The Hidden Robot Concept— High Level Abstraction Teleoperation

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Abstract— This paper discusses the development of new teleoperator systems. While many innovations during the last decade made teleoperation technology progress, some severe well known lacks that we enumerate still persist. With respect to some attractive solutions proposed for coping with these problems, we designed a bilateral control scheme based on what we called the hidden robot concept. The teleoperator achieves tasks manually in a natural way within a virtual environment (VE). Thanks to suitable bilateral tranformations, the virtual tasks are being reproduced by any slave robot within the remote site. Mainly task based, our approach is not considered like a high level task knowledge based control. Rather, we consider it like a more refined shared autonomy control with a high level abstraction interface. Three main components are developped (i) supervision loop (ii) bilateral transformation layer (iii) execution loop. The approach has been validated experimentaly and preliminary results as well as further work are discussed.

1 Introduction

The telerobotics technology and its historical evolution has already been reviewed by [30] and more recently by [25]. Earlier motivations of telerobotics derived from the need to extend the human hand by a tool, and were followed by the human-being's need or desire to be where he is not (or dreams to be). The last goal is refered to as telesymbiosis [30], tele-existence [26], telepresence (most common name)[25] or augmented reality [2] or virtuality! This considerable development gives rise to discussions of relevant topics of this technology that we summarize in the following points:

• The design of masters devices has always been focused on the control of slave robots, not for tasks achievement. Thus the task is perceived through a good manipulation of the master to make the robot converge towards the task goal. The robot is perceived as some kind of sophisticated tool that one must control well, using another sophisticated tool (the master) if he wants to perform remote tasks. In our opinion, this teleoperation scheme (through a direct bilateral link between master and slave) presents some drawbacks:

1. Classical masters have been designed to map easily the slave robot kinematics, or according to other practical considerations [3]. Thus, even if they offer haptic feedback or not, they may be either very constraint mechanically (like master arms) or poor in naturally conveyed feedback (mouses, joysticks, etc.).
2. The operator must adapt his reflex, dexterity and skill to the robot. This may lead to fatigue in system use thus decreasing performance and creating serious barriers to operator skill transfert. Moreover, in many systems, teleoperating without a considerable training period is practically impossible. This training procedures may need different strategies to enhance operator performance [31].
3. In some systems, slave robot capabilities are exploited to a limited extend. Robots can perform many simple, low-level tasks that human cannot do with comparable accuracy or speed. Furthermore, the replacement of a new slave robot in an existant teleoperator, may seriously review many of the previous points. A new control, a new model, a new training and a new master might be necessary.

In our approach the task is not achieved through a direct control of the robot. Instead, control is indirectly achieved by guiding on-line the execution of a "virtual task". We mean by "virtual task" one which is performed within an intermediate functional representation of the real environment, in our case, by means of a virtual environment (VE). The change of the physical state of this simulated remote environment is monitored on-line and used to generate the necessary control signals to be sent to the slave site(s).

• Excellency application domains of teleoperation are hostile environments. Space, undersea and nuclear are such privileged domains. Distance between slave and master station may cause considerable communication time delay, thus affecting transparency and stability; see [1][25] for an overview of proposed solutions to deal with time delay. It seems to be that the solutions suggested by [20]: *teleprogramming* or [9]: *shared autonomy control* are the most attractive ones. Principle of both proposed solutions is to break the main teleoperation bilateral loop in two hi-bandwidth loops linked by a communication channel. We adopt this solution in our scheme.

• New trends also exist in understanding human dexterity, flexibility and skill using teleoperators (for instance, biomechanical studies). However to design efficient telerobotics systems one must take into consideration human perceptual issues and human data processing capabilities. Where may we start the loop?

— We aim to make telerobotics systems an observation base to future autonomous robots control

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schemes.

— We aim to give telerobotics technology a wider public access. This technology has always been focused on hi-tech areas or hazardous environments. Thus only well qualified people are designated for using such systems. Nowadays this technology becomes more open to other areas. Telesurgery is one good example. However, one may notice that although teleoperation matches in concepts and technology the minimally invasive surgery, many reticences and hesitations still exist for expanding its practical use [13].

