TELEOPERATION WITH TIME DELAY
A SURVEY AND ITS USE IN SPACE ROBOTICS

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ABSTRACT

The existence of time delay in the communication link is one of the most important problems regarding the stability of teleoperation systems. Time delay is specially relevant in ground teleoperation of robots orbiting Earth, with values of round trip delay ranging from 5 to 10 seconds.

Many proposals on how to conduct time delayed teleoperation under various circumstances and for different applications have appeared through the years in the literature. This paper presents a survey of most of these proposals, with the aim of identifying those methods and procedures that can be employed to improve the performance of space robot teleoperation.

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). It is well known that the cycle time (round-trip delay) for systems in LEO is at least of 0.5 s. These values are further extended due to the time consumed in data processing by relay satellites and computers on different intermediate stations. Values can vary from 5-10 seconds.

From classic control theory is easy to derive that a delay in a control loop is an important cause of instability. A pure delay decreases the phase of the system in a factor equal to the product between the frequency and the time-delay value. Also, with the presence of a pure delay, as the static gain increases the system deviates rapidly from a stable condition.

It was in the sixties (Ref. 12.) when first became apparent that the existence of time delay in the communication link between the local and the remote zone is one of the more important problems regarding the stability of teleoperation systems. Ferrel conducted in 1962 the first experiments with an unilateral system under time delay in the visual feedback. The 'move-and-wait' strategy was first conceived and employed as a solution to overcome instability. Others experiments carried-out by Ferrel and co-workers showed that even with time delays of 0.3 s a human operator could not maintain sensor-motor coordination during manual teleoperation.

Since then, many other proposals to overcome time-delay have appeared in the literature. They have been conceived for almost all telerobotic applications (space, submarine, internet, tele-surgery, etc., Ref. 40.) and to function under various working conditions.

Proposals can be divided into two different types of approaches: those based on the more traditional manual teleoperation approach and those based on the supervisory control concept conceived by Ferrel and Sheridan (Ref 12.) and further developed by Prof. Sheridan (Ref. 40.)

Both techniques have their advantages and drawbacks, and can be considered as complementary. When fully available, supervisory control will prove very valuable, but current state of technology does not allow to fully implement it.

On the other hand, for time-delayed manual teleoperation there have been a great amount of research and many applications are known. Understanding all the concepts, ideas and results of this research will help to develop more intelligent and autonomous systems in which supervisory control will take the major part.

Moreover, we believe continuous manual teleoperation will keep its role over the years even with the appearance of systems with more autonomous capabilities. Any telerobotic should be first equipped with an effective support system for direct teleoperation, and then the analytically determined part or the part of the operation that can be carried-out autonomously should be replaced by program control.

With so abundant information in the literature about manual teleoperation with time-delay we decided to perform a survey in order to get a global view of the present state of technology. The survey has later served us to identify those techniques prone to be useful for the ground manual teleoperation of robots orbiting Earth, which is the final aim of our work.

There are other sources where to find summarised information on techniques for time-delayed teleoperation of space robots Ref 41. is a very recommended and well-documented study by Prof. Sheridan, although it focuses very much on predictors displays and supervisory control instead on manual teleoperation. Also, although it contains the foundations, many new methods and techniques have been proposed since its publication. Ref 42. is also another good source of information, although no systematic analysis or comprehensive study of the different alternatives available is presented.

Ref 16. is a good and systematic source of information regarding application of telerobotic technology for space robots, whereas Ref. 35. Presents a detailed classification of the types of space robots available along with a thorough analysis of the constraints present for the application of robots in space

The outline of the rest of the paper is as follows. First, to have a better understanding of the problem, section 2 is devoted to give a brief overview of the main features involved in space robot teleoperation. Section 3 contains the description of a framework that will serve to better understand the classification of time-delayed teleoperation techniques later presented in section 4. Finally, the analysis of each method with respect to its use in space telerobotics is performed in section 5.

2. OVERVIEW OF SPACE ROBOTS TELEOPERATION

First, we have to consider the special conditions in which space teleoperation takes place and which makes it a unique problem. It will later help to study the different techniques from the perspective of the constraints imposed in the use of robots in space.

