ETS-7 SPACE ROBOT TELEOPERATION THROUGH VIRTUAL FORCE REFLECTION

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ABSTRACT

The National Aerospace Laboratory (NAL) is participating in the ETS-7 robot experiments in order to establish the basic technologies for on-orbit truss assembly by ground teleoperation. Several different approaches have been tested so far. This paper describes one of them: the application of force reflecting (FR) hand controllers to improve continuous teleoperation with long communication delays.

After a comprehensive analysis of the current state-of-the-art, four distinct fundamental ideas have been implemented: a) the use of FR to limit speed of command; b) the use of potential force fields for guidance during grasping and inspection; c) the use of the FR hand controller to generate physical constraints and d) the use of the FR device to intuitively correct modeling errors after probing the environment.

All of them have been successfully tested on the ETS-7 robot system using NAL's Ground Teleoperation Facility (GTF) and two 2-DOF Force Reflecting Joysticks. This paper reports the conduction and results of these experiments.

1. INTRODUCTION

Space robot systems and on-orbit telerobotics technology will play an essential role in the construction and maintenance of large-scale structures, such as the International Space Station (ISS). The ETS-7 satellite was launched by NASDA in November 1997 to conduct rendezvous docking and space robot technologies experiments. The National Aerospace Laboratory (NAL) of Japan is participating in the robot experiments in order to establish the basic technologies for on-orbit truss assembly and deployment by ground remote operation of the robot located on the satellite.

It is well known that continuous on-orbit teleoperation of robots by operators on Earth is seriously impeded by signal transmission delays imposed by limits on computer processing at transmission stations and satellite relay stations. For the ETS-7 the time delay is normally between 5-7 seconds

NAL has been performing research in the last few years on how to overcome the disturbing effect of time delay to achieve smooth and effective teleoperation. The application of the research on the ETS-7 robot arm has produced several promising approaches, as reported in [1] and [2]. For a detailed description of NAL's complete system and objectives regarding ETS-7 robot teleoperation please refer to the companion paper [3].

This paper describes another of the solutions adopted from conception to final application. The approach makes use of force reflecting (FR) hand controllers to improve continuous teleoperation with long communication delays. It is, to our knowledge, the first extensive application of FR for the ground teleoperation of a space robot.

First, in section 2 a comprehensive analysis of the current state-of-the-art on the use of FR for time delayed teleoperation is presented. The advantages and difficulties introduced by the use of FR are also addressed here. Section 3 is dedicated to describe the system employed to conduct the experiments. Section 4 addresses the tasks being conducted, while sections 5 presents the different fundamental uses of FR implemented so far: a) the use of FR to limit speed of command; b) the use of potential force fields to guide during grasping and inspection; c) the use of the FR hand controller to generate physical constraints and d) the use of the FR device to intuitively correct modeling errors after probing the environment. Finally, section 6 presents the conclusions.

2. A BRIEF REVIEW ON THE USE OF 'FR' FOR TIME DELAYED TELEOPERATION

It is well known that continuous teleoperation can be dramatically improved with the addition of some kind of FR [4]. FR decreases both the time of operation and the forces exerted during contact, making the operation smoother and safer.

It is also known than time delay makes the use of FR extremely difficult. Despite this and owing to its importance there has been extensive research in the field during the last decade, as shown in this section and profoundly explained in references [5] [6]. Proposals for time delayed teleoperation without FR, such as teleautomation [7], tele-sensor programming [8] or control based on a predictive observer [9], are also abundant in the literature.

Existing approaches for time delayed teleoperation with FR can be broadly classified into two groups: proposals for bilateral systems (master and slave coupled in both position/velocity and force with the slave, also known as FFB) and proposals for non-bilateral systems.

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Table 1. Conditions of the experiments conducted with the different proposals for FR time delayed teleoperation.

Method	dof	Freq. (Hz)	Task	Control	Delay
[10]	1	500	Hard contact	Pos.	2 s
[11]	1	N/A	Hard contact	Pos.	1 s
[12]	1	1000	Hard contact	Pos.	30 ms
[13]	1	N/A	Basic contact	Pos.	2 s
[14]	6	1	Basic contact	Pos.	500 ms
[15]	1	350	Basic contact	Pos.	320 ms
[17]	6	30	Following of box contour	Pos.	3 s
[18]	1	15	Grapple and fitting	Pos.	2-4 s
[19]	3	N/A	ORU exchange Open door	Vel. Force	5 s
*	2-3	4 / 10	Assembly	Pos	5-7 s

* This paper

2.1 Proposals for bilateral systems

There are two different approaches to eliminate instability of bilateral systems with time delay. The first one makes use of the two-port approach and passivity theories: FFB with time delay based in passivity [10], FFB using wave variables [11] and FFB for ideal kinaesthetic coupling [12].

