm is carried out at the slave end. $^{skb}T_{see}$ gives the required absolute slave arm configuration with respect to its KB frame.

2.2 Reindexing of the master arm

If the kinematic configurations of the master arm and the slave arm are different, then the singularity configurations of both the arms are also different and they need not attain these configurations simultaneously. The workspace envelope of both the arms are also different and the manipulators will not attain their workspace limits at the same instant of time. For example, in the implementation considered in this report the master arm is a PUMA-250 and the slave arm is a PUMA-560. On attaining either a singularity configuration or a workspace limit on the master arm, the master arm has to be driven back to its home configuration. The process of driving back the master arm to its home configuration is termed reindexing. While reindexing the slave arm remains intact in the configuration reached just before the beginning of reindexing operation on the master arm. In order to cover the larger workspace of the PUMA-560, the master arm PUMA-250 will have to be reindexed many times. The change in configuration of the master arm after reindexing will again be reflected in the change of configuration of the slave arm. The Fig.3. shows the various co-ordinates frames involved in the computation of the effective master arm configuration. The frames of interest are the virtual home configuration of the master end effector(VHMEE) and the absolute configuration of the master end effector(AMEE). To begin with the HMEE and VHMEE, and MEE and AMEE are coincident. On attaining a configuration requiring reindexing, the master arm returns to the home configuration but further changes in the configuration are to be treated as though they had taken place with respect to VHMEE frame. This is achieved by a correction transformation ${}^{mkb}T_{vhmee}$, whose value is equivalent to that of the absolute master arm configuration just before reindexing. When HMEE and VHMEE frames are coincident the ${}^{mkb}T_{vhmee}$ is an identity matrix. The absolute master end effector configuration can be computed from Fig.3. and is transmitted to the slave end.

To begin with ${}^{mkb}T_{vhmee}$ = Identity Matrix , and
on every reindexing ${}^{mkb}T_{vhmee} = {}^{mkb}T_{amee}$ just prior to reindexing operation.
Equation gives the value of the transform to be transmitted to the slave site.

$$ {}^{mkb}T_{amee} = {}^{mkb}T_{vhmee}\Delta T_m = {}^{mkb}T_{vhmee}{}^{mkb}T^{-1}_{hmee}{}^{mkb}T_{mee} \qquad (6) $$

2.3 Macro / Micro Manipulation

Invariabally, performing a task will involve gross manipulations and fine manipulations. The manipulability to an operator increases to a great extent if he or she can change over from one mode of operation to another mode of operation. This subsection describes a

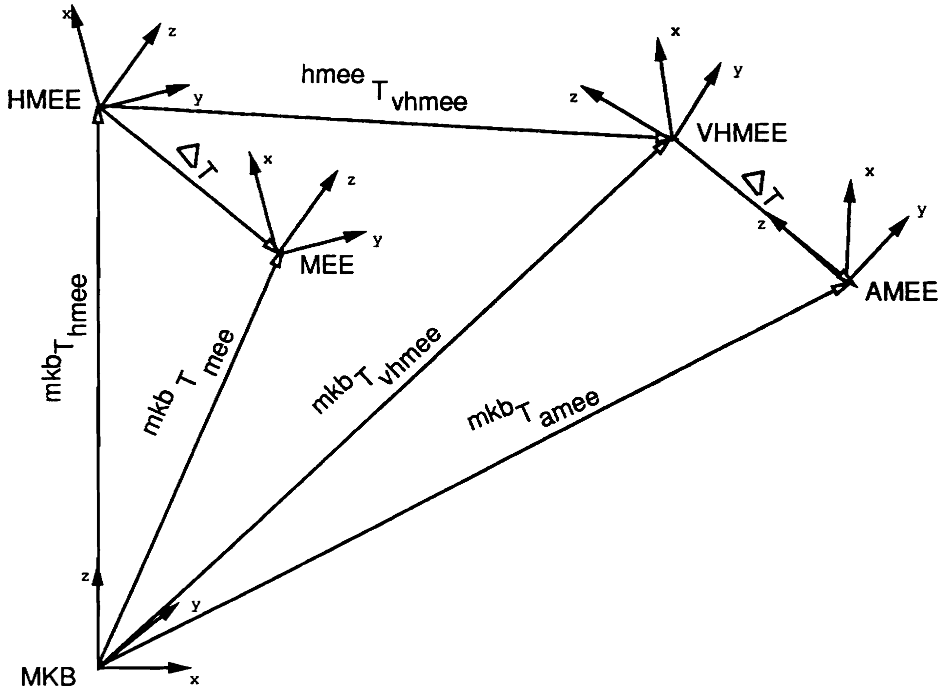

Fig.3. Transform graph for the reindexing and absolute configuration of the master arm end effector

methodology for implementing the modes of operation for gross and fine manipulations. From the previous subsections it is clear that we have ΔT_m, the difference transform with respect to the master end effector home configuration. These modes of operations can be achieved by incorporating a scaling factor on the difference transformation ΔT_m.

2.3.1 Linear Scaling

Gross manipulations are performed until the slave end effector reaches a point of interest and at this instance the operational mode is changed to the fine manipulation, so that the finer movements can be achieved suitable for assembly operations. The linear scaling is implemented as follows,

$$\Delta T_{m,scaled} = \Delta T_m T_{scale} \tag{7}$$

$$where \quad T_{Scale} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & ScaleFactor_{linear} \end{bmatrix}$$

$ScaleFactor_{linear} > 1.0$ is for gross manipulations,

$ScaleFactor_{linear} < 1.0$ is for fine manipulations,

$ScaleFactor_{linear} = 1.0$ is for identical manipulations.

2.3.2 Rotation Scaling

There are situations where scaling may have to be performed on rotations as well. This section suggests a method for such an implementation. Extract the rotation component of ΔT_m and convert into $(\Delta R, \Delta P, \Delta Y)$ angles by performing a transformation operation from XYZ to RPY on ΔT_m . The scaled $(\Delta R, \Delta P, \Delta Y)$ angles are calculated by multiplying each of them with a rotation scaling factor. Then convert back the scaled $(\Delta R, \Delta P, \Delta Y)$ angles into XYZ by RPY to XYZ transform to give the rotational part of $\Delta T_{m,scaled}$.

2.3.3 Practical Considerations

Linear and rotation scaling factors are to be chosen with discretion, otherwise the slave arm can easily attempt a configuration outside its workspace. It is wise to set a limit on the scaling factor such that

$$MINSCALE < ScaleFactor < MAXSCALE, \tag{8}$$

where MINSCALE and MAXSCALE are preset limit of scaling.

2.4 Viewing Transformations

The view of the task performed at the remote site (slave end) is provided to the operator by a camera looking at the end effector of the slave arm. To perform a task it is necessary for the operator to change the position and orientation of the camera at will. It is natural for the operator to seek either a closer view of the task or a different view of the task to perform it in an efficient manner. Whenever a view is changed the operator has to readjust himself to the new image and this can cause an additional strain, possibly impairing performance [3].

For example, a change in camera orientation by 180 degrees around z-axis, would result in the right to left movement on the master arm viewed as a left to right movement of the slave arm. If an automatic correction can be implemented to these viewing parameter changes, so that right to left movement is retained as right to left movement in the image the strain on the operator is reduced to a great extent. Since these corrections are transparent to the operator, the manipulability of the overall system is enhanced. This section describes the method of implementing these corrections. Fig.4. shows the relative configuration of the camera before and after the change in camera position and orientation is made with respect to the slave KB frame.