2 The Hidden Robot Concept

Rather than directly controlling the remote robot by a traditional master device, we propose a generalized telerobotic system where the operator achieves the task needed within an **intermediate functional representation (IFR)** of the real environment (RE), that is, a virtual or augmented environment (VE). To perform the "virtual task", the operator hand(s) is fitted in a hi-tech input/output device(s) which permits necessary data transfer (direct control and haptic feedback). The operator acts on the VE in a more or less intuitive way using natural hand gestures. A module is then in charge of: (i) the perception/interpretation of the "virtual task" and on-line transformation into robot commands. (ii) interpreting local robot sensors to be translated, when possible, into feedback to the operator.

Using an IFR, the slave robot does not have to be rendered, thus it is **visually hidden** from the operator. The latter is performing the *virtual task* rather than directly controling the slave robot which executes the desired task. The operator/VE interaction loop is thus less constraint by the presence of the slave robot. Through the *virtual task* based indirect control, the robot can be also seen as **functionally hidden**. This concept is what we call the *hidden robot* based teleoperator.

As proposed for large-time delay telerobotics problem, we break the classical teleoperation loop into two main loops linked by a communication channel (i) operator-computer loop and (ii) robot-environment loop. We add in each part of the communication channel what we call a bilateral transform bloc, Fig. 1, which will handle bilateral virtual task - real task transformations. The operator transfers the task specification implicitly; no *a priori* task knowledge is provided, the system relying only on low level data extraction during the execution of the virtual task itself and mapped onto robot control commands. The virtual task has to be seen as hand configurable attractors for the slave robot. Feedback is an interpretation of local robot sensors, and is conveyed indirectly through a *virtual task* based feedback.

Within the Operator/VE loop, the transformations can operate on different levels of abstraction, depending on the slave robot degree of autonomy. The extracted bilateral control signals can describe commands ranging from a low to a high level. These transitions between appropriate control levels are transparent for the human operator. Within the Robot/RE loop, the transformations are more concerned with guaranteeing the correct completion of the desired task and ensuring, when possible, automatic local recovery from VE/RE discrepancies.

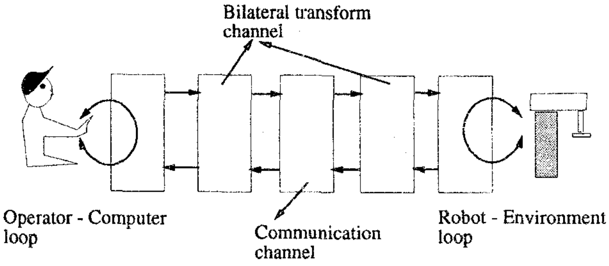

Figure 1: *Enhanced teleoperator network*

This scheme is not a high-level or task knowledge based control, because our purpose is to keep real-time operations when communication bandwith (BW) is high. However, it is also envisageable that this kind of control can be adequate in presence of time-delay.

3 Operator-VE Loop

Operator hand(s) is (are) likely considered to be the input/output control "device", let us say the master. The operator hand is auto-projected [26] in the VE as a virtual hand (VH) which will act on the VE to achieve the "virtual tasks" in a natural manner, as he would do if he was there.

3.1 Justification To Use Hand(s) As Master

Human hand with its complex biological capabilities forms the most versatile manipulation device known. It is the ideal instrument for many manipulative tasks where there is a primary need of dexterity and flexibility [10] [7]. It is therefore intuitive to use our hand as a master device to perform tasks within the VE, see [15] for other considerations. This choice is also confirmed by relevant work in other robotic areas.

In the context of off-line robot teaching, [27] proposed to use direct operator hand input to permit robots learning manipulation skills by observing a human instructor performing assembly tasks. [12] had also proposed a direct operator hand use for automatic robot instruction from perception. They proposed a temporal segmentation of grasping task sequences based on human hand motion. Many other relevant works using direct operator hand input can be found in the related bibliography of [27][12]. Taxonomy of anthropomorphic manufacturing tasks has been proposed as basis in the design of a new generation manufacturing hand [19]. Direct hand mastering has also been proposed in dextrous gripper teleoperation [11][23] and related bibliography.

