ICAR '97
Monterey, CA, July 7-9, 1997

Parallel Multi-Robots Long Distance Teleoperation

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Abstract— On October 10th 1996 and for the first time in teleoperation history, four robots of different kinematics and situated in different locations (respectively Poitiers, Grenoble and Nantes in France and Tsukuba in Japan) were teleoperated simultaneously (in parallel). The experiment was the first general one of a research cooperation programme named TWE (Telepresence World Experiment) linking seven research teams belonging to five countries. The task consisted in assembling a four pieces puzzle. All the robots had to perform the same task at the same time. In this paper, we discuss the preliminary results of this first trial experiment and problems encountered in achieving the matter. The master consists of a high-level abstraction interface based on virtual reality concepts. The operator performed the task within a simulated environment. Based on direct hand use, the operator assembled the puzzle in a natural manner. Bilateral transformations, from the operator to robot control and backwards, from the robot to operator, with time delay considerations, are presented.

1 Introduction

Many experiments have been conducted in the context of long distance teleoperation:

- In early 1993, G. Hirzinger team [5] DLR[1] (Germany), sent a multisensory robot (ROTEX) on board of a spacecraft. It successfully worked in autonomous modes, teleoperated by astraunots, as well as in different telerobotics ground control modes. These ones include on-line teleoperation and telesensor programming and a task-level oriented programming technique involving learning by showing concepts in a virtual environment.

- From 1992 to 1993, three experiments have been carried out between A. Rovetta and al. [14] from the Telerobotics Laboratory of the Politechnic of Milan and L. Angelini and al. [1] from the 4th Department of Surgery of the University of Roma. During these experiments, remote controlled surgical acts have been executed through a master-slave robot system, either via a modem or a satellite link where the delay of signal transmission were analysed. The last experiment was conducted in cooperation with the JPL [13].

- Wakita and al. [16][17] used macro instructions at three levels to control distantly a remote slave robot from JPL[2] (USA) to ETL[3] (Japan). Those macros consisted only on *move*, *grip*, *pick* and *place* tasks. They also proposed a snapshot algorithm to position automatically the remote camera. Authors mentionned that the teleoperation via Internet was somedays unstable due to the large delay, which affected the visual feedback, causing difficulties for the operator to confirm, at each step, correct completion of a macro.

- R. Stain and al. [15] used the teleprogramming concept [11] to control a slave robot situated in JPL (USA) from GRASP [4] (USA). This teleprogramming experiment was based on the human supervisory control approach of a robot performing puncture and slice operations on thermal blanket securing tape of a satellite repair mission sub-task. The transmission support was Internet. Due to the bandwidth and varying time delay, continuous visual feedback was not possible.

- F. Arai and al. [2] demonstrated a simulation of an intravascular neurotelesurgery with color image exchange and force feedback between Nogoya and Toyko (both in Japan at 350 Km distance). A high speed fiber network with ATM (Asynchronous Transfer Mode) at 156 Mbps bandwidth was the support of the data communication.

- A tele-micro-surgery system was demonstrated from Tokyo (Japan) to Washington (US) using Internet and 2 artificial satellites. Forces informations was substituted into auditory signals and fed back to the master. This

[1] German Aerospace Research Establishment, Wessling.

[2] Jet Propulsion Laboratory, NASA Pasadena

[3] ElectroTechnical Laboratory, AIST - MITI, Tsukuba

[4] GRASP Laboratory, University of Pennsylvania

enhanced operator performances beyonds the poor quality of the visual feedback [10].

These experiments, among some others, demonstrate the extension of telerobotics technology to various domains: telesurgery, subsea, space, etc. In our opinion, our studies contributes by two originalities:

- the first one relies on **teleoperation of multiple different kinds of robots at the same time.**
- the second, is in using on-line a very high level abstraction interface for teleoperation: **human natural hand actions**, for performing low level control. This is made possible by designing and performing a *virtual task*, i.e. a task that has to be executed within a virtual environment.

The rest of the paper presents the general concepts of our approach. We then present the experimental setup, followed by discussion of the results and problems encountered during the first trial as well as future experiments and considerations.

2 The "Hidden Robot" Concept

We are developping a novel scheme for teleoperation, we called: *"the hidden robot" concept.* Briefly, it consists of a master station where the operator performs the task in a natural manner i.e. using, in some extent, the dexterity and skills of his own hand(s). The operator executes the tasks in a virtual environment (VE) which contains functional and physical features of the real remote one. Monitoring the state of the virtual task execution, real task specifications are extracted in a low level mode and mapped onto robot, operational-space commands. Control signals/actions that have to be sent to the slave sites, in order to ensure real task achievement, are subsequently determined as well as necessary feedback signals/information that need to be displayed to the human operator while performing the task, see [7] for more detailed discussion.

