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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. 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), but it is well known that in Earth orbit space applications the total cycle time is usually of 7 s. Many proposals have appeared in the literature through the years on how to conduct time-delayed teleoperation, but to date no comprehensive comparison study between them has been carried out.

In this context, we decided to conduct a survey of all the proposals for time-delayed teleoperation present so far in the literature and compare them on the same grounds. This will give researchers in this field a better understanding of the problem and will help them have a clear view as to in what areas more research is needed to achieve continuous and smooth teleoperation in the presence of time delay. We have focused our study on the continuous teleoperation of robotic arms on orbit around the Earth. This will be the area of space robotics applications with the greatest demand in the following years. Special emphasis has been put throughout the study on the specific operational characteristics of this type of systems.

Finally, we have proposed a framework for future research in the field. The framework is based on the definition of a nomenclature and a data flow diagram in which to express in a concise and compact way different algorithms. The utility of this framework is demonstrated both with a general example and with its application to different proposals present in the literature.

Keywords: teleperation, time delay, telerobotics, space robotics

概　要

通信リンクの時間遅れは遠隔操作システムにおける最も重要な課題である。地球低軌道上の宇宙遠隔操作システムではこの通信遅れが約７秒にものぼることは良く知られている。この通信遅れ遠隔操作問題に対してはここ数年多くの提案がなされているが，これまでこれらの提案を技術的に比較検討した報告はなされていない。

このため，本論文では通信遅れ遠隔操作に関する数多くの提案を調査し，比較検討することにより本分野での今後の研究の枠組み，動向を提案する。本論文が本分野研究者の同問題への理解を深め，今後の通信遅れ遠隔操作システムにおいて連続的で滑らかな遠隔操作実現に何が課題なのかを提示したい。

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 was in the 60's-70's when first became apparent [Ferrel-66] that the existence of time delay in the communication link between the local and the re-

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mote zone is one of the more important problems regarding the stability of teleoperation systems.

It is well known that the cycle time (the time between the emission and the reception of a signal) for systems in low earth orbit (LEO) is at least of 0.4 s, while for systems located on the moon is of 3 s. These values are further extended by the time consumed in data processing by computers on the satellite and in relay stations, summing up a total cycle time of up to 6 s in Earth orbit applications. In underwater applications the time delay can also very high, but it is caused mainly by the low speed of sound through water, which is of 1700 m/s approximately.

From classic control theory is easy to derive that a delay in a control loop can cause instability. As the static gain increases the system moves further away from a stable condition. It is also known that the effect of a pure delay is a decrease of the phase of the system in a factor equal to the product between the frequency and the value of the time delay.

The basic reason for instability cause by a time delay can be described intuitively as follows. Most control systems use a negative feedback and a gain above unity, trying to reduce as much as possible the error between the reference and the output signal. In this manner, if a delay exists that in the frequency range of interest has a value equal of higher than the half or a cycle, the feedback becomes positive. This effect is caused by the phase fall introduced by the delay It means that at that specific frequency the energy is always summing up into the system, increasing the amplitude and turning it unstable as a whole.

Therefore, if we work with low frequencies so that at high frequencies (near the critical frequency, in which half the period is equal to the time delay) the gain is below unity, the system will remain stable. This is a basic and simple solution that can be adopted to avoid instability, but there are many others that will be explained in this document, as for example, passivating the transmission line such as to not accumulate energy.

It was in 1962 when Ferrel conducted the first experiments using an unilateral system under time delay in the visual feedback [Ferrel-66]. He demonstrated the crucial importance of the amount of time delay on the global performance of the system. It was then when the 'move-and-wait' strategy was first employed as a solution to overcome unstable behaviors. Other 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 continuous teleoperation.

Since then, many proposals have appeared in the literature, although few of them have been applied practically. They can be separated into two different groups. Proposals with the aim of using bilateral control under (low) time delay and proposals focused for systems with a huge amount of time delay (up to several seconds) where a bilateral scheme is not viable. Instead, predictor displays that show immediately to the operator the result of his actions without having to wait for the return signal are used in this second group. Finally, for applications with several minutes of time delay the methodology called supervisory control [Ferrel-67] is the one most accepted so far. It basically consists in locating the control loop in the remote zone, so that the operator only has to supervise its execution, and change objectives or solve problems intermittently . Extended information about the supervisory control methodology can be found in the book *Telerobotics and Human Supervisory Control* of Prof. T.B. Sheridan [Sheridan-92].

There are others sources in the literature where to find summarized information on how to deal with time delayed teleoperation. A well-documented study of the different proposal presented through the years for space teleoperation can be found in [Sheridan-93]. It is a very interesting paper that includes proposal in the three groups mentioned before but that to our understanding lacks some important aspects. It is relatively too short and does not conducts a comprehensive comparison between the different approaches. Moreover, it focuses relatively more on the use of predictors displays and supervisory control than in continuos teleoperation with force feedback.

The book *Teleoperation and Robotics in Space* [Skaar-94] is another good source of information. The main problem about this book regarding our purposes is that is a collection of papers from different authors ranging from economics of automation in space to the use of manipulators in the International Space Station (ISS). There are only four chapters dedicated to time-delayed teleoperation, which are totally disconnected and present only a general view about different subjects, like human behavior or supervised autonomy. Again, no comprehensive study of different solutions is conducted.

In this context, we decided that it would be very interesting to have all the proposals for time delayed teleoperation under a unified framework in which to compare them. This would give researchers in the field a better understanding of the problem and will help them have a clear view in what areas more research is needed to achieve continuous and smooth teleoperation under the presence of time delay. This has been the main purpose of this document, in which we have included most of the solutions presented in [Sheridan-93] and [Skaar-94], completing the list with more recent ideas. Proposal are not only analyzed individually but they are also compared under common grounds and using the same perspective. Moreover, a common scheme is proposed in order to study in an unified way how information is used and combined to implement each idea is proposed.

For the comparison, we have taken into consideration the suitability of each proposal for space teleoperation. We have focused the attention of our study on the continuos teleoperation of robotic arms on orbit around the Earth, with maximum time delays of up to 10 seconds. We feel that it would be the area of space robotics applications with bigger demand in the following years, especially with the ISS and the next repair satellite missions in mind of the different space agencies [Kasai-99] [Oda-99] [Parrish-99].

The layout of this report is as follows. First, to have a better view and understanding of the problem, section 2 is devoted to do a brief review of the main features and elements involved in space teleoperation. Some typical specifications are given, along with an explanation on the use and performance of different elements that can be present in space teleoperation, such as predictive displays or input devices.

Sections 3 and 4 are dedicated to the individual explanation of the concept behind each proposal individually. Section 3 is dedicated to proposals with bilateral systems, while section 4 is dedicated to the rest of solutions: non-bilateral systems with force reflection and non-bilateral systems without force reflection. Each proposal is described in detail, giving specific data about its practical performance as stated by the authors. Finally we include some comments about its use on space teleoperation and the importance of its contributions.

Finally, section 5 presents, as an outcome of the preceding survey, a global framework in which to study and conduct research about this kind of systems. The framework is based on the definition of a nomenclature and a data flow diagram in which to express in a concise and compact way different algorithms. The utility of this framework is demonstrated with a the use of a generic scheme for space applications and with its application to different proposals present in the literature.

2. Overview of Space Robotics Teleoperation

A brief description of the most important proposals to overcome time delay in remote teleoperation will be presented in the following sections. Some of them are well suited for space teleoperation while others try to solve the problem under other operating conditions. In any case, the ideas and approaches followed by all of them can be considered very useful and have to be taken into account in any research focused on space robotics teleoperation.

It is interesting first 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 proposals with a clearer view of which are the limitations for their application in space.

Typical space teleoperation specifications

- Round trip time delay in the communication for robots orbiting the earth is between 5 s and 7 s. The time delay is cause mainly for the data processing in the different relay stations.
- Low bandwidth in the communication line. For example, in the ETS-7 satellite the bandwidth for the robot experiments is of 1.5 Mbps [Oda-97]. Most of it consumed by the transmission of video images. This means transmitting two different video images at 3 Hz and 1 Hz rate, sending command data at 4 Hz and receiving telemetry data at 10 Hz.
- Manipulators tend to be very light and flexible in order to reduce launch payload. Therefore, they are more difficult to control than their ground counterparts.
- The backslash of the manipulators is always present and very high due to the micro-gravity and vacuum conditions
- The flexibility of the arm structure, the high backslash and the thermal conditions create a significant deviation of the real robot end position from the theoretical position obtained through the joints position sensors.

All this problems are very difficult to solve on their own, much more difficult if they all come together. To cope with all these problems in a general way there are a set of standard tools that are used almost in all space robotics applications. Some are more common than others, and their application can vary, but all of them are very popular among researchers in the field. Therefore, it is very interesting to give a brief overview of the most important ones, explaining their purpose and behavior. Some guidelines drawn from our experience in the use of these tools are also given.

2.1 Predictive displays

To be able to work with delays of 5-7 s it is necessary to use a predictive display. In [Sheridan-93] it is said that 'when there is a significant delay (say more than 0.5 s) and operator movements are relatively slow, say mostly below 1 Hz, a predictive display can be very useful'.

The predictive display shows a model of the environment and of the slave manipulator. The operator performs the task on the display, moving the virtual slave with the master arm without any time delay. The inputs of the master arm or the virtual slave positions are sent to the remote slave who executes them on its own. There are different possible uses of the predictive simulator, like time and/or position clutching. They are explained in [Conway-90].

The main problem of predictive displays is that if the environment and the robot are not perfectly modeled, the commands sent to the remote slave could be ineffective or create high contact forces. But on the other side, if the model is very good, almost perfect, then there is no need to do teleoperation. Instead, the task can be programmed to be executed automatically. This paradox is called the Roseborough Dilemma [Buzan-89].

