VR-based Teleoperation of a Mobile Robotic Assistant: Progress Report

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Abstract

This report presents work in progress within the framework of a research project aiming at the development of a mobile robotic system to perform assistive tasks in a hospital environment. This robotic assistant will consist of a mobile robot platform equipped with a variety of on-board sensing and processing equipment as well as a small manipulator for performing simple fetch-and-carry operations. In this report, we focus on the design of the teleoperation system integrating virtual reality techniques and Web-based capabilities in the human operator interface. Relative work found in the literature in the field of intervention and service telerobotics is reviewed, and an overview of the methodologies that will be followed is presented. Some specific issues requiring particular attention for the design of a teleoperation system for the mobile robotic assistant are investigated and include: (a) the specification of the teleoperation modes supported by the system, integrating various automatic computer assistance and shared-autonomy behaviour-based control modes, (b) the design of the user interface, built on Java technology to enable web-operation and support various multimodal VR-based functionalities, and (c) the integration with the other subsystems and control modules of the mobile robotic assistant, in the framework of a general teleoperation/telemanipulation control architecture.

Keywords: Telerobotics, virtual reality, human/machine interfaces, mobile service robots.

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1 Introduction

Virtual Reality (VR) and its applications in the general field of Telerobotics (VR and Telerobotics - VRT) are research areas that have known a great development during the last decade. Virtual Reality [5] constitutes a multidisciplinary scientific/technological field, which comprises research and development on areas such as computer graphics and animation, physical modeling, mechatronic design and control, as well as human sensori-motor modeling, perception and psychophysics. VR technology, in fact, aims at enabling a more natural and intuitive human/computer interaction, based on the use of multimodal/multi-sensory interfaces. This human/machine interface technology implicating various perceptuo-motor modalities of the human being (not only vision but also direct hand action and manipulation, haptic perception as well as auditive feedback) is recognized as the most promising solution for a number of problems related to telerobot control. All these approaches involving the integration of VR techniques in telerobotics constitute in fact: (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.

Application of VR techniques in Telerobotics and the related concept of telepresence (or telesymbiosis [44]) 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.). 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.

This report presents work in progress, which focuses on the application of these technologies for the teleoperation control of a mobile robot. The work is part of a research project which aims at developing a mobile robotic system for performing assistive tasks in a hospital environment. This robotic assistant will consist of a mobile platform equipped with a variety of on-board sensing and processing equipment as well as a small manipulator for performing simple fetch-and-carry operations. In this report we focus on the design of the teleoperation system integrating virtual reality techniques and Web-based capabilities in the human operator interface. This report begins with a literature survey presenting the state-of-the-art in the general field of telerobotics. Section 2 briefly traces the history of teleoperation systems, the integration of VR technology and the development of a new field called intervention and service robotics. Section 3 presents the general architecture of the mobile robotic assistant that is under development. It briefly describes the main system components and control modules and illustrates some basic interoperability issues. The rest of the report focuses on the design of the teleoperation system for the mobile robotic assistant. Issues related to the modes of teleoperation, as well as to the design and implementation of the human operator interface, are discussed. An initial version of the developed user interface for remote monitoring and control of the mobile robotic assistant, is presented in section 4.1. This human/machine interface is implemented using Java/Java3D, and is designed to support various modes of operation, integrating VR techniques and enabling web-based operation. Section 4.2 discusses some future work directions and research objectives. The hardware configuration of the mobile robotic assistant is then desribed in section 5. The mobile robotic platform will be equipped with a vision system, a ring of ultrasonic sensors for local navigation, a wireless Ethernet link for communication and a small integrated manipulator to enable the execution of simple fetch-and-carry tasks. Some concluding remarks for the work exposed in this report, are finally presented in section 6.

2 Literature Survey

In this section we present a brief survey and a current state-of-the-art of research and development carried out in the general field of telerobotics.

2.1 Teleoperation and Virtual Reality

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 [44].

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 (see for instance http://robotics.jpl.nasa.gov/groups/rv/ for a brief survey). Underwater remotely operated vehicles (ROVs) have also been developed, such as those described in [14].

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 the next section we present some typical examples of such mobile service robots. 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. Unfortunately, military applications are also not excluded and have known a great development in the last decade.

Let's describe now the main problems encountered in general teleoperation systems and some existing solutions as well as some 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 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 intepret). 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 [25] 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 [1], or on the concept of adaptive impedance [30]. 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 have 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. [3], 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.

The integration of more advanced virtual reality techniques in teleoperation systems can be partly seen as a generalization of this concept of predictive displays, 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, wich aims at enabling a more natural and intuitive human/computer interaction based on the use of multimodal 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 [20, 22], where a multi-robot long-distance teleoperation experiment is described. The goal of this scheme is to assist the human operator to perform on-line control of a teleoperation task, concentrating on the task itself and not on the operation of the (multiple) robots performing it. The use of direct hand actions within a virtual environment is a way to enable such a natural/intuitive task execution, but creates new challenging problems for performing efficient dexterous virtual manipulation and generating realistic whole-hand kinesthetic feedback [42]. Research must also be performed in the field of human factors, in order to evaluate the performance of such systems in terms of human perceptual capacities, and find optimum compromises (complexity vs. efficiency) for the design of VR haptic interfaces [41].

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. [17] have proposed the use of a tele-sensor-based scheme for the remote control of a robot manipulator in space. Freund and Rossmann [12] 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.

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 it 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. Off-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 [23], 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 (as described in [44]-vol.B):

- 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 in the previous section, or some form of artificial haptic (kinesthetic and/or tactile) feedback [40]. Other VR-based techniques include the use of virtual fixtures ([31]) or virtual mechanisms([18]).
- 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.

