Virtual Reality in Telerobotics: The state-of-the-art

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Abstract - This paper presents state-of-art issues concerning virtual reality (VR) as applied to robotics and control. After a short outline of the fundamental VR notions, the use of VR in robot (manipulator, mobile) telecontrol is discussed and some principal results are provided. Two representative examples are briefly described along with some concluding remarks.

I. INTRODUCTION

Virtual Reality (VR), or as otherwise called virtual environment (VE), has found wide application in telerobotics, control and manufacturing [1-39]. The existing VR technology is predominantly vision-based, but in many object-handling applications the feel of an object and the feedback of interaction forces are of primary importance. Tactile stimulation of the fingers can be done using gloves and kinesthetic feedback via exoskeletons. VR techniques have drastically enhanced the man-machine interfaces to locally or remotely controlled autonomous systems, and make it possible to convey information in an intuitive way so as to combine supervision capabilities with new heuristic control methods. Remote control of robotic systems is needed in applications such as underwater exploration, maintenance/repair of underwater human-made structures, space exploration, deployment, maintenance and retrieval of satellites, and generally in any hazardous environment (nuclear etc). Telerobotic systems are currently operated by medical, military, construction and security agencies to simulate in VE real scenarios for actual work or for training purposes [1].

In general, all teleoperation tasks are characterized by a number of common features [2]. These are:

- Hazardous environmental conditions.
- Task(s) poorly defined.
- Weak perception in the sense that the sensory feedback is often a degraded form of that achieved by direct human action.
- Non-repetitive tasks.

VR provides the operator with a real-time sensation of presence, giving the ability to project him/herself into the remote area and interact as if actually present physically undertaking the task.

The purpose of this paper is to review the application of VR to robotics and control. Section II demonstrates the basic VR notions provoding the general structure of VR systems. Section III outlines the role of VR in teleoperator control, and section IV discusses the use of VR in mobile robot control. Section V deals with the problem of haptic interaction and feedback control in virtual environments, and section VI presents two representative examples illustrating the applicability and usefulness of VR.

II. VIRTUAL REALITY: BASIC NOTIONS

Three alternative terms which are currently used for VR are: *virtual reality* (VR), *virtual environment* (VE) and *cyberspace synthetic environment* (CSE) [3]. Their common factor is that all of them deal with the stimulation of human perceptual experience to produce an impression of something that does not really occur. Actually VR can be regarded as a type of simulation and, vice versa, simulation is a kind of VR. One way to consider realism with respect to VR is to try to produce a perceptual experience, which would occur or be believed if it were experienced in the real world.

A 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* [3]. 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 an environment other than that from which the impressions physically originate. Virtualisation can be applied to all senses:

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vision, audition, contact (touch), shape and position.

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

- *Sensors* (e.g. head position or hand shape sensors)
- *Effectors* (e.g. stereoscopic displays or headphones)
- *Special purpose H/W & S/W* (connecting the sensors and effectors in such a way 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.

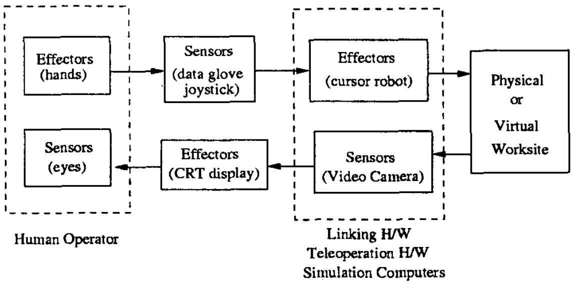

Figure 1: General structure of VR systems

The environment experienced with a teleoperator display is real, while that experienced via a VE simulation is imaginary. Real and simulated data can be combined via digital processing to produce intermediate environments of real and simulated (synthetic) objects. 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.