But in practice, perfect modeling is impossible, so the predictive display has to be considered just as a tool that reduces the amount of information and on-line mental modeling 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 modeled environment has to be coped in real time by the remote slave with the use of some local autonomy, like compliance.

In a rough preliminary classification, two types of predictive displays can be employed: those overlaying delayed video and predicted graphics and those using only predicted graphics, with the video signal in a different display. The option of overlaying [Bejczy-90] can be very useful to check coherency between the model and the environment, but it can be really difficult to maintain for all the movements or views. Also, if the coherency is not good enough the operator gets stressed. On the other side, to have only predicted graphics reduces the fidelity of the information but it allows to have different views of the task. Special care has to be exercise to maintain the propioception of the operator. Almost all of the recent systems have predictive graphics and video on different displays. The graphics are used to perform the operation and the video is employed to get information with more fidelity, although delayed.

Another classification of predictive displays can be done regarding the decision to model or not the dynamic features of the robot and the environment. To have a dynamic model of the robot and the environment will sure add more quality to the prediction, especially during contact tasks. But to obtain a correct dynamic model is very difficult, especially of the environment. Also, in space teleoperation the slave robot moves very slowly so its dynamics can be neglected. This two main reason lead to consider predictive displays that account only for static features.

Finally, predictive displays can also be used to predict contact forces. They can be used to reflect them to the operator or to be used as information for the command sent to the remote slave. In dynamic simulators the forces are calculated directly, but as we usually deal with static simulators spatial constraints have to be defined. This will be discussed with more detail later. It is important to note that to predict the contact forces, even roughly, can be very useful but also very difficult.

2.2 Compliance of the slave robot

Almost all proposals present in the literature use some sort of compliance feature on the slave robot. The compliance is very useful to cope with the error present because of not having a perfect model. It can reduce execution time and the overall forces applied upon the environment, as shown in [Kim-92]. The only problem is that it consists of an automatic remote feature and the operator can get confused if he is not fully aware of its behavior.

A force/torque sensor is needed on the wrist of the robot 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 the master arm. Several researchers [Anderson-89] [Niemeyer-91], instead, point out that is much better for stability reasons to reflect the torque generated by the robot actuators and not the sensed value from the force/torque sensor.

2.3 Task description

It is very important 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 the different possible states of the task through time and the conditions that make the system change from one state to another [Buzan-89]. It can also comprise a complex set of conditions and information about the evolution of sensor data, interactions, etc. [Hirzinger-93].

Without time delay a task description is not necessary because the operator performs the task in real time and he can cope with all the information about constraints, etc. But with the time delay and the use of a predictive display, the system has to have a small knowledge of what is happening to be able to send reasonable information to the remote zone.

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

2.4 Type of input device

The special features of space teleoperation stated above make very important the choice of the input device (master arm, joystick, etc.) and the control mode to employ (position, velocity or force).

The use of master arms for position control can be very useful because the operator only has to worry of moving the hand to the position he likes the robot to be, hence the movements are more intuitive. Also 6 DOFs can be used in a single grip and the operator does not have to think much of how to move the handle to reach an specific position or orientation. Also, two joysticks are needed to account for 6 DOF and their use for orientating the end effector is much less intuitive. On the other hand, it is easier to follow a straight line (in insertion, for example) with a joystick than with a master arm. The trajectory is much more precise and given the low velocity of space robots the operator does not gets tired so easily. Rate control with a master arm is very difficult and leads to larger execution times and forces exerted upon de environment, as shown in [Das-92]. But to use rate control with a joystick is very intuitive and easy for the operator.

Rate control is used preferably when the difference between the working envelope of the master and the slave is very high. That is, it makes sense to give velocity commands to the slave when the slave has a much bigger working envelope than the master. With position commands the master movements must be indexed (loose of intuitiveness) or scaled up (decrease in precision) [Kim-87]. On the other hand, when doing movements of great precision a position command is better, for it gives the operator more control over the task: to put the slave on certain point in space he only has to make one move. With rate control he needs two, one to begin movement and one to stop it. Also scaling can be of advantage in this case. A detailed study comparing position and rate control can be found in [Kim-87]

In space teleoperation with high time delays the operator must have as much control of the slave robot as possible. This means employing joystick position control, although it is interesting to use rate control under special circumstances, as was explained above.

In some of the proposals that will be explained below the master or hand controlled is equipped with a force/torque sensor. It is used to sense the force exerted by the operator to the hand controller during the task. This allows to change from position/velocity control during free movement to force control during contact. It is a very interesting and useful idea.

There are also two more options: the hand controller can be a pure force input device, like the space mouse [Hirzinger-93], or it can also have displacement capabilities [Tsumaki-96]. In the first case, position/velocity control during free movement is achieved through a force-to-position/velocity transformation, although this control is by no means intuitive. In the second case, force control during contact is achieved through force reflection. That is, the hand controller is servo-controlled to maintain the position constraint and the force the operator exercises on the hand controller is the control force to be exerted upon the environment.

2.5 Force reflection

Direct force reflection, that is, a pure bilateral scheme can only be used with delays of up to 1 or 2 seconds, although heavily degraded, as we will see in next section. The main problem is stability. But as pointed in [Hannaford-91], to give the operator some type of force sensation is essential for a good teleoperation.

There are other various ways to present to the operator the force exerted by the slave during contact. The simplest one and used in almost all the systems is to show the force values on a visual display. Another option is what is called the indirect force reflection, in which the delayed force is fed-back 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 simulator and by this way predict the contact force, which can be fed back to the master arm. A combination is also possible [Buzan-89] but neither of them can be classified as bilateral control although they make use of force reflection.

As we have said before, the predictive display or simulator it is almost always a static one. Hence, the computation of the interactions forces has to be done (1) using the *a priori* information from the descriptions of constraints of the task or (2) from the force exerted by the operator upon the hand controller.

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 and tell him how to improve it. This is known as reflection of virtual forces, that is, the use forces that really do not exit to display to the operator information about the task. On example is the use of virtual force fields to guide the operator through the right path. In [Penin-99] several ideas on the use of virtual force reflection are presented and applied over ETS-7 space robot. The main advantage of this concept is that it can be combined with existing visual aids improving the overall performance without compromising the operator attention.

2.6 Model of backslash and flexibility. Bandwidth

The only way to cope with backslash and flexibility is to have a good model of both features or to have some meaning of obtaining the end effector position other than the direct kinematics transform. Models of backslash can be obtained reasonably [Wakabayashi-97], but good model for flexibility disturbance can be very complicated. The best way to obtain the real end effector position is through the use of a set of marks and a computer vision system. This computation can be made on the local or in the remote zone. The position information obtained could be used to update the predictive display or to make a correction.

Bandwidth is an important factor that it has usually been ignored in the proposals that are present in the literature. Special care has be to be taken, as it affects the performance. Less bandwidth means that the remote side has to have more autonomy to decide between commands.

2.7 Use of observers

Some of the systems propose the use of observer (estimator) theory to have a fairly good knowledge of the current state of the robot and the environment. But this theory make use of an almost perfect knowledge of the dynamic behavior of the robot and environment, which is only possible during free movement of the robot and, for example, a free floating object, like in ROTEX experiment. During normal contact situations the dynamic behavior changes and it is not possible to specify it so easily. Even with these drawbacks is a tool that should not to be discarded.

Nomenclature

In the description of each proposal there is section regarding the experiments that the authors of the proposal have conducted using their algorithms. The nomenclature used in this sections is as follows:

- Maximum delay: refers to the maximum time delay under which the experiments have been successfully carried out. The concept of successful performance varies from one proposal to another.
- DOF: Degrees Of Freedom of the task
- Master: it refers to the type of master device: angular configuration (master arm) or joystick.
- Slave: it refers to the type of slave robot: angular configuration or virtual (simulation).
- Sampling: sampling frequency in the master and slave local control loops.
- Transmission: transmission frequency between the local (master) and the remote (slave) zone.
- Model: the need or not of a model of the environment to be able to perform the task.
- Type of task: task successfully carried out during the experiments.
- w/FFB: with Force Feedback
- w/FS: with Force Sensor
- N/A: not available, specified or found

3. Review of Proposals for bilateral systems

Here we being the comparison of proposals made through the years for time-delayed teleoperation. The study begins with bilateral systems because the number and quality of the proposals seem much higher. It will also help us understand sooner and better the difficulties imposed by a time delay in the transmission link

The analysis of systems with force reflection to the operator is very complex. This is due to the fact that the delayed force that the operator senses becomes an active perturbation to his movement. He cannot ignore the force he feels and his response turns the system unstable. On the other side, having only visual feedback, the operator can ignore the information he sees (a passive perturbation) and avoid instability, as for example in the move-and-wait strategy.

In this section we are only going to consider those solutions based on a bilateral control scheme [Peñin-97], that is, both master and slave are coupled together in both directions and continually. This coupling can be in position (velocity) and/or force.

There are two basic approaches to solve the instability of bilateral systems with time delay: the first one makes use of the two-port and passivity theories. The second one approaches the problem from the control theory point of view. They have in common that the solutions obtained can only work with delays of up to 1-2 s. As we will see, longer delays degrade so much the performance that teleoperation becomes impossible.

First we will address the proposals based on the passivity theory.

3.1 Control schemes based in the passivity theory

A teleoperation system (master, slave and communication link) can be represented as a two-port device using the mechanic-electric analogy. One port represents the interaction (force and velocity exchange) of the master with the operator. The other port represents the interaction (force and velocity exchange) of the slave with the environment.

The passivity theory states that a system is stable if it is passive. To be passive means that it always has to dissipate energy and never increment its total energy. Having modeled the teleoperation system as a two-port model the passivity condition is easily translated to a mathematical equation that states that the scattering operator S (which depends of the master and slave dynamics, control scheme, environment, etc.) norm has to be less than unity [Anderson-89].

