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Virtual and Mixed Reality in Telerobotics: A Survey

Costas S. Tzafestas
National Technical University of Athens, School of Electrical and
Computer Engineering, Division of Signals Control and Robotics,
Zographou Campus 15773, Athens, Greece (Email: ktzaf@softlab.ntua.gr)

1. Introduction

Virtual Reality (VR) constitutes now a well-established term, which is employed basically to describe systems that enable an intuitive and natural interaction in real-time between a human and a computer animated 3D graphical environment. The media that are employed to support such a human-computer interaction should ideally involve all human senses (and more generally sensori-motor abilities), that is, not only vision (through the rendering of 3D graphics models) but also audition, as well as the sense of touch, through a haptic interaction with virtual objects (Burdea & Coiffet, 94). The challenge is to develop computer simulation environments (simulating an existent or fictitious world) in such a way as to create to the human user an illusion of reality. VR thus constitutes a multidisciplinary field covering a variety of scientific and technological subjects, from 3D computer graphics and multimedia technologies, to the design and control of mechatronic human-computer interaction devices, human factors and modeling of sensori-motor human skills, as well as topics related to the field of human perception and psychophysics.

VR and its applications have flourished significantly particularly during the last decade, not only through the development of new software and hardware tools, devices and methodologies of human-computer interaction, but also by the implementation of these techniques into a constantly increasing number of new application paradigms and human-centered activities. Augmented and mixed realities constitute in fact one form of applied VR techniques and refer to the processes of overlapping synthetic (virtual) model images onto real world images, that is, to the combination (mixing) of virtual and real world. In other words, in an augmented reality (AR) system virtual models complement or modify in a way reality (providing in a sense some additional information as needed) instead of completely substituting (replacing) reality, as is the objective in VR systems. The goal here is to provide the user with the illusion of 'co-existence' of virtual and real world at the same time and space domain.

Augmented Reality, as a research and technology field, has attracted considerable interest during the last years with new domains of practical applications arising. Much effort is focused on the new potential opened by the application of AR techniques, and concern enhancing the ability of the human user (human operator) to perceive aspects of a real world by overlaying additional (visual or other type of) information, increasing the abilities

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of interacting within this world. The auxiliary information that can be conveyed through the visual, haptic, or other form of display of virtual models may facilitate the user to perceive in a more direct and intuitive way specific “hidden” or else “fuzzy” characteristics of a real world, which may be needed for the efficient execution of a certain task. Therefore, while in general VR promises to revolutionize the way human-computer interaction systems are conceived, AR techniques seem to lead to the creation of excellent tools making execution of complex and demanding tasks more easy and intuitive for the human.

Virtual, Augmented and Mixed Reality technologies are now recognized as constituting a challenging scientific and technological field that can provide breakthrough solutions to a wide spectrum of application domains, where intuitive and natural human/computer and human/machine interaction is needed. Telerobotics, involving a human operator to control a robot from a remote location usually via a computer interface and a computer network, is one of the fields that can directly benefit from the potential offered by VR and AR human/machine interfacing technologies. Application of VR in Telerobotics (VRT) and the related concept of telepresence, or tele-symbiosis (Vertut & Coiffet, 1984), are ideas which have been around for more than twenty years, and have been used mainly for the telemanipulation/teleoperation of robotic mechanisms in hostile environments (such as in the nuclear industry, space, underwater, or for other difficult or dangerous service/intervention tasks, like bomb disposal, civil works etc.). In fact, all the approaches involving the integration of VR techniques in telerobotics, as will be explained further in this chapter, constitute basically: (a) a generalization of the concept of “predictive displays”, coping with the problem of time delay and stability in teleoperation systems, and (b) an attempt to provide human operator assistance and achieve better transparency characteristics for the teleoperation system.

Nowadays, on the other hand, the rapid development of new broadly expanded networking technologies, such as those related to the Internet, and the numerous relevant applications, described by the general term of e-commerce/e-business, can give new potential to the use of VRT in novel application domains. In fact VRT and Internet technologies can mutually benefit from ideas developed in the respective fields. This merging of technological potential can lead to a generalization of the concept of telework, where remote control through the network of actual physical processes will be possible. One can even think, for instance, of supervising and actively controlling a whole manufacturing process without having to move from his home. A major research objective must be of course to enable and promote new potential applications that can derive from the merging of such technologies, so that wider categories of the population can finally take benefit of these technological advances.

At the rest of this chapter, we focus on analysing the theoretical foundations of this field and on describing the practical application domains that are involved, by presenting some characteristic case studies. Section 2 starts with a description of the basic principles related to virtual and augmented reality systems, and then presents an overview of applications related to the field of robotics. In Section 3 we describe the basic concepts that govern telerobotic systems and present a historical survey of the field. Section 4, then, presents typical application scenarios of these technologies, related to the two main robotic systems categories, namely robot manipulators and mobile robotic vehicles, and highlights the link with the new VR-based field of haptics. Concluding remarks and future research directions are given in Section 5.

2. Virtual and Mixed Reality: General Description

During the last ten to fifteen years, Virtual Reality (VR), as a theoretical and applied research field, has attracted the interest of the international scientific community, as well as of the public opinion through extensive use of the term by the information, communication and entertainment media. However, the latter often results in an "abusive" use of this term, which is probably due to the lack of a formal definition of the field. In the sequel, we attempt to describe the basic principles that govern the field of VR, as well as of the more recent domain of Augmented and Mixed Reality systems, and we give an overview of related applications.

2.1 Definitions and Basic Principles

In an attempt to define what is a VR system, in relation to what can be seen as a simple human-computer or human-machine interaction, we can say that VR refers to: (a) computer generated and animated, *three-dimensional realistic visualization space*, enabling (b) *real-time and multimodal interaction* involving multiple sensori-motor channels of the human user, aiming to achieve (c) a sense of *immersion* and (virtual) *presence* in this synthetic (simulated) environment. The common factor here is, thus, the stimulation of human perceptual experience to produce an impression of something that does not really occur, but which is perceived and believed (potentially invoking, at some extent, human *imagination*) as being physically present and existing as a real world. The three important dimensions characterizing VR systems, and differentiating them from typical computer simulation environments, are: *interaction*, *immersion* and *imagination*, all contributing to create a sense of virtual presence and realism (Burdea & Coiffet, 94).

