Interest of the dual hybrid control scheme for teleoperation with time delays for Proceeding of ISER'95

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Abstract

It is well known that classical teleoperation schemes are unstable and even useless when time delays become important. In this paper we propose a new concept called "dual hybrid teleoperation scheme" which really improves the ergonomy of a teleoperation system, even with time delays. Thanks to this concept, the operator can exert forces or perform displacements from the "master" to the "slave". These forces are the ones that the human operator wants to apply for the current task. This is possible thanks to a special law coupling the two robots, each of them having an hybrid position-force control.

This scheme also offers kinesthetic feedback, without compromising the stability, even with time delays. So the operator can feel some useful sensations, as "moving feeling". Besides, this scheme allows to split a complex task into subtasks, during which the operator only manages few degrees of freedom. The attention required to perform a given task is really decreased and the operator can focus on a limited set of degrees of freedom.

The experiments done with an system based on this new concept show that it can be apply even if time delay becomes superior to few seconds.

1. Introduction

A robot with autonomous manipulation capabilities does not always allow to solve complex tasks as space assembly or space maintenance tasks, and specially for the fine manipulations involving contact with the environment. It is not always possible in this case to foresee all the necessary actions for solving any task. Owing to the imperfect knowledge of the real world and the complex interaction with the remote environment, an ability of recovery, which can only be brought by a human being, must be introduced. The teleoperation remains the most interesting way for performing work remotely in some applications.

A perfect teleoperation system would be the one where the operator feels the remote object as if he manipulated it directly (as through a virtual mechanical link, with weak inertia and infinite stiffness). Then the interface between the operator and the remote manipulation would be totally transparent. As the operator cannot be in the remote site, a solution consists of a most exact kinesthetic feedback. It is well known that the kinesthetic feedback is as important as the visual one, in particular when the tasks imply a contact with the environment. The kinesthetic sense is the sense transmitted by bodily movement and pressure, therefore kinesthetic feedback is provided by motion and forces exerted by the master robot in the operator's hand. This force feeling really improves the telepresence. It is well known that the operator, being in the loop of the teleoperation system, realizes a task in terms of a feeling coming from the environment. A small delay in such a feedback loop can create unstabilities.

But the tasks with only visual feedback must be distinguished from the tasks with force feedback. The visual delay creates a disturbance the operator can ignore and avoid instability with an "move and wait" strategy. But the kinesthetic feedback with a delay creates a disturbance in the operator hand that he cannot ignore and which is responsible for unstabilities. Time delays are prejudical to the quality of kinesthetic feelings, and direct teleoperation with force feedback is impossible with a delay of one second and more [1].

Performances of such a system are due to the quality of the mechanical conception of master-slave devices, and more particularly of the master, but the control schemes play an important role in the performances of a teleoperation system. Many schemes have been proposed to solve this difficult problem.

The classical solutions to deal with contact forces in teleoperation are described in part 2. We present then in part 3 our new teleoperation scheme based on hybrid control for both the master and the slave robot. Part 4 described the experimental set-up designed to implement this scheme before the conclusion.

2. Force Control in Teleoperation

2.1. Bilateral Feedback Concepts

Two schemes could be considered without time delay:

-Bilateral position concept

In this case, both robots are position controlled and the inputs of each control loops are the positions measured at the other site. With such a scheme, the force felt by the operator is due to the position errors in the remote manipulator's control loop. In an ideal case, the operator should only sense the forces due to external forces applied on the slave robot. However, in the reality, the unavoidable position errors due to position control loop are responsible for viscous friction.

-Force feedback concept

In this case, this scheme is based on the measurement, with a force sensor, of the force exerted by the slave robot on its environment. This scheme generally increases telepresence because the closed loop takes into account the mechanical imperfections such as friction and flexibilities.

But these methods can only be use when the delay remains low. When the time delay is not too important (inferior to 0.1 second) the system can still be stabilized [2], [3], but the bandwidth of the closed loop system decreases drasticly.

Many schemes have been proposed when the delays become important. One of them, [4], proposes to return the predictive force by using an open-loop model-based prediction. The method used in [5] (called teleprogramming) is based on the generation of commands to the telerobot by moving the teleoperator master while getting both force and visual feedback from a computer-based model slave. The semi-autonomous command proposed in [6] allows the operator to interfere in the autonomous fonctions in a progressive way. Others technics are based on shared control [7] and use a remote and local force control.