2.4.1 Camera Correction

The camera base frame is located at the slave arm site and its position and orientation is defined with reference to the slave arm KB frame. As the camera configuration is changed, the viewing parameters change and this change necessitates the corrections in the transmission of position and orientation information from master to slave. This change will affect only the movements performed on the master arm after the change in viewing parameters and from there on. Thus the corrections are to be applied on to the ΔT_m to find the appropriate slave configuration. The Fig.4.b. shows the differential transform graph as a result of the change in the camera configuration. Let Δ_{cam} be the difference transform of the camera between its home configuration and the present configuration and ${}^{hmee}\Delta_{cam}$ be the correction factor to be applied as a consequence to Δ_{cam} change in the camera configuration. From the Fig.4.b. we we can obtain ${}^{hmee}\Delta_{cam}$ as

$${}^{hmee}\Delta_{cam} = [{}^{cb}T_{kb}\,{}^{mkb}T_{skb}^{-1}\,{}^{mkb}T_{hmee}]^{-1}\Delta_{cam}[{}^{cb}T_{kb}\,{}^{mkb}T_{skb}^{-1}\,{}^{mkb}T_{hmee}] \tag{9}$$

Then the effective slave arm configuration is given by

$$^{mkb}T_{amee} = {}^{mkb}T_{vhmee}{}^{hmee}\Delta_{cam}\Delta T_m T_{scale}{}^{hmee}\Delta_{cam}^{-1} \tag{10}$$

2.4.2 Determination of Δ_{cam}

Imagine for the time being the camera is mounted on the end effector of another manipulator whose position and orientation can be controlled from the master site. Fig.4.a. shows the coordinate frames involved in the calculation Δ_{cam}. Let the initial configuration of the camera be given by $^{cb}T_{hcam}$ and the current configuration of the camera be given by $^{cb}T_{cam}$. From Fig.4.a. Δ_{cam} can be written as

$$\Delta_{cam} = {}^{cb}T_{hcam}^{-1}\,{}^{cb}T_{cam} \tag{11}$$

The rotation components of the above transformation is used in the calculation of correction transformation $^{hmee}\Delta_{cam}$.

Now, consider that camera is moved nearer to the task, then it is natural to adjust the scaling factor for manipulation allowing to perform finer movements. As the camera is moved away, the coarse manipulation would suffice. This would mean the scaling factors are to be calculated as a consequence to the changes in camera configuration. From Fig.4.a, we can write the following transform equations

$$^{hcam}T_{see} = {}^{cb}T_{hcam}^{-1}\,{}^{cb}T_{skb}{}^{skb}T_{see} \tag{12}$$

$$^{cam}T_{see} = {}^{cb}T_{cam}^{-1}\,{}^{cb}T_{skb}{}^{skb}T_{see} \tag{13}$$

From Equations 14 and 15, the distance between the camera and the slave end effector in the two camera configurations d_h and d respectively can be computed easily by utilizing the translation component of the above transforms as follows

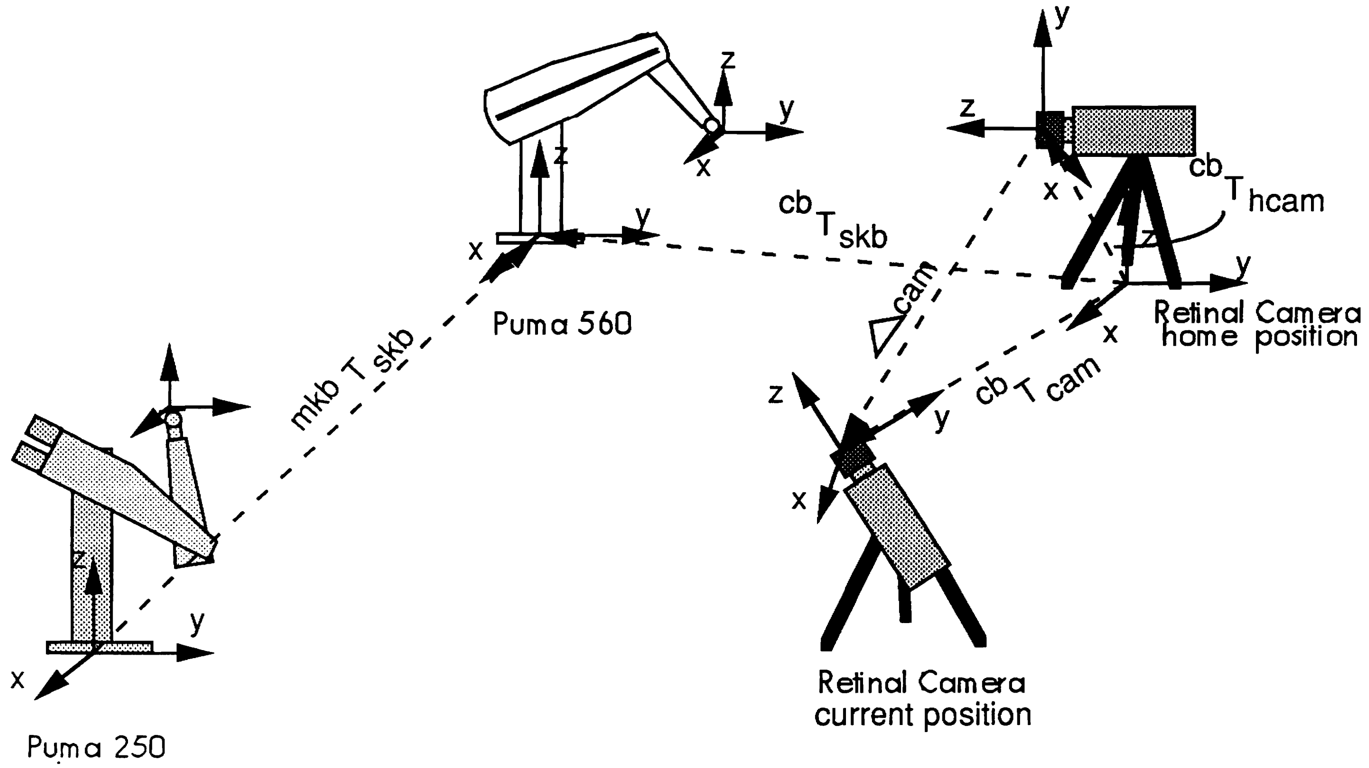

Fig.4.a. Configurations of the frames in two camera positions

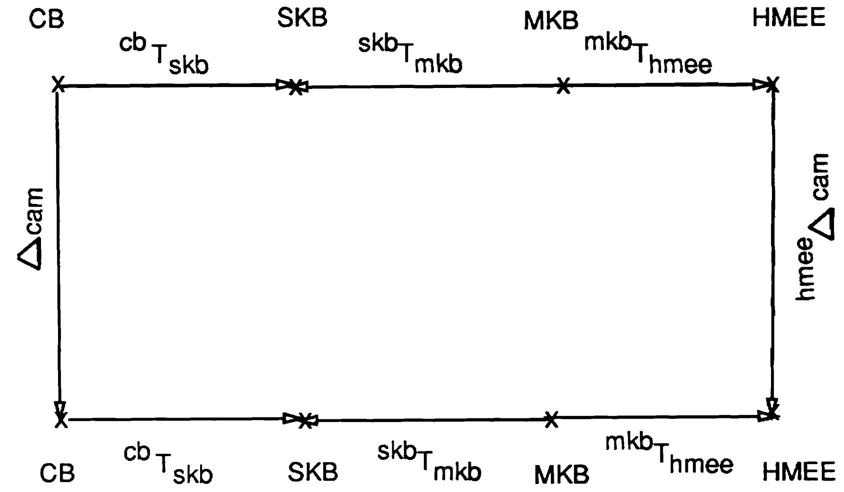

Fig.4.b. Transform graph for the chnge of camera configuration

$$d_h^2 = [{}^{hmee}T_{see}]_{translation} => [x^2 + y^2 + z^2] \tag{14}$$

$$d^2 = [{}^{mee}T_{see}]_{translation} => [x^2 + y^2 + z^2] \tag{15}$$

The linear scaling factor is given by the ratio of the square of the distances as

$$ScaleFactor = d^2/d_h^2 \tag{16}$$

Thus obtained scale factor is used to formulate the T_{scale} in equations 10.