III. VR in TELEOPERATOR CONTROL

Teleoperators (telerobots) are used for work inside highly dangerous environments where the presence of man is not allowed. Such environments are for example space, undersea media, radioactive media, etc. One of the effects of VR is that the term ***teleoperation*** tends to be replaced by the term ***telepresence*** or ***teleexistence*** [4]. This trend is due to the ***immersion*** phenomenon which takes place in VR and projects the human operator into a realistic representation of the true spot. A second effect of VR is that many applications that needed fully autonomous robots, can be implemented via the VR concept (see for example [5]).

Two principal components of teleoperation VEs are: the ***head tracker*** and the ***sensor*** which couples the hand position to the end effector at a remote worksite. Popular head trackers are: the electromagnetic 6-DOF tracker of Polhemus Navigation, accelerometers, optical tracking H/W and acoustic systems (CAE Electronics). The earlier electromechanical sensor used to couple hand position to remote end-effector is the ***joystick***. More complex sensors can determine hand shape and hand position. Joysticks may be ***isotonic*** (CAE Electronics), which allow significant travel or rotation along the sensed axes, or ***isometric*** (Spatial Systems) which sense the applied forces and torques without displacement[6]. Examples of anthropomorphic robotic end-effectors include Tomovic's hand [7] and Utah/MIT hand [8]. Such hand-like end-effectors with many DOFs may be manually controlled directly by hand-shape sensors, e.g. the EXOS exoskeleton hand master [9, 10]. A more recent device provides static and dynamic positional fidelity with instructive operation and convenient donning and doffing [11]. The combination of haptic (touch) and visual feedbacks led to very important results in VR telerobotics in the 1980s. The first VR system was built by NASA (VIVID project) in the period 1981-1983 [12]. To specialize the general structure of VR systems shown in Fig. 1, the human operator is assumed to be divided in three subsystems("sub-men"), namely:

Decisional man: Decides what tasks are to be performed within the VE.

Sensory man: Watches the execution of the desired modifications and induces a control of physical man's commands.

Physical man: Uses body gestures or voice to command appropriate modifications of the VE.

The human operator cooperates with the VR engine which is used to update the VE according to his(her) commands and transmit the generated information to the sensory man. The *VR engine* receives the physical man commands via suitable ***input interfaces***, and addresses the overall sensory system of the man through the ***output interfaces***, namely visual displays (helmets, screens, etc), ***haptic*** displays (haptic feedback, force feedback, tactile devices), and ***auditive tasting*** and ***smelling*** devices. The immersion phenomenon is directly related to the features of the output interfaces.

The above are shown schematically in Fig. 2 where one can see that a VR system can be connected to either a local (closed) system or to a remote (open) system [13]. Examples of remote systems are a remote computer, another human operator, and a robot.

IV. VR in MOBILE ROBOT CONTROL

The remote control of mobile robots is a difficult task since the operator has a limited perception of the remote environment. VR helps in improving the operator's perception by providing him (her) with additional views. A driver on a steered vehicle has multiple sensory information such as vision, audio, speed, acceleration etc. However, when the vehicle is remotely steered the information may be very limited, perhaps one or two images and/or the sound picked by a mike.

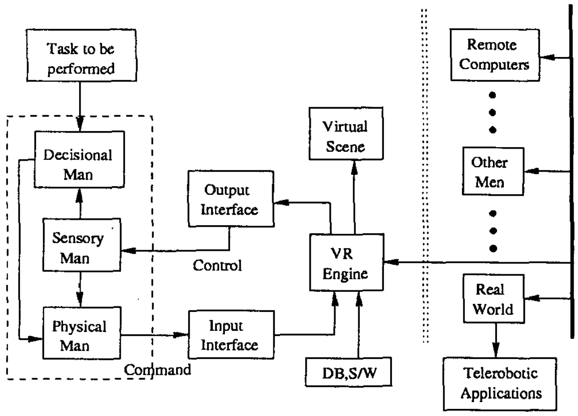

Figure 2: General architecture of a VR system applied to teleoperation

The use of vision sensors on vehicles has serious limitations due to the limited field of view provided by the lenses of the cameras (lenses with wide angles suffer from strong distortion and do not provide accurate judgements of distances and speeds, while cameras that give good depth information have limited fields of view). Also the position of the camera on the vehicle is very crucial.

