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From Teleoperation to the Cognitive Human - Robot Interface

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Abstract

Robots are slowly moving from factories to mines, construction sites, public places and homes. This new type of robot or robotized working machine – field and service robots (FSR) – should be capable of performing different kinds of tasks in unstructured changing environments, not only among humans but through continuous interaction with humans. The main requirements for an FSR are mobility, advanced perception capabilities, high "intelligence" and easy interaction with humans. Although mobility and perception capabilities are no longer bottlenecks, they can nevertheless still be greatly improved. The main bottlenecks are intelligence and the human - robot interface (HRI). Despite huge efforts in "artificial intelligence" research, the robots and computers are still very "stupid" and there are no major advancements on the horizon. This emphasizes the importance of the HRI. In the subtasks, where high-level cognition or intelligence is needed, the robot has to ask for help from the operator. In addition to task commands and supervision, the HRI has to provide the possibility of exchanging information about the task and environment through continuous dialogue and even methods for direct teleoperation. The thesis describes the development from teleoperation to service robot interfaces and analyses the usability aspects of both teleoperation/telepresence systems and robot interfaces based on high-level cognitive interaction. The analogue in the development of teleoperation interfaces and HRIs is also pointed out.

The teleoperation and telepresence interfaces are studied on the basis of a set of experiments in which the different enhancement-level telepresence systems were tested in different tasks of a driving type. The study is concluded by comparing the usability aspects and the feeling of presence in a telepresence system.

HRIs are studied with an experimental service robot WorkPartner. Different kinds of direct teleoperation, dialogue and spatial information interfaces are presented and tested. The concepts of cognitive interface and common presence are presented. Finally, the usability aspects of a human service robot interface are discussed and evaluated.

Preface

This thesis comprises seven publications researched at the Automation Technology Laboratory and Intelligent Machines and Special Robotics Institute (IMSRI) of Helsinki University of Technology during the period 1997 – 2004. The research work has been carried out as part of several domestic research projects: “Liikkuuko”, “Tero”, “Workpartner”, “Tukeva”, which are financed mainly by TEKES and the Finnish Academy. Project “PeLoTe” has been supported by the EC, while the Power Oar development has been carried out in cooperation with RST-Lapit Company.

I would like to express my special gratitude to Professor Aarne Halme, Head of the Automation Technology Laboratory, for his expert guidance, inspiration and patience during this relatively long period of work.

Large research projects always involve teamwork, and so I would like to thank all those who have worked in or supported the projects. Special thanks go to Marko Savela and Riku Pulli for their help in teleoperation tests, Mr. Jari Saarinen for his effort in Power Oar development and the Workpartner and PeLoTe teams.

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Finally my fondest thanks to my wife Liisa and my sons Juho and Juuso, who have supported me and provided the extra time needed to complete this work.