2.4.3 Practical Consideration

In the previous subsection it is considered that the camera is mounted on the end effector of another manipulator, however this is not essential as long as we can obtain its position and orientation by some mechanism. At the beginning the camera is in its home configuration, thus Δ_{cam} is an identity matrix and the scaling factor is unity. Whenever the viewing camera orientation is changed the master arm has to be reindexed and the corresponding corrections are to be applied to the transmitted data from then onwards. In this implementation the camera orientation is entered with the help of master arm. This is achieved as follows. As the camera view is changed at the slave site, the master arm is entered into a mode 'orient camera' for entering the camera configuration. In this mode the master arm is brought to its home configuration and the wrist joints are made free to move so that the operator can orient the wrist in such a way the roll, pitch and yaw of the wrist corresponds to that of the camera orientation, while the main joints of the arm are in locked condition. Under this mode of operation the information exchange between the master and slave does not take place. On setting an appropriate camera orientation, the master arm is again brought to its home configuration and switched back to the normal teleoperation mode. The RPY transform to the roll,pitch and yaw yields the required Δ_{cam}, which is used to obtain the viewing transform correction factor.

3 Force and Torque information from Slave to Master

This section describes a mechanism of providing the feel of forces and torques encountered by the slave arm end effector to the operator leading the manipulations at the master arm. The force reflection to the operator will make him or her feel as though he or she is performing the task in direct contact, thus the ability to perform is enhanced. The slave end effector is fitted with an instrumented compliant wrist sensor capable of providing a measure of forces/torques encountered by it in and around the three principal axes respectively. The forces and torques are measured in terms of the deflections of the compliant wrist, as $f = k_{linear}x$ and $/tau = k_{torsional}\theta$ for small x and θ. Let ${}^{see}T_{env}$ be the transform which describes these deflections with reference to the slave end effector frame, the rotational part of the transform gives the measure of torque and the translational part of the transform gives the measure of forces encountered. Since the ${}^{see}T_{env}$ is defined with reference to the end effector of the slave arm, we have to find equivalent defelections with reference to the master arm end effector frame and then drive the master arm to a new configuration to accommodate these deflections. In doing so the operator would provide the necessary reaction force/torque on the master arm end effector, to keep the overall system of master and slave in a stable tracking kinematic configurations. Thus under the balanced condition of the system the correspondence in position/orientation between master and slave is intact and the operator feels the reflected force in the form of a reaction to him by the master arm end effector. The following subsections describe in detail the various aspects of implementation. The Fig.5.a. shows the various frames involved in the processing of force/torque information.

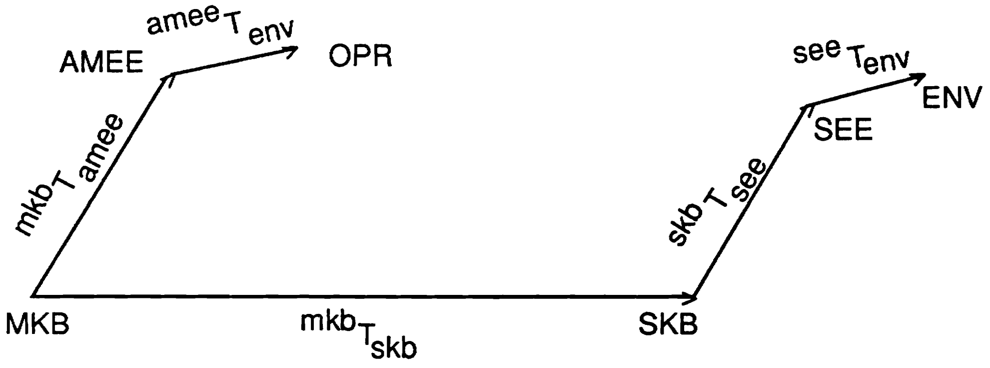

Fig.5. a. Transform graph force reflection from slave to master

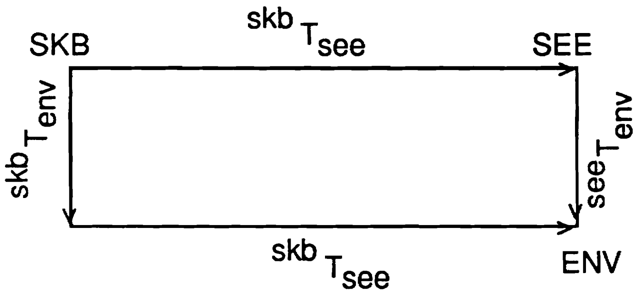

Fig.5. b. Differential transform at slave end effector

3.1 Processing at the Slave end

Fig.5.b. shows the differential transform graph involving SEE and SKB coordinate frames. ${}^{see}T_{env}$ is the transformation of the instrumented compliant wrist with reference to SEE and has to to be transformed to SKB frame giving ${}^{skb}T_{env}$, which is transmitted back to the master end for further processing to provide force reflection. From Fig.5.b. we can write the transform equation

$$ {}^{skb}T_{env} = {}^{skb}T_{see}\,{}^{see}T_{env}\,{}^{skb}T_{see}^{-1} \tag{17} $$

3.2 Processing at the Master end

${}^{skb}T_{env}$ received from the slave end is with respect to slave KB frame, which has to be transformed to the master KB frame. The Fig.6.a. shows the differential transform graph for such a transformation. From Fig.6.a. we have the following equation

$$ {}^{mkb}T_{env} = {}^{mkb}T_{skb}\,{}^{skb}T_{env}\,{}^{mkb}T_{skb}^{-1} \tag{18} $$

To provide the feel to the operator the ${}^{mkb}T_{env}$ has to be transformed to AMEE coordinate frame.The Fig.6.b. shows the differential transform graph for such a transformation. From Fig.6.b..6.b. we have the following equation

$$ {}^{amee}T_{env} = {}^{mkb}T_{amee}^{-1}\,{}^{mkb}T_{env}\,{}^{mkb}T_{amee} \tag{19} $$

Since the operator leads the master arm by moving its end effector, these transformed deflections are used in obtaining the new target configuration of the master arm. The Fig.5.a. shows the differential transform graph for such a transformation and we have from