A solution that leads to highly improved driving performance is to automatically turn the camera into the curve [14]. An other solution is to have a second vehicle also equipped with a camera system which automatically follows the telecontrolled vehicle. Also, some degree of redundancy is needed here to enhance usability and security in case of system faults or breakdowns (usually a second camera and radio link are put on the vehicle). In many cases a 3-D representation of the terrain where the mobile robot has to move is used which is possible only when 3D models are available, eg. when the robot moves in an indoor or a well-structured (medical, industrial) environment. An integrated remotely controlled mobile service robot via suitable multi-modal human-robot interface (MRI), including human-robot natural language commands, was proposed in [15, 16].

A good alternative solution is to use VR and 3D computer graphics [17, 18]. Of course equipping the mobile robot with autonomous functions such as obstacle avoidance, automatic odometry-distance measurement, moving object following, home recovery etc., further enhances safety and operational performance [19, 21]. The teleuser must have the feeling that he (she) totally controls the vehicle.

A particular scheme for controlling a mobile vehicle via VR was proposed in [22]. This scheme, which uses a combination of manual and supervisory control, is called "interactive autonomy" scheme and is based on the idea of providing the operator with virtual views of the mobile robot and its environment (fig.3).

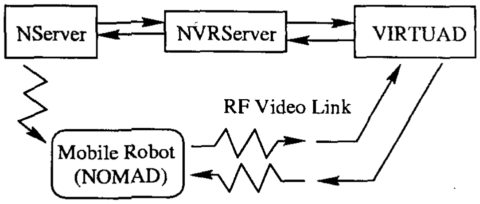

Figure 3: The "interactive autonomy" scheme

The system involves a set of programs running on multi-platforms/OS in a multi client-server structure (Fig.3). All programs communicate via sockets using the TCP/IP protocol. The principal program is called VIRTUAD (VIRTUal nomAD) and runs in a Wintel environment. VIRTUAD provides the user with: (i) a real view from the on-board video camera, (ii) multiple virtual views, and (iii) a joystick interface to control the mobile robot. The other programs run on UNIX machines. The NVR Server performs a connection with Nserver, and has access to the robot's information. It reads the robot's configuration and position (x, y, steer angle and turret orientation) as well as the values returned by the sensors, and sends commands to the robot. VIRTUAD (the client) requests the robot motion data (position, orientation, sensor readings) and can provide configuration and motion commands. The NVR Server is also employed by the NVRNomad applet in the Web version of the system [23].

V. HAPTIC FEEDBACK CONTROL in ROBOTIC VEs

The term "haptic" comes from the Greek word "$\alpha\phi\eta$" (touch) and usually refers to the human hand which can act on the environment and also perceive its physical characteristics. This close interconnection between action and perception in the human hand is expressed by considering the haptic sense as an "active sense" [24, 25]. With reference to Fig.2, a general human/VE haptic interaction involves the interconection of three entirely different systems: the ***human haptic system*** (i.e. the human hand with its functionalities and prehensile skills), the ***virtual engine*** (i.e. the computer simulation and animation modules) and the ***haptic device*** (input/output peripheral). The main properties and functionalities of each of these systems are briefly described in the following.

A. Human hand functionality

The main function of the human hand is to perform intentional prehensile actions on the objects of the surrounding environment, that is to perform grasping and manipulation tasks. Many human hand grasp taxonomies exist which try to divide the different forms of grasping according to the following two criteria:

- the geometrical form of the grasped object, which determines the geometry of the performed grasping (eg. spherical or prismatic grip, [26], etc.);
- the characteristics of the manipulative task to be perfromed, for instance the exerced force requirements

(amplitude and direction of the applied forces) or requirements on precision (fine manipulation, compliance etc.).

Based on such anatomical and functional characteristics, Napier [27] has distinguished two main classes: power grasp and precision grasp.