We aim to realize teleoperators which allow necessary feedback and naturalness to *directly perform the task rather than controlling the robot to perform the task.* The operator may *concentrate his awareness only on the task* and *not on both robot control and the task.* Virtual Reality technology plays an important role in our approach. If we perform directly the tasks using direct hand as master device, the control of the slave robot is made task-based, and *not necessarily* task-knowledge based. A whole virtual or augmented reality representation of the real environment is used as the necessary interface. Within this environment, the operator performs in real time a representation of the real task, which we called the virtual task. As will be described in the following section, the actual state of this operator/virtual-task interaction guides the execution of the real task. We note that in such a whole virtual representation:

1. the slave robot does not need to be rendered (visually hidden),
2. the operator does not control directly the robot (functionally hidden).

The proposed concept was extended to multi-robot teleoperation purpose, as shown in Fig. 1.

When considering the force feedback from a functional point of view, i.e as an important item for task achievement, the synthetic forces displayed from the VE/operator

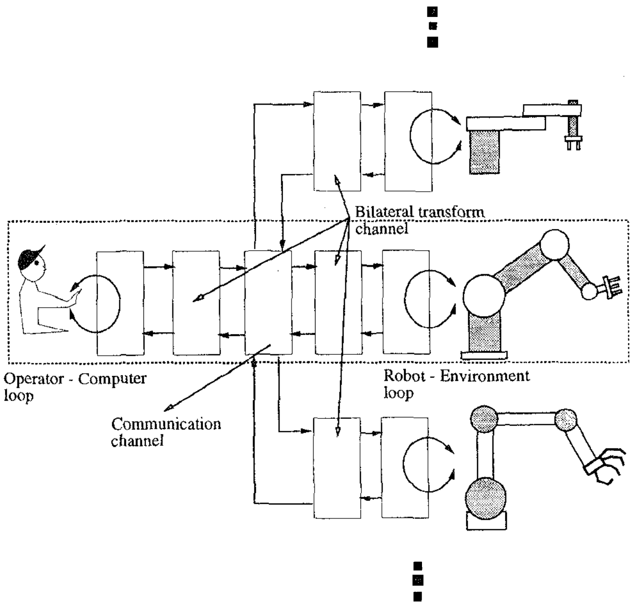

Figure 1: *Proposed teleoperation scheme with an extension to multi-robot teleoperation purpose*

interaction and the real ones displayed from robot/RE interaction can be used independently if an adequate task-based bilateral transformation can be performed. The VE can be modeled such as to guarantee the passivity of the master loop and thus stability of the operator/VE interaction is improved because of the high bandwidth data flow between the operator control devices and the VE. Transparency can also be defined locally. Thus we speak about virtual transparency. Force mapping can be done through a virtual hidden slave robot simulation and can be task-based. Concerning multi-robot control, Fig. 1, a direct force feedback either from the real robots or from the simulated ones has no meaning. It is surely unstable even if temporal multiplexing of data flow is performed.

We must also enable the operator to intervene directly on one robot by switching to a single-teleoperation mode. This is needed in case of one robot is in an undesirable state. Thus the operator can guide the 'robot in trouble' to a recovering state from where it can then easily reach the desired one.

3 Operator/VE Loop

An intermediate functional representation of the RE(s) is synthetically displayed (VE) to the operator. Within this VE, the operator hand is also synthetically represented and rendered according the operator real one using any kind of dataglove. This *hand system* is considered to be the input/output "device", or more explicitly, the master. This choice was motivated by the following points:

• Hands are mostly used in achieving every day tasks. A direct use of operator hand will reduce (see eliminate) the training phase.

• Skill transfert is made possible with less constraints. It will enhance tasks performances.

• Versatility of the human hand facilitates the control of multiple different telerobotic systems, either in parallel or serially.

More discussion about this point is given in [7]. At this level, the operator is executing the task in a VE (master site) using in some extent the dexterity and skills of his own hand. Various parameters, concerning the state of this 'virtual task' execution, can be monitored on-line and used to synthetise:

- the control signals/actions to be sent as commands to the slave sites,
- the feedback signals to be dispalyed to the human operator. These include predictive graphics and/or force displays, virtual fixtures [12] assisting the human operator etc.