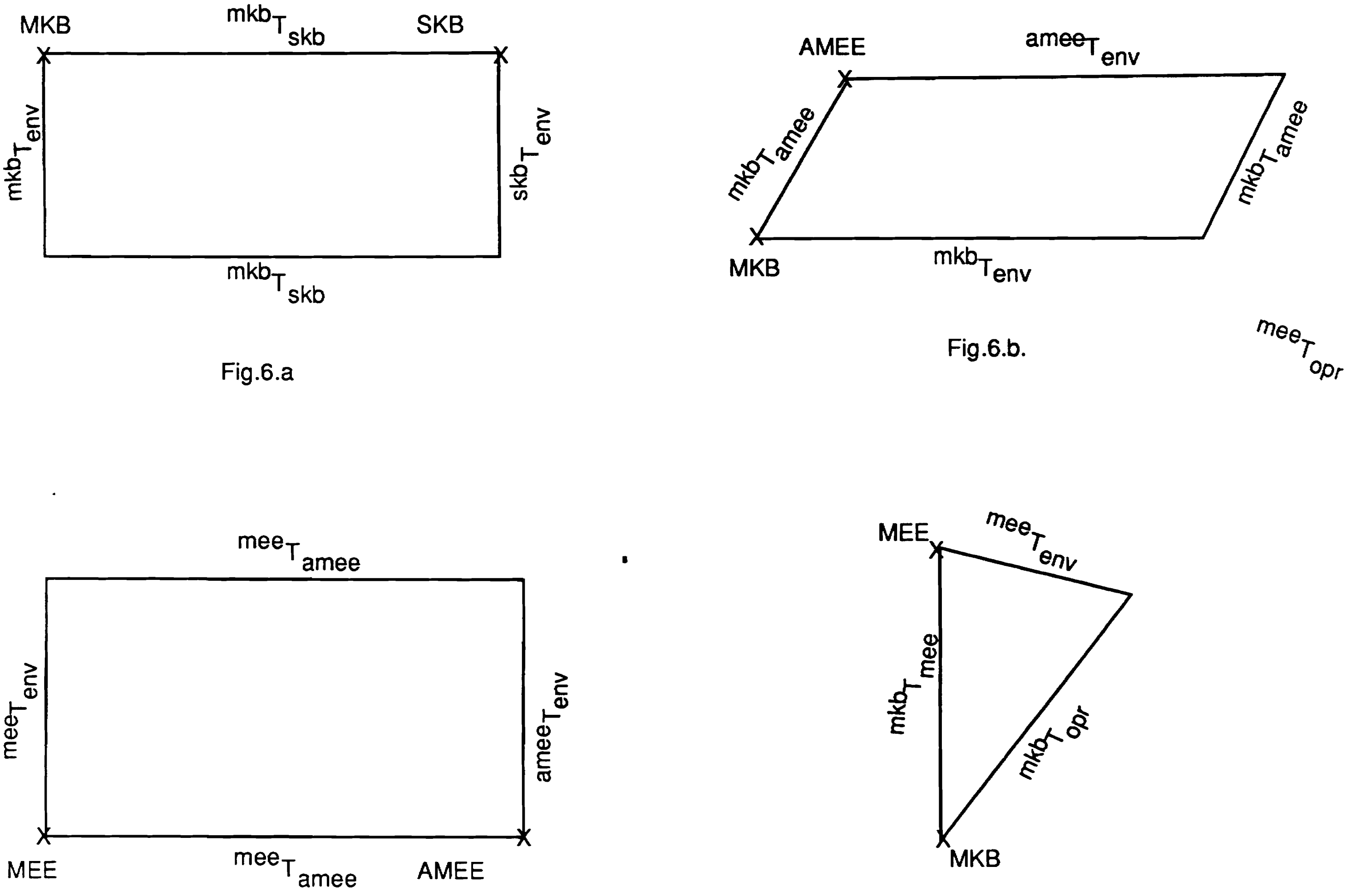

Fig.6.a

Fig.6.b.

Fig.6.c

Fig.6.d.

Fig.6. Transform graph of the force transformations at the master end

the figure the new target for the master arm given by

$$ {}^{mkb}T_{opr} = {}^{mkb}T_{amee}\,{}^{amee}T_{env} \tag{20} $$

On simplification we have the transform equation

$$ {}^{mkb}T_{opr} = {}^{mkb}T_{skb}\,{}^{skb}T_{env}\,{}^{mkb}T_{skb}^{-1}\,{}^{mkb}T_{amee} \tag{21} $$

By driving the arm using the transformation ${}^{mkb}T_{opr}$, the operator would feel the force/torque encountered by the end effector of the slave arm.

3.3 Considerations on Reindexing of the Master arm

Before reindexing the AMEE and MEE coordinate frames are coincident. On reindexing these two frames are no longer coincident and the above equation for ${}^{mkb}T_{opr}$ will have to be corrected further. The operator interaction with the master arm is with reference to MEE frame. The transformation from AMEE to MEE frame will give the required correction factor. Fig.6.c. shows the differential graph and the transform equation is given by

$$ {}^{mee}T_{env} = {}^{mee}T_{amee}\,{}^{amee}T_{env}\,{}^{mee}T_{amee}^{-1} \tag{22} $$

The new target configuration of the master arm is given by from the Fig.6.d. as

$$ {}^{mkb}T_{opr} = {}^{mkb}T_{mee}\,{}^{mee}T_{env} \tag{23} $$

$$ {}^{mkb}T_{opr} = {}^{mkb}T_{mee}\,{}^{mee}T_{amee}\,{}^{amee}T_{env}\,{}^{mee}T_{amee}^{-1} \tag{24} $$

From Fig.3. the transform ${}^{mee}T_{amee}$ is given by

$$ {}^{mee}T_{amee} = {}^{mkb}T^{-1}_{mee}\,{}^{mkb}T_{vhmee}\,{}^{mkb}T^{-1}_{hmee}\,{}^{mkb}T_{mee} \tag{25}$$

On simplification of these equations, we have the result as follows

$$ {}^{mkb}T_{opr} = {}^{mkb}T_{vhmee}\,{}^{mkb}T^{-1}_{hmee}\,{}^{mkb}T_{mee}\,{}^{mkb}T^{-1}_{amee}\,{}^{mkb}T_{skb}\,{}^{skb}T_{env}$$

$$ {}^{mkb}T^{-1}_{skb}\,{}^{mkb}T_{amee}\,{}^{mkb}T^{-1}_{mee}\,{}^{mkb}T_{hmee}\,{}^{mkb}T^{1}_{vhmee}\,{}^{mkb}T_{mee} \tag{26}$$

Let the force correction factor be given by

$$ T_{ForceCorec} = {}^{mkb}T_{vhmee}\,{}^{mkb}T^{-1}_{hmee}\,{}^{mkb}T_{mee}\,{}^{mkb}T^{-1}_{amee}\,{}^{mkb}T_{skb} \tag{27}$$

Then finally the equation for ${}^{mkb}T_{opr}$ reduces to

$$ {}^{mkb}T_{opr} = T_{ForceCorec}\,{}^{skb}T_{env}T^{-1}_{ForceCorec}\,{}^{mkb}T_{mee} \tag{28}$$

By driving the master arm to the new target configuration given by ${}^{mkb}T_{opr}$ provides the required reflection of force/torque to the operator.

3.4 Scaling of reflected forces/torques

The operator may wish to scale up/down the reflected forces and torques for a particular task. Like the scaling of displacements, scaling of forces can be performed in an identical manner. The translation component of the ${}^{skb}T_{env}$ provides forces to be scaled by a factor and the rotaional component of the transform ${}^{skb}T_{env}$ provides torques to be scaled by a factor through RPY transformations.