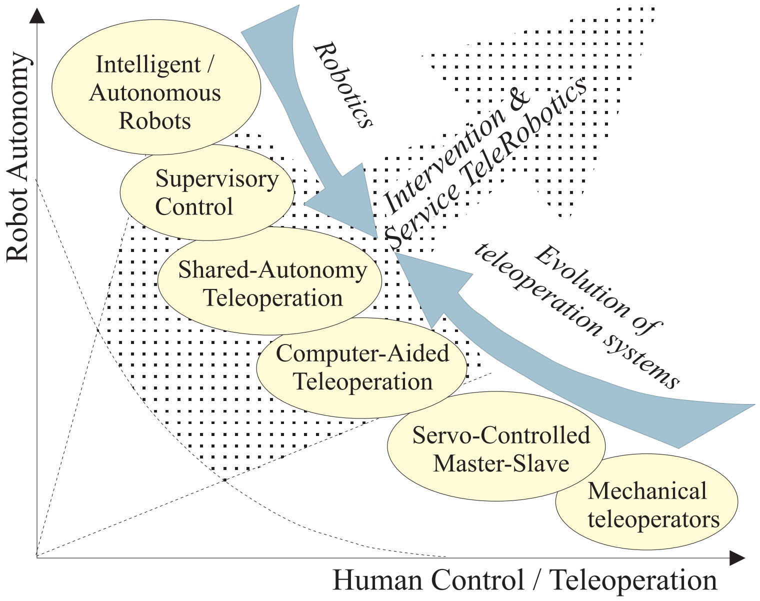


Figure 1: *Evolution of teleoperation systems towards intervention and service telerobotics*

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 [33]. A schematic representation of the evolution of these teleoperation paradigms is illustrated in figure 1. 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 system, 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 task 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.

The work presented in this report focuses on the integration of such methodologies in the case of a mobile robot manipulation system. Most computer-aided and shared-control schemes have concentrated on problems related to the teleoperation of a robot manipulator. Extending and adapting such techniques in a more general system, combining on-line teleoperation of a mobile robot platform and integrating a telemanipulator, constitutes the main subject of this report. This is the case of a general-purpose robotic assistant, such as the system described in section 5 that is under development and will be used as the experimental testbed for future evaluation of the developed teleoperation architecture.

2.2 Mobile Service Robots

In this section we present a brief survey of systems belonging in the field of intervention and service robotics. These systems consist in general of mobile robot platforms integrating manipulation and sensing capabilities, designed for either indoor or outdoor operation. Their goal is to provide some form of assistance to the human by performing a set of physical tasks, which cannot be performed otherwise or which are too dangerous, painful or simply boring for humans. These tasks can be accomplished in an autonomous or teleoperated mode, as described in the previous section.

A very important application domain worldwide of service robots concerns the development of integrated mobile manipulation systems to perform general health-care tasks, such as providing some form of assistance to the disabled or the elderly. The mobile robotic assistant developed in the framework of the MOVAID project constitutes a typical example [6]. The MOVAID system comprises of a number of fixed workstations (PCs), located where main activities are carried out at home, such as the kitchen and the bedroom, and a mobile robotic unit able to navigate in the house avoiding unexpected obstacles. The mobile platform is equipped with a robot manipulator in order to grasp and manipulate common objects, and is able to dock to the fixed workstations for data exchange and power supply. Commands to the robot are given in a high level language through a graphical interface running on the fixed workstation, where continuous visual feed-back from on-board cameras is also supplied to the user, allowing him/her to monitor what the robot is doing. Other research efforts in the field include: (i) the mobile manipulator system called ROMAN, developed at the Institute of Automatic Control Engineering (LSR) of the Technical University of Munich [9], which integrates various advanced task planning, locomotion and human-robot communication features to perform routine manipulative (fetch-and-carry) tasks in a domestic environment, and (ii) a system developed by Fiorini et al. at JPL [11], consisting of a commercial mobile platform built by RWI Inc. and equipped with a manipulator arm designed at JPL. An audio/visual human/robot interface was developed and implemented on a PC, which was connected to the mobile robot via an ethernet link. The interface included real-time video from a camera installed on the mobile robot, voice input and output, recognition of simple spoken commands, and a joystick to control the mobile robot. A task-specific mobile robotic platform has been also developed and commercialized by Helpmate Robotics Inc. [7], now purchased by Pyxis Corporation. HelpMate is a completely autonomous robotic courier system designed to perform material transport tasks (such as pharmaceuticals, lab specimens, equipment and supplies, meals, medical records and radiology films) in a hospital environment. Current research in the field of health-care and rehabilitation robotics also includes efforts concentrating on the development of robotic wheelchairs, such as the systems described in [19] and [26], incorporating various autonomous navigation and human interface features (see also [43] for a brief survey).

Mobile robot platforms have also been developed to perform service tasks in other human populated environment like offices or even factories. Examples of such systems are: (i) MOPS [37], a robotic system for mail distribution in office buildings, (ii) RoboDis [36], a dispatching system integrating a team of distributed mobile robot platforms executing transport jobs, and handling requests over the Internet, (iii) KAMRO [28], an autonomous mobile robot equipped with two PUMA-type manipulators and designed to perform assembly tasks in an industrial manufacturing setting. More general-purpose robotic mobile manipulators have also been built, like: (i) ROMEO [10], developed at the Institute of Autonomous Intelligent Systems (AiS) of the German National Research Center for Information Technology (GMD), designed to perform a range of service tasks involving for instance loading, transporting and unloading goods, (ii) HERMES [4], a humanoid experimental robot designed for mobile manipulation and exploration tasks, or (iii) the Stanford mobile robotic platforms, two holonomic mobile platforms designed and built at Stanford University in collaboration with Oak Ridge Laboratories and Nomadic Technologies, and used to study the development of various robotic “assistance” capabilities involving vehicle/arm coordination as well as cooperative manipulation between multiple platforms.