The second group of approaches tries to solve the problem from the control theory point of view: FFB with tele-monitoring [13], FFB based on a Virtual Internal Model [14] and FFB through a computer network [15] [16]

2.2 Proposals for non-bilateral systems

Non-bilateral FR means that the operator is not kinesthetically coupled with the slave but instead is receiving force information through another physiological channel (visual and indirect FR) or the force reference is different from the one generated at the remote zone. Regarding the latter case the main proposals are: Teleprogramming [17], Predictive Operator Aid with Force Reflection [18] and Predictive system that tolerates geometric errors.

2.3 Discussion

Table 1 shows the characteristics of the experiments successfully carried out with the different methods mentioned above. It includes the number of DOF, the transmission frequency, the type of task, the type of control (position, velocity or force command) and the maximum time delay supported.

Almost none of these has been tested under the difficult circumstances of operation of space robots: high flexibility of the arm, high backslash, low accuracy, low communication bandwidth, long time delay, short operation time, etc. The last line corresponds to the experiments that are presented in this paper and that have been tested with the ETS-7 robot arm.

First, it is worth noting that almost all of these use position command, which is more suitable for complex and precise tasks and more intuitive than rate control when using FR.

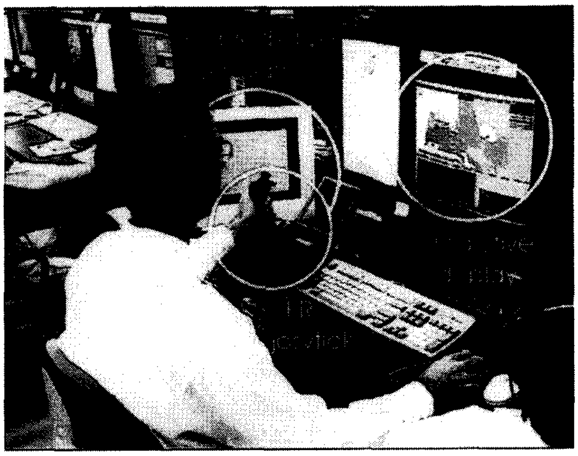

Figure 1. FR Teleoperation of ETS-7 robot arm

It is seen that bilateral schemes are used only in 1 DOF basic contact tasks for delays of up to 1 or 2 seconds, and even so heavily degraded. Hence, it can be affirmed that nowadays they are not well suited for space teleoperation.

On the contrary non-bilateral proposals are operational under several seconds of time delay for more complex tasks and up to 6 DOF. It is true that the main advantage of FR (coupling with the task) is lost but some other advantages, such as intuitiveness, reduction of operating time and safety remain.

Another advantage is that visual aids tend to overload the on-line mental modeling done by the operator, while hand force cues are easily integrated by the human brain with no need of complex processing [20]. Hence FR is a very interesting and direct way of 'displaying' information to the operator and can be used in combination with other visual and acoustic aids without compromising the operator's performance.

Our effort has been to use some of the ideas present in the preceding proposals in combination with new ones to conduct experiments of non-bilateral FR time delayed teleoperation on a real space robot arm. The final aim has been to prove the advantages of this kind of systems in order to overcome time delay and point out the drawbacks that still require more research.

3. DESCRIPTION OF THE SYSTEM

The FR experiments have been conducted using NAL's Ground Teleoperation Facility (GTF) [21] located at the Tsukuba Space Center (TKSC).

Communication between NAL's GTF and the on-board robot arm is done through NASDA's facility. Commands are sent at a frequency of 4 Hz and telemetry is received at a frequency of 10 Hz. Commands in teleoperation mode refer to the arm's tip position. Time delay between command and telemetry is typically 5-7 s.