2.2. Teleoperation with Local Autonomy Concepts

Two types of methods are considered to control the slave robot: the ones are based on active compliance and the others are based on hybrid control. The first type of methods induces a decrease of the gains so as to the slave is not stiffly position-servoed to the master. [8] proposes a compliant system in which the slave robot is compared to a spring with a programmable stiffness. This method allows to maintain the stability still for delays not exceeding one second.

Hybrid control described in [9] is based on a different idea. The choice of the cartesian space partition depends on the local interactions between the slave robot and its environment. The slave is position controlled in the directions unconstrained by the environment while it is force controlled in the constrained directions. This idea initially proposed for others applications can find an interest in many tele-operation schemes. In particular a stiff device can be used as in [10] to transmit commands to the remote manipulator.

3. The Dual Hybrid Position-Force Concept

3.1. General Approach

Let us consider the ideal case of a perfectly force controlled master robot. By setting a zero force input command along its six degrees of freedom, the master device is theoritically weightless. If the operator exerts a force he will encounter almost no resistance, so he can move the master hand freely in all the master robot workspace. It can be used as a single joystick device to transmit position commands to the position controlled remote manipulator. Let us now consider the ideal case of a stiff master device. If this system is equipped with a six degrees of freedom force sensor, it can be used to measure forces exerted by the operator. These measures can be used as input commands for the force controlled remote manipulator.

The concept of our teleoperation scheme combines these two possibilities [11], [12]. To apply this concept, the master robot must be equipped with a hybrid position-force command, dual to the slave hybrid command. It is the reason why we called the system "dual hybrid teleoperation system". Every operation conducted by this teleoperation system needs to separate the cartesian space into two orthogonal subspaces, according to concepts presented in [13]. In the first subspace, called χ_1, the master is zero force controlled in order to appear as transparent as possible. In this subspace, the operator transmits position commands to the slave robot (position controlled in this subspace). In the second subspace, called χ_2, the master robot is position controlled, and the force exerted by the operator are used as input commands for the slave robot (force controlled in this subspace).

This master system can be seen as a dual hybrid sensor. In the subspace where the position is kept constant, it is used as a force sensor. In the complementary subspace, it is used as a position sensor.

The idea of coupling two hybrid robots is already used for the cooperation between two robots handling the same object [14], but not yet proposed for teleoperation application. The figure 1 allows to understand the basic idea on which relies the dual hybrid concept.

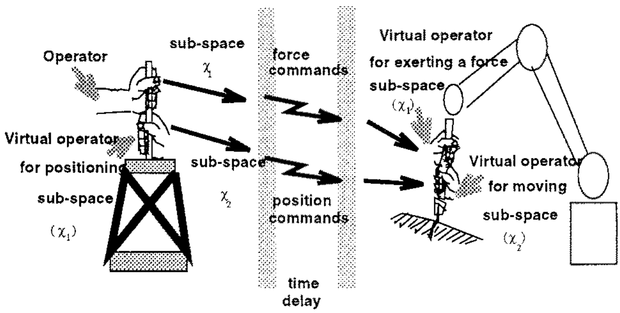

Figure 1. dual coupling (basic idea)

3.2. Definitions

The formalism using this scheme is quite simple. An hybrid task can be described with two frames: a compliant frame and a task frame. Those frames are defined relatively to two other frames, the fixed frame and the mobile frame:

- $\mathcal{F}_f$, the fixed frame, attached to the fixed base of the robot.
- $\mathcal{F}_m$, the mobil frame, attached to the end effector of the robot.
- $\mathcal{F}_t$, the task frame.
- $\mathcal{F}_c$, the compliant frame.

We now define X and F the position and the force measured. The same notations are adopted for both master and slave robots, measured and desired values. The superscript m or s is used to distinguish either the master or the slave robot. The subscript m or d is used to distinguish either the measured or the desired values. X is a six dimensional vector defining the position and the orientation of $\mathcal{F}_c$ relatively to $\mathcal{F}_t$. F is the force wrench in O_c (origine of $\mathcal{F}_c$), written in $\mathcal{F}_t$.

The space partition is described by S a six by six diagonal matrix, the same as defined in [9].

The behavior of a hybrid robot is completely defined by:

-The different frames defined above: $\mathcal{F}_t$ and $\mathcal{F}_c$.

-The configuration matrix: S.

-The position and forces desired (In fact, the teleoperation controller takes only into account the positions in the position controlled subspace, and the forces in the force controlled subspace, thanks to the matrix S).

Besides, a set of maximun speed V_{max}, maximun force F_{max} and maximun position X_{max} are defined for each degrees of freedom.