A Virtual Environment (VE) created via graphics is a communication medium having both physical and abstract components. The three basic constituents of a VE are the *content*, the *geometry* and the *dynamics* (Ellis, 1995). The content consists of objects and actors. The geometry is a description of the environmental field of action, and has dimensionality, metrics (rules establishing an ordering of the contents) and extent (range of possible values for the elements of the position vector). Dynamics is represented by the rules of interaction among the VE contents, describing their performance as they exchange information or energy. The components of a VE are useful for enhancing the interaction of the operators with their simulations. *Virtualisation* is defined to be the process by which an observer (viewer) interprets patterned sensory impressions to represent objects in environment other than that from which the impressions physically originate. Virtualisation can be applied to all senses: vision, audition, contact, shape and position (haptic sense).

The three complementary technologies used to create the illusion of immersion in a VE are:

- Sensors (e.g. head position tracker or hand shape sensors)
- Effectors (e.g. stereoscopic displays or headphones)
- Special purpose hardware and software (connecting the sensors and effectors in such a way as to create experiences encountered by people immersed in a physical environment)

A general diagram showing the structure of a VR-based system and the linkages of its components is shown in Fig. 1. The human operator can interact with a VE presented by means of head and body referenced displays, the success depending on the fidelity with which sensory information is presented to the user. The environment experienced by the user via a VE simulation is of course imaginary. On the contrary, when referring to a teleoperation interface, the human operator is provided with a perception of an environment that is real (e.g. image views of the remote physical-task environment). One can then immediately consider the use of VR environments as intermediate representations "interfacing" the human operator with the remote task environment, with the objective being to assist him in several ways to perform more efficiently the desired physical task. In such teleoperation interfaces, real and simulated data can be combined via digital processing to produce intermediate environments of real and simulated (synthetic) objects. The mixture of real and virtual entities within the same environment refers to augmented and mixed reality interfaces, a new field that has evolved as a special category of VR systems, as described in the following section.

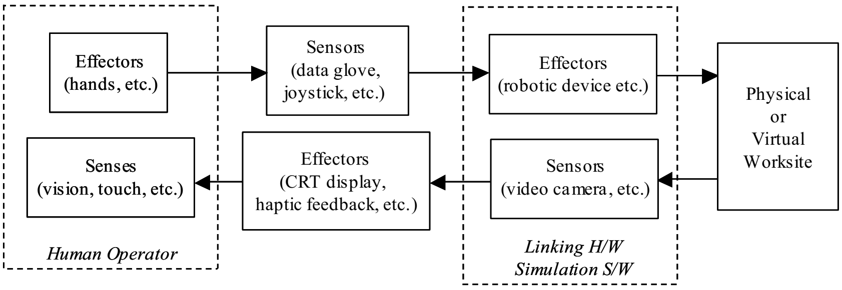

Fig. 1. General structure of VR-based human/machine systems.

2.2 Augmented Reality: Basics

Augmented Reality (AR) systems constitute in fact a category of quite specialized VR technologies, which have attracted significant interest during the last years due to the numerous applications they find in various new domains. While VR has as the main goal to immerse the human operator in a completely synthetic 3D simulation environment, the basic principle of AR systems is to enable the user to experience simultaneously parts of the actual (real) physical world. In other words, AR complements, instead of entirely substituting, the real world, with the ideal situation being to create the illusion that both virtual and real objects "coexist" in a unified (mixed) environment (Azuma, 97).

The question is then: why has this new field of AR systems found such an interest within the scientific community during the last years, and where does the usefulness of such mixed reality environments reside? The answer is that virtual environments can realistically display various data encoding complex information related to the real world, information that is not directly accessible in reality and could not be perceived differently from the human being. One can say that display of this information, which is conveyed by means of virtual objects, in fact "amplifies" the perceptual capacity of the human being, increasing the abilities to perform complex tasks on the real world.

The application domains of AR systems are various and are constantly evolving during the last years. They comprise: (a) *medical applications*, like simulation for education and training in medical (invasive or not) procedures, as well as pre-operative planning and computer-aided (image-guided) operations, (b) *CAD and manufacturing processes*, for instance architectural design of a new building and "previewing" its spatial integration, training in maintenance procedures etc., (c) applications in the *entertainment industry*, e.g. with the production of special effects, virtual actors etc. Military applications are, unfortunately, also not excluded. In the following section, we present a short overview of VR and AR applications in robotics, as introduction to the use of such technologies in the field of telerobotics, which forms the main scope of this chapter.

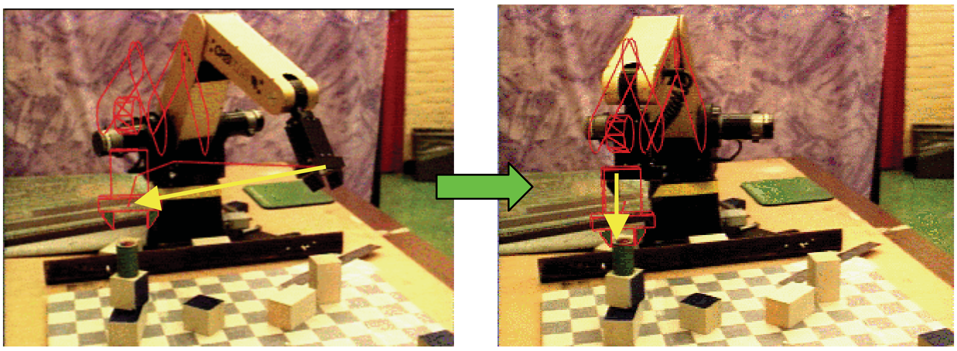
(a) (b)

Fig. 2. Programming of a robot manipulator using augmented reality (AR) techniques. Overlaying virtual model (3D wireframe graphics above) on real robot image (adapted from: Rastogi et al., 96).