B. Human haptic perception

The haptic perception can be defined as the capacity to obtain a variety of sensory information related to the physical properties of the external world, by means of hand actions on the surrounding environment (physical contact between fingers and objects). The complexity and variety of the sensations provided by the human hand has often lead the researchers to describe this sensory modality as a complex set of senses, called "sense of touch". Generally, haptic perception is often considered to be divided in two distinct sensory modalities:

- *kinesthesis*, that is the perception of mouvements (proprioception) and forces [28].
- *tactile sense*, that is the perception of cutaneous stimuli (local deformation of the skin, temperature, vibration etc.).

The haptic sense relies on a multitude of afferent sensory signals provided by a variety of mechanoreceptors which are situated on different areas of the human hand and arm: the skin, muscles, tendons and joints.

The complexity and redundancy of generally all the human sensori-motor systems is often taken into account for the design of VR systems based on the use of *sensory substitution* techniques [29]. This means that information usually related to one sensory domain are conveyed through a different sensory modality (for instance, visual presentation of feedback forces etc.). The same principle could also be applied for a single sensory modality.

C. The LRP force-feedback exoskeleton glove

The problem mentioned above was in fact the starting point of the work reported in [30, 31], which was based on the LRP exoskeleton force-feedback glove (fig.4). This glove consists of five fingers and has 19 degrees of freedom (dof) (14 actuated and 5 passive). Total weight of the mechanism does not exceed 350 gr. Two types of sensors are integrated in the system. Optical encoders are mounted on pulleys situated close to the motor shafts and measure the displacement of the cables. Based on these measures, the finger joint flexions are estimated using a simplified calibration model. Miniature force sensors (strain gauges) are also mounted on the endpoint of each cable. These sensors measure the traction force exerced by each cable and allow the estimation of the torque applied on the corresponding joint of the human hand. These sensors have a linear behaviour for measured forces up to 4.5 *Nt.*

The LRP hand master has a double functionality: from one hand, as an input device, it monitors the joint mouvements of the human hand fingers allowing either the remote control of a mechanical hand or the animation of a virtual hand within a VE. On the other hand, as a feedback device, its main function is to apply torques on the joints of the fingers and to convey haptic sensations relative to virtual or real telemanipulation tasks.

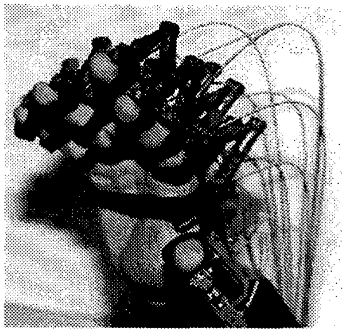

Figure 4: The LRP force-feedback exoskeleton glove.

VI. Examples

Here two examples are reviewed (Dortmund, Paris) which show the structure, actual components and capabilities of VR systems applied to robotic applications. Of course many other similar systems exist in the literature [32, 33].

A. Multi-Robot VR-based control and supervision (CIROS)

The CIROS multi-robot testbed was developed at the Institute of Robotics Research (IRF) in Dortmund, Germany [34]. It consists of two redundant robots with six revolute and one translational axes, and it is equipped with a tool exchange capability. This 2-robot system with the torque/force sensors at the wrists allow fully coordinated operations which resembles the cooperation of two human arms. The robots are equipped with mounted cameras and one additional camera supervises the scene of the overall laboratory.

The VR-based man-machine interface was designed so as to permit the intuitive definition of new tasks, the checking of status information and the transmission of emergency messages and messages indicating the successful completion of tasks [35].

The motivation for designing the VE for the CIROS testbed was to provide "a familiar" environment to an operator who performs experiments in the space laboratory from the ground with the aid of the CIROS-VR system. To immerse into the VE, the operator (experimenter) wears a head-mounted display (HMD) and a data-glove. A PC-based version of this VR-system was designed as a result of cooperation between Dortmund's IRF and the Institute of Robotics and Intelligent Systems of the University of Southern California (USC). This version was able to successfully control the CIROS testbed in Germany from the USC via the Internet. The

VR-system was based on the COSIMIR (Cell Oriented Simulation of Industrial Robots) system which has been developed at Dortmund's IRF [36]. COSIMIR can run on different platforms (PCs, Silicon Graphic machines, etc.) and the VR-system was implemented using the standard client-server approach. The DB contains information about ***change-reaction*** and ***interaction*** models, which enable the VR-system to deduce control information for the robotic system in the same way as actions performed in the VE can be transformed into programs to make phsical robots do the same thing in reality. This capability was named ***projective virtual reality*** (PVR) since the actions performed by humans in the VE are projected onto the robots to carry out the task in the physical environment.