Figure 1 shows a photo taken during one of the experiments. The main devices involved are shown highlighted. They include 1 or 2 FR joystick, an FR predictive simulator and a predictive display

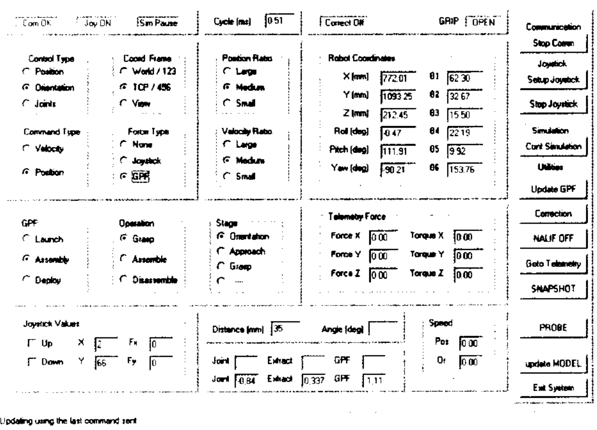

Figure 2 Interface of the FR predictive simulator

- *FR Joystick*

The FR hand controller is a 2 DOF Joystick from Immersion Inc. It has a workspace of 15.2 x 15.2 cm and is capable of generating output forces up to 8.9 N with a bandwidth of 120 Hz. The joystick deflection in both axes is used as position command for the on-board robot's tip.

Since the joystick workspace is much smaller than that of the robot, it is necessary to scale and re-index the joystick movements to generate the commands. Scaling is particularly useful when carrying out precise tasks. Re-indexing permits the operator to be in a comfortable posture at all times.

On the other hand, since one joystick has only 2 DOF, different modes of operation have been defined to allow each task to be performed in different steps. Experiments have been conducted both with only one or two joysticks, up to a total of 4 DOFs.

- *Predictive display*

The commercially available simulator Telegrip is used as the predictive display. It makes use of a CAD model of the TSE and of the robot arm.

Three different robots are displayed at the same time during operation: a) command robot, b) telemetry robot and c) FR robot. The command robot shows where the robot is commanded to go. The telemetry robot shows the delayed information of the robot's current position. And the FR robot shows the actual robot model that is used by the FR engine to generate the forces on the joystick. See section 5.4 regarding the *snapshot* approach.

- *FR predictive simulator*

This computer is the system core and acts as the interface between the FR joystick and the computer responsible for transmitting commands to the robot arm.

It generates position commands for the robot's tip using the joysticks encoders values as a reference. In addition, it is also responsible for giving the appropriate force commands to the joystick actuators to implement FR.

To achieve both functions, the FR predictive simulator includes the following features:

- Force reflection engine.
- Motion planning engine
- CAD model of the environment (i.e. TSE).
- Kinematic description of the various tasks.
- Library of different type constraints (planes, cylinders, etc.)
- Library of different types of contacts (hard, soft, informative, etc.)
- Interface (see Figure 2).

The motion-planning engine calculates the final commands for the robot using the references coming from the joystick and the current mode of operation specified on the interface. Velocity and acceleration motion planning is also performed here to keep them under a specific profile. The cycle time is 4 Hz.

The FR engine calculates the forces to be generated by the joystick actuators. It makes use of the design model static and kinematic features, the FR robot's tip current position and the current mode of operation, as well as the libraries of constraints and contacts, explained in the next section. The cycle time varies, but is commonly between 1000-2000 Hz, which is high enough for the FR to provide a good sense of touch to the operator.

The interface, shown in Figure 2, allows the operator to keep track of all variables deemed important (robot position and speed command, force being generated, telemetry force, parameters specific to the task, etc.). It also permits switching between different modes of operation and activating specific functions, such as the *snapshot* or *update model* features.

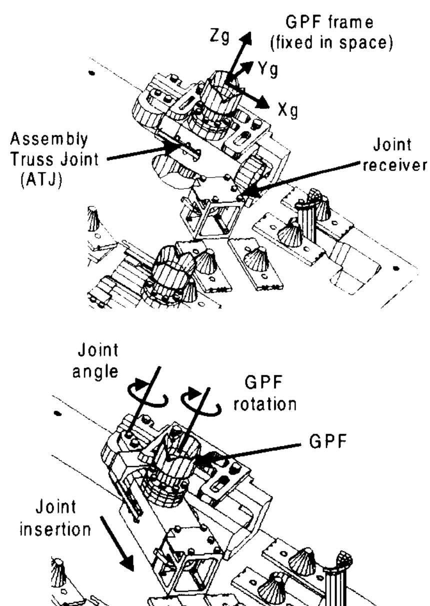

Figure 3 TSE's assembly Truss Joint (TJ) in a) stowed and b) assembled configurations

4. TASKS CARRIED OUT

Three different tasks have been conducted in order to demonstrate the advantages of the new FR system. They have been tested using the ETS-7 robot arm working on NAL's TSE. Apart from the difficulty of each task, one of the main concerns has been execution time, which owing to operability reasons is nominally of 20 minutes. The tasks successfully accomplished are the following:

- *Safe inspection of the TSE unit.*

Movement of the robot close to the TSE surface for visual inspection. The FR capability is used to avoid collisions and follow virtual contours around objects.