Espoo, November 2004

Jussi Suomela

Contents

Abstract 3

Preface 4

Contents 5

List of Abbreviations 6

List of Publications 7

1 Introduction 9

1.1 Background 9

1.2 Scientific contribution of the study 10

1.3 Summary of publications 11

2 From teleoperators to robots 13

3 Human - machine interaction in teleoperation 15

3.1 Definitions 15

3.2 Traditional teleoperation 15

3.2.1 Improving usability 16

3.3 Telepresence in teleoperation 17

3.3.1 Definition 17

3.3.2 Measuring presence (in teleoperation) 18

4 Human - Robot Interaction 21

4.1 Introduction 21

4.2 Interfaces 21

4.2.1 Command and dialogue interfaces 22

4.2.2 Direct control interfaces 25

4.2.3 Spatial information interfaces 26

4.3 Matching the cognitions 26

4.4 Common presence 27

4.5 Usability of a HRI 28

4.5.1 Comparing usability in different cases 29

5 Conclusions 31

References 33

List of Abbreviations

AGV	Automatically Guided Vehicle
AI	Artificial Intelligence
ATV	All Terrain Vehicle
AWD	All Wheel Drive
CAN	Controller Area Network
CHMI	Cognitive Human – Machine Interface
CMU	Carnegie Mellon University
DOF	Degree of Freedom
EC	Electrically Commutating
EKF	Extended Kalman Filter
FSR	Field and Service Robot
GPS	Global Positioning System
GUI	Graphical User Interface
HE	Human Entity
HMD	Head Mounted Display
HMI	Human – Machine Interface
HRI	Human – Robot Interface
HUT	Helsinki University of Technology
IMU	Inertial Measurement Unit
LHD	Load-Haul-Dump
MMI	Man – Machine Interface
NLSP	Natural Language and Speech Processing
OC	Occupancy Grid
OCM	Occupancy Grid Map
PAS	Power Assistance System
PC	Personal Computer
PDA	Personal Data Assistant, hand held computer
PeLoTe	EU-project: "Building Presence through Localization for Hybrid Telematic Systems"
Pose	Position and attitude
RE	Robotic Entity
SLAM	Simultaneous Localization and Mapping
SS	Simulator Sickness
WLAN	Wireless Local Area Network
Wopa	WorkPartner robot
WP	WorkPartner robot
2D	Two Dimensional
3D	Three Dimensional

List of Publications

The thesis consists of an introduction and summary, and the following original seven publications.

Paper I

Halme A., Suomela J., Savela M., *Applying Telepresence and Augmented Reality to Teleoperate Field Robots*, Robotics and Autonomous Systems Journal, Vol. 26, No. 2-3, 28 February 1999

Paper II

Suomela J. and Halme A., *Tele-Existence Techniques of Heavy Work Vehicles*, Autonomous Robots, Vol. 11, No. 1, July 2001

Paper III

Jari Saarinen, Jussi Suomela and Aarne Halme, *The Power Oar – Mechatronic Rowing Assistant*, 2nd IFAC Conference on Mechatronic Systems, December 9-11, 2002, Berkeley, California, USA

Paper IV

Suomela J. Halme A., *Novel Interactive Control Interface For Centaur-Like Service Robot*, 15th IFAC World Congress on Automatic Control, July 21 – 26, 2002, Barcelona, Spain

Paper V

Halme, Aarne; Leppänen, Ilkka; Suomela, Jussi; Ylönen, Sami; Kettunen, Ilkka, *WorkPartner: Interactive Human-like Service Robot for Outdoor Applications*, The International Journal of Robotics Research, 2003. Vol. 22, No. 7-8, pp. 627-640.

Paper VI

Suomela J, Halme A., *Human Robot Interaction – Case WorkPartner*, 2004 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2004, Sendai International Center, Sendai, Japan, September 28 - October 2, 2004

Paper VII

Suomela J., Saarinen J., Halme A., Harmo P., *On-line Interactive Building of Presence*, Field and Service Robotics: Recent Advances in Research and Applications, Springer-Verlag, 2004

In papers I, II, IV, VI and VII, the author is the main writer and generated the main ideas and results in the papers. In papers I and II, the author also did most of the practical work together with Mr. Marko Savela. In the papers IV and VI, the practical work was supported by the WorkPartner team, which consisted of over ten people. The author is the father of the power oar concept (Paper III) and the first inventor in the Power Oar patent [Suomela 2003]. The practical work was mainly carried out by Mr. Jari Saarinen, the first author of the Paper III. In paper V, the author contributed to the HRI part and has been involved in defining and controlling the WorkPartner project from the start.

1 Introduction

1.1 Background

Robots are slowly moving from factories to mines, construction sites, public places and homes. The trend is not only in research but also business. Traditional cleaning [Siemens], transporting [Cardinal Health] and guiding [Thrun 1999] type applications in environments like metro stations, hospitals and museums have got followers from consumer-targeted robots like vacuum cleaners [Electrolux a], [iRobot], lawn mowers [Electrolux b], [Husqvarna], and entertainment robots like Aibo [Sony]. These new robots are called field and service robots. Multipurpose service robots are still missing from the market. Eventually, these robots will most likely be humanoid robots able to operate within the home infrastructure designed for humans. Some research prototypes – like Asimo [Honda] and Workpartner [Paper V] – support this view, Fig.1. The human-like mobility and manipulators are needed because of the human-targeted design of all the existing infrastructure.

Figure 1: Humanoid Asimo and centauroid WorkPartner

Two main technological steps will take robots from factories to homes. The first is the development of perception and the capability of navigating in an unstructured, changing environment; the second is the development of the capability of continuous communication with humans and rapid learning/adaptation to new work tasks. The first step has almost been taken. The rapid development of sensor technology – especially commercial laser scanners – and the continuous increase in processing power, allowing heavy image processing and SLAM (Simultaneous Localization and Mapping) techniques, have made it possible to allow slowly moving robots to enter into the same areas as humans. However, if we compare the performance to animals it becomes clear that a lot of work remains to be done.