Ref 35. presents a very complete and comprehensive description of typical requirements and constraints present in space robotics applications. For our analysis we will consider the following:

- Round trip delay of 5-10 seconds. Time delay is mainly caused by data buffering and processing on relay stations.
- Low communication bandwidth, which can severely limit the transmission of video images.
- Space manipulators tend to be very light and flexible, which make their control more difficult than their terrestrial counterparts
- Micro-gravity, vacuum and thermal conditions degrade the manipulator performance.

If any of this four constraints is very difficult to be tackled independently, much more difficult will be if all of them come together. To cope with them, a set of tools or techniques, such as predictive displays, have been developed and are used in almost all time-delayed space teleoperation applications.

We will briefly review them along with other common devices present in manual teleoperation systems, such as input devices. Some guidelines are given.

2.1 Predictive displays

Sheridan proposes (Ref 41.) that "when there is a significant delay (say more than 0.5 s) and operators movements are relatively slow, say mostly below 1 Hz, a predictive display can be very useful."

Predictive displays show a model of the environment and of the slave manipulator. The operator performs the task on the display moving the master arm without any time delay. The inputs of the master arm or the virtual slave positions are sent to the remote slave, which executes them.

In practice, perfect modelling is impossible. If it were possible, the Roseborough Dilemma would appear (Ref 37.), that is, if we have a perfect model, why teleoperate? So, predictive displays have to be considered just as a tool that reduces the amount of information and on-line mental modelling that the operator has to do. It helps bridge the time gap, offering approximate cues until the actual information is available. The difference between the real and modelled environment has to be coped in real time by the remote slave with the use of some local autonomy.

Two main basic types of predictive displays are available: a) those overlaying delayed video and predicted graphics (Ref 3.) and b) those using only predicted graphics, with the video signal in a different display. The latter one is by far more common due to the difficulty of mixing video and graphics with enough quality and robustness.

In another classification we can find: a) predictive dynamic simulators and b) kinematic only simulators. To have a dynamic model of robot and environment will sure add more quality to the prediction, but to count with an adequate dynamic model is very difficult, especially during contact tasks. Also, space manipulators move very slowly, so its dynamic features can be neglected (except when dealing with free-flying robots).

Finally, a third classification of predictive displays is: a) with prediction of contact forces and b) without prediction of forces. Both options are available, and although some applications are known (Ref 23.), the prediction of contact forces is extremely difficult and complex, specially for space environments where drastic changes in operating conditions take place.

2.2 Prediction techniques

There are two basic types of prediction techniques: a) those based on the extrapolation of a Taylor-series upon current state and derivatives and b) those based on the use of model.

The second type is the most common one, since the first type is only valid for short time predictions. In the second case, some authors propose the use of estimation to have a fairly good knowledge of the current state of the robot and the environment. But this theory needs to make use of a very accurate knowledge of the dynamic behaviour of both. The dynamic model of the robot is rather easy to obtain, as well as, for example, the dynamics of a free-floating object.

On the other hand, it is practically not feasible to employ closed-loop estimation theory during contact due to the complex, discrete, not-linear dynamic interactions that make the synthesis of a adequate model very complex, if feasible at all.

2.2 Input devices

Two features have to be considered: a) the type of input device properly (master arm, joystick, etc.) and b) the control mode to employ (position, velocity). Interaction between the two features need to be investigated.

There are two types of control modes to be considered:

- <u>Position control</u>: it is very intuitive, since the position of the manipulator corresponds to the position of the input device. It has the disadvantage that may need to be indexed for large or precise manipulator motions.
- <u>Rate control</u>: rate control is used preferably when the difference between the working envelope of the input device and the manipulator is very large. It is less intuitive than position control but it can be more comfortable and allows to achieve better controllability for simple tasks.

A detailed study comparing position and rate control can be found in Ref 17. and some practical experiments comparing them using a master arm are available in Ref 9.