There are a lot of references on the subject of passivity applied to bilateral systems with time delay. In this section the original idea is presented followed by other proposals that appeared later and seemed more relevant to the authors.

3.1.1 Bilateral control with time delay based in passivity

In [Anderson-89] a bilateral control scheme is presented to specifically tackle the effects of time delay in the stability of bilateral systems. This scheme is based entirely on the passivity theory.

The authors first demonstrate that the main cause for the instability of this kind of systems is that time delay transforms the communication link between the local and remote zone into a non-passive element. Based on this result, they try to define a new transmission block between the master and the slave that would remain passive for any value of the time delay. They make use of electric network theory, in particular the definition and characteristics of wave propagation in a loss-less transmission line [Stevenson-82]. They later apply this theory to a teleoperation system modeled as a two-port device. Hence, they obtain several control laws that assure the passiveness of the transmission line (and therefore the stability of the whole system) whatever the time delay present.

This control scheme effectively dissipates energy, imitating the wave flow going through electric energy transmission networks. Experiments and simulations that validate the proposal with time delays of up to 2 s are presented in [Anderson-89], while in [Anderson-92] the scheme is extended for n degrees of freedom, taking into consideration all the elements present during the teleoperation, such as the operator and the environment. With the use of a non-linear model of the transmission line, asymptotic stability is proven to exist when interacting with non-linear passive environments.

In the experiments performed by [Lawn-93], the basic bilateral control schemes (position-position, force-position) are compared with their passive counterparts under different time delays and on various types of tasks. The results show that with passive systems a 50% more time is needed to complete the task, while the total force exerted upon the environment is very similar. Trials with time delays over 1 s were not possible due to the low performance of the passive systems.

<u>Experiment conditions</u>

Maximum delay:
200ms (good) - 2 s (very bad)   DOF: 1
Master: angular w/FFB   Slave: angular w/FS
Sampling/Transmission Freq. :   500 / 500 Hz
Model: No
Type of task: Hard contact [Anderson-92].
Precise positioning, hard contact and non-linear task [Lawn-93]

<u>Comments on the proposal</u>

The maximum time delay in which this proposal is operational is too low for space applications. What is more, it is a scheme that only focuses on stability, without considering overall performance. So, stability is maintained theoretically for any time delay, but in practice systems with this type of control degrade very much (slow and difficult operation) for high values of time delay, over 1 or 2 seconds. It is interesting , on the other hand, to study or consider how the magnitudes (position and force) on the local and remote side are interrelated in order to maintain stability.

3.1.2 Bilateral control using wave variables

The bilateral control based in passivity presented in [Anderson-89] is improved in [Niemeyer-91]. They make use of what has been called wave variables. A detailed description of the concept of wave variables and their applications can be found in [Niemeyer-97a]. Basically, wave variables are a new way of expressing the interacting energy (force and velocity) of a system with the environment. This energy is expressed as an input and an output wave which represent the power coming in and out of the system.

The idea of the proposal is to transmit wave variables through the communication link instead of force and position (velocity). In [Niemeyer-97a] it is proven that by just transmitting wave variables the passivity of the communication channel and of the whole system is maintained, whatever the delay may be.

In other way, in [Anderson-89] is shown that the communication link becomes non-passive with time delay, so they propose a control scheme to tackle the problem. The procedure is basically damping the system. With wave variables the communication link remains passive with no need to use a special control scheme. Another advantage of wave variables is that they contain information of both velocity (position) and force, so their behavior can adapt to the nature of the task.

Following the analogy with physical systems, waves tend to reflect and provoke oscillations when the impedance of the medium they are travelling within changes. In a teleoperation system a change of impedance appears at both ends of the transmitting medium (that is, at the operator and the environment). The solution then is to include some specific impedance at the ends to try to smooth the impedance discontinuity. This solution effectively reduces oscillations but eventually causes a drift in the position error between master and slave. This problem can be solved transmitting also the wave variable integrals [Niemeyer-97a] or by correcting directly the values [Niemeyer-97b].

The wave variables can also be used to implement filters. Filters constructed using wave variables maintain their passive features and allow to reduce noise. Another possible application of wave variables is the use of predictors in the wave domain [Niemeyer-97a].

An advanced use of wave variables for time delayed systems is proposed in [Niemeyer-97b]. It makes use of what is called a virtual tool. The idea is to hide to the operator the dynamics of the system. Using the impedance of the wave variables (a parameter that relates the wave variables value and the force and velocity) a more or less rigid system can be implemented.

Experiment conditions

Maximum delay: 1 s	DOF: 1
Master: N/A	Slave: N/A
Sampling/Transmission Freq.:	N/A / N/A
Model: No	
Type of task: Hard contact	

Comments on the proposal

The maximum time delay under which a system using this proposal is operational is too low for space applications. On the other hand, it is very important to consider the fact that passivity can be maintained just by transmitting wave variables.

It is also very interesting the dual behavior of wave variables regarding force and velocity. We feel that this property could be ver useful in other applications regarding force reflecting teleoperation. Predictors in the wave domain also sound promising.

3.1.3 Bilateral control for ideal kinesthetic coupling

A bilateral scheme that achieves an ideal kinesthetic coupling between master and slave (forces and positions of both master and slave always have the same value) with time delay is presented in [Yoshikawa-96]. The passivity of the control laws is demonstrated although no information is given of how those control laws were derived. It is understood that the same philosophy employed in [Yokokohji-93] was followed.

The equations derived must be fulfilled by any system with time delay that wants to maintain stability and an ideal kinesthetic coupling between master and slave. The scheme finally proposed is based upon these equations and it seems a little complex.

The control law basically tries to cancel the dynamics of both arms. It also makes use of a weighting function for the forces acting upon each arm and for the position error between them. Eventually not all the dynamics is cancelled because it is something that cannot be achievable in practice and would cause critically stable behavior. Important is to note that all the signals are filtered before going through the transmission link. The experiments carried out to prove the validity of the scheme were conducted under a maximum time delay of up to 30 ms.

In [Yoshikawa-96] passivity theory is also employed to demonstrate the instability of classic bilateral schemes (with the exception of force-force) with some degree of delay in the transmission link.

Experiment conditions

Maximum delay: 30 ms DOF: 1
Master: angular w/FFB w/FS Slave: angular w/FS
Sampling/Transmission Freq.: 1000 / N/A Hz
Model: No
Type of task: Hard contact

Comments on the proposal

Once more, the maximum time delay under which a system using this proposal is operational is too low for space applications. An interesting idea drawn from this proposal is that the transmission of position seems to be the major driving force against stability. It is also very interesting the idea of filtering the signals before they are sent through the transmission link.

3.2 Bilateral control schemes based in control theory

3.2.1 Bilateral control with telemonitoring

The telemonitoring concept was first proposed in [Lee-93]. The objective of this scheme is to be able to perform teleoperation with force feedback with delays of up to several seconds without trying to have a stable system for any time delay. Telemonitoring means that the scheme allows the operator to have precise knowledge of the performance of the slave. This is very important when, for example, using a compliance loop on the robot side, in which the robot makes some corrections in an autonomous manner. If the operator does not has a precise knowledge of how or when that correction is performed instability is due to appear.

First the monitoring force fmon, which the operator is going to feel is defined. It is made of two components: one that depends of the position error between master and slave and other that depends on the force error between a reference force to maintain and the force exerted by the slave upon the remote environment. The operator is then capable of monitoring simultaneously the position and the force errors, that is, the global performance.

An impedance control scheme [Hogan-85] is implemented in the master and the slave so that they behave with some specific dynamic features (inertia, damping and stiffness). The generalized impedance control is employed.

The authors finally construct the control scheme with the use of the following guidelines: maintenance of stability and maximum force and position error gain. It is interesting to note that the final control laws look very similar to the ones of a position-position scheme with remote compliance and with the addition of a component that monitors the force error.

The performance of the scheme is compared under a certain set-up with other typical schemes for bilateral systems. Several values of time delay ranging from 0 to 3 seconds are used. The results seem very promising in free movements with delays of up to 2 seconds, while the other well-known schemes become unstable with 0.7 and 1.5 seconds, respectively. In contact operations, the telemonitoring approach shows again a better performance, with the other two systems becoming unstable with 0.5 seconds of time delay.

Experiment conditions

Maximum delay: 2 s (free) - 1 s (contact)
DOF: 1
Master: joystick w/FFB Slave: vehicle w/FS
Sampling/Transmission Freq.: N/A / N/A
Model: No
Type of task: contact with a plain wall

Comments on the proposal

Again, the maximum time delay by which the system can be used is too low for space applications. The idea of monitoring (reflecting) a force constructed by summing up components of totally different origin seems very promising , especially when compliance is present and the operator can get confused. But it has to be constructed very carefully to be useful practically useful. As in most of the proposal for bilateral systems, the tasks conducted to prove the validity of the proposal are very simple.

3.2.2 Bilateral control based on a Virtual Internal Model (VIM)

Bilateral control using virtual internal models (VIM) was proposed by [Otsuka-95]. It is based on three main premises: (1) the instability caused by time delay is basically due to the transmission of position error, (2) teleoperated systems must have a good performance even with low transmission bandwidth, and therefore (3) the slave should have some semiautomatic feature, like compliance.

The proposal is based on the use of a VIM upon the two manipulators. First it interesting to describe what a is VIM. Its origin can be found as one method to specify compliant motions in industrial robots. The procedure to implement a VIM is to add to the robot's tip a rigid virtual object that has on the other end a virtual mass. The compliant correction of the robot position is made applying a force to the virtual mass and calculating how it affects the robot's tip.

In this proposal a VIM is placed in each manipulator. By this manner the movement of the slave is calculated by applying to the virtual mass of its VIM the force exerted by the operator upon the master arm. On the other side, force reflection to the master is be implemented by applying the force exerted by the slave upon the environment to the virtual mass located in the master's VIM. In this scheme, hence, only force information is transmitted between the local and the remote sites.