3.5 Viewing Transformation correction factor

The change in viewing parameter affects the frames of forces reflected on the master end effector. The correction has to be applied to the force reflection transform ${}^{skb}T_{env}$, so that the feel for the forces at the master end effector is appropriate. The modified force reflection transform will therefore take the form

$$({}^{skb}T_{env})corrected = \Delta_{cam}^{-1}\,{}^{skb}T_{env}\Delta_{cam} \tag{29}$$

3.6 Audio feedback of force signals

The video image of the task environment being a two-dimensional image, the precise interpretation is often difficult. The kinesthetic feedback in the form of force reflection provides a feel for the task although the sensitivity is not very good. The quality of telepresence can be enhanced by providing an audio feedback to the operator of the forces encountered at the slave end effector in performing a task. The multi-axis force/torque information is transformed into sound information, so that the operator can easily recogonise and interpret the instance of contact, progress of task and other interacting parameters between slave manipulator and the objects involved in the task. This concept has been described and demonstrated in a micro machining task through teleoperation [4]. It may also be noted that teleoperator systems implemented on a computer network has large delays in communication of data between master and slave stations. It is known that even a delay of the order of 100 milliseconds is enough to create operator induced instabilities. It has been suggested by many researchers that force feedback in a non-reactive manner is more advantageous to the operator particularly under time delayed teleoperations. A number of experiments to compare the effect of force reflection in active and non-reactive sense have been reported [5]. The absolute magnitude of the encountered force signals is modulated to generate an audio signal in the frequency range of 320 to 460 Hz triangular wave in discrete steps of 20 Hz. The audio port of the slave controller is used to synthesize the audio signal. It has AM79C30A Digital Subscriber Controller chip with a built-in analog-to-digital and digital-to-analog converter that can drive a speaker or headphone. The audio signal generated is then transmitted to the master station via separate audio channel.

4 Experimental Setup

The experimental setup consists of a master arm, a slave arm and controlling processors for each arm and finally an ethernet communication link between the processors. This section describes each of the sub systems involved. Fig.7. shows the schematic of the overall setup.

4.1 Master Arm

Master arm is a PUMA-250,fitted with LTS-200 force/torque sensor at its end effector. The actuating motor drive control is provided by the modified Unimation drive unit. The drive signals to the motors are issued by IBM PC-AT computer system. The PC-AT system also reads the position encoders and the force/torque sensor values at the servo rate. The joint level position and force reflection servo loop algorithms are implemented on a JIFFE co-processor. The hardware schematic of the master arm site is shown in Fig.7.a. The operator leads the master arm to perform a task. The operator should not feel the mass of the arm, and the gravity and inertial forces and the mass of the sensor assembly. Position control loop algorithm has a compensation for gravity forces incorporated in it. The operator by leading the master arm creates a force/torque on the sensor assembly and this force/torque causes the setpoint to be changed for the the master arm to the intended configuration under a closed loop position control. The VME bus interface links the PC-AT and JIFFE co-processor. The user interface to the JIFFE is provided through Silicon Graphics IRIS work station. JIFFE and IRIS are linked through VME bus interface unit. The JIFFE co-processor provides 40 real MFlops of computational power. The control software of the master arm is computation intensive and is run on JIFFE as a real time process, however