Three types of input devices can be considered:

- <u>Master arm</u>: the use of master arms is very intuitive. 6 DOF can be used on a single grip. It can be tiring for slow movements and difficult to operate for precise positioning.
- <u>Joysticks</u>: are less intuitive and two joysticks are needed for 6 DOF. They are very good for precise positioning and the operator does not get tired.
- <u>Space mouse</u>: force input device is not intuitive, but can integrate a 6 DOF in a single device. It can be used intuitively to give force commands during contact.

Rate control with a master arm is very difficult (Ref. 9.) and position control is advantageous only when doing dextrous tasks at rather high velocity. Not very recommended for space teleoperation. It is also very complex to give position commands with the space mouse. It should be use for rate control or force control during contact.

Joysticks can be used either way, but rate control seems more intuitive due to the small working range of joysticks joints and the ability to stop the robot very precisely on a given point.

Table 1 presents a comparison of different input devices for space teleoperation. It considers the master arm with position control and the joystick and the space mouse with velocity control. A similar table, constructed during the design of the ETS-7 teleoperation system, comparing a 6 DOF master arm and two 3-DOF joysticks is available in Ref 31. Other very exhaustive comparison between different control modes and the use of one or two-handed displays appears in Ref. 6.

Table 1 *Comparison of input devices for space teleoperation*

	Master arm	Joystick	Space mouse
Easiness of operation	++	+	-
Large arm motion	-	++	++
Input precision	-	+	-
Operator comfort	-	++	+

2.3 Task description

It can be very relevant to have *a priori* information from the task so that the system can interpret correctly the operator's actions. This information can be as simple as specifying different possible states of the task through time and the conditions that make the system change from one state to another (Ref 7.). It can also comprise a complex set of conditions and information about the evolution of sensor data, interactions, etc. (Ref 15.).

But on the other side, to try to define perfectly in advance the task leads us again to the Roseborough Dilemma (Ref 37.). If we can do it, why teleoperate? So, the concept again is to give some help, simple and useful enough so the operator can perform the task on its own.

2.4 Local autonomy loop

Almost all proposals present in the literature use some sort of compliance feature on the slave robot. Compliance is useful to cope with the error caused by an imperfect model. It can reduce execution time and overall forces applied upon the environment. The only problem is that it consists of an automatic remote feature and the operator can get confused if not fully aware of its behaviour.

Refer to Ref 18. for the detailed analysis of the advantages and application of active compliance local loops. A force/torque sensor is required on the robot's wrist to implement an active compliance. The force sensed can also be sent back to the local zone in order to monitor its value or to reflect it to the operator through an input device.

2.5 Force reflection

As pointed out by Hannaford (Ref 14.), to supply the operator with some type of force sensation is essential for the performance of a teleoperation system.

Direct force reflection, that is, pure bilateral schemes (Ref 33.) cannot be used with time delays over 2 seconds (see section 5). But there are other ways to present the operator with the force exerted by the slave during contact. The simplest one is to show the force values on a visual display. Another option is indirect force reflection, in which the delayed force is fedback to the hand which does not take part in the command.

A more complex but better solution is to simulate the interaction between robot and environment in a predictive simulator and by this way predict the contact force which can be fed back to the master arm (Ref 23.). It is complex solution, as explained when talking about predictive displays.

Although less extended, force reflection can be used not only to reflect interaction force to the operator but also to help him know how the task is being performed. This is known as reflection of virtual forces or synthetic fixtures (Ref 39.), that is, the use of forces that do not represent a real force to convey information to the operator information about the task (Ref 34.)

3. FRAMEWORK OF ANALYSIS

There are a wide variety of proposals and ideas on how to overcome time-delay. The approach and nomenclature differ and sometimes is difficult for the researcher to compare them even from a high level point of view.