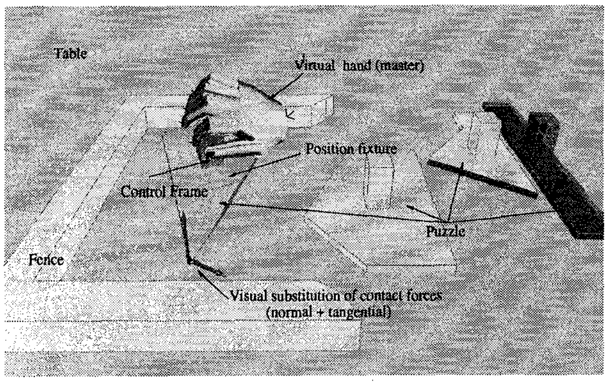

Figure 2: *The master control environment*

In our experiment, this was implemented using one HP workstation (WS) with graphic software facility. Manipulated objects was 4 puzzles rendered in high α-transparency. The task was to assemble them within the fence as shown in Fig. 2. For operator hand position/orientation tracking, we used 3D Polhemus tracker attached to the operator hand. Open/close action of operator fingers will be monitored using a data glove. For the first trial, this was performed using a mouse. The visual arrows are a representation of contact forces. For each contact a pair of arrows (red for normal and green for tangential) is dynamically rendered, disappearing when the contact is broken.

4 Bilateral Transformations Level

This level has in charge the most important item of the proposed scheme. It must deal with data flow transformations between operator/VE interaction and robots/RE interaction. It has a dual goal:

- First, to extract robot motion/force commands that have to be sent to the slave site. These control signals derive from the operator/VE interaction in the master site and represent the state of the virtual task being achieved by the operator hand.
- Second, to provide to the operator pertinent feedback information deriving from the state of either robots/RE or operator/VE interaction (or a combination of both).

No precise model of the task, in terms of primitive actions or macro commands, is needed in this stage. The slave robots can be seen as being directly controlled by the state of the task execution in the master site VE.

In the experiment, another HP WS was used for the bilateral transformation processing. The result of this transformation is displayed using graphical images of the four robots including predictive model (wireframe representations, also called 'phantom' robots) and solid graphical models driven by the real feedback data of the slave robots. A snapshot of this display is shown in Fig. 3.

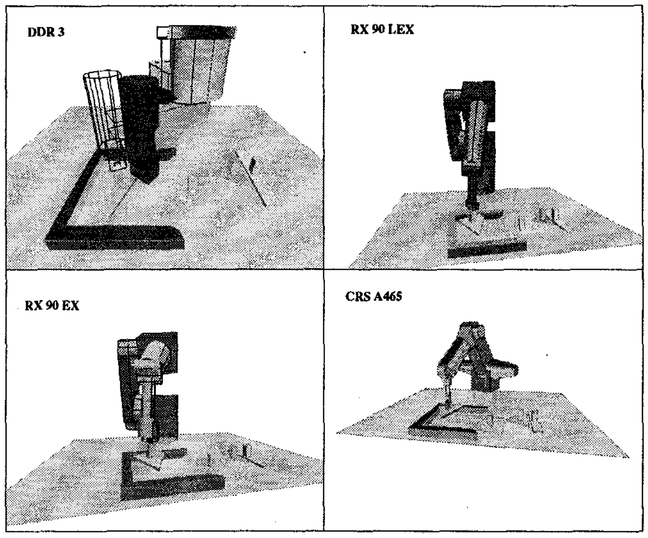

Figure 3: *Graphic images of the four robots during task execution*

We split actions performed by the human operator into 4 phases. These phases are identified by simple real-time monitoring of operator/VE interactions and used on-line to control the robots.

4.1 Free Motion Phase

The free motion phase is identified by: (a) no payloaded virtual hand (VH) motion and (b) no VH/VE interaction. While these two propositions are true we consider the system as being in the free motion phase. The control strategy adopted during this phase consists in adding two control frames: VH control frame (CH) and Robot control frame (CR). These control frames are just 4×4 transformation matrices linked in a static or dynamic manner to the VH frame and to the robot gripper frame. The robot is then controlled by the simple equation:

$$ {}^{\mathrm{CR}}_{\mathrm{VE}}T = \alpha\, {}^{\mathrm{CH}}_{\mathrm{VE}}T + \beta \qquad (1)$$

where α and β are scaling and distance off-set matrices.