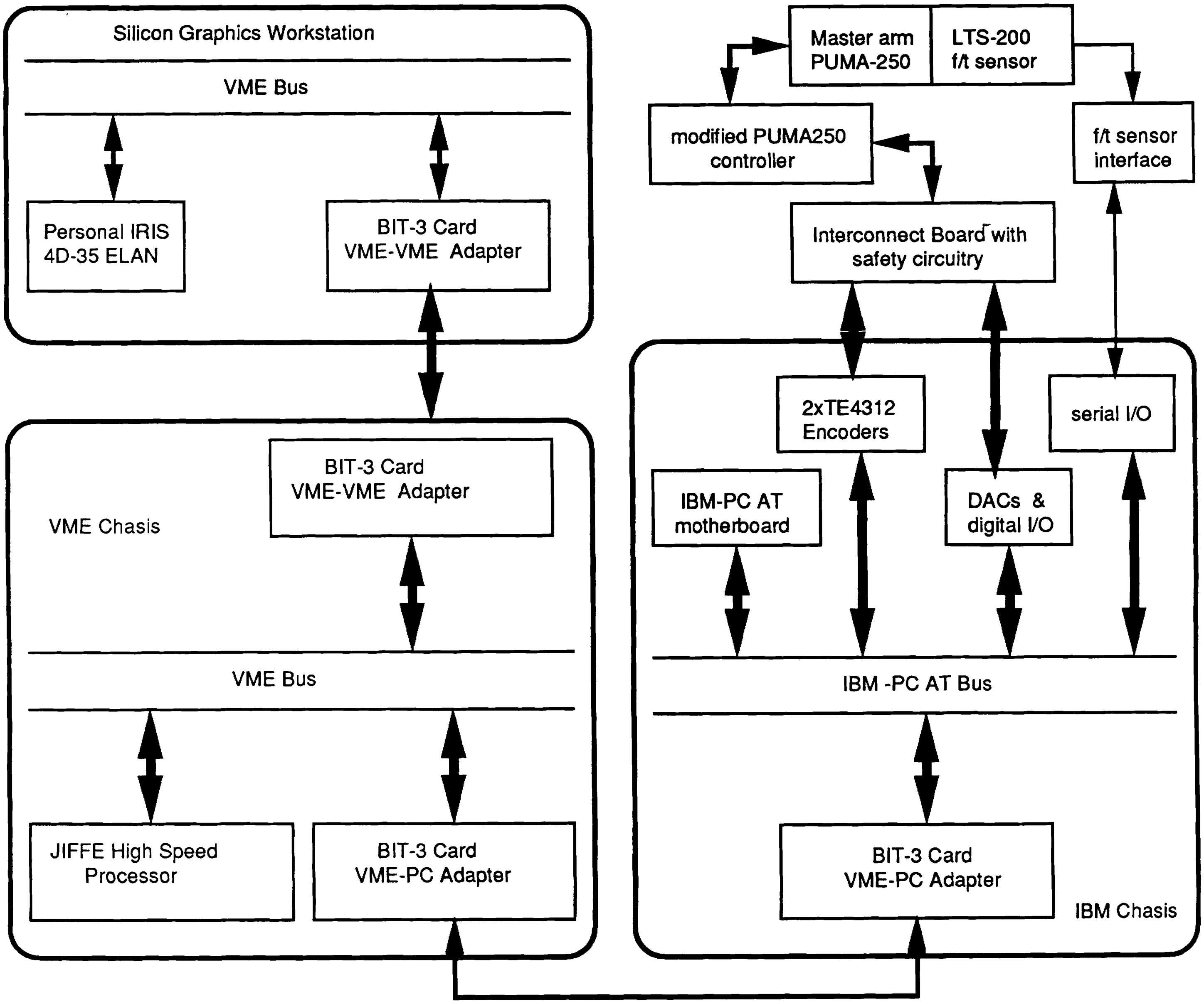

Fig.7.a Schematic of the hardware details at the master site

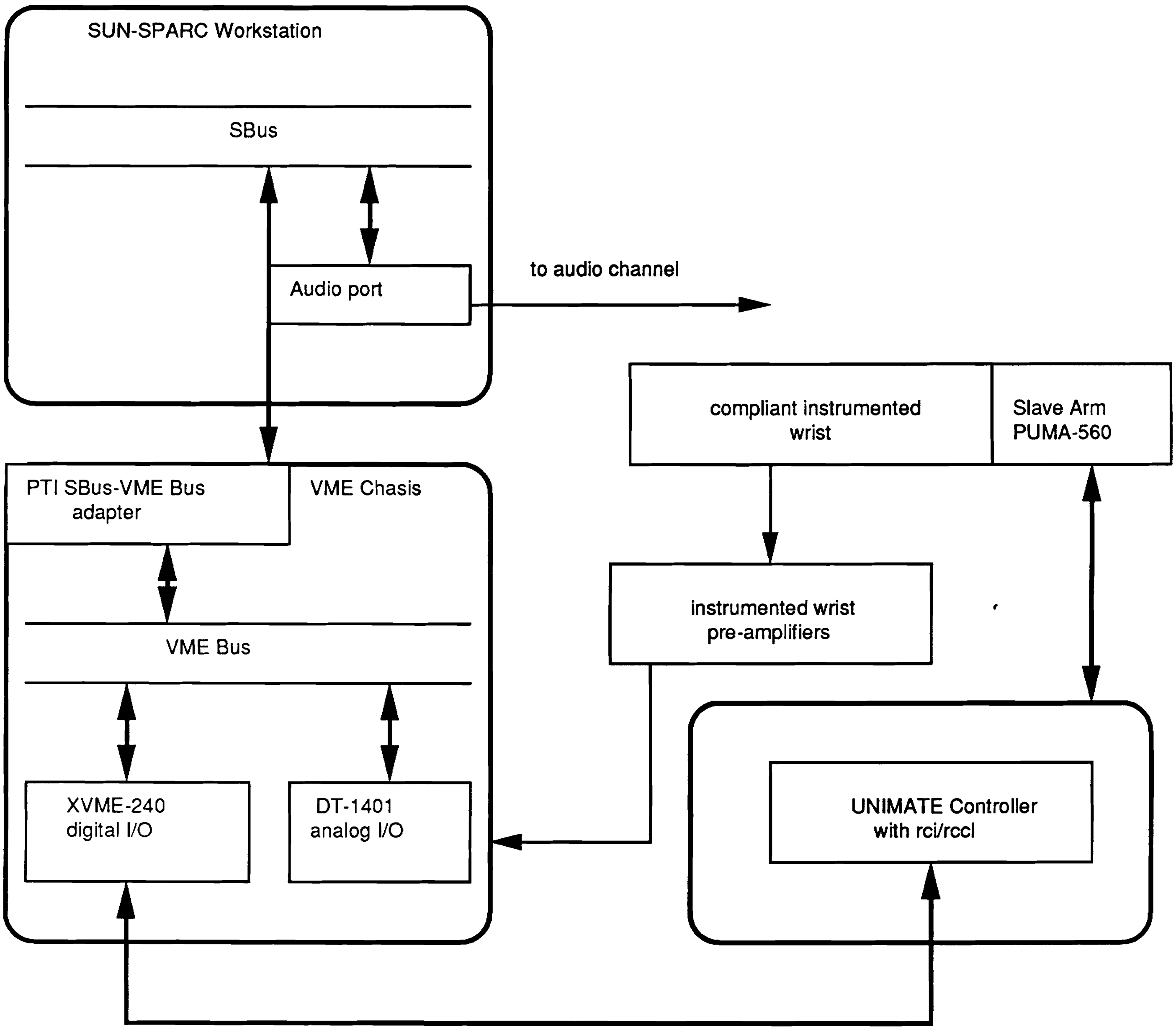

Fig.7.b. Schematic of the hardware details at the slave site

the real time clock support is provided by the IBM-PC AT interrupt service routines.

4.2 Slave Arm

The Slave arm is a PUMA-560, fitted with an instrumented compliant force/torque sensor at its end effector. The actuating motor control drive is provided by the Unimation motor drive unit.The Unimate controller is working under RCI/RCCL environment providing the real time control capability. The controlling processor is a SUN work station. The hardware schematic of the slave arm site is shown in Fig.7.b. The control program of the slave arm has two sections, namely, the real time control interface and the planning level control. The real time control algorithm provides the position and force reflection servo loops. The planning level control is a non real time process and provides the user interface.

4.3 Master - Slave Communication

The position information from master to slave and the force information from slave to master are to be communicated at servo rate. In the existing set up, the communication link between master controller IRIS and the slave controller SUN is through an Ethernet network. Though this channel does not support real time communication, it provides a test bed for the concepts described in the earlier sections. Fig.8. shows the type of signals and its flow mechanism from one system to another. The position information from master is brought to IRIS through a ring buffer in shared dual port memory. The same is transmitted to the SUN via ethernet link. The received position information on the SUN is brought to the real time control interface section through a ring buffer. Exactly the same technique in the reverse direction apply to the transmission of force signals from the SUN to the