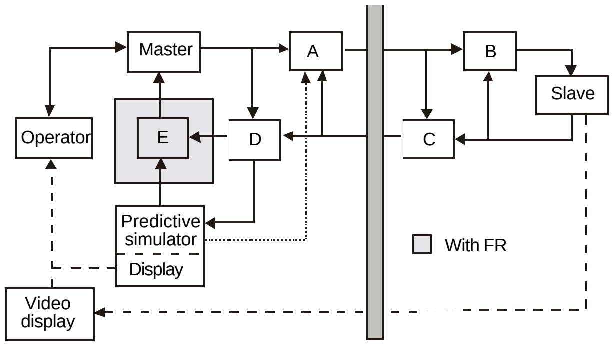

Figure 1 *General scheme for time-delayed teleoperation*

For the purpose of our survey we constructed the diagram present in Figure 1. It can be demonstrated that almost all proposals present in the literature can be described through this diagram.

It is made of a set of blocks and data flowing from one block to another. This data is made of a set of given magnitudes (position, velocity, force, etc.) in a n-DOF domain.

Operator, master, slave and visual displays are represented through the corresponding blocks. Blocks A and C represent the pre-processing of signals before their transmission through the communication link. Block B represents the local autonomy loop of the slave robot. Block D works as a hub on the master side, combining and distributing information. Finally, block E is responsible for implementing the FR on the master arm.

The predictive simulator block represents a model-based simulator, which can be employed with its display to implement a predictive scheme. The simulator can include the simulation of contact forces .

4. CLASSIFICATION OF METHODS

Classification of teleoperation techniques is not an easy task. There are a great variety of methods and combinations, and it is difficult to assign a particular label to each one.

One classification could be based on the characteristics of the time delay (amount, variable or fixed, etc.) for which has been designed or to classify methods regarding its preferred application (internet, space, underwater). Neither of both classifications say much about each technique itself.

We finally decided to first distinguish techniques that attempt to have bilateral coupling between master and slave from those which not. The objectives are different and both group of methods should not be compared on the same grounds. Afterwards, further classification regarding the control methods employed is carried-out for each group of techniques.

4.1 Bilateral systems

Bilateral systems are those in which master and slave are directly coupled in position (velocity) and force through any of the so called bilateral control schemes: position-position (common error or symmetric position servo), force-position (force feedback), force-force (force servo-position or force-feedback servo).

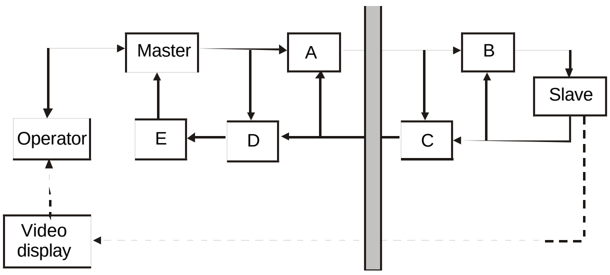

Figure 2 *Bilateral manual teleoperation technique*

It is the objective of bilateral systems that the operator feels directly on its commanding hand the contact force of the slave.

Classical bilateral schemes are very unstable under time-delay (Ref 49.). To solve the instability two basic approaches on the design of bilateral systems under time delay are available:

- Based on the passivity theory: the teleoperation system is represented as a two-port device using the mechanical-electrical analogy. The design is based on passivity theory which states that a system is stable if always has to dissipate and never increment its total energy. Special mathematics (scattering theory) is available for passivity applied to two-port devices, using also tools of electrical network theory.
- Based on control theory: is a more classical approach. A linear model of each element is proposed and block diagrams are constructed. System stability, performance, etc. are studied with classical and advanced control tools.

Figure 2 presents the scheme in which to develop bilateral systems for time-delayed teleoperation.

4.2 Non-bilateral systems

Non-bilateral systems can be classified attending to two different factors: the presence or not of force reflection, and the mechanism by which commands are generated.

4.2.1 Classification as a function of FR capabilities

To have a non-bilateral system does not mean that there is no force reflection (FR). It only means that coupling between the master and slave takes place only in one direction. There can be non-bilateral systems with FR.

There are two basic types of non-bilateral FR systems:

- Virtual forces FR: the operator senses in the commanding hand some type of kinaesthetic cue which is not directly related to the contact force being generated by the slave. They can be based on a model or simply used to display other kind info rmation.
- Indirect FR: to directly sense the contact force in a the passive hand, that is, the hand that is not generating the command.