The second step is still far from being completed. Traditional industrial robots are mechanically capable of changing tools and performing different work tasks. Due to the nature of factory work, the time between reprogramming is relatively long and therefore interactive communication and continuous learning is not needed. The most sophisticated programming method allows task design, testing and programming off-line with a simulation tool without any contact with the robot itself. Commercial mobile robots like vacuum cleaners and lawn mowers are limited to a single task by their mechanical construction. A multitask service robot needs both mechanical flexibility and a high level of "intelligence" in order to carry out and learn several different tasks in continuous interaction with the operator. Instead of being a "multitool", the robot should be capable of using different kinds of tool designed for humans. Due to the fast development in mechatronics, mechanical manipulators and tools are not a technical problem, although their prices can be high. The main bottlenecks are at the human - robot

interface and robot “intelligence”, which is efficiently limiting both interfacing and task-learning capabilities. By *interfacing* the author generally means, in this context, the ability to initialize missions, communicate tasks to a robot and supervise the performing of its tasks.
Despite the huge efforts in AI and robotics research, the word “intelligence” has to be written in quotes. Researchers have not been capable, so far, of modeling either the complex functions of human brains or human communication, thus robots have neither creativity nor the ability to think. This handicap can be partly compensated by forming an interaction between the robot and its user, where human brains can be used to solve the most difficult problems related to the robot task execution.
The main demand of robotic interfaces – or in fact all human - machine interfaces that are aimed at the interactive use of machines – is to provide easy humanlike interaction. The interface should be natural for human cognition based on speech, gazes and gestures. On the other hand, the robot cognition and learning capabilities are still very limited. The interface should be optimized between these limits and robot “intelligence” developed further.

1.2 Scientific contribution of the study

The scientific contribution of the thesis resides in each of its three parts:
The first part (Papers I and II) compares different level/grade telepresence interfaces in different types of driving tasks and shows both performance-based measurements (objective) and the experience of the drivers (subjective) of the differences in the interfaces and the tasks. The contribution of this part of the thesis may be seen in the new results that indicate that the nature of the task has an essential influence on the benefit of the advanced telepresence interface, and that the greatest benefit of the deepened presence can be achieved in complicated single-driven tasks. Additionally, the tests show that an increasing feeling of presence does not necessarily increase task performance. This phenomenon is analyzed in more detail in Chapter 3.3.

The second part (Papers III – VII) describes the development of a cognitive HRI for a centauroid-type service robot. The robot, WorkPartner, is a multitask outdoor service robot for janitorial services and garden works. As the name indicates, the robot works in a close cooperation with its master. The interface will support task commanding and supervising as well as teaching of new tasks. WorkPartner’s HRI is based on a continuous dialogue between the operator and the robot. The high-level decision-making and perceiving capabilities of the human can be included in the dialogue as part of the robot’s control loops. In addition to verbal communication, the dialogue is supported with several novel interface devices in order to match the very different levels of cognition between a human and the robot. The operator can point to targets and positions, teach movements by teleoperation and understand the environment in a way similar to the robot. The contributed new result shows the way, including the technical means and the principle of task communication, how common presence is created between the robot and its operator.

The third part (Chapters 2-4) shows the development analogue of the telepresence (teleoperation) interfaces and the robot interfaces. In teleoperation, the operator is continuously part of the control loop; the evolution of teleoperation into telepresence binds him more closely into the loop by increasing the amount of sensor data and control actions. The amount of data between the operator and the robot increases and more sophisticated interface devices are needed in order to improve the interaction. In robotics, the simplest interface is an on/off-interface, which is typical for single-task service robots, such as vacuum cleaning robots. However, the service robots should be capable of doing several tasks in differing environments. Due to their limited "intelligence", the robots will need the help of the operator during complicated tasks. Direct teleoperation can be used only in special situations – otherwise the benefits of the robot are missed. Therefore, the interaction between human and robot is increased by continuous dialogue with the help of special equipment. Again the amount of data between the robot and the operator increases, except now the data is mostly on the higher conceptual level than in telepresence. However, the operator cannot be loaded too much or the robot changes from a helper to a burden. The optimal use of the operator's help is highly dependent on the task. The contribution of this part of the thesis is the light it throws on the principle of the dialogue between the robot and its operator that enables them to perform complicated tasks with minimal interaction effort.

1.3 Summary of publications

All the publications are based on my work in the automation laboratory. Most of the work was done together with colleagues in the laboratory and in Finnish industry. Papers are in chronological order. The first two present teleoperation research from 1996 to 2000. After this, the papers concentrate on the human - robot interfaces from 2000 until now.