In fact, the problem resides on the strategy employed for the choice of these control frames. The constraints which may guide such a choice are:

- While the VH belongs to the robot reachable space, the robot must be servoed in position, speed and acceleration.
- Gripper configuration must be such as to avoid collision with the RE when the operator VH is not in contact. Otherwise, it must be due to the RE/VE discrepency.
- Positionning of the gripper must exhibit functional similiraties between VH pre-grasping posture and robot pre-grasping function.

As for this experiment, all the grippers are a classical two *fingers* one and because of previous physiological research shows that the thumb is of great contribution in hand grasping and manipulation. We choose the thumb to be the CH. The hand control frame was linked to the operator virtual thumb. It was represented by an XYZ red frame, see Fig. 2. To keep this functionality, one of each robot gripper *fingertips* was candidate to correspond to the *thumb*. It was determined according to intial configuation of the hand and the robots (zero position and orientation). Then we make so that the opening joint (when not binary one) of each remaining gripper *finger* to fit inside the volume of the remaining VH fingers one. For the general case, we are investigating many possibilities [7].

4.2 Grasp Phase

The grasp phase is identified when both of the following conditions hold: (a) no payloaded VH, i.e. no object is being manipulated by the VH (b) collision between the VH and the VE. The grasp phase is assumed to transit to a manipulation phase when the grasp of a virtual object (VO) is stable. We can use many simple strategies to decide whether a grasp in the VE is stable or not. However, if we want to gain in realism and local feedback, mathematical models including physical laws interpretation and realistic grasping behavior must be implemented.

For robot grasping, much work has been done treating stability issues. Results can be directly applied. For safety reasons, it would be better that, when a contact occurs between the VH and the VO, the robot stands at a fixed position. The gripper will then grasp the real object (RO) only if the virtual grasp is stable. This will allow the robot to apply a local strategy for grasping optimization, based on the set of contact points between the VH and the VO. This last issue is also not a simple problem. We note that the grippers may be of different nature, presenting different mobility and dexterity properties relative to the human hand ones.

The second problem (assuming there are no discrepancies between the VE and the RE) concerns the estimation of the RO position and orientation in the RE. In some cases calibration and image processing techniques might be of a great importance. In some others, tactile sensors interpretation might be necessary. Considering the presence of serious discrepancies between the VE and the RE, the problem becomes much more complicated and necessary recovery procedures should be added.

4.3 Manipulation Phase

The manipulation phase is identified when the following conditions become true: (a) the VH is stably holding a VO (b) the robot is stably grasping the real object (RO). To deal with VH and gripper differences, we have added a control frame (CO) on the VO and similarly positionned on the RO. When the VH grasps the object and the gripper performs the same thing, the CH moves to the CO. The robot is then controlled through the CO in such a way as to ensure that the RO position matches the VO one while optimizing the difference between internal force tensor on the RO and the VO one, Fig. 4. During the grasping and manipulation phases, synthetic haptic informations are displayed on the human operator hand through an appropriate device which do not constraint operator hand and finger mobility and dexterity. Dextrous force feedback datagloves are an instance of such devices [7]. They have been refered to as *bilateral universal floating-handle controllers* [3].

In term of pure low level control, each local control loop can be considered as independant. Thus, we can establish laws that take benefit of what robot can perform better than operator [9] and what operator can perform better than robots [4].

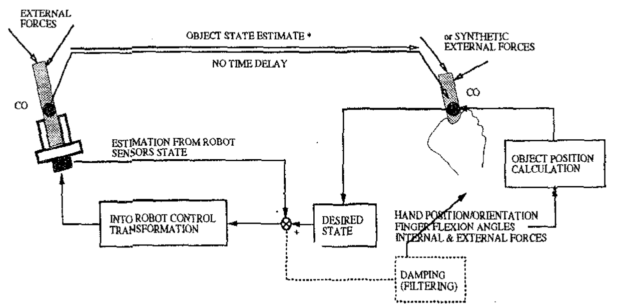

Figure 4: *Object-based simplified bilateral scheme. The black point is assumed to be the CO.*

4.4 Release Phase

The release phase is activated when the following conditions become true: (a) the VO is stably positionned or assembled in the VE (b) similarly in the RE. We have forbidden release operations of any grasped VO if it is not constraint by the VE features. The reason is to minimize geometric discrepancies between the VO and the RO. In another words, if the VO is released in free space, it will down. Thus, the software must compute, according to many parameters, the VO object final position and orientation (when linear and angular speeds become equal to zero). The same operation in the RE may lead to unpredictable errors between the VE and RE final states.