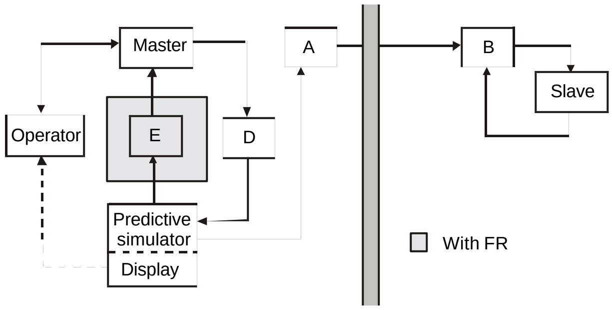

Figure 3 *Teleprogramming with or without FR*

4.2.2 Classification as a function of command generation

How commands are generated is an important feature that distinguish different methods. We have identified two different types of systems, somewhat in relation with the use or not of the time/position clutching concept proposed by Conway (Ref 8.).

- Tele-programming: it consists in performing the manual teleoperation task in a simulator before real operation to gather data of how the task must be carried-out. Afterwards, high level commands are sent to the slave to duplicate the actions on the real environment. (Figure 3)
- Predictive techniques: those techniques that employ a predictive simulator in which the operator carries out the task interactively, while its commands are being sent in real time to the remote slave for execution (Figure 1).

5. ANALYSIS

This section is devoted to analyse different techniques presented by the robotics community through the years to tackle time-delay in teleoperation. We will follow the classification carried-out in the preceding section. In the case of non-bilateral systems we have followed the division regarding the use or not of FR.

Tables summarising the experimental conditions in which each technique has been tested have been constructed. The data was extracted from the literature. The tables compare the number of degrees of freedom (DOF), the frequency of transmission between the local and the remote zone, the type of master (S simulation, J Joystick, A master arm, M space mouse and its control (p position control, v velocity control), the type of slave (S simulation, A slave arm, V vehicle), the type of task carried out, and the maximum time delay between the local and remote zone for which the system remained operational.

5.1. Bilateral systems based on passivity theory

The passivity theory was first applied to the study of bilateral system by Raju (Ref 36.) and was quickly adopted by almost every researcher in the field.

The first application of passivity theory for time-delayed systems was performed by Anderson and Spong (Ref 1.) for 1 DOF, and was later extended for n-DOF, including models of the operator and the environment (Ref 2.). The proposed scheme effectively dissipates energy, imitating waves along electrical networks, and theoretically works for any amount of time delay. This approach is very effective for short time delay but suffers from poor tracking and loss of intuitiveness for longer delays (Ref 24.).

The preceding technique was improved by Niemeyer and Slotine in their seminal work about wave variables (Ref 27.). Basically, wave variables are a new way of expressing the exchange of energy (force and velocity) of a system with its environment. Hence, their idea was to transmit wave variables through the communication link instead of traditional magnitudes such as position or force. It was later proved (Ref 28.) that passivity is maintained just by transmitting wave variables, whatever the delay may be.

An advanced use of wave variables for time delayed systems is proposed in Ref 29. It makes use of what is called a virtual tool. The idea is to hide from the operator the system dynamics. Also, Yokokohji (Ref 48.) made use of wave variables to minimise the performance degradation due to the possible fluctuation of time-delay.

A bilateral scheme that achieves an ideal kinaesthetic coupling between master and slave with time delay was presented by Yoshikawa (Ref 49.). It is also derived from the passivity formalism. The resulting control law basically tries to cancel the dynamics of master and slave. It also makes use of a weighting function for the acting forces and the position error. Another of their results is that transmission of position seems the major driving force against stability. The experiments carried out by the authors were conducted under 30 ms of time delay.

Another solution employing passivity theory, devised for internet teleoperation was proposed by Kosuge (Ref 21.). It tackles the varying time-delay by establishing an upper bound. The approach is later extended (Ref 22.) to when time-delay varies depending on the transmission direction. In Ref 19., this bilateral systems is combined with a predictive display.