Two different experimental conditions were successfully tested by the authors with a basic contact task: low delay and bandwidth of 5 Hz; 0.5 s of time delay and a bandwidth of 1 Hz.

Experiment conditions

Maximum delay: 500 ms DOF: 6
Master: angular w/FFB w/FS Slave: angular w/FS
Sampling/Transmission Freq.: 500 / 1 Hz
Model: No
Type of task: basic contact task

Comments on the proposal

The time delay in which this system is operational is too low for the values typical in space teleoperation. Something similar can be said of the task in which it was tested, which is very basic and simple, although 6 DOF were employed.

An interesting idea to consider is the movement of the slave by the use of a compliance loop with the master force as the reference. Also it is worth to mention the fact that a very low bandwidth is used as only force information is transmitted through the communication link.

3.2.3 Bilateral control through a long distance computer network

In this section we consider those solutions specifically developed to perform bilateral control of a teleoperation system through a long distance computer network, like Internet, in which delays can be high and unpredictable. It can be proved [Kosuge-96] that although a system can be stable for a given range of fixed time delays it will become unstable if the value of the delay varies during the operation.

In this context, [Kosuge-96] proposed a simple solution. It consists in defining a maximum permissible time delay that has to include at least the 95% percent of all the values of time delay actually present during operation. Once this value has been defined, all the information received is delayed to that specific time delay, so that globally the delay remains fixed. It is a simple but efficient solution.

In [Kosuge-97] the approach is extended to the case in which time delay varies depending on the direction of the transmission. It also takes into account the usual case in which the bandwidth is much less than the sampling frequency of the master and slave control loops. The results seem reasonable for delays of up to 1 s.

Another recent proposal is presented in [Oboe-98]. In this paper, the typical problems of Internet teleoperation are addressed first: (1) variable time delays, (2) loose of data. The authors assure that some information about the variation is needed to overcome the variable time delays. To solve the problem of lost data, the only solution proposed is to fill the gap with the previous value.

The architecture employed is based on a computer that probes the network to obtain its current parameters (the average time delay, the standard deviation and the rate of change). With this information, the control parameters of the real-time controller located in other computer are updated on-line.

The bilateral control scheme proposed is rather basic. It is a position-position scheme with no compliance. Space-state internal representation is used due to the no-linear behavior of the system caused by the time delay. The state vector is constructed using the position and velocity of the master and the slave. The control parameters that remain free are a proportional position error gain in both arms and the value of the inner velocity loop, also in both manipulators. Four parameters in total.

The only restriction for the synthesis of the control parameters is to maintain stability. A Lyapunov functions is used to calculate them. The mathematical derivation is complex (despite the simplicity of the model) and the conditions obtained depend on two free parameters and one which it is tightly related with the network current behavior. Finally, a Kalman filter is employed to filter the noise in the transmission line. This filter affects both the amplitude and phase of the transmitted data.

Experiment conditions [Oboe-98]

Maximum delay: 320 ms DOF: 1
Master: angular w/FFB Slave: virtual
Sampling/Transmission Freq.: 350 / 350 Hz
Model: No
Type of task: basic contact task

Comments on the proposal [Oboe-98]

The results of the experiments carried-out in 1 DOF and with a virtual slave and environment do not seem very good, although stability, as required, is always maintained. They use a virtual slave and a virtual environment, and the procedure is just a simple contact task. The maximum time delay employed is very low, under half a second, and it not suitable for space teleoperation.

Is Interesting the state-space representation and the Lyapunov function used, but the mathematical derivations are too complex despite it is only a 1DOF model.

4. Proposals for non-bilateral systems

We have seen that bilateral systems can only work with small values of time delay, which is not the case of space robots applications. But many of the ideas in the design of these systems can be extended to be use in space teleoperation. On the other hand, there are a number of interesting proposals for non-bilateral systems that can withstand longer values of time delay.

To be non-bilateral does not mean that there is no force reflection to the operator. It means that coupling between the master and the slave is only done in one direction, but it does not says nothing about if the operator can receive force feedback from other source. This is the case of the first group of proposal presented in this section. Finally, there are systems which do not present force information to the operator in any way and therefore are called non-bilateral systems without force reflection. They will be described later.

4.1 Non-bilateral systems with force reflection

4.1.1 Teleprogramming

One of the more extended proposals is the idea of teleprogramming presented in [Funda-92]. The concept is very simple. The task is done first in a simulator with force reflection capabilities. All the information gathered from how the operator performs the task (position and force values, events, etc.) is translated into high level robot commands (like instructions from a typical robot language) and sent to the remote zone to be executed by the slave. In this manner, high frequency local control loop can be closed in the remote location avoiding instabilities caused by the time delay. The robot commands must be of symbolic nature and have to take into consideration the unavoidable discrepancies between the model and reality. There has to be a way to handle major errors that can occur during automatic execution.

The authors of the paper propose the use of a non-dynamic simulator, that is, a simulator that only takes into account cinematic features. This is due to the complexity of the dynamic modeling of the environment and that the information obtained would be very complex and not relevant in most cases. The authors note that it is very important to have knowledge of the trajectory constraints for the generation of commands and to be able to implement the force reflection to the operator. Different types of contacts are classified so that the behavior of the slave during the interaction can be completely defined.

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. In the remote zone, the robot has some capacity of adaptation using the information provided by the different sensors, using both active and passive compliance.

The experiment carried-out by the authors was the following of a box contour with delays of up to 3 s. It is found that the main problems arise because they did not model the static and dynamic effects of the real interaction between slave and environment.

Experiment conditions

Maximum delay: 3 s DOF: 6
Master: angular w/FFB w/FS Slave: angular w/FS
Sampling/Transmission Freq.: 500 / 30 Hz
Model: Cinematic with force reflection
Type of task: following the contour of a box

Comments on the proposal

Teleprogramming is a proposal very well suited for space teleoperation, although is a concept very easy to describe but difficult to implement.

The potential of this method lies in the capacity of extracting the right information from the performance of the task by the human operator and of codifying it correctly. The performance will depend of the intelligence of the commands

The paper presents at the beginning an interesting equation that relates the time delay in the communication link with the autonomy needed in the remote zone so that a task can be successfully carried out.

4.1.2 Predictive Operator Aid with Force Reflection

This idea was proposed by [Buzan-89] in the MIT. It consists basically in combining adequately the delayed information coming from the remote zone with the information supplied by a local predictive simulator working in open loop both in position and force.

It is shown that to use only a position predictor in open loop is not a good solution. As depth and interaction cues are not available to the operator is very difficult for him to do the task. Moreover, there are always errors between the model and the real environment.

In [Buzan-89] it is demonstrated that it is not possible to use a closed loop predictor that uses both the information of the operator's command and the delayed data from the remote zone. The reason lies mainly in the no-linearity of the different states related to the execution of the task. Therefore, the use of an open-loop predictor that works somewhat like a 'Smith predictor' is proposed. The performance of the open-loop predictor employed will depend on the accuracy of the model and of the processing being made to combine the predicted and delayed data.

It is very interesting the mathematical derivation done to prove that the feedback loops from the predictor and from the real system (delayed data) have to be complementary in the frequency domain. That is, data flowing from the predictor will go through a high-pass-filter while data from the real system must go through a low-pass-filter, being both filters complementary in nature.

The authors propose four different ways of reflecting force to the operator: indirect, predictive, complementary and dual force reflection. They represent the different combinations available between the simulated and the real force.

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, as stated above. And finally, dual force reflection makes use of the indirect and predictive methods at the same time.

It is important to remark that the work presented in [Buzan-89] to test the performance of the different approaches has been made with a master arm connected to a work station in which everything is simulated: including the real environment and the slave.

Two different tasks with 1 DOF are defined. The different force-reflecting methods are tested under various operation conditions: variability of the of the model preciseness, different slave behaviors, variance of the environment dynamic features and visibility during operation. Delays between 2 and 4 seconds were employed for the experiments.

The main conclusions drawn from this study is that the predictive aid is very useful and substantially increases the performance of the task. The predictive simulator or display is 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 are not as good as desirable, although it is stated that with the use of the six degrees of freedom it will improve considerably. Dual force reflection with 6 DOF would be very confusing for the operator. The use of a different slave impedance for each task was essential.

<u>Experiment conditions</u>

Maximum delay: 2-4 s	DOF: 1
Master: angular w/FFB	Slave: virtual
Sampling/Transmission Freq.:	N/A / 15 Hz

Model: Cinematic with force reflection
Type of task: Grapple and Fitting tasks

<u>Comments on the proposal</u>

The working methodology followed by the author during the investigation on the use of force reflection is very logical, well-thought and effective. Clean, concise and direct derivations and explanations are presented for all the different ideas that are presented on the document. The results obtained are very important due to the fact that experiment conditions, except for the type of slave, are very similar to that of space teleoperation.

The considerations made about the visibility during task execution are very important, and should be taken into consideration also for space robot teleoperation.

4.1.3 Predictive system that tolerates geometric errors

This proposal makes use of a predictive simulator for both graphic display and computing of force reflection. The main contribution is the development of an algorithm that tolerates geometric errors between the model and the environment [Tsumaki-96].

A three DOF hand controller with force reflection and a force/torque sensor is employed. 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. The principle of the optimum approach velocity [Kitagaki-94] is used. The optimum approach velocity is defined as the optimum velocity of the robot so that when interacting with an object the resulting force converges as quickly as possible to a reference force. In this application, the reference force is defined as the force that the operator applies over the master arm. The optimum approach velocity is computed using the mechanical and dynamical features of the environment.

It is very important to note that in the present system the master has tranlastional features and can be moved when the robot is moving freely. This is totally different than, for example, when using a space mouse in which the mouse senses forces/torques but it cannot be moved. When contact is detected the control mode is changed automatically to force control using as the force reference the force applied by the operator upon the master. The change of mode is done independently in the real and virtual robots depending on when contact is detected. By this manner the geometric errors of the virtual environment model are avoided.