All these mobile robotic manipulators have as a goal to operate mainly indoors, in a more or less autonomous way. Mobile robot platforms designed to support operations in an outdoor environment have also been developed and are generally described by the term *field robots*. Typical application areas include bomb disposal [15], fire fighting or nuclear waste handling, and generally intervention and service tasks in hazardous and extreme environments (see for instance the systems developed by the German Company Telerob- http://www.telerob.com, or the TSR202 and Centaure robots built by Cybernetix in collaboration with the French Atomic Energy Committee (CEA)- http://www.cybernetix.fr/en/robotique_gb.htm). In such extreme working conditions, demanding complex transportation/manipulation tasks in a highly unstructured and changing environment, fully autonomous operation is still not possible. The need of a human operator constantly present in the control loop seems indispensable for reliable and timely execution of such service tasks [16]. Moreover, different forms of locomotion are potentially needed (other than mobility based on wheels), such as legged locomotion on uneven terain (like, for instance, Dante [2] developed at the Robotics Institute of Carnegie Mellon University, or the Sherpa hexapod robot developed by the CEA - http://www-dta.cea.fr/CEREM/UK/Pages/robotexemple5.htm), underwater operation (see [14] for a review in the area) or even unmanned remotely piloted airplanes (RPVs) and teleoperated helicopters (designed mainly for military applications involving surveillance operations over the battlefield). Studying the control problems related to this last class of robotic systems is beyond the scope of this report.

Reviewing all the research efforts and experimental systems cited above, one can conclude that a lot of research still needs to be done before service robots could reliably perform everyday tasks that seem obvious for the humans, such as navigating in a crowded, unstructured and uncertain environment, and performing even simple manipulation tasks. Advanced solutions seem to come from the merging of methodologies derived from the field of robot teleoperation (based, for instance, on VR techniques for the design of intuitive multimodal human/machine interface) and artificial intelligence, aiming from one hand, to interpret, learn and transfer onto the machine human actions and skills, but also to endow the mobile robotic assistant with some human-like autonomy characteristics based on sensor fusion and behavior-based task planning and reasoning. The work presented in this paper focuses on the first of those targets, that is the design of a human-robot interface enabling a more efficient on-line cooperation between the human operator and the slave robotic system by integrating various computer-aided, shared-control and semi-autonomous modes of operation.

2.3 Internet-Based Teleoperation: Robots on the Web

Until quite recently, that is before the last five to six 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 widespreading 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 for the work presented in this report, since one of our main final objectives for the mobile robotic assistant, which is under development, is to enable teleoperation control through the Internet.

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 (http://telerobot.mech.uwa.edu.au/). It 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 developed and tested [38], which are 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 through the Web is the PumaPaint system [35], 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 robotic 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. This is closer to the application we are considering, that is controlling a mobile robotic assistant (incorporating both mobility and manipulation capabilities) through the Internet. One of the first mobile robots to operate in a populated office building, controlled through the web, was probably Xavier [34]. 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 traveled 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. Currently, the tasks that Xavier can perform at a destination include taking a picture, saying "hello" or telling a robot-related joke! 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. The tasks are processed during special working hours. 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 [39], like the Rhino robot deployed in the Deutches Museum in Bonn, or its successor, Minerva [32], 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. Physical and remote visitors can operate the robot simultaneously using the same interface, one executed on-board and displayed on a touch screen on the robot, and one downloaded as an applet and executed by the remote user's web browser. To decide which tour should be chosen next and which exhibit is to be visited, Minerva uses a simple approach. Physical visitors in the museum select tours on a first-come first-serve basis, while web users vote for the next tour. Minerva's shared control interface was on-line for 91 hours and was accessed by 2885 people. The robot traveled 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 [13]. The NASA Space Telerobotics program website (http://ranier.oact.hq.nasa.gov/telerobotics_page/realrobots.html) currently 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 (the requests issued by different client sites are scheduled by the robot server). 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/slave robot deteriorates the transparency and telepresence characteristics of the teleoperation system. In other words, the user feels distant from the teleoperated system, and is forced to employ some form of move and wait strategy. More advanced 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), which will enable a more natural and intuitive, real-time interaction between the user and the web-based teleoperation system.

3 Mobile Robotic Assistant: General System Architecture

The work presented in this report is carried out in the framework of a research project called "HygioRobot" (Health-Robot), funded by the Greek General Secretariat for Research and Technology and the European Commission. The aim of the project is the development and implementation of control algorithms for a mobile service robot, consisting of an integrated robotic platform equipped with a vision system and a light manipulator. The system is targeted towards a particular class of applications, namely to perform assistive tasks in a hospital environment. These will include tasks such as transportation of specific items (like pharmaceuticals, lab specimens, medical records etc.), accompanning a patient from one location to another within the hospital building, or even surveillance of an area, in other words, a combination of simple displacement and manipulation (fetch-and-carry) operations in a potentially human crowded indoor environment. Specific topics of research that will be investigated include: vision guided navigation, motion planning as well as teleoperation based on a user interface that will integrate features such as natural language communication and virtual reality techniques.