5.1.1 Application for space teleoperation

Table 2 presents a summary of the bilateral schemes based on passivity. Some conclusions can be derived about their suitability for space systems. First, no out-of-laboratory experiments are available. All tasks demonstrated are only 1 DOF tasks and very limited in its complexity (only hard contact). Finally the maximum delays that these systems can sustain are very low, usually under 1 second. It is clear that under current circumstances they are not suitable for ground teleoperation of space robots.

Table 2 *Bilateral schemes based on passivity*

Ref	Delay (s)	DOF	Master Slave	Freq. (Hz)	Task
1.	2	1	Sp / S	500	Hard contact
27.	1	1	-	-	Hard contact
49.	0.03	1	Ap / A	-	Hard contact
22.	0.7	1	Ap / A	500	Hard contact

5.2 Bilateral systems based on control theory

Another approach to bilateral system is the use of classical control theory, as detailed in Ref 33. In this sense, Eusebi presented in Ref 10. the definition of a framework for stability analysis based on existing results in the area of linear time-delay dynamics systems.

One of the most significant results is the telemonitoring concept proposed by Lee (Ref 25.). It is based on the idea that it is of no use obtaining a system theoretically stable for any time delay, but to focus on some specific practical value and a particular application. Another idea is that the operator should have a precise knowledge of the slave performance (like compliance).

After constructing an impedance control scheme on both master and slave, the authors come out with a scheme that very much resembles bilateral position-position control with remote compliance and the addition of a component for force monitoring. Successful experiments with limited simulations were carried out under time delays of 2 s.

Bilateral control for time delay using virtual internal models (VIM) was proposed by Otsuka (Ref 32.). It is based on the premises that instability caused by time delay is basically due to transmitting position error, that teleoperated systems must have a good performance even with low transmission bandwidth and that the slave should have a local autonomous loop.

The proposal makes use of a VIM (virtual mass associated to the end of a manipulator to specify its compliant motions) on each manipulator. Slave and master arms are moved by applying upon its VIM the force sensed on the other one. Hence, only force information is transmitted between local and remote zones.

Lately there has been many research in the area of Internet teleoperation. Variable time-delays and loss of data are two important problems in this application.

One example is the proposal made by Oboe and Fiorini (Ref 30.). The bilateral control scheme they proposed is rather basic (position-position with no compliance) but their idea is to continually probe the network to update the control parameters depending on its current behaviour. They use the space-state internal representation due to the non-linear behaviour of the system. Their experiments under 0.5 s are carried-out in 1 DOF and using a virtual slave, which make them rather limited.

Leung et al (Ref 26.) were the first to use H_∞ control theory and μ-analysis for time-delayed teleoperation. They modelled the time delay as a perturbation and designed the system to be robust to such perturbation by using μ-synthesis. Their results have been extended by Sano (Ref 38.) for varying time-delay systems making use of the framework of gain scheduling..

Table 3 *Bilateral schemes based on control theory*

Ref	Delay (s)	DOF	Master Slave	Freq. (Hz)	Task
25.	1.4	1	Jp / V	-	Hard contact
32.	0.5	6	Ap / A	5	Basic contact
30.	0.32	2	Ap / S	350	Basic contact
38.	0.4-0.8	1	Jp / A	410	Hard contact

5.2.1 Application for space teleoperation

Table 3 presents a summary of the bilateral schemes based on control theory. Same conclusions as for the passivity based systems apply. Maximum delay is under 1 s and only simple tasks under laboratory conditions have been demonstrated. We can affirm that bilateral control is not practically applicable for space robot teleoperation.

5.3 Non-bilateral systems without force reflection

Here we will briefly review the ideas that do not make use of force as an input to the operator. It includes both concepts based on the tele-programming technique and concepts based on predictive displays.

The generic concept of tele-automation was presented by Conway (Ref 8.). Teleautomation should be considered as a framework in which to develop different schemes. It is based on a kinematic predictive simulator with time and position clutching capabilities. Time clutching means that the timing between when the operator does the task in the predictive simulator and when is performed by the remote robot does not need to be the same. The operator can go faster when the task is easy and slower when is difficult. The remote robot will execute the commands in a pre-specified manner.