3.3. Dual Coupling of Two Hybrid Controlled Robots

The configuration definition for one hybrid robot can be extended for a couple of hybrid robots:

- Master: $\mathcal{F}_c^m$, $\mathcal{F}_t^m$, S^m, X_d^m, F_d^m, V_{max}^m, X_{max}^m, F_{max}^m
- Slave: $\mathcal{F}_c^s$, $\mathcal{F}_t^s$, S^s, X_d^s, F_d^s, V_{max}^s, X_{max}^s, F_{max}^s

A connection between the master and the slave along any of the 6 degrees of freedom links the measurements (force or position) of one robot to the commands of the other. In theory, all the connections are possible, hence we have a lot of possibilities. In opposition to the classical teleoperation system, coupling two hybrid robots leads to a lot of configurations, since any axis can be force or position controlled.

In reality, a lot of connections are out of interest. The dual coupling is obtained by simply setting:

- S^s=I-S^m where I is the identity matrix.
- $F_d^s = F_m^m$
- $X_d^s = X_m^m$

The space partitions of the master robot and the slave robot are dual. For any value of the matrix S^m, there is a dual value for the matrix S^s, defining a configuration characteristic of a special behaviour of the master-slave couple.

The configurations corresponding to a dual coupling are:

-The master robot is position controlled at a constant value in the subspace χ_1. It is then used as a force sensor.

-The master robot is force controlled with zero input in the subspace χ_2. It is then used as a position sensor.

Many other configurations can be proposed. For example, the input of some control loop can be provided dy autonomous task (this configuration is similar to the "shared-control" concept). The connections described above transmit the data from the master to the slave (forward connections), but the data can also be transmitted from the slave to the master (backward connections). The various possible connections are despicted on figure 2.

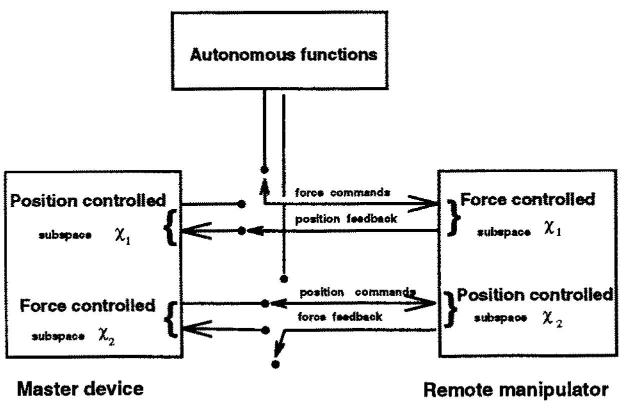

Figure 2. backward and forward connections

We will see in a next part that some of these connections are possible even with time delays.

The following example shows the interest of this new scheme. Only the connections from the master to the slave are taken into account.

In order to illustrate this remark, let us consider the task which consists in sliding a parallelepipedic object on a plane (figure 3) while maintaining a plane on plane contact.

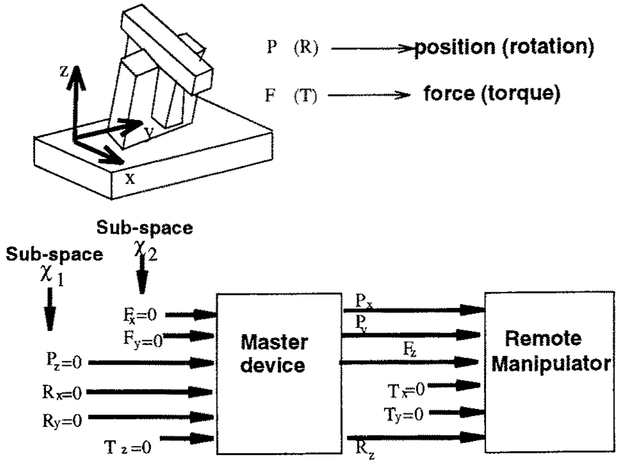

Figure 3. Example: plane on plane contact

Three master degrees of freedom are position controlled in the subspace χ_1 (orientation around x and y axes, and translation along z axis). Only the force measure along z axis is sent to the slave robot. The others are not used. In this example the torques, constantly set to zero, constraint the object to remain in a plane on plane contact situation with the environment. But they could also come from the master system.

The three complementary degrees of freedom are zero force controlled in the subspace χ_2 (translation along x and y axes, and orientation around z axis). The master robot is used as a position sensor for the slave robot.

The operator must only take into account four degrees of freedom, and two of them are critical: they correspond to the displacement in the plane.