- *Vision guided GPF grasping.*

Grasping of the GPF guided by the data provided by the vision system. FR is used to guide intuitively the movement of the operator's hand during grasping.

- *Assembly of the Assembly Truss Joint (TJ)*

Both assembly and disassembly of the Assembly Truss Joint (TJ) have been accomplished.
To assemble the TJ requires the most precise, difficult and strong arm tip motion control of the ETS-7 tasks. This is mainly because of the features of the TJ (Figure 2), which was designed for assembly without any hand-over tasks [22].
The TJ assemble operation has four stages: a) to swing the TJ to the front of the joint receiver (JR), b) to rotate the GPF 60 degree to unlock and extend the TJ top, c) to insert the TJ into the JR and d) to lock the TJ by rotation. The TJ has a spring for automatic stowing.
It is a 3 DOF task. When using a unique 2 DOF joystick, automatic adjustment of roll rotation was done.

- *Deployment of the Deployable Truss Structure (DT)*

This task was successfully carried out at the end of May combining the FR system with the output of the generalized visual aid presented in a companion paper [1]. No detailed analysis of the results have been done yet

4.1 Robot control

Figure 3 shows the reference frames and parameters used. All experiments were conducted by moving the robot in the hand frame system (XYZ). The FR joystick was employed as a generator of position commands to the robot's tip. One joystick (X_jY_j) is always used to move in the robot's hand frame (YZ) plane. If two joysticks are employed, the use of second one depends on the task. The frame $X_gY_gZ_g$ is a fixed frame located at the TJ GPF stowed position.

5. APPLICATION OF FORCE REFLECTION FOR SPACE TELEOPERATION

Four different uses of FR have been tested so far both in isolated conditions and in combination. They have been successfully applied to the different tasks mentioned.

5.1 Monitoring and limitation of command speed

This is the most basic use of FR. As the FR joystick has been employed as a generator of position commands to

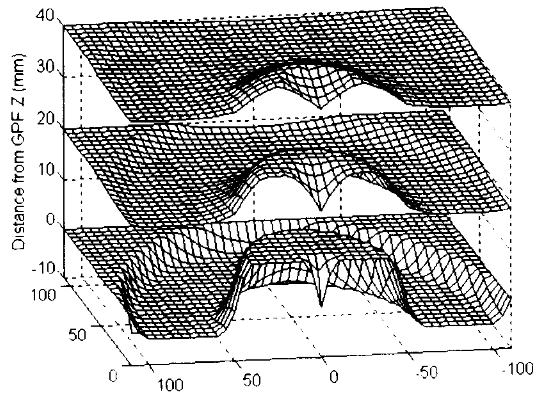

Figure 4 Force field for GPF grasping

the robot's tip, the speed of the robot is linearly related to the speed of the movement made by the hand.

In this context, it is very useful to limit the joystick speed using FR. Two approaches have been implemented: a) generation of a force that keeps the joystick fixed at the position where the violation occurred until the operator decides to continue, and b) generation of a damping force against movement that limits the speed.

5.2 Implementation of a field of virtual forces

The second application for the use of FR has been the development of a guiding system based on the concept of potential force fields.

The basic idea is to generate forces on the FR hand controller to indicate to the operator where he should move to successfully complete the task. He then only has to follow this movement with his hand. The important fact is that he keeps the control over the movement and can stop it, reverse it or even overrun the guiding cue whenever he thinks necessary.