3.2 Virtual Hand Model

A virtual hand (VH) is a model of the operator hand acting on the IFR. Its motion is controlled on-line by tracking the position/orientation of the operator hand using a Polhemus 3D sensor. The VH is made entirely parametrizable according to real operator hand data in order to gain in realism, see Fig. 2. Each fingertip position and orientation is obtained by traditional transform matrix computation. For the moment only fingertips are candidates for hand - VE interaction. The synthesis of human hand motion and grasping of arbitrary shaped objects is a very complex problem. Rijkpkema and Girard [22] proposed a hi-level control to perform these actions. However this kind of control is knowledge-based and somehow autonomous. In our case grasping is performed according to operator hand position and orientation and fingertip penetration within the grasped object by means of a mathematical model under real-time constraint.

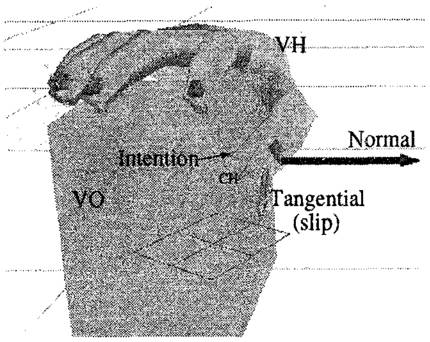

Figure 2: *Virtual hand model*

As a haptic sensory substitution, we associated to each fingertip a visual arrow representing the eventual wrenches issued from a contact with the VE. These arrows are of different colors to differentiate between object surface normal forces, tangential forces and tortional moment as we are using the soft finger model with friction. Length of the arrow is filtered and linearly proportional to respective forces intensity.

The interactions between the VH and the VE, is monitored by collision detection algorithm and position tracking. In our case, considering a few simple geometry, the collision detection algorithm is based on point-volume penetration checking. A more refined algorithm for a widely general objects interaction was demonstrated by [28]. Reaction forces are computed from fingertip penetration by using a simple dynamic model $F_i = K_{obj}.\mathrm{x} + B_{obj}.\dot{\mathrm{x}}$, where x is the distance of fingertip point penetration to the object surface.

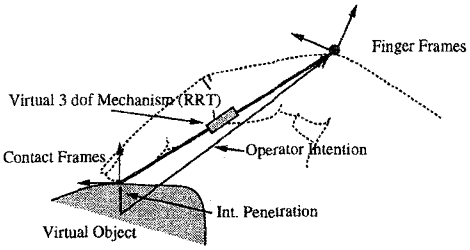

Figure 3: *Virtual finger/object interaction*

To each finger is associated a virtual 3 dof mechanism (VM). When a collision of the fingertip occurs, the reaction is computer on this VM, Fig. 3. This allows a fast direct inverse geometry solution to constraint each finger, as using dynamic or pseudo-inverse Jacobian, lead to more time consuming solution. There are 3 goals we want to achieve this way:

- Gain in visual realism during VH/VE interaction.
- Pre-computation for haptic display.
- Making the VH/VE interaction passive in order to allow low level VH/gripper mapping extraction.

The animated finger joints and reaction forces are computed from the VM joints thus from the operator intention and the equations of constraint.

3.3 Haptic Display

The term "haptic" designates both kinesthetic and tactile informations. Our goal is to allow the operator to achieve tasks in a natural manner. Indeed, we must provide input (control)/output (local feedback) devices which do not constraint operator hand and fingers, and provide haptic feedback while he manipulates the virtual object (VO) or is constraint by the VE. Those kinds of devices have been refered to as bilateral *universal floating-handle controllers* [3].

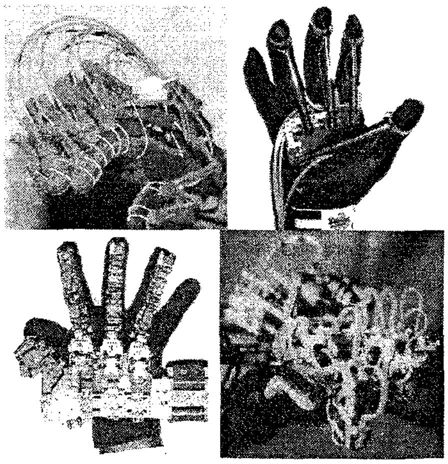

Figure 4: *Glove controllers : the LRP DHM (up left), the CAIP DHM (up right), the JPL DHM (down right), the PERCRO's DHM (down left),*