A new mode of operation of the VR-system was developed, called ***task deduction mode***, which exploits the capabilities of an advanced multi-robot control structure, named IRCS (Intelligent Robot Control System) [37, 38]. With this scheme, during the operator's work, the various subtasks that are performed by him (her) are recognized, and tasks descriptions for the IRCS are deduced. These task descriptions are then provided to the ***action planning*** component of the IRCS and carried out successfully by the IRCS.

B. Hand-distributed kinesthetic feedback system (LRP Hand Master)

This system was developed at the LRP (Laboratoire de Robotique de Paris) [29]-[31] and was built around the LRP hand master (fig.4). The system was used as the experimental platform for the evaluation of hand-distributed kinesthetic feedback methods and human haptic perception.

The overall hardware architecture of the experimental system is illustrated in figure 5. It consists of:

- two Hewlett-Packard (HP) workstations equiped with graphics accelerator. The first workstation (HP-A) performs graphic rendering of the virtual scene (virtual hand and objects), while the second one (HP-B) assures operations such as collision detection and computations concerning feedback-force distribution on the hand.
- a 3D tracking sensor, of type Isotrack™ of Polhemus. This sensor provides real-time information on the position and orientation of the human hand in space. This information is subsequently used by the virtual engine to animate and control the motion of the virtual hand.
- the LRP hand master which is a prototype force-feedback exoskeleton glove developed in our laboratory. It is controled by a PC (Pentium 133MHz Processor) equiped with a number of AD/DA boards allowing data acquisition for the optical encoders and for the force sensors, as well as data conversion for the control of the DC motors. All these boards are interfacable on the ISA bus of a standard PC. Communication between the control PC and the HP-B workstation is performed using a RS-232 serial communication link. The two HP workstation communicate with each other using an Ethernet network connection.

The goal of kinesthetic feedback is to provide to the human operator pertinent sensory information concerning his interaction with a VE and therefore improve his perception of virtual physical properties. For instance, in the context of a robot telemanipulation application this could mean feeling the interaction of the robot with its environment and therefore the characteristics of the manipulated objects and in general of the remote environment. These characteristics can be related to static parameters (such as the stiffness or the weight of a manipulated virtual object), as well as to dynamic parameters or events (such as collisions with obstacles, friction characteristics etc.).

One question that can be raised is: how can the external wrenches, related to static or dynamic characteristics simulated within a VE, be distributed on the human operator hand in order to generate the appropriate sensations for the creation of the corresponding "perceptual images". This problem was formulated as a non-linear optimization problem and solved using the Lagrange multipliers technique [31]. The solution was based on a quadratic optimization criterion which introduces terms interpreting human intention (squeezing coefficients for the manipulated virtual object) and biomechanical grasping data (finger-phalangeal contribution to grasping). A method was also developed for computing the distribution of "external forces" on the human hand during a virtual prehensile task [31].

Numerical simulation results demonstrated that the complexity of the method is approximately linear with respect to the number n_c of the contact (grasping) points of the virtual object being grasped by the virtual hand. Even in the case of the most complex grasping type (power grip with 20 contact points) execution time does not exceed 20 msec, which is acceptable for applications that need real-time interactions with a VE.