Position clutching means that at some point the task being done by the operator using a predictive display is not sent immediately to the remote robot. Instead, the operator can try different approaches and when the generated path is good enough download the data to the remote site.

The concept of tele-sensor-programming, developed in the frame of the ROTEX project (Ref 15.), should be considered as one of the most ambitious proposals to cope with time-delay. Tele-sensor-programming was successfully employed for real space robot teleoperation under 5-7 seconds of time delay.

The idea is to use a predictive simulator but also to have a certain degree of autonomy in the remote zone through the use of several sensors (force, proximity, contact, etc.). The predictive simulator also models the behaviour of the sensors and how the slave makes use of them to acquire a certain degree of autonomy. The operator, hence, only commands the gross motion of the slave while it is helped for detail movements by the automatic corrections made by the system using the data provided by the sensors. The trajectory information sent to the remote robot is relative to the environment and includes sensor's data patterns. It is executed by the remote robot with the use of the real data from its sensors and its own autonomy functions.

Tarn and Brady (Ref 43.) propose a closed-loop approach to the predictive control of time-delayed systems. It does more than simply display the predicted state of the remote robot. They use of predictive observer that combines the delayed state and the command that is currently being sent to the robot. Instead of using classical trajectory generators between points, the authors use what is called an event/references generator. It works basically generating trajectories as a function of the sensor data and not as a function of time. The approach is later extended for internet teleoperation (Ref 4.).

Wakabayashi and Matsumoto (Ref 46.) developed in the frame of the ETS-7 project, a visual aid system for direct teleoperation applied for a truss deployment experiment. This aid system does not depend on a designed model of the workplace. It introduces the predictive force concept to calculate the appropriate joystick input, and displays it to the operator in the joystick coordinate system to enable the operator easily follow the direction. This method is later extended to automatic programming to make an efficient teleoperation system that combines direct teleoperation and program control.

Breedveld (Ref 5.) developed the concept of on-line set point displays, in contrast to tele-programming which are off-line set-point or preview displays. He developed afterwards two types of set-point displays: indicator and pyramids displays, which were compared under time delay with the ERA (Ref 6.)

Table 4 *Non-Bilateral schemes without force reflection*

Ref	Delay (s)	DOF	Master Slave	Freq. (Hz)	Task
8.	4	2	Mp/ A	60	Fine positioning
15.	7	6	Mv / A	-	ORU exchange
43.	1.5-7	6	Jv / A	2	Avoid collision
6.	3	6	Mv / A	-	Fine positioning
46.	5-7	6	Jv / A	4/10	Deploy truss

5.3.1 Application for space teleoperation

Table 5 presents a summary of non-bilateral techniques that does not make any use of force reflection. First, we have to emphasise that two of the methods proposed have been tested in the two most renowned projects of space robotics: ROTEX and ETS-7, an IVA robot and a free-flying robot.

This demonstrates that prediction techniques and predictive displays are a inestimable aid for this kind of applications and should be considered as the baseline from which begin to build more complex architectures. Velocity control, either with joystick or space mouse seems also very adequate, given the characteristics of present space teleoperation systems.

5.3 Non-bilateral systems with force reflection

Both tele-programming and predictive techniques can be found in this section.

5.3.1 Predictive techniques

The use of a predictive operator aid with FR was first proposed and studied in detail by Buzan (Ref 7.). Buzan demonstrated that it is not always possible to use a closed loop predictor that uses both the information of the command and the delayed data from the remote zone. The reason lies mainly in the non-linearity of the different states related to the task execution. He then proposed the use of an open-loop predictor, but pointing out that it cannot work on its own, since there are always modelling errors and depth and interaction cues are not available to the operator

Buzan proposed four different methods for reflecting force to the operator: indirect, predictive, complementary and dual. Indirect force reflection means reflecting the delayed force in the hand that is not controlling the task. Predictive force reflection feeds back to the operator only the force obtained from the predictor. Complementary force reflection combines predicted and delayed force through two complementary filters. And finally, dual force reflection makes use of the indirect and predictive methods simultaneously.