Consider the GPF grasping application. GPF position is known from design data. A 3D force field is created around the GPF like in Figure 4. The GPF grasping point is in the origin of the GPF frame (X_g=Y_g=Z_g=0

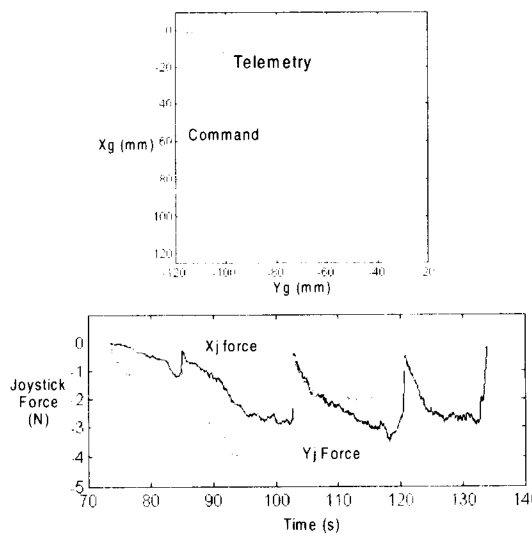

Figure 5 a) Command and telemetry position and b) virtual force generated in the joystick during the TSE inspection

mm). Positive values of force indicate attracting forces to the Z_g axis, while negative values indicate repelling forces. Joystick movement is in the X_gY_g plane while advance in the Z_g axis is made at a specific speed by pressing a pushbutton of the joystick. Vision data is used to update the GPF location and the corresponding force field along with it. By this method, the grasping is done very smoothly and data from the visual system is conveyed to the operator in an intuitive manner.

An identical approach is used in the orientation domain to move the robot to have its hand frame parallel to the GPF's frame at the beginning of the grasping operation.

Fields of virtual forces can also be used very easily for inspection. They can be put around objects to avoid collision and at the same time to guide the operator along the right path.

A part of the TSE has been safely inspected using this approach. Figure 5a shows the trajectory of both the command and telemetry robots while avoiding collision with the TJ GPF. The robot describes an almost perfect circle around the GPF area. The virtual field pattern felt by the operator is the one shown in Figure 4 with Z_g=0; Figure 5b presents the force generated by the joystick axis. It seems somewhat degraded because of the joystick indexing but it does not affect the final results.

5.3 Use of force cues and virtual constraints

To increase the flexibility of the use of virtual forces two new developments have been made: force cues and virtual constraints.

A library of common 3D geometric surfaces has been developed. It includes scalable planes, cones, spheres, etc. They can be easily placed in the environment to represent virtual constraints so that the FR engine can recognize them and generate the appropriate force when contacted by the robot's tip.

Each surface has some special features for FR that can be updated or changed anytime during operation. For example, consider a plane (Figure 6a). Contact can be simulated only in one of either faces (i.e. contact with a stiff surface) or in both at the same time (i.e. constrained movement along the plane). But moreover, FR does not have to be limited to the plane itself, but potential fields can also be applied on the surroundings of the surface.

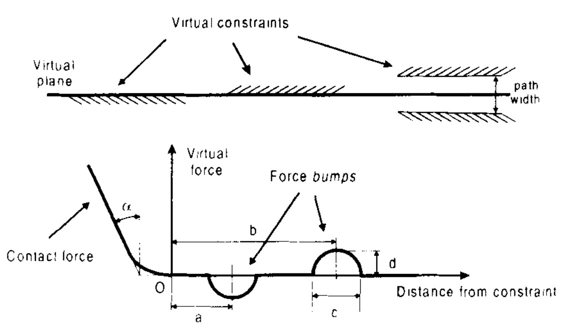

Figure 6 a) Types of constraints in a plane and b) parametric definition of a constraint

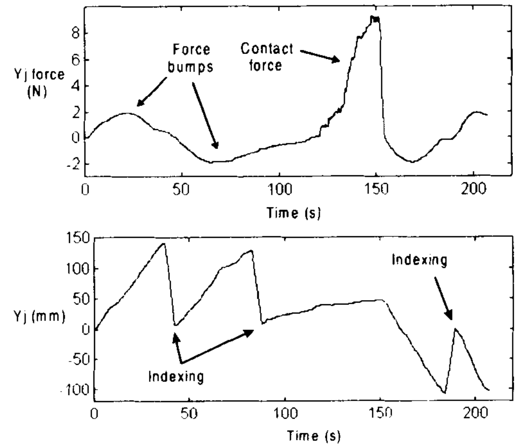

Figure 7 a) Force cues and b) axis evolution of the joystick when approaching a virtual plane.

Figure 6b shows the parametric force profile that is defined for each face of the plane. Before contact there are two *force bumps*. The first one is used to tell the operator that he is approaching contact. The second one helps him to maintain the contact. Finally, different contact behaviors can be specified to simulate complex interactions.