The haptic sensations created to the human operator using the proposed hand-distributed kinesthetic feedback were evaluated relatively to the perception of the weight of a manipulated virtual object. The performance of the system was evaluated by estimating the Weber fraction (defined above) related to the perception of the weight of a manipulated virtual object. These estimates constitute a measure of the resolution of the haptic feedback system and indicate with which precision the human subject can discriminate between different sensory stimuli (in this case virtual weights applied/distributed on the human hand via the described glove-based kinesthetic feedback). The perception of the weight of a virtual object, by the application of the proposed kinesthetic feedback, is of particular interest. It involves the application not only of internal grasping forces (squeezing forces during active deformation of the manipulated virtual object), but also the distribution of an external static wrench on the human hand.

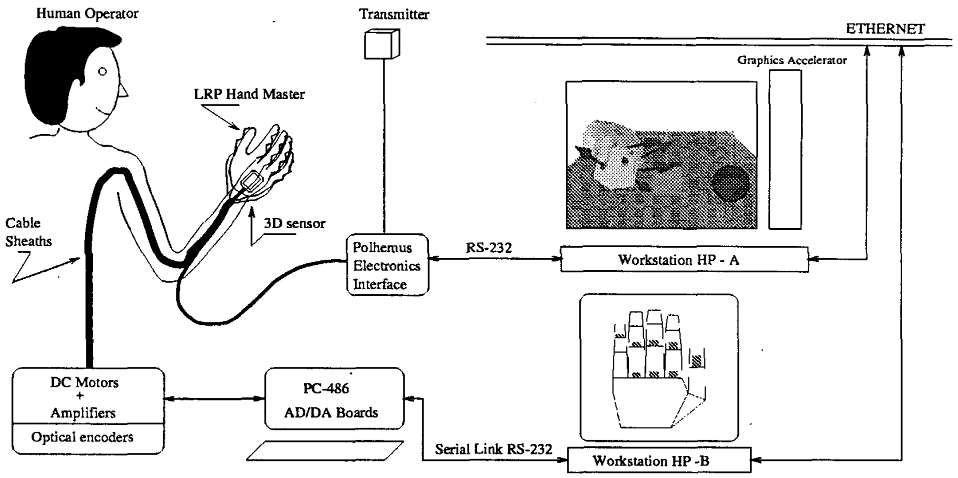

Figure 5: Hardware architecture of the LRP experimental VR system

VII. CONCLUDING REMARKS

This paper has reviewed the fundamental concepts involved in VR/VEs with emphasis on the problems related to haptic interaction between the human operator and a virtual environment. Two case study examples have been discussed.

The first concerns the VR system realized to cope with the various tasks carried out by autonomous multi-robot systems for space-laboratory servicing or autonomous walking robots. This system enhances the "plain VR" to the so-called "projective VR" where VR-technology is employed as an intuitively operable man-machine interface for robotic systems.

The second example concerns the VR system realized for the integration of an exoskeleton glove device (the LRP hand master) and the realization/synthesis of hand-distributed kinesthetic feedback to be applied on the fingers. Using this system, a series of experiments were performed concerning the perception of the weight of manipulated virtual objects. The results obtained are based on the estimation of the Weber fraction. The Weber fractions obtained for virtual reference weights $F_r = 2N$ and $3N$ are similar with a mean value equal to 14.9%. This result is close to the ones reported by other researchers concerning the perception of external forces applied on the human arm or fingers.

Further work is needed to integrate the above kinesthetic feedback for telemanipulation applications based on human actions and on the use of VR techniques. Other forms of sensory feedback must also be integrated, and their relative contribution evaluated, such as a tactile feedback (vibration or heat) on the palmar surface of the fingers, or a force feedback on the wrist. In the field of Robotics, a lot of work is actually concentrated on the study of problems such as:

- off-line robot programming and learning by human demonstration, especially based on virtual task execution using natural human hand actions;

- dextrous on-line telemanipulation using virtual reality techniques.

The transfer especially of the human hand dexterity towards the robot manipulator system still constitutes a great challenge and is a topic of active modern research. VR can also also be used for knowledge elicitation in robotic, manufacturing and other systems [39]. This is a good problem to explore.

References

[1] S. G. Tzafestas (ed.), *Intelligent Robotic Systems*, Marcel Dekker, New York, 1991.