Dextrous Hand Masters (DHM) are instances of such needed devices. Fig. 4 shows four kinds of force feedback datagloves. The LRP DHM has been developped in our laboratory [5]. In this device forces are displayed by cables and deported DC motors which are used also as finger flexion sensors. It provides force information in 16 hand locations. The CAIP DHM [6] uses pneumatic actuators and applies forces only on fingertips. The PERCRO DHM [4] uses embedded DC motors and cables. It displays forces on 4 fingers including abduction and adduction of fingers and wrist. Weight of the device is compensated by the exosqueleton which provides forces on the whole operator arm. The JPL DHM [11] is also such a device that has been used for teleoperating an anthropomorphic robot hand.

Tactile displays have also been developped but mostly for sensory substitution for disabled and have poorely been considered in teleoperation systems. The difficulty in tactile feedback lies on the tactile information which is of multiple physical nature: thermal, slip, static and dynamic texture, micro-forces, shape.

All must fit in one device which must be portable and robust to handle important force feedback. [17] [7] tactile device, might be an instance of such a system. It has been used in teleoperation experiment and showed benefict of tactile feedback for dextrous manipulations.

3.4 Head Coupled Navigation

When hand is involved in achieving *virtual tasks*, it is difficult to use it again in viewpoint changing for visual feedback. This generates many task breakpoints which may be time wasting and not ergonomic for the operator. The long navigation (VH is coupled to the navigation process) and short viewpoint changing (no VH coupling) are related to operator head behavior or mouvement. Preliminary description of the proposed strategy can be found in [16].

The principle is to tilt the operator head reach space onto basic navigation primitives in such a way to ease the naturalness of use. This strategy has many advantages:

1- it allows to extend the small operator hand workspace into a wider infinite one,

2- it avoids overloading the operator screen by multiple images of static viewpoints,

3- dynamic point of view can be used to know the whole work area and predict tasks that can be done using hidden VO,

4- makes possible the use of two-hand control in cooperative or none cooperative telerobotics,

5- teleoperating (working) and viewpoint changing can be done in parallel (no switching breakpoints).

4 Bilateral Transformations

At the master part, this level is in charge of extracting data from the VE and to transform it into robot commands. It also extracts from the real robot sensors, pertinent information and transform it into operator feedback by combining the synthetic one provided by the VE when possible.

At the slave part, it deals with task supervision for local recovery from VE/RE discrepancies and makes sure that the task is going on correctly. When this fails, it must inform the operator to proceed in another way.

In the following, only the master part is presented. Any virtual or real teleoperation task can be described by 4 states (phases) automata: (i) free motion phase (ii) grasp phase (iii) manipulation phase and (iv) release phase. For each state we must ensure (i) real-time commands to make the slave robot copy the virtual task (thus achieving the real one) and (ii) efficient feedback synthesis under transparency, stability and manoeuvrability constraints.

4.1 Free Motion Phase

The free motion phase is identified by: i) no payloaded VH motion and ii) no VH/VE interaction. While these two conditions are true we consider the system as being in the free motion phase. Thus, we suggest to add control points linked respectively to the operator hand (CH) and to the robot gripper (CR). The transformation matrix for the CH, with respect to the VE frame, is given by:

$$ {}^{\mathrm{CH}}_{\mathrm{VE}}T = {}^{\mathrm{VH}}_{\mathrm{VE}}T\, {}^{\mathrm{CH}}_{\mathrm{VH}}T \qquad (1) $$

where ${}^{\mathrm{VH}}_{\mathrm{VE}}T$ depends on data given by the hand tracker and finger flexion sensors through additional software procedures (i.e. calibration, off-set, ...) and, ${}^{\mathrm{VH}}_{\mathrm{CH}}T$ is set according to the control strategy used.
In a similar way we can write

$$ {}^{\mathrm{CR}}_{\mathrm{VE}}T = {}^{\mathrm{TP}}_{\mathrm{VE}}T\, {}^{\mathrm{CR}}_{\mathrm{TP}}T \qquad (2) $$

where ${}^{\mathrm{TP}}_{\mathrm{VE}}T$, is the transformation matrix of a robot terminal point (TP) according to the same VE reference frame and ${}^{\mathrm{TP}}_{\mathrm{CR}}T$ is also set, according to the mapping strategy adopted.
The robot is then kinematically governed by the simple equation

$$ {}^{\mathrm{CR}}_{\mathrm{VE}}T = \alpha\, {}^{\mathrm{CH}}_{\mathrm{VE}}T + \beta \qquad (3) $$