Paper I describes teleoperation experiments with different levels of (tele) presence. Experiments were made with an ATV modified for teleoperation and automatic driving and they included different driving tasks, like corridor driving, unknown terrain driving, loading, etc. The level of (tele)presence varied from simple camera-monitor combinations to stereo HMD – servo camera combination.

In Paper II, the previous experiments were completed with a similar type of telepresence tests with a real-work machine at its natural work tasks. The chosen machine was a 40-ton LHD, which was tested in the test mine of Sandvik Tamrock Company. The variety of test drives was narrower than with the ATV tests due to the simple Load-Haul-Dump (LHD) cycle of the machine. However, the tested presence configurations were the same. Finally, both tests (ATV and LHD) were evaluated together and summarized.

Paper III presents a description of a power-assistant type interface for a rowing boat – called "Power Oar". Both system and test results are presented. The system includes a strain gage-based force measurement from the oar, measurement and control electronics, power system, DC-motors and mechanics. A similar type of robot control interface is later presented in paper VI. Power Oar has been patented [Suomela 2003].

Paper IV presents the design of the Human - Robot Interface for a multipurpose service robot WorkPartner. The idea of cognitive control is based on matching the human and robotic cognition with different types of interface from direct teleoperation interfaces to the WorkPartner (Wopa) language, which is a dialogue-type language based on speech and gestures. Tasks are commanded by simple imperative-based commands. If the command is not perfect or if an object or a position in the command is unknown, the robot will make a spoken query. Speech is completed with simple gestures, which can be used in noisy situations especially. The robot interprets the gestures either by vision or by a special hand-tracking interface.

Paper V presents the history and subsystems of the used test-bed robot WorkPartner. WorkPartner is a centauroid robot with four wheeled legs and a human-type upper body. The hybrid locomotion system provides unique locomotion capabilities in different environments. Especially combined rolling and walking – rolking [Glaskin] – provides new possibilities of stable locomotion in difficult terrains. The human-like torso enables multiple work tasks and the use of normal tools. The other subsystems and functions are also presented.

Paper VI concludes with the WorkPartner-HRI development so far. All the implemented and planned interface methods/tools are presented with test results. The cognitive model of WorkPartner's communication – including both the wopa language (Operator ←→ Robot) and WorkPartner's intermediate language – is reviewed. The tools and method for creating common presence between the robot and the operator are also presented.

Paper VII describes the scope of an EU-project called PeLoTe. The scope is to build a collaborative human - robotic team for different types of mapping tasks. The main topic of the research is to combine the mapped data supplied by both types of entities as a common presence that is understood by both humans and robots. Even though the robots in PeLoTe are much simpler than WorkPartner, common presence is one of the main topics in HRI design.

2 From teleoperators to robots

Unmanned vehicles have developed from teleoperated machines to multitask service robots during the last 60 years. The very first teleoperators were mechanical pantographs with direct visual feedback targeted for chemical/nuclear material handling [Vertut]. Mechanical manipulators developed rapidly to electric servos and finally to unmanned vehicles. Vehicle teleoperation was enabled by the possibility of transferring control and image data between the vehicle and the operator. This can already be seen as a primitive HRI. Despite the fact that a teleoperated vehicle does not fulfill any of the definitions of a robot, it can still be seen as a precursor to the robot. Step-by-step, the teleoperation technology was improved to telepresence-based technology by increasing the sensory feedback and the possibility of the operator controlling the sensor positions. Both traditional teleoperation and telepresence include the operator as “a main processor” in the control loop [Sheridan 1992a]. All the sensor information is brought to the operator and he controls all the actuators directly. In telepresence, the amount of sensor data and controllable actuators have been increased with the help of special interface devices like HMDs, head trackers, data gloves, etc. [Tachi 1989]

Robotics emerged along with digital processor technology, which made it possible to program autonomous functions of a vehicle or a manipulator. Most of today’s robots are manipulators, which typically repeat the same task continuously and are reprogrammed infrequently. Typically, operator’s help is not needed during the operation. The existing commercial service robots – like vacuum cleaners and lawn mowers – are similar types of single-task robots. The operator simply switches them on and leaves them to perform the task. If the robot has problems during the task – it gets stuck, for example – it has to wait until the operator notices the situation and solves the problem.