This section presents a brief overview of the system and a general outline of its architecture. The system will consist of the following main functional modules:

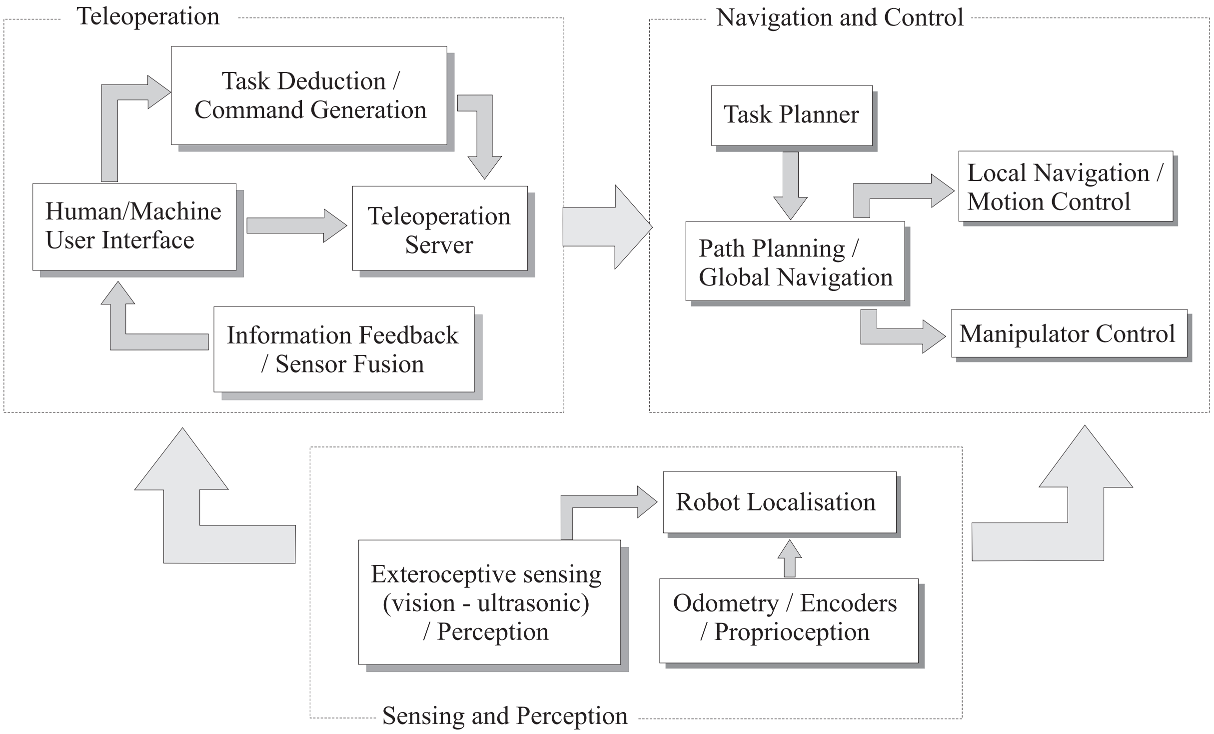


Figure 2: *Mobile robotic assistant: general architecture of the system*

(a) The *navigation and control* subsystems, including the task planner, the global and local path planning and navigation modules, as well as the manipulator control module. Major issues that must be investigated include here: (i) the real-time collision avoidance to ensure safe operation of the mobile platform in a dynamic environment, (ii) the development of a number of autonomous low-level sensor-based behaviors, and (iii) the coordinated action of the mobile platform and robot manipulator to optimally exploit the redundancies offered by such an integrated mobile manipulation system,

(b) The *sensing and perception* subsystem, performing fusion and interpretation from a variety of sensory feedback information, provided by the odometry and optical encoders (proprioceptive feedback), as well as from the vision and ultrasonic sensors (exteroceptive feedback). The goal of this subsystem on its whole is to update internal representations regarding: (i) the robot's actual state (positioning, i.e. robot localization) and (ii) the external world map (i.e. dynamic moving obstacles etc.)

(c) The *teleoperation subsystem*, which aims at integrating the decision and action capacities of a human operator in the control loop, and consists of: (i) a multimodal user interface (which will be designed to enable Web-based remote control of the robotic platform), (ii) a sensory feedback acquisition and processing module and (iii) a task deduction and command generation subsystem. All these modules are coordinated by a teleoperation server, which will support various modes of operation ranging from direct on-line remote monitoring and control, to off-line teleprogramming or simple supervisory control of the system.

These subsystems, with their main functional modules and interconnections, are schematically represented in figure 2, which illustrates the general architecture of the integrated robotic system. The work reported here focuses more specifically on the design and implementation of the teleoperation system for the mobile robotic assistant, integrating virtual reality techniques within a Web-based user interface, to assist the human operator and enhance the functionality of the system. In the following section we will discuss specific problems related to the teleoperation control of a mobile robotic manipulation system, and the issues that have to be taken into consideration to perform complete specification of the requirements for an efficient teleoperator system.

4 Teleoperation System Design for a Mobile Robot: Problem Formulation

In this section we discuss and analyze specific issues that need to be taken into consideration for the design of an efficient teleoperation system for a mobile robotic assistant. First of all, what do we mean by the term “efficient” teleoperation and what are the basic requirements that have to be fulfilled? Efficiency in remote operation and control of a mobile robotic system can be defined in terms of:
(a) making “good use” of the available communication bandwidth between the master and slave systems, and
(b) enabling the system to best exploit and integrate both: (i) the human operator capacity to take rapid decisions and intuitively indicate the most appropriate (coarse or detailed) plan for system action (e.g. robot motion) in complex situations, and (ii) the robotic system capacity to perform, with controlled speed and precision, a variety of autonomous (sensor-based) physical tasks.