2.3 Overview of VR Applications in Robotics

A very important domain where VR and AR technologies find many and interesting applications concerns the field of robotics and robot integrated manufacturing systems. It is now asserted that the use of such technologies can provide significant benefits in all the phases of a manufacturing procedure, from initial design to implementation and control, particularly when these involve the integration of robotic systems. As outlined previously, given that a VE constitutes in fact an *integrated human-machine interaction* system, VR can contribute significantly in all the processes where human intervention (and human factor in general) plays an important role, like for instance:

- The design of *virtual prototypes* and the evaluation / assessment of various characteristics (including aesthetic, ergonomic etc.) and parameters related to functionality, feasibility tests, reliability, consistency of operation etc., which can be performed by means of interactive VR simulation environments.
- The *programming and control* of automated (robotic) procedures, with the goal being to better exploit the skills of the human operator, as well as his capacities to evaluate complex situations and solve decision problems, such as task and path planning involving a robot manipulator.

One very useful related application of AR concerns programming of robot manipulation tasks. The basic idea resides on the use of virtual models representing the robot and its task environment as an intermediate representation to guide and assist the robot action planning process. Overlaying 3D graphical models, representing the robot and the planned motion (action) sequence, on real views of the actual task environment, enables the human operator to perform a “previewing” of the system operation, potentially off-line, facilitating the programming and validation of complex robotic tasks, without the need to constantly work with the real robot in an on-line programming scheme (with all the advantages that such an off-line robot programming presents in practical scenarios). Of course, VR models must be correctly superposed on the real world images, for such systems to be of any practical use. This is called *3D image registration*, which constitutes one of the basic problems that needs to be tackled in any AR system, based on camera calibration techniques, and probably making use of (image- or sensor-based) *3D tracking* methodologies (if such a system is to operate in real-time).

Fig. 2 presents an application example of such an AR-based programming of a robot manipulation task (Rastogi et al., 96). The graphical model (wireframe) shown in this figure constitutes in fact a virtual representation of the real robot, which is overlaid on real robot image views assisting the human operator to better evaluate the anticipated outcome of a programmed action sequence. In this case, the task consists of grasping an object and performing a "pick-and-place" operation. Fig. 2(a) shows the "predicted" path of the robot manipulator, as this is programmed using this AR interface. Fig. 2(b) displays a subsequent view with the robot manipulator having moved according to the planned operation, with both real and virtual robot images being registered (i.e. correctly aligned), demonstrating the accuracy of this robot planning scheme. It must be pointed out here that the additional use of stereoscopic images with 3D graphical models can significantly enhance the efficiency of the human operator in performing such robot programming tasks, by providing visual feedback information in a more intuitive way and increasing the overall performance of the system (reducing time, minimizing false maneuvers etc.).

Based on the above concepts, virtual and augmented reality techniques have evolved substantially during the last decade finding significant and interesting new applications particularly in a special field of robotics called *telerobotics*, which can be mainly characterized by the direct involvement of a human operator in the control loop. The theoretical and practical foundations of this domain form the main scope of this chapter and are thoroughly analysed in the following section.

3. Telerobotics: Historical Evolution

Telemanipulation as a scientific term describes all the methodologies and techniques enabling a human operator to perform from a distance a manipulative task, using his own hand through the use of an intermediate mechatronic system. Telemanipulation control of a remote manipulative task, besides its fascinating character related to the notion of extending human capabilities by some tool beyond usual space or time limits, it can prove extremely beneficial in cases where human intervention is indispensable to perform a task taking place in an unstructured "hostile" environment, due to the increased uncertainty and non-repetitiveness characteristics of such tasks, and the complex task/path planning required for timely and correct execution. Original master-slave telemanipulation systems consisted of a couple of mechanical or electromechanical arms (one called the master, controlled by the human operator, and the other, called the slave, performing the remote manipulation task). Bilateral exchange of energy (position and force signals) was initially ensured through a mechanical linkage and, later-on, through the use of electrical links and servo-control loops. In its infancy, telemanipulation technology found outstanding applications in the nuclear industry for the remote manipulation of radioactive materials in environments where human presence was hazardous. Typical example is the work accomplished by Raymond Goertz at Argonne National Laboratories, USA, or by Jean Vertut and the French group at the CEA (Vertut & Coiffet, 84).

Bilateral servo-controlled telemanipulation and industrial computer-controlled robotics were two technological fields developed originally in parallel and, in some extent, independently. The awareness that both these fields can benefit from development accomplished in each other has led to the fusion of these technologies and the creation of what is generally described under the term of telerobotics. Robotics was initially concerned with the development of industrial manufacturing systems performing programmable, repetitive operations in an autonomous sensor-based manner, while telemanipulation was focusing on a different class of tasks, which should clearly rely on the predominant presence of a human operator in the control loop. Telerobotics, which globally describes the fusion of these general technological fields, is a very challenging and promising research field, which aims at exploiting in a full extent both human operator skills and machine intelligence capabilities within a human/robot interaction and cooperation context.

The integration of some mobility characteristics on a remote manipulation system, has extended the workspace and, generally, the functionality of these systems in terms of space and task limitations, and has led to the creation of new application domains covered under the more broad term of teleoperation. Such application domains include the development of mobile telemanipulator vehicles for space operations (e.g. Mars Rover etc.), with typical examples being the mobile robotic systems developed by NASA, for future Mars exploration missions[1]. Underwater remotely operated vehicles (ROVs) have also been developed, such as those described in (Gracanin & Valavanis, 1999). All these systems belong to the general field of intervention and service robotics, which focuses on the development of integrated mobile robot platforms with embedded manipulation and sensing modules, operating under direct remote control or semi-autonomously under high-level human supervision. Such systems aim mainly at substituting the human being in the execution of hazardous (e.g. handling of explosives), painful (e.g. lifting heavy weights, for instance civil works), or else boring every-day tasks (e.g. vacuum cleaning etc.). In section 4.2, we will present one example of such a mobile service robot. This general field also comprises systems that aim at assisting humans when performing delicate operations, requiring increased precision, which is the case of the research performed in the field of medical robotics, dexterous telemanipulation and telesurgery.