5 Robots/RE Loop

At this level, a local, sensor-based low level control of the robots is necessary to assure correct completion of the performed task at the slave site. This includes force/impedance control when contact occurs, control of the grasping action performed by each gripper etc. The level of automation provided by the robot control systems has to be taken into account when choosing the appropriate command signals that have to be sent by the master to the different slave sites, at each time instant.

Robot name	dof	Location
ShinMaywa DDR R3	3	MEL Tsukuba Japan
Staübli RX90 LEX	6	LRP Poitiers France
Staübli RX90 EX	6	INRIA Grenoble France
CRS Robotics A465	6	EMN Nantes France

Table 1: Robots used

During the robot/RE interaction various parameters can be monitored and used to provide feedback information that, combined with the one extracted by the interaction state in the operator/VE loop at the master site, generates the appropriate, pertinent feedback signals, displayed to the human operator. This may include: (i) monitoring of the slave robots joint angles, that can be transmitted to the master site and used to drive the real robots graphic model rendered on a workstation near the operator as shown in Fig. 3, (ii) acknowledgment signals of correct grasping, (iii) video images of the slave robots in action, transmitted and displayed on monitors at the operator site etc.

Location, type and number of degrees of freedom for each of the slave robots are shown in Tab. 1. Three of them were situated in France and one in Japan. At this stage the robot part transformation level is not used, it will concern local discrepancies recovery procedures.

6 Experimental SetUp

The first trial of multiple robots teleoperation was performed the 10^{th} October 96[5] at the Futuroscope of Poitiers (France).

6.1 Problems Linked to the Teleoperator

The first trial was performed using only kinematics (static mode). We was suspecting some troubles during the teleoperation. As no realistic dynamic behavior was implemeted in the master station and no force control was implemeted on the slave robots, makes the robots follow the operator in all his movements. This makes in one case trial the robot stopped because of the excess of torques in posing a puzzle. The operator had also no direct information about the grasp state of each robots. In one case one of the puzzle was not correctly grasped and affects the rest of the teleoperation. Due to the time constraint, the experiment was trully the first one (first trial one demonstration), three of the robots was already teleoperated in a stand alone (single) teleoperation. Another problem, was in the small opening capabilities of the grippers used, in one robot gripper case the openening capacity was 3.5 *cm*, for 3 *cm* puzzles edges, thus it remains only 0.5/2 *cm* error tolerance obliging us to share some autonomy on the slaves.