To approach towards these general targets, a set of requirements have to be specified and fulfilled by the teleoperation system and all its submodules. The final system design must converge towards the merging between a number of often contradictory functionalities, in search of an “optimum” compromise and increased “efficiency”. A number of issues that have to be considered and specified for the design of such a telerobotic system, are first of all related to the **modes of teleoperation** that will be supported by the system. These include:

(a) *Direct teleoperation* control, based on an on-line master-slave exchange of low-level commands (e.g. move forward distance d with speed v, rotate right 10^o etc.) and raw sensory feedback (velocity signal, provided by the odometry, visual feedback from an on-board camera etc).

(b) *Computer-aided master control* of the mobile robot platform, with the computer system at the master control station providing some form of assistance to the human operator, such as: (i) performing information feedback enhancement, like for instance model-based predictive display, (ii) undertaking active control for some of the dofs of the system, (e.g by constraining the motion of the platform on a set of prespecified paths, related to the desired task, to assist the human operator), thus substituting or complementing some of the human operator’s actions, or even (iii) providing some form of active guidance to some of the human operator’s actions (e.g. an anti-collision module), based on a VR model of the slave robot environment and a set of desired task models. In other words, this mode of teleoperation control is based on a set of functions supported by the master control system by performing active monitoring and real-time model-based correction of the human operator actions, to satisfy a number of task-related constraints.

(c) *Shared-autonomy teleoperation control* of the robotic system, using a set of sensor-based autonomous behaviors of the robot, such as a real-time automatic collision avoidance behavior, based on data from ultrasonic (or/and infrared) sensors. This mode of teleoperation control can be extended to incorporate a large set of intermediate-level, behavior-based, hybrid (qualitative/quantitative) instructions, such as for instance: move through point A, B, C while avoiding obstacles, pass through the door on the left, move at distance d from the wall on the right, follow corridor etc. These commands will trigger and make use of respective behavior-based control modes of the robot, incorporating automatic path generation functions. In other words, this mode of teleoperation control is based on some form of basic autonomy (local path planning and reactive sensor-based behaviors etc.) embedded on the slave robot. Of course, the master control system should enable this form of intermediate-level, behavior-based remote control by allowing the human operator to intuitively indicate the robot plan, interpreting his actions/indications and transforming them into appropriate robot instructions that fall into this category.

(d) *Semi-autonomous teleoperation*, based on a set of high-level qualitative task-based instructions, such as: go to location X, grasp object A on table B of room C etc. This set of instructions must be built upon a combination of task-planning, path-generation and environment-perception modules that will be incorporated on the robot control system.

(e) *High-level supervisory control*, that is, simple monitoring of sensory feedback, and limited human intervention on specific complex situations, requiring difficult decision making and task planning.

All these modes of teleoperation can be used for on-line monitoring and remote control of a mobile robotic platform. The system however should also support some or all of these control modes in an off-line teleprogramming scheme, where the human operator controls the robot task in a simulated environment, and checks the validity of his actions before actually sending the commands (registered action plan) to the slave robotic system for real execution.

A combination of the control modes described above will be considered in the design of the teleoperation system for the mobile robotic assistant we are developing. We must thus specify:

- what form of assistance will the system provide to the human operator, in the framework of a computer-aided master control mode of operation, as described above. In the first place, two main functions will be integrated: (i) an active anti-collision and (ii) an active motion-guide, both based on the use of a virtual reality model of the robotic platform and its task environment.
- what sort of autonomous behaviors can the robotic systems support, depending on the sensors that will be integrated on the robotic platform and on issues related to the safety of operations. A set of sensor-based behaviors will be developed and implemented in the first place, namely: (i) wall-following, (ii) doorway-passing and (iii) collision avoidance behaviors.
- what type of information (robot commands, sensory feedback etc.) has to be exchanged between the master and slave control stations, depending on the mode of operation that is active. The point here is to specify the information that is pertinent for the remote control of a task, in order to make optimal use of the communication bandwidth, and minimize time-delay constraints.

Specifications of all these issues, will determine the efficiency of the system, as defined above, and will play a major role in the final user-friendliness and overall system performance. The use of VR techniques and tools to enable and enhance some of the above mentioned teleoperation modes is considered as a first priority issue. Merging all these functionalities in an integrated telerobotic system is a challenging task. Some specific problems that must be studied are described hereafter:

1. One of the major difficulties is how to enable both: (a) the human operator to perform actions in a natural and intuitive manner within the master control environment, and (b) the system to interpret these actions, extract critical task-related parameters and synthesize appropriate robot commands. The first issue is related to the design of the human operator interface, where we have opted for the use of VR techniques to enable such an intuitive interaction with the system, while providing active assistance functionalities, as described above. On-line monitoring and analysis of the human operator's actions is then necessary, to deduce a correct robot