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

Now the problem is how to choose CH and CR ? The requirements are:

- the robot must follow the operator hand trajectory: position, speed and acceleration (when possible).
- gripper configuration must be such as to avoid collision with the RE while operator VH is not in contact.
- positionning of the gripper must enhance the functional similarities between hand grasping/manipulation and robot grasping/manipulation.

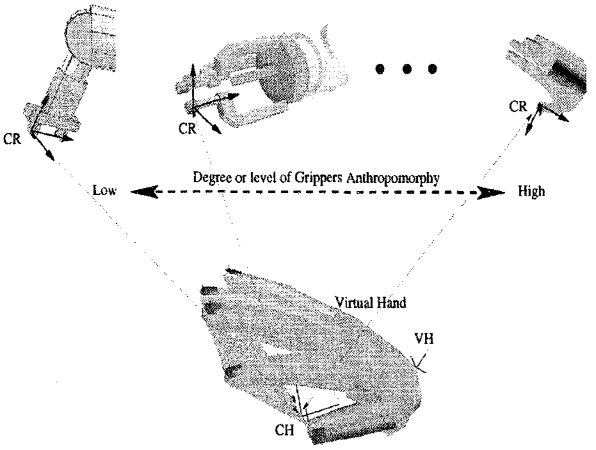

Figure 5: *Free motion phase: a gripper's anthropormorphy-independant cross-coupling*

Previous physiological research on human hand shows that the thumb is of a great contribution in hand grasping and manipulation. Therefore, according to [10] we choose the CH to be linked to the the thumb fingertip frame. In this case, one of the robot gripper "fingertips" is candidate to be the "thumb" which will match the CR.

One must afterwards take care of the remaining gripper fingers positionning, with respect to the VH fingers configuration and contact state with the environment. A strategy could be to maximize the volume intersection so that the gripper is envelopped by the operator hand according to a fixed same frame. A general analytic method for this problem is difficult to establish due to the large variety of grippers. Until now we solved a solution to each kind of gripper we used.

4.2 Grasp Phase

When collision between the VH (fingertips) and the VE occurs while the VH was not payloaded, the grasp phase starts. Up to date, we forbade possible manipulations without grasping. Thus a VO is manipulated only if the grasp is stable. In the free phase the gripper finger configuration is established to avoid collision which may change objects position in the RE and may lead to VO and RO discrepancy.

Grasping phase is in charge of ensuring stability of slave robot grasping when the VO is grasped. Stability of VO grasping is easy to establish. High level realism might not be needed depending on robot autonomy capabilities. We can implement many simple instructions to state/make the virtual grasp stable. If needed, high realism virtual grasping and manipulation is implemented [29]. Tools also exist to perform stable gripper grasping of real objects, for instance based on tactile sensor interpretation. This problem is widely treated in the robotics fields and many results can be readily applied. However, some problems that need to be overcome at this stage are:

- Optimal cross-coupling between the virtual grasp and the robot gripper grasp.
- How to estimate the grasped object position according to the robot TP. In some cases, calibration and image processing techniques might be of a great importance. In some others, tactile sensors interpretation might be necessary.

4.3 Manipulation Phase

Manipulation phase starts when the VO is grasped. The CH and the CR move respectively to the virtual object control point and to its similar point on the real object CO. As in the free phase, those two control points must match.

On the VO, the object state is deduced from VH parameters and external forces dynamics. The resultant external force is computed either from the synthetic ones (performed from VO-VE collision deetction algorithm) or the real ones (estimated from the robot force sensors). The CO is chosen to be the object center of mass to ease calculation, but it can be chosen anywhere else related to the object. If there is no time delay, the real object (RO)/VO state error is mapped on efforts to be applied on the operator hand which will feel the constraint (like a classical position-force scheme), see Fig.6. In the presence of small time delay the error is mapped onto damping to slow the operator VH motion. In large time delay two local loops are just linked by the communication channel (as proposed for traditional teleoperators).