[2] S. Tachi, T. Arai, E. Maeda, E. Oyama, N. Tsunemoto, & Y. Inoue, "Tele-existence in real world and virtual world", *Proc. 5th Int. Conf. on Advanced Robotics* (ICAR'91), Pisa, Italy, pp.193-198, 1991.

[3] S.R. Ellis, "Virtual environments and environmental instruments", Chapter 2, *Simulated and Virtual Realities: Elements of Perception*, ed. K. Carr and R. England, Taylor & Francis, London, pp. 11-51, 1995.

[4] S. Tachi, H. Arai, & T. Maeda, "Robotic teleexistence", *Proc. NASA Conf. on Space Telerobotics*, Vol.III, Pasadena, CA, pp. 171-180, 1989.

[5] Teleborg ACTS 216, *European Program*, EEC, Brussels, 1997.

[6] B. D. Adelstein & M. J. Rosen, "A high performance 2-DOF kinesthetic interface", in: *Human Machine Interfaces for Teleoperators and Virtual Environments*, NASA CP 91035, NASA Ames Res. Center, Moffett Field, CA, 1991.

[7] R. Tomovic & G. Boni, An analytic artificial hand, IRE Trans. Automatic Control, pp.3-10, 1962.

[8] S. C. Jacobson, E. K. Iversen, D. F. Knutti, R. T. Johnson & K. B. Biggers, "Design of the Utah/MIT dexterous hand", *Proc. IEEE Intern. Conf. on Robotics and Automation*, San Francisco, CA, pp.1520-1532, 1986.

[9] Exos, Product Litterature, Exos Inc., Burlington, MA, 1990.

[10] T. L. Brooks & A. K. Bejczy, "Hand controllers for teleoperation", *NASA CR 175890, JPL Publication 85-11*, 1986.

[11] J. Kramer, Company litteratute on head-mounted displays, *Virtex/Virtual Technologies*, Stanford, CA, 1992.

[12] G. Burdea and P. Coiffet, *La Réalité Virtuelle*, Hermès Publ., 1993.

[13] P. Coiffet, "Robotics and Virtual Reality techniques: A new look on man-machine relations", *Proc. 1st Mobinet Symp.* (S.G. Tzafestas, D. Koutsouris & N. Katevas, eds.), Athens, May 15-16, pp. 11-25, 1997.

[14] W. Krüger, F. Pitrella, H. L. Wolf and K. P. Kärtner, "Improving remote manual control of unmanned ground vehicles through automatic TC camera motion", *Proc. ISMCR*, Brussels, 1996.

[15] C. Fischer, M. Buss and G. Schmidt, "Hierarchical supervisory control of service robot using human-robot interface", *Proc. Intl. Conf. on Intelligent Robots and Systems*, (IROS'96), Osaka, Japan, 1996, pp. 1408-1416.

[16] C. Fischer and G. Schmidt, "Multi-modal human-robot interface for interaction with a remotely operating mobile service robot", *Advanced Robotics*, vol.12, no.4, 1998, pp.397-409.

[17] K. T. Simsarian, "Virtual reality control of a semiautonomous robot through a multi-reality and speech control interface", *Proc. ISMCR*, Tampere, 1997.

[18] M. Siuko, P. Kilpeläinen, R. Tuokko, "Use of 3D graphical telerobotics software in design, development and control of machines and equipment", *Proc. ISMCR*, Tampere, 1997.

[19] S. G. Tzafestas (ed.), "Intelligent Mobile Robots" (special issue), *Advanced Robotics*, vol.12, no.4, 1998, pp.313-482.

[20] N. Katevas, N. Sgouros, S. G. Tzafestas, G. Papakonstantinou, P. Beattie, J. M. Bishop, P. Tsanakas and D. G. Koutsouris, "The autonomous mobile robot SENARIO: A sensor-aided intelligent navigation system for powered wheelchairs", *IEEE Robotics and Automation Magaz.*, vol.4, no.4, 1997, pp.60-70.