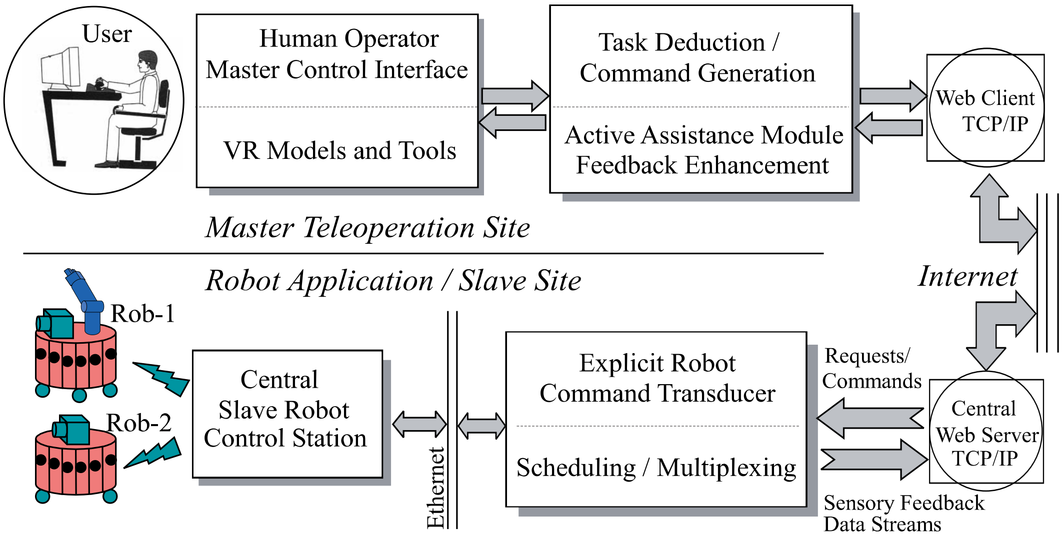


Figure 3: *Schematic representation of the overall teleoperation system for the mobile robotic assistant*

task plan as specified/indicated by these actions. This means, in other words, to incorporate some form of "intelligence" in the master control environment, capable of performing these task-deduction and robot-command-extraction operations, based on observation of human actions within a simulated virtual representation of the slave site. This problem of robot action tele-planning from observation and learning of VR-based human demonstration, is discussed in section 4.2, where some guidelines for future research work are given.

2. An important research topic concerns the design of the human operator's interface to enable remote monitoring and teleoperation control of the mobile robotic assistant, as specified above. A basic requirement for the system we are considering is to enable Web-based operation, that is, to perform remote control of the robotic system through the Internet. The use of Virtual Reality models and tools, is also considered of primary importance, as mentioned earlier. Other issues that must be specified concern:
(a) the input devices that will be used to provide human actions to the system, for instance not only traditional two-dimensional devices like a mouse or a joystick, but also 3D devices like spaceballs (or position/orientation trackers) for the control of camera movements and for a more natural human operator interaction with the system (for instance, to incorporate/enhance virtual navigation and/or direct virtual manipulation features)
(b) the output/feedback devices, for instance, a force-feedback joystick to enhance the active human operator guidance and assistance functionalities described above (more general purpose desktop haptic feedback devices, like the Phantom™ device [29], could also be considered in a future system configuration).
An other important topic of research is to evaluate the design of the interface in terms of usability, ergonomic and human performance characteristics, in order to find an optimum compromise for a number of different performance indices and specify an efficient interface layout and arrangement. Some of these issues are discussed more in detail in section 4.1.

3. The interfacing between the teleoperator and the rest of the system must also be specified. The mode of operation that is active at a particular time instant must determine the interconnections of the teleoperation system with the other sensing/perception and robot navigation/control modules, in other words, the type of sensory feedback that is required or the type of commands that must be send, and thus the information that must be exchanged with

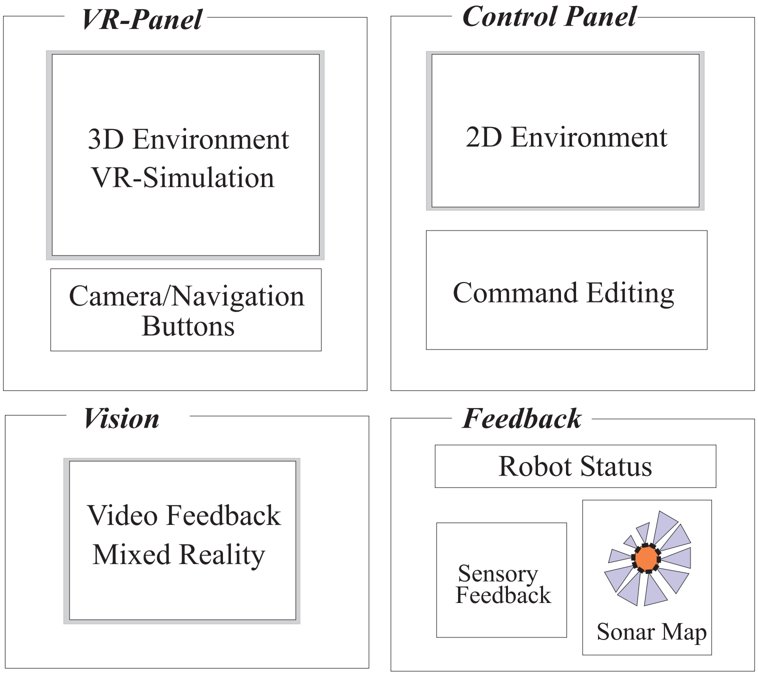


Figure 4: *Teleoperation Interface: General Layout*

other specific system submodules.