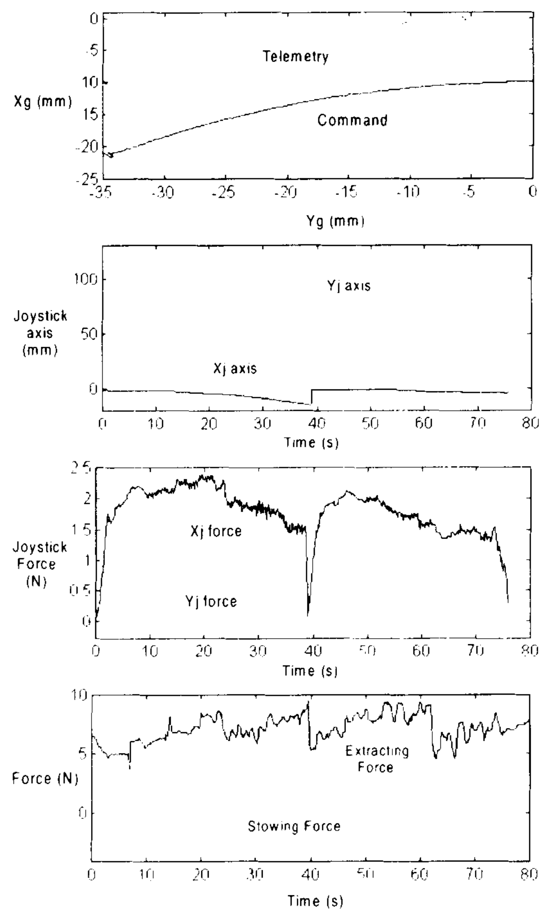

Figure 8 Evolution of different variables during the stowing operation of the TJ using force constraints

Figure 7a shows an actual force pattern of contact with a virtual plane. Note that the abscissa is time. The actual joystick movement is displayed in the lower figure.

Figure 8 shows the application of a constraint in the form of a cylinder for the stowing of the TJ. Both cylinder faces act as virtual walls that guide the movement of the joystick through space. The TJ was pushed constantly to be completely retracted creating a gap between telemetry and command due to the compliance of the arm. One sole indexing operation is required at around 40 s. Force reflected to the operator allows him to follow the path very intuitively. Joystick's DOF are directly related to the robot hand frame, but as orientation is automatically adjusted the operator advances moving one DOF (Y_j) while feeling the constraint in the other (X_j).
The inserting force to keep the joint retracted is perfectly maintained in the 5-10 N range, while the stowing force due to the spring in the joint decreases as the joint is being stowed.

5.4 The *snapshot* approach

The disadvantage of the system presented so far is that it does not account for mismatching between robot command and telemetry due to the high compliance of the robot arm (see Figure 8a). To solve this problem the *snapshot* approach was conceived.

For safety reasons and to help perform contact tasks the compliance of space robots is deliberately high. Nominal values for the ETS-7 robot arm are between 0.2-0.8 N/mm. Such compliance creates an important mismatching between command and telemetry positions of the arm when high forces are present.

This effect is particularly harmful to the approach described in the preceding section. Virtual forces cannot be generated based either in telemetry or in command robot models. A new robot model, called FR robot model, is needed. Virtual forces are generated regarding the FR robot's tip position in the environment.
The idea is to try to use as much as possible FR based on where the robot currently is but without compromising smoothness and speed of operation. In this context the FR robot is always between the command and telemetry robots, trying to be close to telemetry as much as possible.

We will now describe the operation procedure. If no real forces are present in the environment, the three robots will follow the same trajectory and there is no need to perform a *snapshot* (Figure 5a). When forces appear command and telemetry robots tend to separate. But as command separates from telemetry the virtual forces generated by the FR engine loose validity. In this situation a *snapshot* is required.