Let's describe now the main problems encountered in general teleoperation systems, as well as some existing solutions, methodological approaches and guidelines proposed in the literature, in order to situate the current state-of-the-art of research carried out in the field of telerobotics. The major problem and certainly the most cited one is the presence of time delays in the bilateral communication loop, which is mainly due to the distance separating the master from the slave site, but may also be due to the processing time required for coding and data transmission. Such delays may be constant (e.g. in the case of direct ISDN link), but may also be varying in an unpredictable manner due to the load of the network servers (which is the case of the Internet), causing additional difficulties in coping with the problem. For instance, time delay for transcontinental teleoperation when a satellite link is used may exceed 1 second, while when teleoperating a rover on the moon, round-trip time delay approaches 3 seconds. The human operator is in such cases obliged to apply a ``move-and-wait'' strategy, that is, to make small moves while waiting for the images (and in general, the sensory feedback) to be updated. As a

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[1] (see for instance: http://robotics.jpl.nasa.gov/groups/rv/ for a brief survey)

consequence, communication time delays cause certain degradation of the teleoperation system's performance; but what is even more critical, their presence may jeopardize safe operation and cause dangerous instabilities especially when force-feedback is involved in a long-distance bilateral telemanipulation system.

Degradation of sensory feedback may also be due not only to the presence of time delays and limited bandwidth, but also to noise and other sort of disturbances in the communication channel. Problems related to the quality of sensory feedback may also derive from the nature of the task itself, for instance when a slave robot operates in low visibility conditions (e.g. video feedback from an underwater remotely operated vehicle, which may, in some cases, be completely useless or extremely difficult to interpret). In all these cases, when sensory feedback is deteriorated, due to time-delays, noise or other source of signal degradation, some task-specific methodology or advanced remote control strategy has to be followed to assist the human operator to perform the task goals, and ensure safe and efficient operation of the system.

Time-delay has long been known in classical control theory as a very challenging problem, and various predictive control schemes have been proposed based on some a-priori knowledge of the delay (for instance, the predictor of Smith, proposed around 1956, see: (Laminat, 1993) for a survey). In the teleoperation field, more recently, some new control schemes have been proposed to cope with this problem, based on passivity theory (Anderson & Spong, 1992), or on the concept of adaptive impedance (Niemeyer & Slotine, 1991). All these approaches converge to the fact that, in any case, stability and transparency (defined in terms of force/trajectory tracking between the master and slave) of the teleoperation system are two contradictory objectives, and some trade-off between these characteristics has to be achieved most of the times. All these approaches in fact slow down the control system coupling the master with the slave, that is, diminish the control bandwidth of the system leading to a more compliant (less stiff) teleoperator. This ensures the stability (passivity) of the system, under some constraints related to the magnitude of the time delay, but has as a counter-effect to deteriorate the transparency of the teleoperation system (for instance, the human operator does not feel the real profile of the force generated at the slave site). The problem becomes even more difficult when time-delay is randomly varying, with no a-priori knowledge available on its order of magnitude.

Another class of techniques trying to cope with the problem of communication time-delay, is based on the use of *predictive displays*. Graphical predictors, supplying visual cues (estimations) on the evolution of the teleoperation task, are the most commonly used. Bejczy et al. (1990), for instance, have proposed the use of a wireframe graphical model of the slave robot, overlaid on the usual video feedback provided to the human operator. This combination of both synthetic and real images (that is the display of a graphical model, directly following the movements of the human operator and showing what the state of the robot will be before the actual delayed video images arrive from the slave site) greatly facilitates the task of the human operator. The paradigm of graphical predictive displays has been greatly adopted since, and extended to cope not only with problems related to the presence of time delays in the bilateral communication loop but also to perform visual feedback enhancement and assist the human operator in quickly assessing a situation and performing teleoperation tasks.

3.1 Teleoperation and Virtual Reality: Synergy

The integration of more advanced virtual reality techniques in teleoperation systems can be partly seen as a generalization of the concept of predictive displays described above, where the term display may now refer not only to the visual display of simple graphical cues, but also to other forms of sensory feedback such as haptic or auditive display. Virtual Reality is in fact a multidisciplinary scientific/technological field, which aims to enable a more natural and intuitive human/computer interaction based on the use of multimodal/multisensory interfaces. This human/machine interface technology involving various perceptuo-motor modalities of the human being (not only vision, but also haptic interaction and auditive feedback) can provide a technological solution of excellence for the human/robot interaction and communication systems constituting the field of telerobotics. Virtual environment simulations of teleoperation systems can indeed be used as predictive models performing the role of a mediator between the human operator and the remote (slave) robotic system. This means, in other words, that the human operator could be provided with realistic three-dimensional graphical images of the remote operation site, while being able to interact with these images and perform the desired teleoperation task in a natural and intuitive way (that is, for instance, by feeling the reaction forces during the execution of this virtual task model), and all that before the actual (delayed or deteriorated) real sensory-feedback signals arrive from the remote slave site. In fact, this interaction between the human operator and the virtual environment (that is, the virtual task performed by the human operator) can be used to generate the appropriate command signals that have to be sent to the slave robotic site, and guide the on-line execution of the real teleoperation task. The use of such an intermediate virtual representation of a teleoperation task is reported in (Kheddar et al., 1997), where a multi-robot long-distance teleoperation experiment is described, as will be presented more in detail in Section 4.1.1.