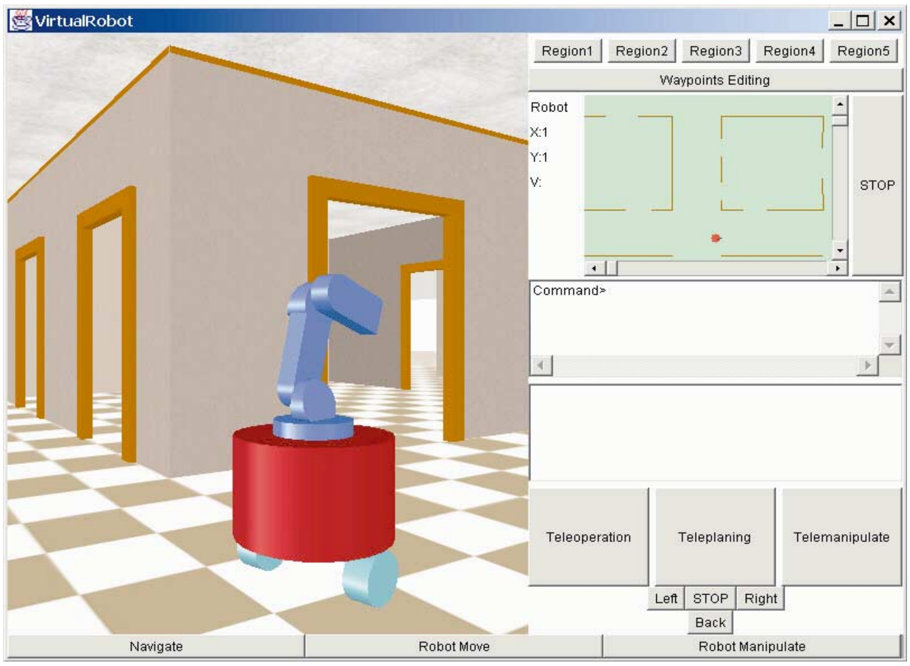
A schematic representation of the overall teleoperation system, from the human operator (user) to one or more (cooperating) mobile robotic systems (Rob-1 etc.), is shown in figure 3, which illustrates the general architecture of the system incorporating the main system modules, described above, and their global interconnections.

4.1 Design of the Human Operator Interface

The human/computer interface for the teleoperation of the mobile robotic assistant will have the general layout shown in figure 4. It consists of four main components:

(i) The *VR-panel*, where the 3-dimensional graphical models of the robotic system and its task environment will be rendered. This simulation environment constitutes the first modality for inserting instructions (motion commands etc.) to the system in a natural and intuitive way. The human operator navigates within this 3D virtual world, and guides the virtual robot directly towards the desired target location. The input devices that will be used in the first place are: a joystick for virtual robot motion control and a trackball for virtual camera control and navigation. The active assistance modules will have as a function to reduce the workload of the human operator by performing on-line motion/action correction according to task-related constraints. Moreover, some form of sensory feedback information will be intergrated in this virtual environment, like for instance the actual robot position (provided by the robot localisation module), which will be represented by a wireframe graphical model of the robot platform.

(ii) The *control-panel*, containing a 2D top-view graphical representation of the mobile robot environment (corridors, doors, rooms, obstacles etc.) and a command editing panel. The 2D graphical environment will contain accurate map information of the whole indoor environment, where the robotic assistant will operate, allowing the human operator to obtain rapidly a top-view of any required region (using scrollbars or predefined region-buttons). The human operator will also have the ability to directly edit commands/instructions that need to be send to the



Robot
X:1
Y:1
V:

Command>

Figure 5: *The first version of the human operator interface implemented using Java/Java3D*

robot but also to monitor the whole system operation through the sensory feedback and robot status panels.

(iii) The *sensory-feedback panel*, where information on the actual status of the robot, as well as other required sensory feedback signals (except real video feedback) will be represented (for instance a sonar map, representing information provided by the ultrasonic sensors and showing the location of obstacles detected by the robot).

(iv) The *visual-feedback panel*, where the images obtained by the on-board robot camera will be displayed. The refresh-rate of this video feedback will of course be reduced, since the bandwidth available for communication through the Internet is limited and a real-time access to other more critical information, such as actual robot location and sensor status, is indispensable. Thus, real visual information of the slave robot environment will be used as a means to validate correct execution of robot tasks, or else, as a final solution to obtain direct teleoperation control of the robot when all other sensory feedback and status information is considered to be corrupted.

One of the main design objectives for the human operator interface is to enable Web-based teleoperation, that is, remote monitoring and control of the mobile robotic assistant through the Internet. For this reason, we have chosen to use Java technology for the development of the human/machine teleoperator interface, since Java applets can be easily downloaded and executed on any computer connected to the Internet, using a standard web browser. Figure 5 shows a snapshot of the of the first version of this interface that is currently under development. We can notice: (a) the VR panel, which includes real-time animation of 3D graphical models for the mobile robotic platform and its task environment (corridors, rooms, doors etc.) (b) the 2D control panel, providing command editing functionalities, and (c) the feedback panel, supplying robot status information. The 3D graphics rendering routines for the VR panel are implemented using the Java3D API, which supports the OpenGL operations of the H/W graphics accelerator board.

An extended version of this human/computer interface will thus constitute in the future the Internet-based teleoperation control platform for the mobile robotic assistant. Some development that remains to be done as well as future research work and objectives are described in the next section.

4.2 Future Work and Research Objectives: Robot Action Teleplanning by VR-based Human Demonstration

The teleoperation interface described in the previous section will be augmented in the near future to incorporate: (i) a visual feedback panel, displaying real video images captured by the on-board robot camera (mixed reality techniques will also be investigated), and (ii) human operator automatic assistance functionalities, such as automatic VR-based collision avoidance, virtual guides etc. Teleplanning/teleprogramming will be the first control mode to be implemented on the real robotic system, since it constitutes the safest mode of operation in the presence of large and variable time delays. The main goal here is to automatically generate a correct robot action plan from observation of the actions performed by the human operator within the VR panel. This constitutes one of our main research objectives for the future. A preliminary solution consists of registering critical waypoints containing information such as robot position and orientation, navigation speed etc. Interpolation between these waypoints by the local navigation module of the robot must result in the desired motion for the mobile platform. Motion commands sent to the robot will thus contain couples of such waypoints with potentially additional information related to the task that is to be executed on each location. The problems that need to be tackled then are:

(a) to analyze the actions performed by the human operator, as interpreted by the motion imposed on the virtual robot within the VR control panel. The goal is to extract critical task-related parameters and deduce the intention of the human operator with respect to the motion/actions that must be executed by the real robot. Various methodologies can be developed and tested, using for instance some form of finite-state machine potentially integrating a fuzzy reasoning scheme.