To make a *snapshot* means that the FR robot is automatically moved to telemetry without changing the command. That is, the relative positions of the FR and command robots change and the computer stores the transformation between them. After the *snapshot* the operator movements and sensation of virtual forces are

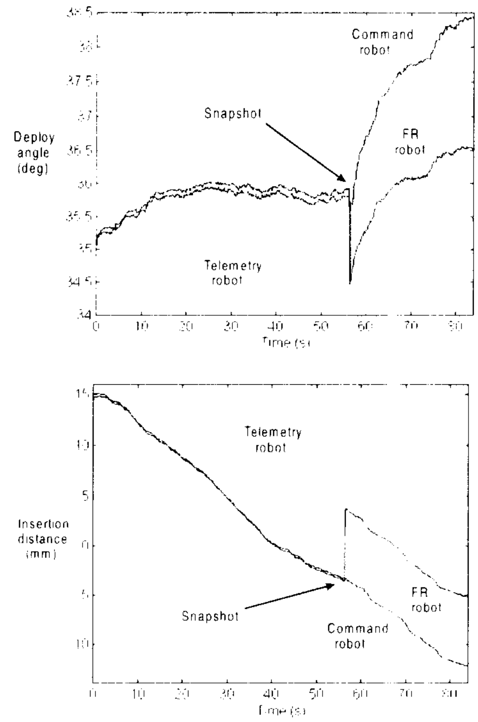

Figure 9 Application of a snapshot during disassembly of the TJ. a) stowing angle and b) insertion distance

close related to where the actual robot is. He continues with the movement of the FR robot and the computer calculates the command relative to it. Eventually the FR robot will depart again from telemetry and it is the operator's decision when to apply another *snapshot* to superimpose telemetry and FR robots again.

This procedure is seen in Figure 9 during disassembly of the TJ using a virtual constrained path (between 35.5 and 36.5 deg). Graphics for both the deployment angle and insertion distance are displayed.
Due to the TJ spring the swing angle of the TJ tends to go to the stowing side. Also, because of friction there is a misalignment in the insertion distance. The operator then performs a *snapshot* to *feel* where the on-board robot really is. After the *snapshot* the virtual forces guide the FR robot again to the right position to finish extraction and for subsequent insertion. The telemetry robot is brought along with it.

A *snapshot* takes almost no time, although it has to be applied off-line so that the change in virtual forces before and after do not confuse the operator. It can be done as many times as the operator considers necessary. With a little practice the operator soon learns how to take advantage of this novel system.

In the stowing of the TJ (Figure 8) one *snapshot* at the beginning was enough to keep the FR robot as same as the telemetry robot during the entire task. In contrast, several where needed during assembly

5.5 Probing and model correction

Telemetry force is of great importance because the high flexibility of the arm renders telemetry position calcula-

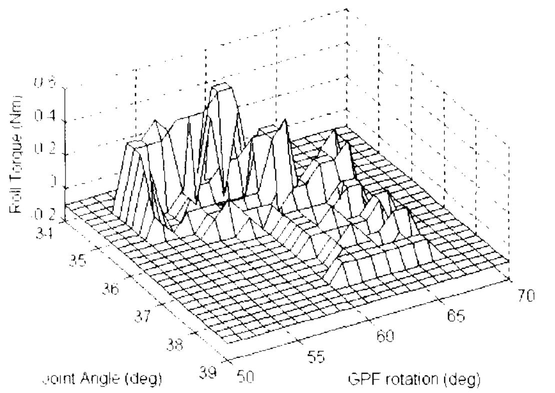

Figure 10. Results of probing the environment to look for the right joint angle for insertion.

tion inaccurate. Using an FR hand controller it is sensible to try to use telemetry force in some way.

We studied several possibilities and the most promising one turned out to be the use the force telemetry to create an on-line map of the environment. We called this the 'probing' approach.

To create a static map of a dynamic magnitude is extremely complex, if not impossible. Furthermore, the poor repeatability and high flexibility of the ETS-7 robot arm would add even greater difficulty.

Instead we decided first to create a map of virtual forces based on the library of constraints, and then update that map using the telemetry force. The development of a general algorithm for more DOFs is still the subject of research, but we have successfully applied this idea to a specific case.

Consider the TJ assembly. One of the main difficulties lies in finding the right deploying angle for insertion. There are inaccuracies in the model and telemetry information cannot be trusted hundred percent. It is then