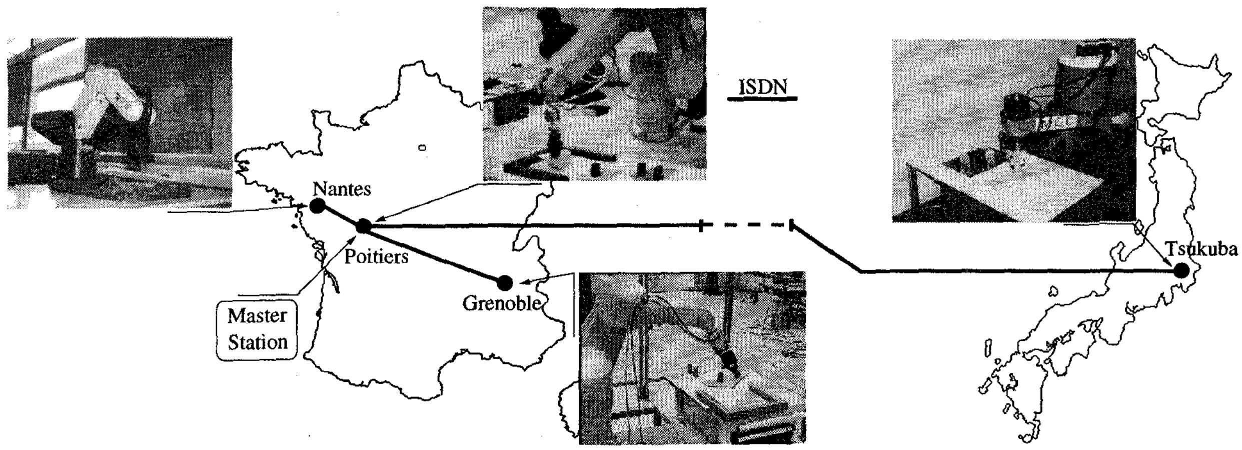

Figure 5: *Experiment Set-Up*

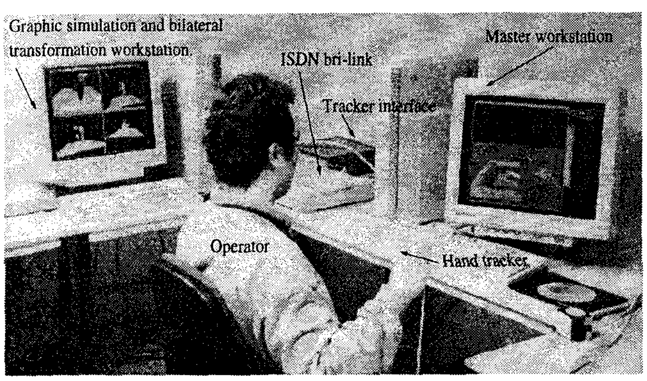

Figure 6: *Master station: operator during teleoperation*

Three Silicon Graphics (SGI) WS were provided to display real video/sound between the different REs. The standard InPerson software of SGI WS was used for this reason. Exchange of both control data and video images was performed through ISDN communication lines. All the WS were linked by a local Ethernet network. It allows quick exchange data between the two HP WS and, dispatching the data between the HPb and the SGIs.

6.2 Problems Linked to Networking

The client/server architecture becames the unavoidable method for point to point communication. This model is motivated by the fact that TCP/IP protocol family suffers a lack of automatic process execution at the reception of a message (data). If data were sent in an asynchronous mode, the WS may be overflowed and data may be lost because of the different WS processing speed. If a synchronisation is established (wait to receive before sending) the time delay is equal to a whole round trip one, thus obliging the operator to adopt a move and wait strategy. The delay in the synchronous mode is then equal to the maximum delay if the data are sent at the same time. Otherwise it is equal to the sum of the delays if we send, then wait to receive from each station. It is really wastefull not to use asynchronous communication. In this case, two major problems must be treated: 1- we must ensure non-blocking reading and writing procedures on the ports, and 2- solve the buffering problem to avoid loosing data.

ISDN network suffers from a none standard setup and installing procedures which are different from a workstation to another one. Between HP WS and SUN WS we spent more than two weeks for setting procedures and IP adressing configuration. In the case of SGI WS, it seems rather impossible, using the standard configuration, to es-

[5] Date and time was imposed by the French Academy of Application of Science CADAS, which ask us to exhibit the demontration during its annual meeting

tablish a point to point communication with either HP or SUN WS. As two communication channels are available for ISDN, we planned to use one for video picture exchange and the other one for robot data exchange. Unfortunatly, the InPerson standard software uses the two channels and when sending robot control data the bandwidth was the same that the one of picture/sound exchange which make the teloperation quit difficult in a synchronous mode. All those problems obliged us to supress video/sound exchange for this trial.

7 Conclusion and Further Experiments

Further experiments will be performed in the future in order to study different networking setup and communication possibilities. Asynchronous communications will be investigated using either sockets, remote procedure calls or programming at the TCP/IP level. As we mentionned local force control and feedback will also be implemented to deal with the geometry discrepencies and improve the teleoperator performance. A grasp sensor which may inform whether the object is grasped or not must be implemented. Several teleoperators schemes will be implemented. As a conclusion we can say that the performed first trial of a multirobot, long-distance teleoperation experiment showed the feasibility of the proposed goal and gave guidelines related to the direct use of the operator hand within an intermediate, simulated VE as a guide for task execution and teleoperation.

Acknowlegments

Authors are very thankful to the Conseil Générale de la Vienne (France) for the general support of the experiment as well as France Telecom (ISDN lines), Staübli S.A. (RX90 robot), SGI Company (SGI workstations) and the Laboratoire de Mécanique des Solides of Poitiers University that offered any welcome facilities.

The French Academy of Sciences and more particuliarly the Council for Applications of the Academy of Science (CADAS) is also thanked to have suggested the occasion of the demonstration and easied the sponsoring.

Without the concurrency of these private companies and public institutions this worldwide first trial of multirobot teleoperation could not take place.

As an information, the authors think intersting to note that if we take under consideration all expances concerning this experiment, work time of researchers, and different places equipments, travels, etc. the overall cost trespassed 2 million US $. For next experiments, due to present acquired facilities, the cost should be shorted by 1/10.

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