(b) the automatic registration of critical waypoints and the corresponding robot command generation, must find an optimal compromise between the available communication bandwidth and the required control bandwidth. In other words, submission of redundant command signals and exchange of superfluous, not pertinent information between the master teleoperation interface and the slave robot, must be avoided. However, when performing close turns or maneuvering in tight areas, additional waypoints must be registered, in order to provide adequate command information and correctly guide the robot's local trajectory generation module.

(c) to implement some automatic correction features for the motion plan generated by the master control system, in order to satisfy a number of constraints relative to the status of the robot and the task that is to be executed. The human operator may, in other words, introduce and impose additional motion constraints limiting the degrees of freedom of the system, in order to increase the safety margins and ensure correct task execution in the presence of uncertainties. An on-line teleoperation scheme will require such automatic validation/correction modules, as opposed to a teleplanning framework, where the human operator can verify the correctness of the deduced action plan, prior to submission of the commands to the real robot.

These issues are currently under consideration and constitute our objectives for future research work. A shared-autonomy control mode will also be considered. A scheme based on robot action tele-planning by VR-deduced human demonstration, will again be employed, but now the motion imposed by the human operator on the virtual robot must be analyzed in combination with more complex interactions within the VR control platform. The deduced robot task plan and commands will be created based on elementary operations and primitive tasks. These generated robot commands will make direct reference to corresponding sensor-based, local

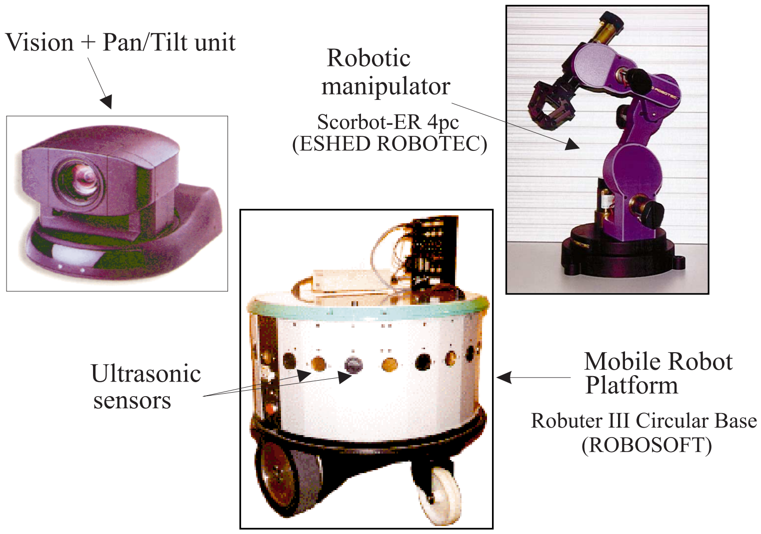


Figure 6: *Harware configuration of the mobile robotic assistant*

navigation behaviors, implemented autonomously by the on-board robot control system. These may include a "wall following" behavior, using ultrasonic sensor data, an automatic "doorway-passing" behavior, where visual servoing may be considered etc. A similar strategy will also be employed for the control of telemanipulation tasks, where one of the primary difficulties is to perform cooperative control of combined motion and manipulation, and to take benefit of the redundancies (in terms of degrees of freedom) offered by such a system.

5 Experimental System: Hardware Configuration of the Mobile Robotic Assistant

The hardware configuration of the mobile robotic assistant that is under development is shown in figure 6. This system will serve as the testbed for the experiments that will be carried out in the near future, in order to evaluate in practice various teleoperation control schemes. It consists of:

(a) a mobile robotic platform, manufactured by Robosoft, France, and equipped with a ring of 24 ultrasonic sensors,

(b) a vision system (color camera plus frame grabber), mounted on a pan/tilt platform, and

(c) a small 5 dof manipulator arm, manufactured by Eshed Robotics, which will also be integrated on the platform.

The robot platform will be equipped with with on-board computational power consisting of a Linux PC and a VME-based controller (running on a Motorolla 68020 CPU processor), which uses the Albatros$^{\text{TM}}$ operating system for real-time robot monitoring and control. The on-board control PC will communicate using a serial link with the controller of the integrated manipulator arm, and via a wireless Ethernet link with the off-board central control server. Figure 7 shows a photo of the integrated mobile robotic assistant's current configuration, with the manipulator arm and the vision system mounted on the platform. The whole system should be operational for teleoperation experiments by the end of the year.

Figure 7: *Integrated mobile robotic assistant*

6 Conclusions

This report has presented work in progress in the framework of a research project, which aims at the development of a mobile robotic assistant. We focused on the design of the teleoperation system, which will integrate virtual reality techniques and web-based functionalities within the human operator interface. This includes:

(a) specification of the teleoperation modes that will be supported by the system, which will range from direct human operator control to simple remote supervision. The first approach that we investigate is based on a teleprogramming/teleplanning paradigm using a combination of computer assistance and shared-autonomy control functions.

(b) the design of the teleoperation user interface incorporating a VR-based platform to facilitate intuitive real-time interaction with the human operator. The first version of the system, which is presented in this report, is built on Java technology to additionally enable web-based operation in the near future.

Future work includes: (i) integration of the teleoperation interface with the rest of the robot control modules, (ii) research and development in the framework of a robot action tele-planning paradigm, by VR-based human demonstration, and (iii) evaluating the performance of the system, both in terms of human factors and remote robot control, when performing simple fetch-and-carry tasks such as those required for a robotic assistant operating within a hospital environment.

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