VR-based models of teleoperation tasks can also be used in off-line *teleprogramming* schemes, in which case the master and slave control loops are completely decoupled. The human operator performs a virtual task in a completely simulated manner, within a 3D graphic environment representing the slave site. This virtual task is analyzed and the appropriate sequence of robot commands is extracted and recorded. The sequence of command signals is then evaluated by the human operator before its subsequent transmission to the slave robotic system, where real task execution will take place. Communication time delay is generally not a problem in this approach. However, this is not applicable for all kind of teleoperation tasks, for instance when fine telemanipulation of a dextrous robotic mechanism is required, since programming such complex tasks in the form of simple sensor-based operations is very difficult. The key issue in teleprogramming schemes is the type of commands that will constitute the robot programs, which must make use in full extent of any autonomy features supported by the slave robotic system, in the form of reactive sensor-based behaviours or elementary task operations. Such approaches are especially applied in super-long-distance teleoperation systems, for instance when guiding the operation of a rover on the surface of a distant planet such as Mars. Of course, the same idea of semi-autonomous teleoperation control can also be applied in an on-line direct teleoperation scheme, where more high-level command primitives can be send in real-time to the remote robot, instead of the traditional, continuous force/position/speed signals. In this general framework, Hirzinger et al. (1993) have proposed the use of a tele-sensor-based scheme for the remote control of a robot manipulator in space. Freund and Rossmann (1999) have proposed a task deduction/action planning approach (called projective virtual reality paradigm) tested on a variety of applications, from simple teleoperated robotic assembly tasks up to the control of multirobot telemanipulation systems for space applications. In

Section 4.1.2, we will present an example of a similar telerobotic system, but with the application being that of a "remote laboratory" for education and training in robotics.

VR technology and its applications in different scientific fields have known a rapid development during the last five to ten years. We can now say with confidence that VR has the potential to become a key technology for the design of modern man-machine interfaces, as is the case of teleoperation systems. It can provide the tools and techniques to establish a multimodal, natural and intuitive human-machine interaction, increasing the feel of *telepresence* for the human operator, which constitutes the ultimate goal of any teleoperation/telerobotic system. Of course, many challenging problems have to be tackled and appropriate (generalized or task-specific) solutions must be proposed, taking into consideration not only ergonomic issues and human factors, but also more technical problems such as image calibration (Kim, 96), coping with discrepancies and modeling uncertainties, as well as control issues and stability of human-machine active interfaces.

The use of VR techniques in telerobotics can be seen as an evolution of general *computer-aided teleoperation* schemes, developed to facilitate the task of the human operator and provide assistance in one of the following ways:

- by performing the functions of an *information provider*, that is, by enhancing the sensory feedback provided to the human operator and helping him to better understand the state of the remote task execution. Typical examples are the graphical predictive displays, described above, or some form of artificial haptic (kinesthetic and/or tactile) feedback. Other VR-based techniques include the use of virtual fixtures (Rosenberg, 1993) or virtual mechanisms (Joly & Andriot, 1995).
- by performing some form of *decision support* function, that is, by providing suggestions or indications concerning the most suitable action plan and assist the human operator at the decision making process.
- by interpreting the actions of the human operator and performing a function of *substitution* or cooperation, to provide *active assistance* for the on-line control of a teleoperation task. This is the case of an active intervention of the master computer, with typical examples being a system undertaking the control of some degrees of freedom (dof), or ensuring that the commands issued by the human operator satisfy some constraints related to safety issues.

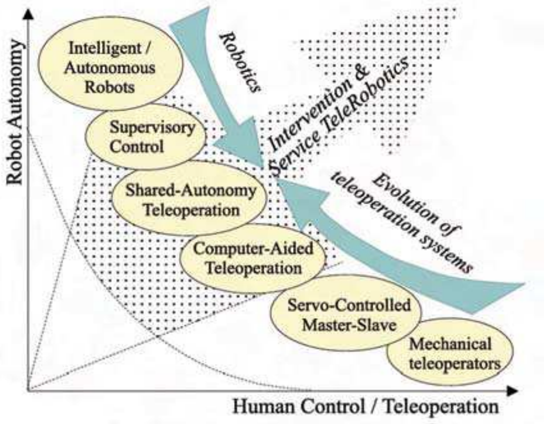

Fig. 3. Evolution of teleoperation systems towards intervention and service telerobotics.

All these features (i.e. providing perception, decision or action assistance to the human operator) concern functions performed by the system within the master control station and are generally described by the term *computer-aided teleoperation*. Similarly, some form of computational intelligence can be embedded to the slave control system, which is for instance the case of a slave robot supporting some kind of autonomous sensor-based behaviors. In this case, we refer to a *shared-control* (or *shared-autonomy* control) mode of operation, with the slave robot executing a set of elementary (or more complex) operations in a completely autonomous mode. The commands issued by the master control station (that is, by the human operator) are described in a higher level of abstraction and include some form of implicit task representations. In an even higher level one could then think of a telerobotic system where the human operator is in charge of simply supervising the remote task execution, with active intervention only in extreme error recovery situations. All these paradigms are generally grouped under the term *supervisory teleoperation*, described in (Sheridan, 1992). A schematic representation of the evolution of these teleoperation paradigms is illustrated in Fig. 3. The interaction and merging of machine intelligence features with the human operator capacities and skills is the key issue that will lead to the creation of more advanced telerobotic systems, capable to perform more complex task such as those required in the field of intervention and service robotics. It is certainly one of the most challenging tasks for the designers of modern teleoperation systems, to find the "optimum line" between robot autonomy and human operator control, in order to exploit in a full extent the potential of such human/machine interaction and cooperation systems.

3.2 Web-Based Telerobots

Until quite recently, that is before the last five to ten years, telerobotic systems were remotely operated through dedicated fast network connections, and their use was exclusively reserved to trained specialists. The integration of teleoperation technology with new rapidly evolving media/network technologies, especially the Internet and the World Wide Web technologies, promises to open the door to a much wider audience, by creating and wide spreading new application domains. Controlling a real distant device over the Internet and performing a physical process in a remote location (as opposed to simple information processing) will extend the scope of telework applications, most probably having a significant impact in many aspects of both social and economic life. This section presents a brief survey of such web-based telerobotic systems. Situating the current state-of-the-art for this promising and challenging research area, is of particularly interest within the scope of the survey presented in this chapter.