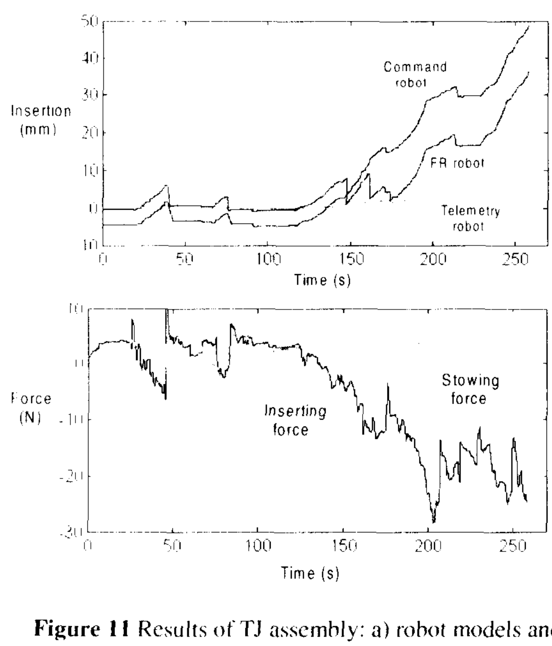

Figure 11 Results of TJ assembly: a) robot models and b) telemetry force.

interesting to probe for the assembly 'hole'.

The operator spends some time moving the robot according to a specific procedure to analyze the environment. The procedure consists in moving slightly in and out along the insertion direction while moving in the deployment one.

When the GPF is rotated a peg comes out of the AJ for insertion. This special feature allows us to use the roll torque as a measure of the contact between the TJ peg and the TJ receiver.

Figure 10 shows the experimental results of probing done with the TJ to look for the right deployment angle for insertion. It is seen that the right angle is around 36 deg, that is, where GPF rotation (extraction) is maximum with less torque.

This map is superimposed with the map of virtual forces already generated to guide the operator through the assembly. Figure 11 shows the final results for both the three robots and telemetry force during successful assembly of the TJ using this method.

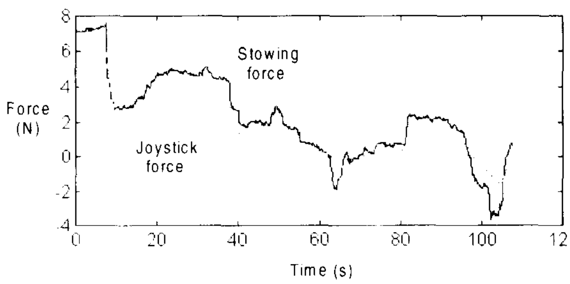

Figure 12. Stowing force and indirect joystick force during TJ assembly using indirect FR teleoperation

5.7 Indirect Force Reflection

We have also performed experiments of indirect FR. Indirect FR means that the telemetry force is reflected on a the hand that is not performing the task.

We have performed the TJ assembly 3DOF task using two joysticks. The right joystick was used to control robot's tip YZ movement. One DOF of the left joystick was used to control the third DOF of the task (the roll axis) while the other DOF reflected the real telemetry force acting on the stowing direction. The value of this force had previously been ruled out as crucial to accomplish an adequate insertion. It had to be under 4 N. Its value is very important to inform the operator where the robot is during insertion.

With indirect FR the operator could *feel* the force to keep it under the 4 N threshold (Figure 12). A nonlinear function for FR was employed to warn the operator of the increasing force.

Therefore, indirect FR can be very useful for some tasks. The force reflected does not has to be a one-to-one value of the telemetry force. It is interesting to consider transformations that yield a significant force pattern in 1 or two DOF for the operator.

6. CONCLUSIONS

This paper has presented what is, to our knowledge, the first extensive application of FR for the ground teleoperation of a space robot.

It has been demonstrated that despite time delay there are ways in which FR can be successfully used to improve the performance of the operator.

It has been experienced several times during experiments that continuous teleoperation is extremely important to allow a rapid reaction to unexpected circumstances, or for trying different approaches in a very tight time frame. FR supports this mode operation by increasing its safety and speed. Moreover, it can simulate computer control having the operator in the loop.

On the other hand it is important to consider that FR is by no means a global solution. It should be considered as an important aid for the operator that can easily be combined with visual aids without overloading the operator's decision capability.

Also, it is necessary to study each task and application carefully to decide what is the most practical way to use FR to improve the overall performance.

In the experiments presented in this paper, FR is almost completely used based exclusively on a CAD model of the environment. We tried to overcame this fact by building a force map of part of the environment, although the solution adopted was specific to the task and by no means complete.

This does not means that FR can only be used combined with a CAD model. For example, FR can be easily and intuitively used to present the operator the output of a guiding system which relies only on telemetry and not on a CAD model, like we did with the one described in [1]. Many other ways of using virtual FR can be thought of depending on the task, objectives and circumstances, being a promising field for new research and new applications.

7. ACKNOWLEDGMENTS

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