The operator will feel the contact force when there is an interaction in the virtual environment. The force will correspond with the same force applied by the operator so that the master arm remains fixed, just like when contacting a very stiff object. Hence, static features are only considered in the virtual model.

Because the authors work with velocities instead of positions, a drift in the position error of both slave can appear after some time. To solve this problem a parameter is introduced to correct the virtual slave position using the real slave position. The same procedure is used for the environment. Experiments of an ORU exchange and the opening and closing of a door are presented with a time delay of up to 5 s.

In [Tsumaki-96b] an improvement is made to the predictive display in order for the operator to know in every moment the distance between robot and environment. A 'virtual beam' is projected in the tool direction towards the object.

<u>Experiment conditions</u>

Maximum delay: 5 s DOF: 6
Master: Cartesian w/FFB w/FS Slave: angular w/FS
Sampling/Transmission Freq.: N/A / N/A
Model: Cinematic with force reflection
Type of task: ORU exchange
Door opening

<u>Comments on the proposal</u>

It seems very promising the working methodology followed regarding the exchange between rate and force control depending on the evolution of the task. This can be done because the master arm is equipped with a force sensor, which is of great advantage.

One interesting result to consider is that rate control can cause problems of position error drift between the virtual and the real slave. Also is very interesting the mixture of a graphical aid to help the operator, such as a virtual beam, with the force aids.

4.2 Non-bilateral systems without force reflection

4.2.1 Teleautomation

The concept of teleautomation is presented in [Conway-90]. It is based on the use of a cinematic 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 have 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 he considers that the generated path is good enough he downloads the data to the remote site.

To implement the time and position clutch concepts is necessary to have a set of command queues both in the local and remote zone that manage the data in order to maintain coherency. They are explained with detail in [Conway-90]. A time brake to allow for reaction during errors is also implemented along with the corresponding procedure for recovery.

<u>Experiment conditions</u>

Maximum delay: 4 s DOF: 2
Master: Force joystick w/FS Slave: virtual
Sampling/Transmission Freq.: 60 / 60 Hz
Model: Cinematic
Type of task: positioning a graphic PUMA robot over various squares.

<u>Comments on the proposal</u>

Time and position clutching are very good theoretical ideas, but are only possible with a very good model of the robot and the environment. The task carried-out by the authors is very simple and does not considers interactions with the environment, which is the more challenging problems appear.

4.2.2 Tele-sensor-programming

It is the most ambitious proposal to cope with time delay proposed so far. It has been applied on a real space experiment (ROTEX) [Hirzinger-93]. 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 behavior 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.

A very detailed model of the environment, of the sensors and of the autonomous behavior of the robot using the sensor data is required to implement the system. No dynamic properties of the environment, like compliance or friction, are used. Also, the dynamics of the robot is neglected due to its slow movement. A space mouse is used as the master device. Therefore the input are forces and torques. This is very useful in order to implement a position (velocity) or force loop depending on the state of the task.

It is also very relevant to note the importance given by the authors to have a good task description so that each state can be identified with the use of the sensor data. This fact makes easier the extraction of coherent information from the system and to generate autonomous behaviors.

Prediction techniques based on the extended Kalman filter were used to capture a free-flying object. They allow to predict with some degree of error the current state of the free-flying object and of the robot.

Experiment conditions

Maximum delay: 7 s DOF: 6
Master: Space mouse w/FS Slave: angular w/FS
Sampling/Transmission Freq.: N/A / N/A
Model: Cinematic
Type of task: Several real space tasks

Comments on the proposal

From the authors experience, it is very important to have a good task description so that each state and the transitions between them can be clearly identified. It is very interesting the duality between force and velocity control that appears when using a space mouse. It is important to note that the use of a Kalman filter or of traditional observers was possible due to the non-linearity of the task in which it was employed.

4.2.3 Control based on a predictive observer

This is a very recent proposal [Tarn-97] [Brady-89]. It has been designed especially for systems with a huge amount of time delay. The main idea is the use of a predictive observer (in the local zone) of the current state of the robot (in the remote zone). To predict the state it is necessary to use the delayed state coming from the remote zone and the command that it is currently being sent to the robot from the local zone.

The implementation explained in [Tarn-97] makes use of the result of a predictor to visualize the position of the robot on a display, although it can also be used to modify the current command. The slave robot is commanded to follow a given path and the operator acts as a supervisor. He can intervene by moving a joystick that will override immediately (after the corresponding time delay) the robot trajectory.

Instead of using the usual trajectory generators between points, the authors use what is called an event/references generator. It works basically generating trajectories as a function of the sensors data and not as a function of time. That is, the basic trajectory is the same but it will be modified as it is being executed and therefore the result will not be always the same in the time domain.

An events/references generator is used in the local zone to simulate the behavior of the remote one. Its output is used as an input to the predictor and to the dynamic simulator of the robot behavior. The weighted sum of the state observer and of the output of the simulator is considered the current value of the robot. It is used to update the graphic display and as a feedback signal for the events/references generator of the local site.

Experiment conditions

Maximum delay: 1.5 - 7 s DOF: 6
Master: angular Slave: angular
Sampling/Transmission Freq.: N/A / 2 Hz
Model: Cinematic predictive
Type of task: Moving freely avoiding collisions

Table 1 Comparison between different proposals for time delayed teleoperation

Proposal	Type	Delay (s)	DOF	Master	Slave	Sampling/ Transmission (Hz)	Model	Task
[Anderson-89]	BFR	0.2- 2	1	Angular FR	Angular FS	500 / 500	No	Hard contact
[Niemeyer-91]	BFR	1	1	N/A	N/A	N/A	N/A	Hard contact
[Yoshikawa-96]	BFR	0.03	1	Angular FFB FS	Angular FS	1000 / N/A	No	Hard contact
[Lee-93]	BFR	1-2	1	Joystick FFB	Vehicle FS	N/A / N/A	No	Hard contact
[Otsuka-95]	BFR	0.5	6	Angular FFB FS	Angular FS	500 / 1	No	Basic contact
[Kosuge-96] [Oboe-98]	BFR	0.32	1	Angular FFB	Virtual	350 / 350	No	Basic contact
[Funda-92]	FR	3	6	Angular FFB FS	Angular FS	500 / 30	Kinematic w/FR	Following box contour
[Buzan-89]	FR	2-4	1	Angular FFB	Virtual	N/A / 15	Kinematic w/FR	Grapple Fitting
[Tsumaki-96]	FR	5	6	Angular FFB FS	Angular FS	N/A / N/A	Kinematic w/FR	ORU exchange Opening of a door
[Conway-90]	NFR	4	2	Joystick FS	Virtual	60 / 60	Kinematic	Precise positioning over various points
[Hirzinger-93]	NFR	7	6	Space mouse FS	Angular FS	N/A / N/A	Kinematic	Several real space tasks
[Tarn-97]	NFR	1.5 - 7	6	Angular	Angular	N/A / 2	Kinematic	Free movement avoiding collisions

BFR: Bilateral Force Reflection; FR: Force Reflection; NFR: No Force Reflection
FFB: ForceFeedback; FS: Force Sensor.

Comments

The use of a predictive observer to know in every moment the current position of the robot seems very promising., but in the proposal no continuos operation is performed and no solution is given to robot-environment interaction. The authors state that the use of some force reflection (it does not has to be exactly the force coming from the remote zone) to the operator can greatly enhance the performance, but in their experiments there is no interaction with the environment.

5. Framework for the Analysis of Time Delayed Teleoperation Systems

When trying to define the specifications of a teleoperation system with big time delay the Roseborough dilemma, explained in section 2.1, always appears. The first impulse is to design a system so complex that it could work on its own doing the task almost completely autonomously with no help from the operator. It would be desirable, theoretically, to have such system, but there are so many technological problems to overcome and the system would be so expensive that in reality is not practical.

The objective is to use the human in the loop to simplify the system architecture as much as possible; to give the operator some kind of tool to help him perform the task quicker and better. That has been the idea behind all proposals presented above: to help the operator overcome the time delay through the use of algorithms not excessively complex and taking into consideration that the environment is not perfectly known.

We have seen that almost all the proposals to overcome the problem of time delay consider these assumptions. They all work under the same basic common ground. But we have also seen that there is a great variety of ideas in how to approach the problem and find a solution. Moreover, the nomenclature differs widely and its difficult for the researcher to have a clear view of what is the contribution of each proposal in a common framework of knowledge.

Therefore, we decided that in order to keep doing research in this area with a clear understanding of what has been done before it is crucial to have a framework in which to compare and analyze the different proposals present in the literature for time delayed teleoperation. The framework will also serve as the starting point in which to begin further investigations.

Section 2 gave an overview of the main elements present in space robot teleoperation. The present framework takes into special consideration the ideas described there but it is not restricted only to space applications. Its main goal is to consider any system designed for time delayed teleoperation.

5.1 Data Flow Diagram for Time Delayed Teleoperation (DFD-TDT)

The framework is completely based on the definition of a nomenclature and a data flow diagram in which to express in a concise and compact way different algorithms. Figure 1 shows the proposed Data Flow Diagram (DFD). We will know describe each component of the DFD and how to use them. Appendix A demonstrates that almost all the proposals for time delayed teleoperation present in the literature can be described in a easy and compact way through this DFD.