[21] S. G. Tzafestas (ed.), "Autonomous Mobile Robots in Health Care Services" (special issue), *Journal of Intelligent and Robotic Systems*, vol.22, nos.3-4, 1998, pp.177-374.

[22] E. Colon, "Virtual reality and mobile robots", *Proc. Virtual Reality in Mechanical and Production Engineering Conf.*, Brussels, no. 26-28, pp.119-124, 1998.

[23] E. Colon and Y. Baudoin, "Viewing and controlling a mobile robot with common Web technologies", *Proc. Aerosense 98*, Orlando, SPIE, 1998.

[24] J. J. Gibson, "Observations on active touch", *Psychological Review*, Vol. 69, pp. 477-490, 1962.

[25] S. J. Lederman & R. L. Klatzky, "The Intelligent Hand: An Experimental Approach to Human Object Recognition and Implications for Robotics and AI", *AI Magazine*, pp.26-38, 1994.

[26] M. Cutkosky & R. Howe, "Human Grasp Choice and Robotic Grasp Analysis", *Dextrous Robot Hands*, S. Venkataraman & T. Iberall (eds.), Springer-Verlag, pp. 5-31, 1990.

[27] J. R. Napier, "The Prehensile Movements of the Human Hand", *The Journal of Bone and Joint Surgery*, vol.38B, no.4, pp.902-913, 1956.

[28] D. I. McCloskey, "Kinesthetic Sensibility", *Physiological Reviews*, Vol.58, No.4, pp.763-820, 1978.

[29] P. Richard, *Analyse de l'interaction homme - monde virtuel lors de tâches de manipulation d'objets déformables*, Thèse de Doctorat de l'Université Pierre et Marie Curie (Paris 6) (in french), 1996.

[30] C. Tzafestas & P. Coiffet, "Computing Optimal Forces for Generalized Kinesthetic Feedback on the Human Hand during Virtual Grasping and Manipulation", *Proc. IEEE Int. Conf. on Robotics and Automation* (ICRA'97), Albuquerque, New Mexico, 20-25 Avril, pp. 118-123, 1997.

[31] C. Tzafestas & P. Coiffet, "Dextrous haptic interaction with virtual environments: Hand-distributed kinesthetic feedback and haptic perception", *Proc. 1st IARP Int. Workshop on Humanoid and Human Friendly Robotics*, Tsukuba, Japan, 1998.

[32] J. Vertut & P. Coiffet, *Teleoperation and Robotics*, Kogan Press, London, 1984.

[33] R. C. Dorf, *International Encyclopedia of Robotics*, J. Wiley & Sons, New York, 1992.

[34] E. Freund & J. Rossmann, "Autonomous operation of multi-robot systems in factory-of-the-future scenarios", *Proc. 6th Int. Conf. on CAD/CAM, Robotics and Factories of the Future*, London, Vol.1, pp.269-274, 1991.

[35] J. Rossmann, "Virtual reality as a control and supervision tool for autonomous systems", In: *Intelligent Autonomous Systems*, U.Rembold (ed.), IOS Press, pp.344-351, 1995.

[36] E. Freund, A. Hypki, J. Uthoff & U. van der Valk, "COSIMIR & PCROB: Integration von Zellensimulation und Robotersteuerung anf PCs", *Fachtagung Intelligente Steuerung und Regelung von Robotern*, Langen, Germany, Nov. 1993.

[37] E. Freund & J. Rossmann, "Control of multi-robot systems for autonomous space laboratory servicing", *Proc. Int. Symp. on AI, Robotics and Automation in Space* (SAIRAS), Toulouse, France, Vol.1, pp.443-453. 1992.

[38] U. Kernebeck, "Action planning for multiple robots in space", *Proc. 5th Int. Conf. on Ind. Engrg. Applications of AI and Expert Systems*, Paderborn, Germany, 1992.

[39] J. M. Ritchie, J. E. L. Simmons, I. D. Carpenter and R. G. Dewar, "Using VR for knowledge elicitation in mech. assembly planning environment", *Proc. 12th Irish Manuf. Committee Conf.*, Cork, 1995, pp.1037-44.