By web robots we mean robotic devices that are accessible from any computer connected on the Internet. Remote control of these systems via the Internet is possible by any site using a standard web browser incorporating the human operator control interface. Even though there exist by now many robots available for teleoperation on the web, the development of such systems is still more or less in its infancy and consists mainly of "playing" with a distant robot over the Internet, issuing simple motion commands to perform elementary tasks. A typical example is the Australia's telerobot, developed at the University of Western Australia[2]. It

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[2] http://telerobot.mech.uwa.edu.au/

consists of a six-axis robot manipulator, remotely controlled with one fixed observing camera. The initial system, originally demonstrated in 1994, required users to type in spatial coordinates to specify relative arm movements. Since then, various user interfaces have been developed and tested (Taylor & Dalton, 2000), which more recently embed Java technology to enable the human operator either to choose from a prespecified set of target positions or to click on the image and issue robot motion commands relative to the position of a cursor. The problem of course still remains to associate the position of the cursor that is being dragged on a 2D image, with the position of the robot end-effector and the other objects in the 3D world. An other very good example of a robotic manipulator being controlled over the Web is the PumaPaint system (Stein, 2000), which was on-line from June 1998 until March 2000. It consisted of a Puma 760 robot controlled over the Internet using a Java compatible web browser. The task performed by the robot was painting on an easel, reproducing in real the paintings created by the user on a virtual canvas, which was incorporated in the user interface running a Java applet. The interface forwards all commands to the robot so that almost the same image appears on the real canvas. The system also provides visual feedback in the form of periodically updated live images from the robot.

Besides these systems consisting of robot manipulators controlled through the Internet, there is another class of web robots involving teleoperation of mobile platforms over the www. Most of these systems provide exclusive remote control to a single person or provide queues to schedule user requests. One of the first mobile robots to operate in a populated office building, controlled through the web, was Xavier (Simmons, et al., 2000). This system was created by the end of 1995 to test the performance of various navigation algorithms, but has soon become very popular with more than 40,000 requests and 240 Kilometers travelled to date! The command interface of the robot provides a discrete list of destinations to send the robot and a list of simple tasks to perform there. When a user submits a task request, this task is scheduled for execution and a confirmation web page is sent back indicating when the robot will most likely carry out this task. If the user had registered using a correct e-mail address, the system will send an e-mail after completion of the requested task. In addition to the command interface page, there is a monitoring web page that includes the robot's current status, a map of the floor the robot is currently on and a picture of what it currently sees.

A very interesting application of such web-based systems involves remote control of mobile platforms moving in a museum. These are called tour-guide robots (Thrun et al., 1999), like the Rhino robot deployed in the Deutches Museum in Bonn, or its successor, Minerva (Schulz et al., 2000), installed successfully in the Smithsonian's National Museum of American History. These robots are operated either under exclusive control by remote users on the web (virtual visitors), or under shared control by both real (on-site) and remote (virtual) visitors of the museum. Under exclusive web control, the user interface is implemented as one Java applet incorporating a map of the exhibition area and two live images, one from the robot and the other from a ceiling-mounted camera. Minerva's shared control interface was on-line for 91 hours and was accessed by 2885 people. The robot travelled 38.5 Km under shared web and on-site control, providing information about 2390 exhibits.

There exist many other Web robots on the net, performing a variety of tasks such as those described in (Goldberg, 2000). The NASA Space Telerobotics program website[3] currently

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[3] http://ranier.oact.hq.nasa.gov/telerobotics_page/realrobots.html

lists over 20 Real Robots on the Web. Reviewing all those web-based teleoperation systems, it is clear that the main problem is of course the unpredictable and variable time delay for communication over the Internet, which calls for the use of some form of supervisory control or off-line teleprogramming scheme to ensure stability. Most of the systems currently available on the web incorporate user interfaces, which implement basic functionalities, such as enabling the user to choose from a prespecified set of tasks (e.g. target locations). These interfaces use some combination of HTML forms or Java consoles to enter data and issue simple commands for immediate or future execution. Sensory feedback is usually limited to the display of images that are captured at the remote site, and the presentation of some status information in text form. It is obvious that this separation between the actions of the human operator (user) and the response of system fed back by the remote robot deteriorates the transparency and telepresence characteristics of the teleoperation system. More advanced "interactive telepresence" techniques need to be investigated, like for instance the integration of VR models and tools within the master control interface (including predictive displays and automatic active-assistance operations) to enable a more natural, intuitive and direct, real-time interaction between the user and the web-based teleoperation system.

4. VR in Telerobotics: Application Scenarios

As already stated, VR can be used in various ways to enhance robot teleoperation systems. Since it can be seen as constituting, in fact, a pool of advanced multimodal human/machine interaction technologies, VR can be employed at a "mediator" level between the human-operator and the remotely controlled robotic system. The performance of any telerobotic system can be measured in terms of two, often contradictory, indicators:

(a) *Transparency*, that is, the fidelity with which the human operator can perceive the remote robot environment, and the easiness by which he can perform the remote task via the telerobot, and

(b) *Stability*, particularly in the presence of large time delays in the bilateral communication and control loop that can jeopardize smoothness of operation, especially when force-reflecting bilateral telemanipulation is involved.

The goal of using VR interfaces as mediators in human-robot interactive communication systems would thus be twofold:

- to increase naturalness and intuitiveness of human operation, by: (i) enhancing information visualization via virtual and augmented reality displays, (ii) exploiting the use of multimodal sensori-motor interfaces taking into account human factors, and (iii) providing active assistance to the human operator; the goal of all these being, therefore, to improve transparency of the telerobotic system, facilitating the task from the human operator perspective.
- to cope with the presence of large time delays, (i) through the use of predictive displays by means of virtual and augmented reality models, and (ii) by applying some form of off-line teleprogramming scheme based on a virtual representation of the remote task environment; the goal being, here, to improve stability of operation and robustness for the telerobotic system.

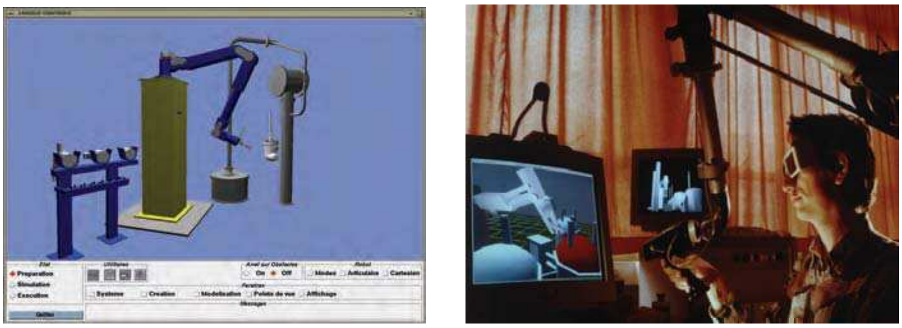

Fig. 4. TAO 2000 VR based teleorobotic interface (CEA, France).