Generalized matrixes

The proposed DFD is based on the use of generalized matrixes $\boldsymbol{V}$ that describe the data flow from one block of the DFD to another. Each matrix $\boldsymbol{V}$ is made of a set of vectors that represent a given variable in the n-DOF domain. For example, matrix $\boldsymbol{V_m}$ composition could be:

$$V_m = \left[x_m \;\; x_m' \;\; f_m \right] \qquad (1)$$

Where $\boldsymbol{x_m}$ is the master position vector, $\boldsymbol{x'_m}$ is the master's velocity vector and $\boldsymbol{f_m}$ is the vector of forces sensed on the master arm. So the dimension of the $\boldsymbol{V}$ matrixes will be $n \times v$, where n is the degrees of freedom being considered and v is the number of variables transmitted from one block to another, which is not fixed and depends on the implementation. The matrixes with the $\boldsymbol{T}$ sub-index are the delayed counterpart of another matrix. That is, $\boldsymbol{V_{uT}}(t) = \boldsymbol{V_u}(t\text{-}\boldsymbol{T})$ and $\boldsymbol{V_{dT}}(t) = \boldsymbol{V_d}(t\text{-}\boldsymbol{T})$ where $\boldsymbol{T}$ is the one-way time delay.

The basic purpose of using generalized matrixes is to handle elemental information. Looking to the DFD is perfectly clear how information flows through the system. Generalized matrixes also makes the DFD more general and able to suit to a larger range of teleoperation schemes.

Description of blocks

The DFD basic functionality is based in two types of blocks: source/sink blocks and processing blocks. They are linked through the information present in the generalized matrixes, represented in Figure 1 as black arrows. The dashed arrows represent information that flows through the system in a different manner, as can be video signal, interaction between operator and master arm or the visual feedback through the predictive display.

The processing blocks (A to E) receive a set of generalized matrixes and give one or more generalized matrixes. It is important to note that the processing does not have to be linear and can take the form of complex algorithms. Hence, block A, for example, could be expressed by:

$$A \equiv \;\; V_u = f\left(V_m, V_{ps}, V_{dT}\right) \qquad (2)$$

The source/sink blocks represent those elements on the system that are a main source or sink of data and have a direct link to the human operator. They are the master arm, the slave and the predictive simulator/display. Since there can be many different types of masters, slaves, etc. the blocks tend to represent basic functionality, so that

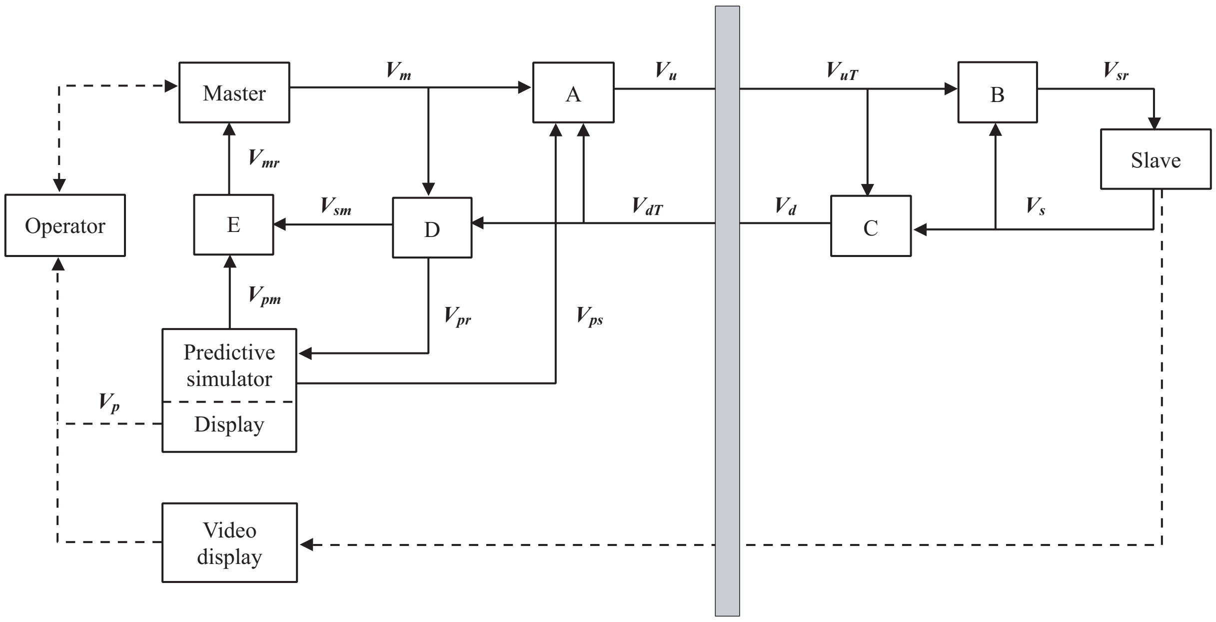

Fig. 1 Data Flow Diagram for Time Delayed Teleoperation (DFD-TDT)

the generalized matrixes interacting with these blocks can only be made of a specific set of variables vectors.

The master and slave arms are considered a source and a sink of position and/or velocity and/or force. This means that V_m , V_s , V_{mr}, V_{sr}, can be constructed using only by a combination of vectors representing those magnitudes.

For example, for the master to be a source of position means that its current position is used to construct a vector of the generalized matrix going out from the master block. To be a sink of position means that the generalized matrix going to the master has a position vector that the master has to follow through the use of its own control loops. The local control loops in the master and slave, of course, play an important role in the performance of the system and have to be taken into account but just as in any other teleoperation system. They do not represent any new contribution for time delayed teleoperation, so they are not represented explicitly in the DFD. It is worth to remark that computations are always done in the operational space.

In the case of the predictive simulator/display the functionality is a little different. The block represents two distinct modules: the predictive simulator and the predictive display. The predictive simulator is not apparent to the operator and only processes data. It could have been classified as a processing block, but since it has a tight relation with the predictive display and is a fundamental block in the DDF concept, it has been considered apart. The predictive display shows a graphic simulation of position and/or velocity and/or force of the slave. This information is supplied to the predictive display by the predictive simulator algorithms.

Operator and Video Display are considered part of the DFD as mere blocks from which no special control or definition can be specified. The description of the operator block is done elsewhere [Peñin-98].

Nomenclature

V_m / V_s: Master-Slave generalized matrix

V_{mr} / V_{sr}: Reference generalized matrix for the Master-Slave

V_u / V_d: generalized matrix going up/down

V_{uT} / V_{dT}: delayed counterpart of V_u / V_d

V_{pr}: Input generalized matrix for the predictive simulator

V_{pm},$/V_{ps}$: Output generalized matrix of the predictive simulator going to the Master-Slave side

V_{sm}: Generalized matrix going from the slave side to the master side.

Example

We will now show an example on the use of the DFD-TFT explained above. We will consider the classic force-position bilateral control scheme [Peñin-97] with the use of the simulator to visualize the delayed position of the slave.

First it is necessary to define the master and slave generalized matrixes:

$$V_m = \left[x_m \;\; x_m' \right] \qquad V_s = \left[x_s \;\; x_s' \;\; f_s \right] \tag{3}$$

The force-position algorithm will be defined by the behavior of the different processing blocks:

$$\begin{aligned} \boldsymbol{A} &\equiv \quad V_u = V_m \\ \boldsymbol{B} &\equiv \quad V_{sr} = V_{uT} \\ \boldsymbol{C} &\equiv \quad V_d = V_s \end{aligned} \tag{4}$$

Processing block $\boldsymbol{D}$ has a little more complex behavior. The predictive simulator will pass the position and velocity of the slave to the display, show the operator can see the movement of the slave robot. There is no other output from the predictive simulator.

$$\begin{aligned} \boldsymbol{D} \equiv \quad & V_{sm} = \left[f_{dt} \right] \\ & V_{pr} = \left[x_{dt} \;\; x_{dT}' \right] \end{aligned} \tag{5}$$

And finally processing block $\boldsymbol{E}$ will only get the force information from block $\boldsymbol{D}$ to the master arm:

$$\boldsymbol{E} \equiv \quad V_{mr} = V_{sm} \tag{6}$$

5.2 How to use the DFD-TDT

In order to explain better how the DFD-TDT works and can be utilized, we will propose a basic teleoperation system for space robots teleoperation. This proposal is based on our experience and makes use of many of the comments presented in section 2.

The DFD-TDT presented in the previous section shows the main elements from which to build the teleoperation scheme. They are: the master, the slave and the predictive simulator/display. The features selected for them will decisively affect how the teleoperation scheme is implemented as well as its final performance.

Recalling the comments made in the discussion section, here we present the basic configuration we think best suits time delayed teleoperation with 6 DOF.

- The master arm is made of two joysticks: one for Cartesian motions and one for rotational motions. Both joysticks are of displacement type. The joystick for Cartesian motions is equipped with force-reflection capabilities. It will be desirable to have a force/torque sensor too, although it is not a indispensable condition. It would also be very beneficial to have force reflection in the joystick for rotational motions for some particular uses.

- The slave arm has the common features of space robots. Its control scheme is based on the operational space. It is either basic PD or an inverse dynamic control, both with the desired position as input (in the inverse dynamic control the velocity and acceleration are also needed). More complex interaction schemes (with compliance, parallel force control, hybrid force control, etc.) can be implemented around the basic position loop through block B in the DFD.
- The predictive simulator uses pure cinematic and geometric features of the environment and the slave. The predictive displays shows 3D graphics of the position of the slave in the remote environment. A minimum task description has to be maintained here. It does not need to be too complex, just a description (using different characteristics, such as desired force between two objects) of the different possible states and the transitions from one to another.

5.2.1 Control scheme with ideal behavior

We refer to ideal behavior when the model of the robot and the environment in the predictive simulator is perfect. The operator then can perform the task on the predictive simulator and the robot will precisely execute every command, even when interacting with the environment. We know this behavior is not attainable in practice but it is very didactic to describe how the corresponding control scheme should be. It allows us to describe the basic working procedure with the DFD-TDT. It also allows us to have a start-off control scheme from which to make the necessary modifications to solve the problems that appear because of model inaccuracies.