Some hypotheses must be added: (i) we assume that, during the grasp, the CO is known or at least can be estimated by exteroceptive or proprioceptive robot sensors (ii) fine forces and forces applied on the objects can be mesured (iii) object position can be known or at least estimated.

In terms of pure control, each local control loop can be considered as independant. Thus we can establish laws that take benefit of what the robot can perform better than the operator and what the operator can perform better than robots [18] [8].

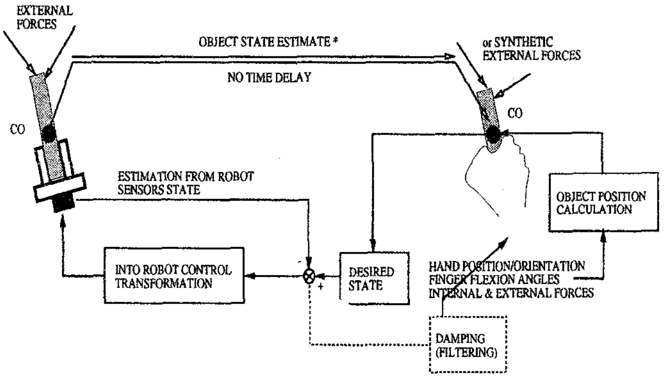

Figure 6: *Object-based simplified bilateral scheme. The black point represents the CO.*

4.4 Release phase

The release phase is the phase when the object being manipulated is released. To implement such a phase the design of release conditions is needed. For instance, an object can not be released if it is not constraint by the environment (stable pose or assembly within the VE and the RE). This can limit geometry discrepancy which may occur when we release an object in any position of the environment space. The difficulty will be to accurately predict the new object position and orientation (under reserve that this information can be given from the RE, for instance by artificial vision).

Release conditions offer the operator the possibility to change hand configuration during the manipulation. When the operator releases the VO and the latter is not in a constraint state (not a stable pose), the VO stands in a fixed position and orientation. As the RO is controlled by the VO, the robot fixes the RO at a constant position and orientation. In this case manipulation or grasping of other VO is forbidden. The operator may need this feature to change hand posture and manipulate the VO after re-grasping it.

5 Robot-Environment Loop

The slave robot is controled by the operator while the CH frame matches the CR frame. We can then achieve position control, velocity control and when adding a mass to the CR point, dynamic control.

The ideal simple case control cited can be achieved only under severe hypotheses (i) the grasp is stable and (ii) no discrepancy between the RE and the VE. While the hypothesis (i) is envisageable, the second one is certainly difficult to assume, especially in hazardous environments. Thus a strategy which does not take into account the above problem will not be considered.

To deal with this problem, a realistic robot sensors simulation is necessary [9]. Range sensors are simulated by distance algorithms, but force and tactile sensors are more complicated. We succeeded in simulating a specific force sensor behavior based on dynamic implementation of object interaction and experimental gains tuning for the virtual force sensor. Work is still undertaken to generalize the method to a more wide kind of force sensors.

As in free motion phase, robot is controled by hand parameters; we provide the operator with the possibility to stop the teleoperation mode by a switch (by feet for instance). In this case manipulation of objects is forbidden and the operator can only navigate through the VE. This can be useful for planning or to control by hand other automatic tasks; for instance, by pushing on a button that sends a signal which will trigger an automatic task in the RE.

When the robot is in off-control mode (out of reachable space, or switched off by operator or cannot reach a desired position ...), a virtual fixture VF is rendered at the CH (for instance a sphere, a cube or another hand in low α-transparency). To trigger on the robot (on-control mode) the operator must match the CH with the VF. This feature is implemented within the 4 phases.

To take advantage of the robot capabitities, *virtual fixtures* [24] may be added in the VE. A virtual fixture can be considered as a static or dynamic functional feature associated with a specific shared control directly linked to the slave robot. It could be placed every where in the VE. For instance, a special cylinder can indicate to the robot to move only on its center when the CR is inside the cylinder volume.