In the rest of this section, we present some typical examples of VR-based teleoperation systems, for the two main classes of robotic systems, namely: (a) robot manipulators, and (b) mobile robotic platforms.

4.1 Robot Telemanipulators

Many experiments have been conducted, since over a decade now, in the context of robot telemanipulation, with main application fields being the nuclear industry (handling of radioactive material), and space telerobots (long-distance telemanipulation). The French Nuclear Centre (CEA – Commissariat à l'Energie Atomique) is very active in the field, since the very beginning of the teleoperation history. One of the most recent advances is the TAO 2000 system, a VR based graphical programming interface, for nuclear servicing using a master-slave robot telemanipulator system. The whole system is illustrated in Fig. 4, with the graphical tele-programming interface (left) and the master force-feedback manipulator arm (MA-23, on the right). G. Hirzinger and his team (1993) at DLR[4] have developed a multisensory telerobot and conducted the first actual space experiments on a space telerobot technology (ROTEX). The system has flown in a space-shuttle mission and worked successfully in various modes, including autonomous operation, teleoperation by astronauts, as well as telerobotic ground control using either on-line direct teleoperation or, what was termed, a telesensor programming mode.

Since then, numerous telemanipulation systems have been developed, applying various methodologies adapted from the field of virtual and augmented reality, with many different applications (from telesurgery to nano-scale telemanipulation). In the sequel, we present two typical examples of VR-based robot telemanipulation systems based on the application of VR concepts and technologies: (a) a long distance, parallel teleoperation of multirobot systems, and (b) a distance training (remote / virtual laboratory) system, for teaching robot manipulator programming using a multimodal VR-based web-enabled interface.

4.1.1 Long-Distance Multirobot Telemanipulation

On October 10th 1996, a teleoperation experiment was performed involving four robot manipulators of different kinematics and situated in different locations (respectively Poitiers, Grenoble and Nantes in France, and Tsukuba in Japan). The robots were teleoperated simultaneously (in parallel) by the master control station situated in Poitiers.

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[4] German Aerospace Research Establishment, Wessling

This experiment was the first general one of a research cooperation programme named TWE (Telepresence World Experiment) linking seven research teams belonging to five countries (among them, the Laboratoire de Robotique de Paris in France, and the Mechanical Engineering Laboratory in Tsukuba, Japan).

The main challenge of this "*telework experiment*" was to demonstrate the possibility offered by VR technologies to ameliorate the human operator master control interface and enhance the capabilities of such robot teleoperation systems. With four different robots controlled in parallel to perform the same task, a common intermediate representation is imperative, to let the human operator focus on the task to be performed and 'mask' any robot manipulator kinematic dissimilarities and constraints. Fig. 5 shows an overview of the experimental setup, with the master control interfaces, and two robots in parallel operation (one in France and one in Japan). As can be seen in this figure, the task consisted of assembling a four-piece puzzle within a fence on a table. The operator performs the virtual puzzle assembly using his own hand and skill on the master control virtual environment, constituting an intermediate representation of the real remote assembly task. The visual and haptic feedback is local and concerns only the graphic representation of the remote task features without any remote robot. The operator / VE interaction parameters are sent to another workstation in order to derive robot actions (graphically represented for software validation and results visualization) and does not involve any direct operator action/perception. A video feedback was kept for safety and error recovery purposes.

The ultimate goal of such research efforts is to study the role that VR concepts and techniques can play towards the development of "efficient" interaction and communication interfaces between humans and robots. In the direction of ameliorating the transparency of the telerobot system, which constitutes a major target as has been already stated, such a human-robot interface must enable the human operator:

- to remotely perform the desired task in a natural and intuitive way, as if he was physically present at the remote (slave robot) site, without feeling obstructed or constrained by the telerobotic system, an objective that is often described by the term "*telepresence*",
- to use his manual dexterity in remotely conducting the desired manipulation task, meaning that the system must support *natural skill transfer* between the human operator and the remotely controlled (slave) robot.

To approach these key objectives, it is particularly important for the master teleoperation environment to display information to the human operator not in a static way but through a multimodal / multisensory dynamic interaction environment. VR concepts and tools play a significant role in this direction. Particularly, interacting via the (active) sense of touch is of primary important. This is termed "haptic interaction", or *haptics*, which is now a very active research field worldwide, with numerous applications, as we will see later on in this chapter.

These haptic systems are often based on the development of special purpose glove-like devices, often termed "data-gloves", or "force-feedback gloves" if application of forces on the human-operator's hand is possible. One such example is illustrated in Fig. 6, where the human-operator wearing a specially designed exoskeleton device on his hand (the LRP dexterous hand master, see for instance (Tzafestas et al., 1997)) can interact, in a direct and intuitive way, with a virtual environment representing the task to be performed. The virtual manipulation actions performed within this VR simulation environment on the master control site are transformed into an appropriate sequence of commands for a robot manipulator to execute, and are then transmitted to the slave robot site(s).