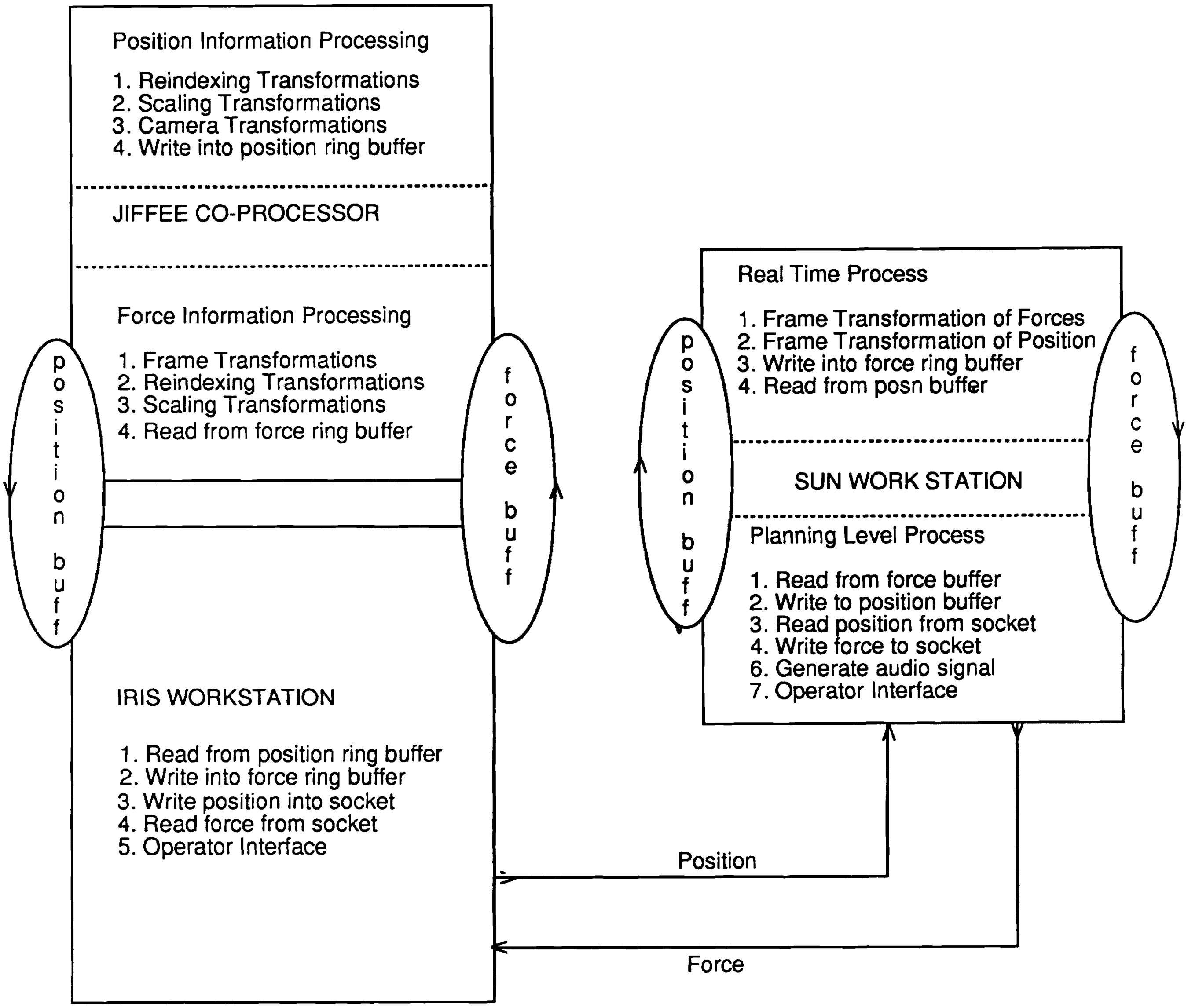

Fig.8. Information Processing and Communication

IRIS. It is obvious that the overall system is running under different operating systems utilizing a number of buffers for signal transmission. The communication process between the IRIS - SUN - IRIS is initiated by a handshaking protocol. At first the IRIS begins the communication by sending a packet of position transformation and then waits for the acknowledgment from the SUN in the form of a packet of force transformation. The master arm and the slave arm control processes are running in real time and at the same servo rates. The position/force data are acquired at this rate .The overall communication delay is the addition of the time required to read/write into ring buffers at both the stations and the time taken in adhering to TCP protocol. Experiments were conducted to evaluate the average communication delay between the master and slave stations. In these experiments the position data packets were sent from master station and a corresponding force data packet was received at the master station from the slave site. The round trip delay in communication for a set of data transfer was found to be in the order of one second. The real time processes are running at a rate of 50 samples per second. The ring buffers are therefore have to be of size to hold at the least 50 position / force data packets. A buffer of size less than this will result in loss of position / force information. The position data acquired at servo rate is also being consumed at the same rate, the velocity information is implied in it. Therefore it is of importance to ensure that at no time the buffer is completely filled up to cause a overflow and the velocity correspondence is lost. A buffer size of 1000 data packets is chosen in this implementation. However due to the uncertainty of timings in the ethernet communication link, the receiving ring buffer can become empty and wait for a further data arrivals. Under these circumstances the resulting movements of the slave arm will be discontinuous and for the similar reasoning the forces felt at the master arm would be jerky. The average delay of one second is considerable for direct teleoperation experiments. The force feedback with high delays result in instability of the operation and thus impairing the operator's ability to judge the situation rather than aiding him. Moreover the delay in communication is time varying and is dictated by the load on the network. The audio feedback of the force signals have shown to give a better feel of the task environment in our experiments.

4.4 Experimental Results

The experiment devised to evaluate the performance of the thus described teleoperator system is to slice a membrane of a tape pasted on two wooden blocks separated with a small gap between them. The membrane of a tape is the simulation for a thermal blanket of a satellite, which is removed through teleoperations. The experiment is divided into two sections.

1) The membrane of the tape has to be cut along a direction and later has to be cut in a direction at right angles to the previous cut. The viewing camera mounted on a tripod is focussed on to the task area, so as to provide the direction of cutting as view into the screen. Under teleoperation mode the first cut is completed and the camera is moved manually to the new location so as to keep in the viewed image the direction of cutting as a view into the screen. The teleoperator system is entered into 'orient camera' mode, the viewing parameters of the camera is entered into the system by moving the wrist of the master arm. On completion of updating the changes in the viewing parameter the teleoperator system is switched back to the 'teleoperation mode' and to continue the slicing at right angles to the previous cut. The automatic correction of the transforms due to changes in viewing

parameters keep the movements of the slave manipulator in the viewed image to correspond to that of the master manipulator movements and has considerably reduced the strain on the operator in giving appropriate interpretation to the image on the video screen.

2) The second part of the experiment is in performing the task of slicing the membrane of a tape about 30 cms long pasted on two wooden blocks separated by a gap of 2 mms. The experiments are conducted (a) with active force reflection and (b) with non-reactive force reflection in the form of auditory data. The Figs. 9 a&b show the graph of sum of squares of forces encountered in performing the task. The variation of the forces encountered by the slave manipulator is more in the case of active force reflection, which is attributed to the operator induced instability. The time delay makes it difficult for the operator to keep the forces to a steady value. The table I provides the comparison of results of the experiment.

Table I

parameter	active force	auditory force
task time	—— 176s——	155s
time delay	—— 1.22s——	1.14s
average of sum of square of forces	—— 22.8——	5.1

It may be noted that average round-trip delay in communication between master and slave is almost same and the total amount of time taken to perform the task is also of similar, but the average sum of squares of forces is significantly less in the case of auditory feedback. This reduction can be attributed to the absence of operator induced instability in the case of non-reactive feedback. The comparison made in the experiments are not completely conclusive, due to the fact that due to the active force reflection mode the round trip delay