4. Interest of the Dual Hybrid Position-Force Scheme for Complex Task Realization

The first important point is the possibility of backward connections. Indeed, time delays create instabilities in a force feedback teleoperation loop in a classical scheme. The position commands are sent from the master to the slave and the force commands are sent from the slave to the master.

In our teleoperation scheme, the master robot is position controlled in the subspace χ_1 and allows to transmit force commands from the master to the slave. The loop can be then closed and slave position measurements can be returned to the master robot, without disturbing the stability.

Indeed, the coupling between the master and the slave is not very strong in this case. In this subspace χ_1, the force exerted by the operator on the master hand is not disturbed by a modification of the position command coming from the slave.

However, this feeling of "moving", even weak, gives important information to the operator on the task success.

One can imagine the interest of this possibility when an insertion is added to the last example. The displacement of the slave robot during the insertion phase is then returned in the operator hand. The progression of the insertion could be felt with time delay of course, if there are communication delays.

A second important point deals with the decrease of the operator attention. Indeed, when working in teleoperation, the operator has difficulties to manage six degrees of freedom. Our scheme allows to split a complex task into subtasks, for which the operator manages only the critical degrees of freedom. Many of the complex assembly tasks can be split into subtasks, which require no more than two or three degrees of freedom at the same time.

5. Experimental Set-Up

We developed an experimental teleoperation set-up composed of two robots, each of them having six degrees of freedom. The slave robot is RCE1, a prototype developed at the CERT-DERA between 1984-1986. It is controlled by an hybrid position-force control scheme. RCE1 is a macro/mini device: the macro robot is a SCARA type robot and the mini is a fully parallel six degrees of freedom wrist. The advantage of this prototype comes from the hybrid position-force control scheme based on the macro/mini architecture, as shown in [15] and [16]. This architecture combines the advantage of both a serial robot (extented workspace) and a parallel robot (lightness and high quality force control). The mini robot is controlled by six pneumatic linear actuators driven by servo-valves. Four processors (68000) host the hybrid control of RCE1 with the real time system CESAR, also developed at CERT. The experimental set-up is depicted in Fig. 4.

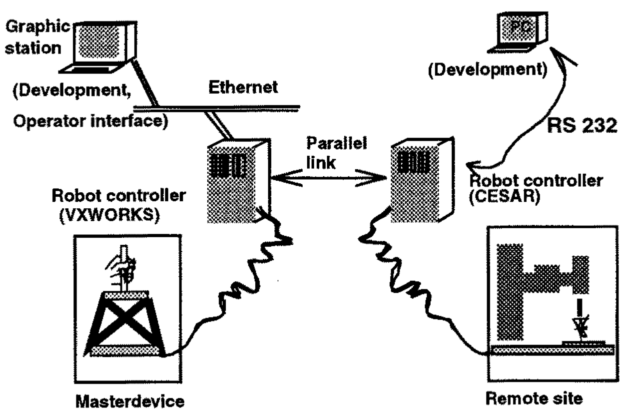

Figure 4. experimental set-up

The master robot is a fully parallel device having six degrees of freedom.The real time system, VXworks, is supported by two processors running in parallel (one 68040 MVME167 and one 68030 MVME147) and mounted on a VME rack. The sampling period of the two robots is about 3ms. A third processor is used for master-slave communication. Operator interface and development are done on a INDY graphical workstation.

6. Conclusion

In the classical teleoperation schemes, the forces are sent from the slave to the master. In this case, the force displayed on a screen or returned in the operator hand gives a true feeling about the interactions between the manipulated objects by the slave and its environment. As these schemes are instable and useless when the time delays are important, a new scheme, called "dual hybrid teleoperation scheme", is proposed. In this scheme, the operator can send the forces from the master to the slave. In fact, at the inverse of classical schemes, the forces which are sent, are the forces that the operator wants to impose during the current task.

This is possible thanks to a coupling between the two robots. But this scheme requires two robots equipped with hybrid position-force control.

This scheme also offers some possibilities of feedback connections, without creating instabilities in spite of time delays. A position command can be returned in the operator hand, which creates useful kinesthetic feelings. These kinesthetic feelings are less important that the ones obtained without time delays in the classical schemes, but they allow to better appreciate the success of each subtask and improve significantly the operator's feelings.

Besides, this scheme allows to split a complex task into subtasks, during which the operator only manages few degrees of freedom. The intellectual work is really decreased and the operator can focus on the critical degrees of freedom.

The experiments conducted in our laboratory show that these new concepts allow to achieve difficult tasks, such as insertions with very small clearance.

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