The main conclusions drawn from the study were that predictive simulators are always very useful with or without force reflection. When low visibility is available the force predictor working in open loop is very important. The use of the dual force reflection is possible but needs special training from the operator. The results obtained with complementary force reflection were not as good as expected.

Another proposal regarding the use of predictive simulation including force reflection was presented by Tsumaki (Ref 44.). Its main contribution is the development of an algorithm that tolerates geometric errors between the model and the environment, and that was later extended to tolerate dynamic errors (Ref. 45.). They use the principle of the optimum approach velocity (Ref 20.). Various space teleoperation like experiments (ORU exchange and opening/closing doors) were carried-out with a time delay of up to 5 seconds.

The force sensed on the master is used for rate or force control of both the real and virtual slave. Rate control is used when there is no interaction with the environment. When contact is detected the control mode is changed automatically to force control selecting as force reference the force applied by the operator upon the master. The change of mode is done independently for the real and virtual robots depending on when contact is detected. By this manner the geometric errors of the virtual environment model are avoided.

Finally and in the frame of the ETS-7 project, FR was demonstrated to be a very valuable tool to display guiding information to the operator (Ref 34.). Experiments carried-out under 7 s of time-delay demonstrated the use of synthetic fixtures for carrying complex tasks, and the usefulness of limited indirect and complementary FR.

Finally, a major result was the use of FR to display the operator the outcome of a prediction algorithm that does no use any kind of model. Experiments with position and velocity control were carried out. A detailed comparison can be found in Ref 47.

5.3.2 Tele-programming techniques

A paradigmatic example of tele-programming with FR is the concept developed by Funda (Ref 13.). The task is performed first using a simulator with force-reflecting capabilities or upon a simulated environment itself. All the information gathered from how the operator performs the task (position and force, events, etc.) is translated into high level robot commands and sent to be executed by the remote slave. The commands must be of symbolic nature and must consider the unavoidable discrepancies between model and reality.

To be able to identify more easily the type of contact that takes place it is essential to rely on *a priori* knowledge of the task. The robot must have some adaptation capacity by employing sensor information.

The experiments carried-out by the authors consisted in following the contour of a box with delays up to 3 s. Problems were found due to not modelling in detail the static and dynamic features of slave-environment interaction.

Table 5 *Non-Bilateral schemes with force reflection*

Ref	Delay (s)	DOF	Master Slave	Freq. (Hz)	Task
13.	3	6	Ap / A	30	Following box
7.	2-4	1	Jp / S	15	Fitting
44.	5	6	Av / A	-	Open door
34.	7	3	Jp / A	4/10	Space assembly

5.3.3 Application for space teleoperation

Table 5 presents a summary of the application of non-bilateral techniques that use FR in some way or another. It is seen that relatively complex tasks involving contact, with several DOF and under several (up to 5-7) of time delay are demonstrated with the use of FR. Even a real space application that makes use of FR is available (Ref 34.).

FR increments the operator telepresence. The operator is coupled with the environment, hence, the task is carried-out more smoothly. It also decrease the operator's mental overload. The operator can allocate his attention to other displays while being guided by the FR hand controller.

FR can also be used to simulate computer control, maintaining the operator in the loop and keeping the advantages of both methodologies.

FR can be used to help the operator to monitor intuitive and actively when he is doing something wrong or dangerous, and finally FR hand controllers can be used as tools to display different type of information.

It is necessary to remark that FR is not a solution on its own, ant that it should be combined with other techniques, such as teleprogramming or predictive displays to make use of all its advantages, as seen in the previous sections.

6. CONCLUSIONS

Teleoperation with time delay is a very challenging problem and a very active field of research. Application to space robotics it is even more demanding due to the high value of time delay, limited communication bandwidth and poor control capabilities of space robots.

After the survey of current state-of-art technology for time-delay teleoperation, we can affirm that there exist many proposals prone to be successfully employed for space robots teleoperation, although most of them have only been tested under laboratory conditions. Only a few practical demonstrations can be found.

More research is needed to be able to translate simulated results to implementations closer to space systems, were real problems arise. Moreover, no sole technique is good enough on it own, an approach that combines the best of each one is necessary.

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