The operator works only with graphic information on a 2D display of a 3D pure cinematic simulator. Because the model of the robot and the environment are perfect two different control loops can be established. The first one is closed by the operator using the predictive display. He moves the master arm and sends, through block D, a position/velocity command to the virtual slave of the predictive simulator. The loop is closed with the visual feedback from the predictive display.

The second control loop works in open mode. The same command sent from the master to the simulator is sent to the robot through blocks A and B. Because the model is perfect the robot will interact with the environment exactly as predicted by the predictive display. So no compliance or local autonomy of the robot is needed. Telemetry data can be sent back to the predictive display through blocks C and D just to give an idea of in what stage of execution the task is.

5.2.2 Complete use of the capabilities of the DFD-TDT

In the previous section we presented the basic use of the DFD under ideal conditions. Some of the components of the DFD were not mentioned at all because the were not needed. But, even using a perfect model, real operation has some limitations cause by the use of predictive displays that have to be taken into account.

The main ones are:

1. The operator misses some important information when working with video and graphics displays. He does not get any information about the dynamic behavior of the environment during interactions between objects. He also can have problems regarding depth perception or 3D interpretation.
2. It is very difficult for the operator to maintain contact between the virtual robot and an object. Sometimes it would get inside the object and sometimes it would get away from contact.
3. The commands are purely of a position/velocity nature. This leads to not have a specification of the desired contact force between the robot and the environment.

We see that even with a perfect geometric modeling there are some problems to be resolved. Difficulties can greatly aggravate when there are differences between the model of the robot and environment and their real counterparts. That is the fourth main problem to resolve:

4. Inaccuracies of the robot and environment model. Some of the more typical problems are shown in Figure 2 for a 3 DOF task (two for position and one for orientation). It is important to note that a modeling error can exist while modeling the environment, the robot or both at the same time. What it is important in practice is the error in the relative position between them.

The first 4 examples of Figure 2 show typical problems that can occur while trying to grasp an object. These are simple problems that in practice are combined into more complex ones. The same examples can be used for the remaining 3 DOF.

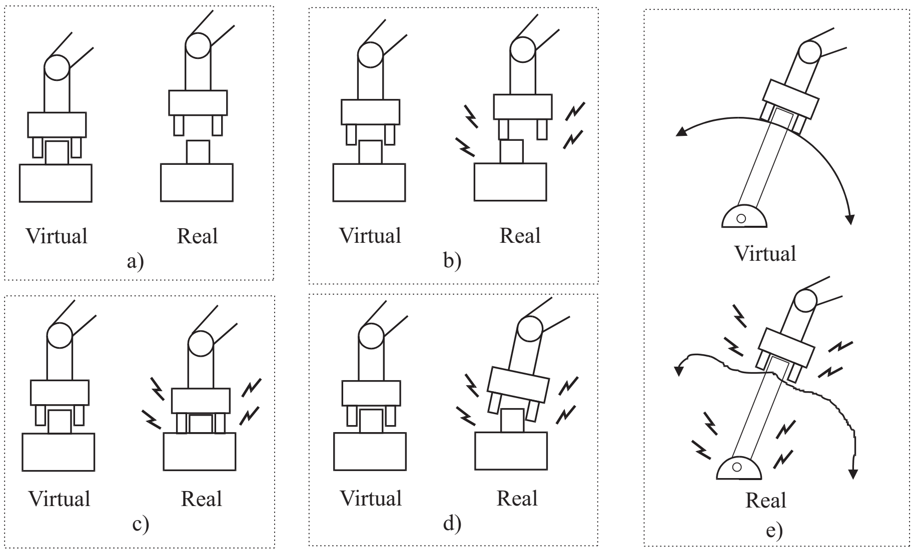

Fig. 2 Typical problems arising because of poor modeling

In example (a) the virtual slave is actually ready to grasp the virtual object while the real one is far from it. If grasping takes place the real robot will miss the object. A modeling error was made in the vertical direction. In example (b) the robot collides with the object before getting a grip on it. A modeling error was made in the horizontal direction. In example (c) the robot has been commanded to go to far and it generates an excessive force while colliding with the object. A modeling error was made in the vertical direction

In example (d) the robot tries to grasp the object with a bad orientation, generating excessive interaction forces. A modeling error has been made in the orientation degree of freedom. The fifth example (e) tries to show how the combination of the previous four errors can affect in a constrained motion along a path. It is clear that if nothing is done to prevent this from happening, the system could easily brake apart.

5. Another important practical problem appears because of the compliance loop always present in the slave for safety reasons and to help perform contact tasks. In the case 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

All the capabilities of the DFD-TDT have to be employed in order to try to solve the five basic problems stated above. That is what all the proposals try to resolve in order to achieve smooth and continuous teleoperation under the limitation of time delay.

We will give now several hints on how the different elements of DFD-TDT can be used to solve some of the problems mentioned above. This ideas have been mostly extracted from the proposals present in the literature and reviewed in section 3 and 4. It is important to have always in mind that some of the problems can be reduced or avoided with some of the new features of the control scheme, but others must be solved by the operator. The control scheme has to prevent the system from collapsing and at the same time help the operator know what is happening so he can find a solution as soon as possible. If the system could solve all the problems by itself we would not need the operator (the Roseborough Dilemma again).

- **Geometric constraints and the predictive display as a filter**

Problems #1 and #2 appear because no geometric constraints have been taken into account. The interaction of robot and environment has to be considered form the static or geometric point of view, so that commands sent to the slave robot never violate those geometric constraints.

A very simple geometric constraint is that the robot cannot penetrate rigid objects. That means that when contacting an object the position of the robot cannot move in the direction normal to the surface of the object. There can be more complex constraints, like for example, the ones present when opening a door or moving a crank [Sciavicco-96].

The idea then is to define a set of geometric constraints that correspond to the real constraints in every stage of the task. They have to be maintained as simple as possible in order to ease up the calculations and the execution.

With the use of the geometric constraints and position commands the basic control scheme changes as follows. The operator moves the master to give a position command to the virtual slave through block D. The predictive simulator makes the corresponding calculations and moves the virtual slave taking special care as to not violate the geometric constraints. So, for example, the virtual slave will never transverse a stiff surface even if commanded to do so.

The position of the virtual slave that follows the constraints is displayed to the operator and sent to block A through generalized matrix $\boldsymbol{V}_{ps}$ and from there to the remote slave going through block B. So, in case of perfect geometric and constraint modeling, the slave will execute the task without major problems. By this manner the predictive display acts as a filter of the commands generated by the operator so that they are coherent with respect to the constraints.

The problem of using constraints is that a misalignment appears between the master (joystick) and the virtual and real slave position. There are various ways to solve this problem depending of the features implemented in the joystick.

We have said before that we are using a Cartesian joystick with force feedback capabilities. In this case the joystick will be stopped making use of block E. I will be halted in the interacting direction when a constraint is encountered, but it will remain free in the directions without constraint

In case the joystick does not have force reflection capabilities the solution is to work with relative position values instead of absolute values. Working with relative values means that in each sampling cycle the increment on the master position is computed and sent as an increment of position to the virtual slave. If the virtual slave is under position constraint it will not move in the constrained direction, following the constraint rules. But as soon as it receives an increment in the opposite direction it will immediately move apart from the object.

- **Sticky contact**

In position control it is often difficult to maintain a continuos contact of the robot with the environment without provoking high contact forces or intermittent interaction. This is aggravated when using a computed graphic display as visual feedback.

The idea is to help the operator maintain the contact as easy as possible using what we have called a sticky contact feature. It is especially designed to tackle problem #2. It consists in defining a 'surface adhesion' coefficient as in [Funda-92], which represents a distance in the normal direction to the object surface. As long as the projection of the moving vector of the robot on the direction orthogonal to the surface is less than the surface adhesion coefficient the robot will remain in contact, although it remains free to slide over the surface.

- **Reference of force**

This is straightly related with drawback #3. One of the major problems in any teleoperation system is to exercise just the right force upon the remote environment during operation. We have seen that this problem aggravates with time delay. We could compute the forces on the predictive display and reflect them to the operator but, as we have said before, we are using a strictly cinematic simulator.

So the problem has to be solved the other way around. Instead of sensing the forces and act accordingly we have to define in advance the force we want the slave to generate upon the environment, send it through block A and let a force control loop to be closed in the remote zone.

But, how do we specify the force? There are two ways: (1) using a priori information from the description of the task present in the predictive simulator or (2) letting the operator to specify it on-line. The first one is only applicable for simple contact tasks and assuming that is possible to identify in every moment the stage of the task. It can be done but requires much development, which leads us again to the Roseborough Dilemma.

It is then desirable that the operator could decide the applying force in every moment interactively. If the joysticks have force reflection capabilities, the value of force /torque can be obtained by the force being applied by the joystick drives to maintain the constraint against the movement of the operator. This function can be implemented through block E. If also a force/torque sensor is present in the joystick (both for position and orientation) its values can be used directly as force/torques references making use of block D. In both cases the operator exerts the force he wants to command, which is later sent to the slave through block A.

There is the special case of the space mouse in which there is no force reflection although a force sensor is used. But the fact that the space mouse does not has displacement capability makes feasible to use the sensed force as the reference feasible.

For systems without force reflection and without a force/torque sensor the solution is somewhat more difficult.

- **Energy approach**

The aim of the previous idea was to aid the operator to have a closer knowledge of what is happening in the remote zone. Instead, this idea will try to cope with problems #4 by providing the remote robot with a certain degree of autonomy to be able to work with a poor model.

A first step to the energy approach is the use of a compliance loop locally in the remote robot. This is not a new idea and almost all the researchers agree that is indispensable. But most times the compliance is not enough to guarantee a good behavior. It can be useful in cases c) and d) of Figure 2 for example, but totally useless in cases like a) and b).