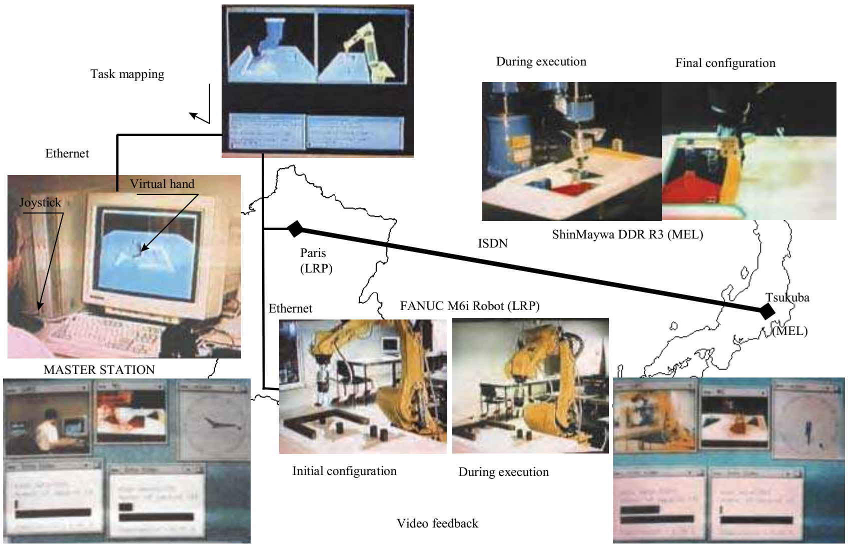

Fig. 5. Multi-robot long-distance teleoperation experiment (adapted from (Kheddar et al., 97)).

This general concept according to which, in an ideal telerobotic system, the human operator must feel as if he directly performs the task, instead of controlling the robot to perform the task, was called the *"hidden robot" concept*, and was also applied in the context of the multi-robot teleoperation experiment depicted above in Fig. 5.

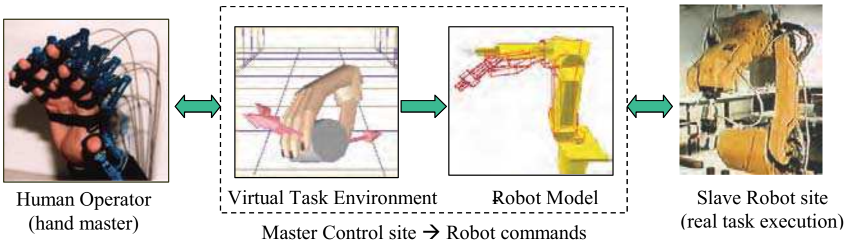

Fig. 6. Robot teleoperation by means of a virtual tele-work environment (adapted from (Kheddar et al., 97)).

The idea here is to let the human operator concentrate his awareness only on the task at hand and not on both the robot control and the task. The human operator is, thus, not concerned with the constraints imposed by the robot mechanisms (e.g. kinematical dissimilarities, etc.). Such issues are resolved by the system and are transparent to the user, giving him the opportunity to better concentrate on the task to accomplish. Of course, the system must possess adequate "intelligence" to interpret correctly the human manipulative actions performed within the master virtual environment. It must analyse these actions, extract the critical task parameters and deduce (in real-time, in case of direct teleoperation, or off-line, in case of teleprogramming) the commands that need to be sent to the slave robot for execution.

We can thus conclude that the application of VR-based concepts and tools in the control of robotic telemanipulation systems, aims principally the development of a human-robot interactive communication framework that allows to exploit in a better extent: (a) from one hand, the dexterity and skills of the human operator to conduct dexterous manipulation tasks and solve complex decision problems, and (b) on the other hand, the capacities of robot manipulators to execute, with superior speed and accuracy, a combination of sensor-based primitive tasks.

4.1.2 Distance Training in Robot Manipulator Programming

Substantial application scenarios of VR technologies can be found in the field of education. If these technologies are combined with teleoperation concepts and tools they can lead to the development of very efficient *remote and virtual laboratory* platforms, aiming to enable distance training in a number of engineering disciplines. One such application is described in (Tzafestas et al., 2006), presenting a platform that aims to enable student training in robot manipulation and control technologies from any remote location via Internet. Access to robot manipulator arms and other similar mechatronic devices and laboratory equipment is often either limited by specific time restrictions or even not provided at all. One prohibitive factor is the high cost of such equipment, which makes it very difficult for many academic institutes to provide related laboratory training courses in their educational curricula for engineers. Therefore, the benefits from providing a means for any-time/any-place (virtual and/or remote) experimentation, in a "lab facilities sharing" context, are evident from a socio-economic point of view, apart from a pedagogical point of view related to the completeness and quality of practical training possibilities offered to their students.

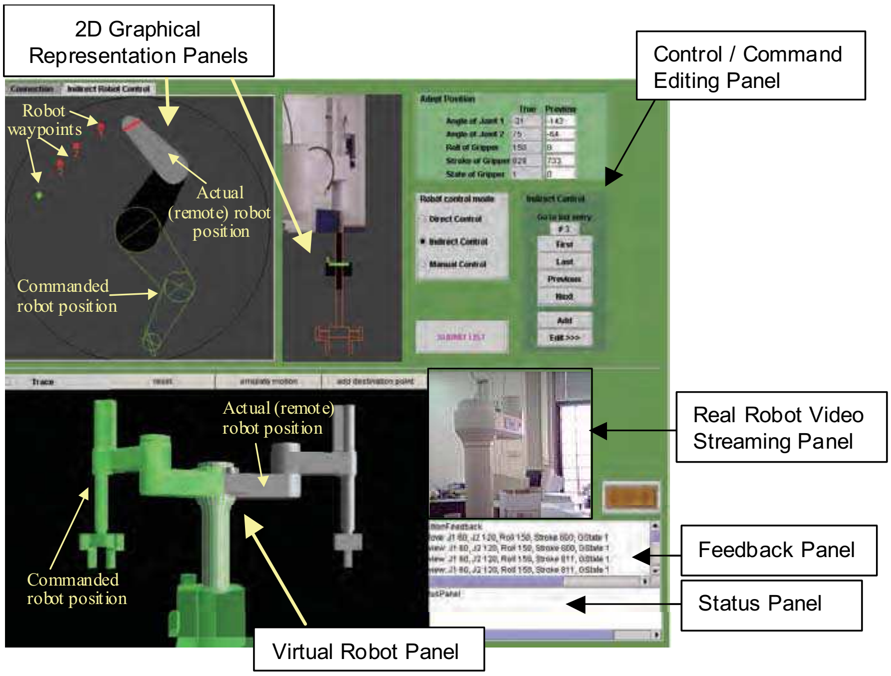

Fig. 7. The graphical user interface of the virtual robotic laboratory platform.