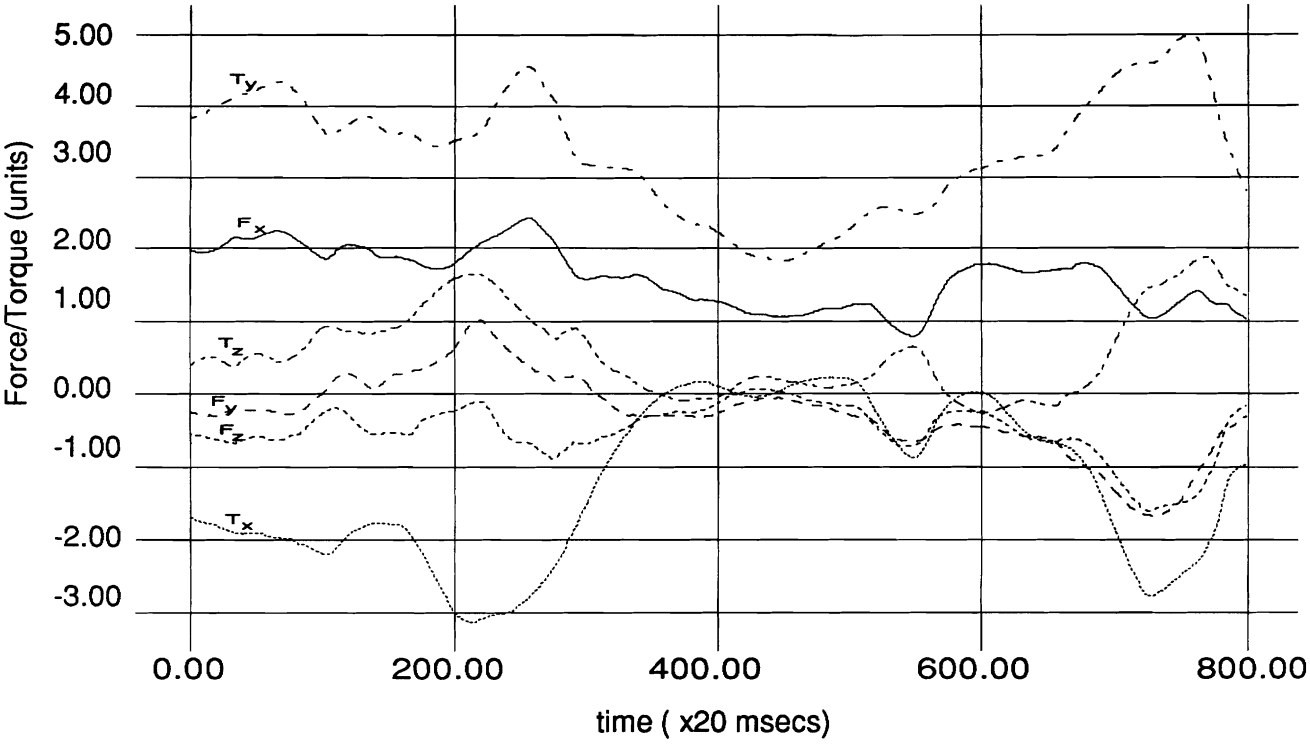

Fig.9.a. Graph of force vs time under auditory feedback

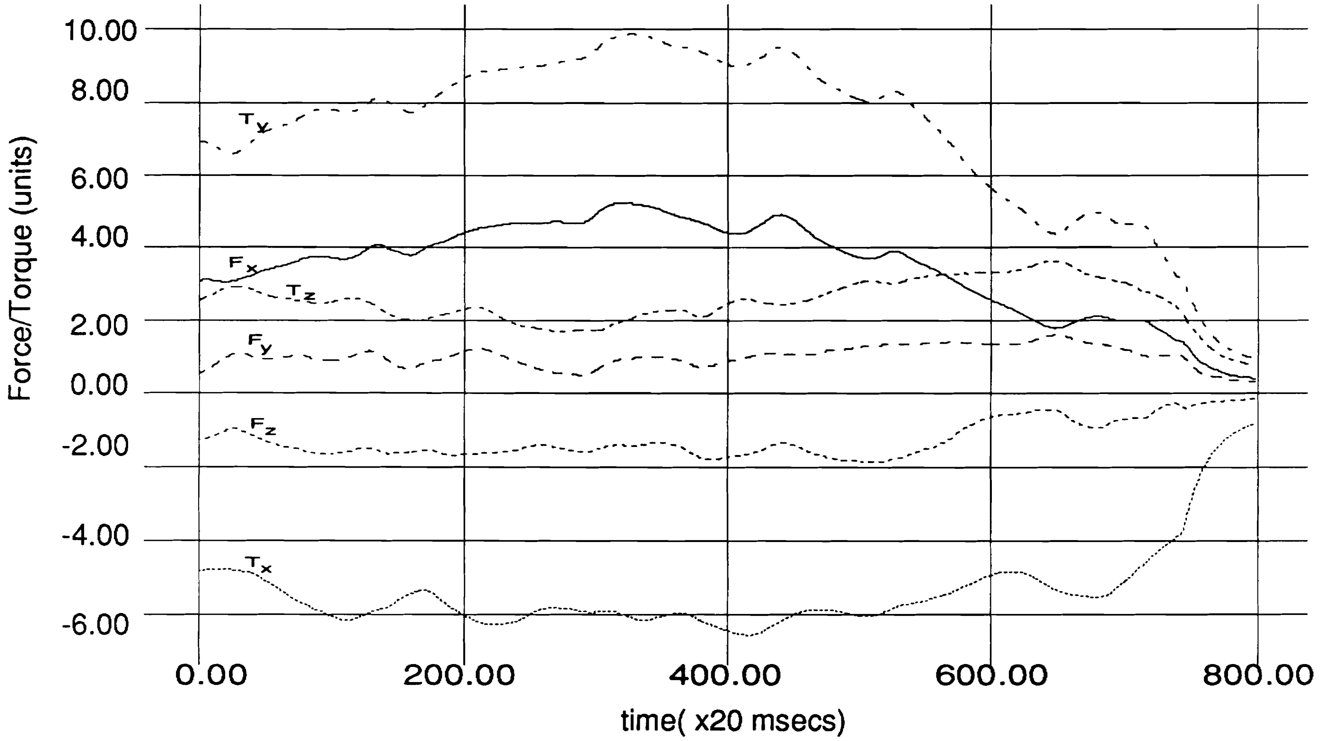

Fig.9.b. Graph of force vs time under active force reflection

of around 1 second plays a dominant role, whereas in the auditory feedback mode the delay is in one direction from master to slave and the audio signal is a direct analog feedback with no comparable delay. However, the conclusions drawn are true for situations representative of the real world.

5 Conclusions and further work

A step by step implementation procedure of a direct teleoperator system with communication between master and slave stations through a computer network is described. The corrections to the transforms to nullify the effect of change in viewing parameters are discussed. The experimental results showing the effectiveness of the change in camera orientations and the comparison of active force reflection to the non-reactive force reflection in the form of auditory signal is presented.

The implementation uses the master and slave manipulators with dissimilar kinematic configurations. The issues relating to the master manipulator reaching either its singularity configuration or attempting to move outside its workspace has been discussed. Further work is needed to tackle the conditions of slave reaching its singularity configuration or attempting to move outside its workspace limits.

As pointed out in the introduction section, the motivation for this work is to develop a teleoperator system using a high bandwidth and decreased error rate communication network. The key requirements for such a network service is

a) to have a non-cumulative delay in communication between master and slave tolerated up to 10 msecs.

b) to have a through put of 400 bit data packet corresponding to the position/ force from master/slave to be delivered at a servo rate of 2 msecs.

c) to have extreme reliability in data transfer and to maintain always a first-in first-out data sequence.

d) to have efficient failure recovery techniques, so that the master and slave manipulators can be re-synchronized with an operator assistance. However, the service setup time is not very critical as it does not play a role in the closed servo loop operation of the teleoperator system.

e) to have two video channels with a data transfer rates of atleast 10 frames/sec and an audio channel.

The high speed network is being implemented on two RS-6000 computer systems located at master and slave sites. The communication protocols and data transfer for the position and force data are realized between RS-6000 and the real time process of each manipulator. Since the data transfers have no intermediate storage buffers and are not influenced by the operating system, we hope to achieve communication at the servo rates of 500 per second. At the time of writing this paper the testing of the communication system is being carried out.

6 References

1. A.K.Bejczy and J.K.Salisbury.Jr, " Kinesthetic Coupling between operator and remote manipulator", Proc. of the International Computer Technology Conference, ASME, San-Fransisco, CA, 1980., pp.197-211.

2. Robert J.Anderson and Mark W.Spong," Asymptotic stability for force reflecting teleoperators with time delay", International Journal of Robotics Research, vol.11, No.2, April 1992, pp.135-149.

3. S.Hayati and S.Balaraman, " Supervisory Telerobotics Testbed for Unstructured Environments ", Journal of Robotic Systems 9(2), 1992, pp261-280.

4.Mitsuishi,M., Warisawa,S., Higashi,T., Kobayashi,O., Hatamura,Y., Nagao,T. and Kramer,B., " A Tele-Machining System Using Multi-Axis Force Data and Stereo Sound Information ", Proceedings IEEE International Workshop on Robot and Human Communication, Tokyo, Japan, 1992, pp.227-234

5. Micheal Massimino and Thomas Sheridian, " Using auditory and tactile displays for force feedback" , Telemanipulator Techology, Proc. SPIE, vol.1833, 15-16 November,1992., Boston, Massachusetts, pp325-336.

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