6 Experimentation

The hidden robot concept has been implemented on our VR testbed station. The experimental site is composed of: (i) two Polhemus trackers with their interface, which are used for head and hand position and orientation tracking (ii) Two Hewlett Packard workstations with graphic facilities. The first is dedicated to operator-VE interaction and rendering. The second one, is for real robot simulation and mainly to the two bilateral transform bloc (iii) Two 486 PC, one for the LRP DHM , Polhemus data acquisition and navigation parameters calculation, the second one for robot control. Each PC communicates with its related station by serial 115000 Baud channel while the two workstations communicate via an Ethernet network (see Fig.7). At first we experimented mono robot simple task consisting of assembling a 4 pieces puzzle. Then the experiment was extended to an international multi-robot teleoperation purpose which was held last october 10th [14].

Experiments were conducted without force control on the slave robot and only visual substitution forces on the master site. Despite these conditions (which must be considered as the worst case), the puzzle assembly was successfully performed by the operator many times. An average time completion was about 5 mn without a considerable time delay between the master station and the slave robot. In a single teleoperation mode, puzzle assembly task was also successfully achieved between the Mechanical Engineering Laboratory[1] in Japan and our laboratory in France. In this case, the round trip delay was about one second, using ISDN network and a synchronous protocol.

In some experimental cases, a few problems were encountred. No realistic force behavior implementation in the master makes the slave follow the operator in all his movements. Thus, when posing a puzzle, robot torques were sometimes high and triggered the security system stopping the robot. This problem will be overcome by a realistic dynamic behavior implementation in the master site and force control in the slave site. A preliminary calibration step was also necessary to eliminate the geometry discrepancy between the VE and the RE. The other significant problem was related to the opening capacity of the gripper (4cm) to grip an object of 3cm edge. The remaining margin was then 0.5 cm for each side.

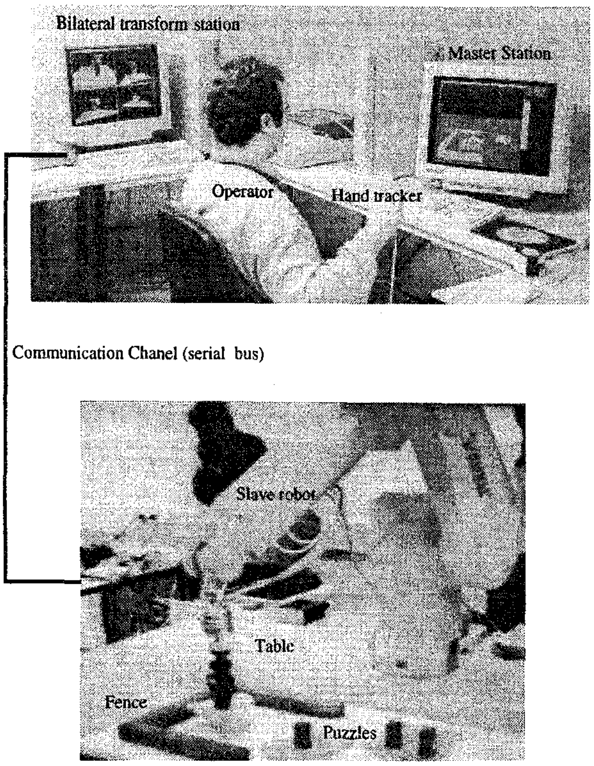

Figure 7: *The telerobotic test-bed system. Teleoperation from direct operator hand actions*

Of course many of the above problems can be solved by shared control or adding local autonomy. Because we did not want to limit our design, our aim was to validate first a low level control before adding progressively higher level functionnalities.

7 Summary and Conclusions

An overview of a new teleoperation scheme, which we called the hidden-robot concept based teleoperation is presented. Concepts and motivations, lacks and new problems to overcome are developped and an approach to potential solutions is discussed. Preliminary experimental results are presented. We can say that these experiments showed the feasibility of the proposed goal.

Many points of interest are under active consideration. Conceptually, we did not proove which is the best between using hand gloves or a universal tool. Other considerations are concernerd with a general analytic method for hand/gripper mapping, enhancing operator-computer interaction by kinesthetic and tactile feedback in the VE and using robot tactile sensing for position estimations and slip detection and finally VE/RE discrepencies recovery procedures.

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