A different approach is needed and that is the energy approach presented here. It is based on the idea of transmitting to the remote zone patterns of energy interchange between the robot and the environment. Then the remote robot will try to mimic the energy interchange pattern during its movement; something similar in concept to the telesensor programming used in ROTEX [Hirzinger-93].

Energy patterns make reference as how the energy flows or is present in the system: pure kinetic energy, potential energy, etc. By this way, tasks can be specified as a function of energy and not of fixed values of position and force. By using energy we have a magnitude that is function of the relative distance or interaction between robot and environment, and not just absolute values.

If in the remote environment the energy pattern is somewhat similar to the one obtained with the predictive simulator we can be almost be sure that the task is being executed maintaining the same relation between robot and environment.

How do we specify the energy exchange? One option is the use of wave variables [Niemeyer-97a]. The wave variable transformation makes use of the velocity and force magnitudes to obtain an ongoing energy wave u and a reflecting wave v. (Figure 3). The idea is to transform the velocity and the force of the interaction between virtual environment and virtual slave into corresponding wave variables with a given wave impedance. Then transmit the two wave variables to the remote zone along with the absolute position value of the virtual slave. In the remote zone the slave will follow the position reference while trying to also mimic the wave variables values received by closing a loop in the wave variable domain through block B. It would act as a compliance loop that instead of using only the force sensed it was an energy pattern.

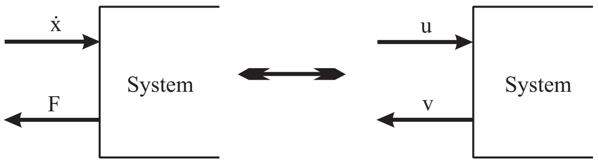

Fig. 3 Transformation to wave variables

- **Guiding Force**

It is clear from Table 1 that the use of bilateral force reflection upon the master arm with high time delays is not possible. The system becomes unstable very easily. But there are other ways to use the force reflected to the operator. A detailed account of real space robots experiments on ETS-7 robot arm using force reflection can be found in [Penin-99]. Here we will just describe briefly some of the ideas.

One option is to the use the FR hand controller to generate physical constraints of a task known in advance. The constraints can have or not a real counterpart, so is not just predictive force reflection. They can be virtual constraints that tell the operator where he must not go. A step further is the implementation of a potential field of virtual forces that actually guide the operator through the task. One interesting application is the use of force fields for grasping. Information about the current position of the object can be used to update continuously the potential field, so the operator just has to follow the force he feels in his hand without having to worry about anything else.

Force can be used in many other ways. Generally speaking, it is just another way of displaying information to the operator, but with the advantage that kinesthetic sensations are easily integrated by the human brain with no need of complex processing [Penin-98]. Hence, it can be used in combination with other visual and acoustic aids without compromising the operator's performance.

6. Conclusions

Teleoperation with time delay is a very challenging problem. Its application to space robotics is even more difficult because of the high values of time delay, communication bandwidth or poor control capabilities of the space robot.

Many proposals for time delayed teleoperation can be found in the literature, although few of them have been applied practically. The ideas proposed are diverse and range from pure bilateral control to having some autonomy in the remote site. Moreover, no common nomenclature had been established and it was difficult to make a comparison. No existing document brings them together under a same perspective.

In this report we first reviewed those we thought were more relevant. During this review we explained in detail the concept behind each of them and tried to point out their usefulness from the space teleoperation point view. This work is unique on its own and can be of inestimable use for any researcher who wants to get a general view of the problem.

After performing the review we thought that all the knowledge obtained could be used to create a framework in which to express, compare or study any proposal. The framework is based on a common nomenclature and the definition of a data flow diagram.

We have proved with various examples the flexibility of this framework to represent such diverse kind of proposals. We feel it would give researchers in this field a better understanding of the problem and will help them have a clear view in what areas more research is needed to achieve continuous and smooth teleoperation under the presence of time delay.

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Appendix A

This appendix presents the application of the data flow diagram for time delayed teleoperation (DFT-TDT) to some of the proposals described in sections 3 and 4. For details of the DFT-TDT, please refer to section 5.

Bilateral control with time delay based in passivity [Anderson-89]

Generalized matrixes of master and slave:

$$V_m = \left[x'_m\right] \qquad V_s = \left[x'_s \;\; f_s\right] \tag{7}$$

Processing blocks:

$$\begin{aligned} A \equiv \quad & x'_u = x'_m \\ & f_u = f_{dT} + n^2(x'_m - x'_{dT}) \end{aligned} \tag{8}$$

$$B \equiv \quad x'_{sr} = x'_{uT} + \frac{1}{n^2}\left(f_{uT} - f_s\right) - \alpha f_s \tag{9}$$

$$C \equiv \quad x'_d = x'_{uT} + \frac{1}{n^2}\left(f_{uT} - f_s\right) \tag{10}$$

$$D \equiv \quad f_{sm} = f_{dT} + n^2\left(x'_m - x'_{dT}\right) \tag{11}$$

$$E \equiv \quad V_{mr} = V_{sm} \tag{12}$$

Notes:

- The slave position is controlled with PD.
- α is a compliance factor
- ***n*** is a scale factor between forces and velocities
- f_s in the proposal is not the force sensed by the force/torque sensor on the slave, but the force/torque command to the actuators.

Bilateral control for ideal kinesthetic coupling [Yoshikawa-96]

Generalized matrixes of master and slave:

$$V_m = \left[x'_m \;\; f_m\right] \qquad V_s = \left[x'_s \;\; f_s\right] \tag{13}$$

Processing blocks:

$$A \equiv \quad V_u = \mathrm{LPF}\left(V_m\right) \tag{14}$$

$$\begin{aligned} B \equiv \quad & x'_{sr} = x'_{uT} \\ & f_{sr} = k_f f_s + f_{uT} \end{aligned} \tag{15}$$

$$C \equiv \quad V_d = \mathrm{LPF}\left(V_s\right) \tag{16}$$

$$\begin{aligned} D \equiv \quad & x'_{sm} = x'_{dT} \\ & f_{sm} = k_f f_m + f_{dT} \end{aligned} \tag{17}$$

$$E \equiv \quad V_{mr} = V_{sm} \tag{18}$$

Notes:

- Inside the master and the slave blocks there is an algorithm for the cancellation of their dynamics
- k_f is a force reflection factor.
- LPF: Low Pass Filter.

Bilateral control with telemonitoring [Lee-93]

Generalized matrixes of master and slave:

$$V_m = [x_m] \qquad V_s = [x_s \;\; f_s] \tag{19}$$

Processing blocks:

$$A \equiv \quad V_u = V_m \tag{20}$$

$$B \equiv \quad x_{sr} = x_{uT} - \alpha f_s \tag{21}$$

$$C \equiv \quad V_d = V_s \tag{22}$$

$$D \equiv \quad f_{sm} = f_{ref} - f_{dT} - \beta(x_m - x_{dT}) \tag{23}$$

$$E \equiv \quad V_{mr} = V_{sm} \tag{24}$$

Notes:

- The master and the slave are controlled under a Generalized Impedance (GI) [Lee-93] algorithm. The slave also uses a PD loop for position.
- α is a compliance factor.
- β is position error factor.
- f_{ref} is the desired contact force.

Bilateral control based on a Virtual Internal Model (VIM) [Ostsuka-95]

Generalized matrixes of master and slave:

$$V_m = [f_m] \qquad V_s = [f_s] \tag{25}$$

Processing blocks:

$$A \equiv \quad V_u = V_m \tag{26}$$

$$B \equiv \quad V_{sr} = \mathrm{VIM}(V_{uT}) \tag{27}$$

$$C \equiv \quad V_d = V_s \tag{28}$$

$$D \equiv \quad V_{sm} = \mathrm{VIM}(V_{dT}) \tag{29}$$

$$E \equiv \quad V_{mr} = V_{sm} \tag{30}$$

Notes:

- VIM: Virtual Internal Model [Ostuka-95]
- Master and slave have an internal position loop with a PD

Bilateral control through a long distance computer network [Oboe-98]

Generalized matrixes of master and slave:

$$V_m = [x_m] \qquad V_s = [x_s] \tag{31}$$

Processing blocks:

$$A \equiv \quad V_u = V_m \tag{32}$$

$$B \equiv \quad V_{sr} = V_{uT} \tag{33}$$

$$C \equiv \quad V_d = V_s \tag{34}$$

$$D \equiv \quad V_{sm} = V_{dT} \tag{35}$$

$$E \equiv \quad V_{mr} = V_{sm} \tag{36}$$

Notes:

- PD position control loop in master and slave
- It is similar to a classic position-position bilateral control scheme.

Predictive Operator Aid with Force Reflection [Buzan-89]

Generalized matrixes of master and slave:

$$V_m = [x_m] \qquad V_s = [x_s] \tag{37}$$

Processing blocks:

$$A \equiv \quad V_u = V_m \tag{38}$$

$$B \equiv \quad x_{sr} = x_{uT} - f_s \tag{39}$$

$$C \equiv \quad V_d = V_s \tag{40}$$

$$D \equiv \quad \begin{aligned} f_{sm} &= f_{dT} \\ x1_{pr} &= x_m \\ x2_{pr} &= x_{dT} \end{aligned} \tag{41}$$

$$E \equiv \quad \begin{aligned} &1.\; f_{mr} = f_{sm} \\ &2.\; f_{mr} = f_{pm} \\ &3.\; f_{mr} = \mathrm{LPF}(f_{sm}) + \mathrm{HPF}(f_{pm}) \end{aligned} \tag{42}$$

Notes:

- LPF/HPF: Low/High Pass Filters based on a Butterworth filter
- The position information going to the simulator has two components: $x1_{pr}$ (master position) and $x2_{pr}$ (slave position)
- There are several different proposal on how to reflect the force to the operator. They are expressed by block E. 1) Force from slave, 2) Force predicted by the simulator and 3) Complementary force.