The situation changes dramatically when the robot has to solve several more complicated tasks, including object/environment recognition and manipulation. Despite the continuously increasing computing power and development in “artificial intelligence”, the autonomous abilities of robots remain very limited. In all the more complicated tasks, human help is needed. Human help can take the form of direct teleoperation or higher-level action like giving verbal advice, but in all cases it involves the human as part of the task execution control loop(s) of the robot [Fong 2002]. The human effort can be either pre-planned or non-planned. The non-planned effort is usually called intervention [Huang 2003a, b], [Fong 2002] and it can be activated by both the robot and the operator. However, the need for the operator effort decreases the autonomy of the robot [Scholtz], [Yanco], [Parasuraman] and increases both the operator load and the transferred amount of information between the robot and the operator. The development of the needed operator effort between a robot and an operator is illustrated in Figure 2.

Instead of a single robot, the robot can also be of a swarm type that includes several independent entities [Vainio]. One operator is not capable of operating such a swarm by direct teleoperation. However, increasing the autonomy of the robots and operator actions to task level, the teleoperation of swarming robots is also possible and can be achieved based on the same principles as the control of a single robot.

The aim of the robots is to serve and help humans, not vice versa. In a way, the single-task robots are perfect: they don’t need human intervention during their task and so release the operator for other tasks. If the human effort is anyway needed to control the robot, it has to be in a sensible relation to the realized payback of the robot performance in a certain task. As mentioned before, the formula is totally task dependent. In some simple tasks, even a minimal intervention of the operator is too much, whereas the unmanned aerial vehicle Predator requires continuous control of several operators [U.S. Air Force]. The best way to study this optimization problem is to use the well-known definition of usability [UsabilityNet]. First of all, *effectiveness*: Can the robot complete the commanded tasks and achieve the goals? If yes, the next question relates to *efficiency*: How much effort does the robot, and especially the operator, require to perform the task? If the operator effort is too big in comparison to the result, the robot should not be used at all. And finally comes *satisfaction*: What does the operator think about the ease of use?

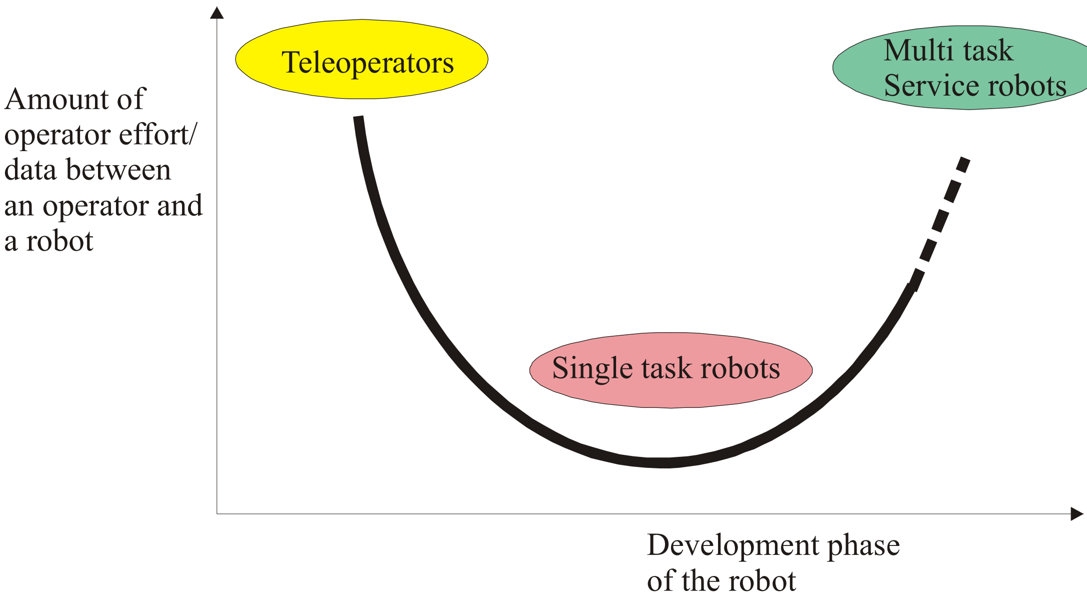

Figure 2: Development of operator effort in robotics

3 Human - machine interaction in teleoperation

3.1 *Definitions*

The term *teleoperation* refers simply to the operation of a vehicle or system over a distance [Fong 2001]. Broadly, understanding all interaction with a mobile robot comes under this definition. Traditionally, teleoperation is divided into direct teleoperation and supervisory control [Sheridan 1992a]. In direct teleoperation, the operator closes all control loops himself, while when in supervisory control a remarkable amount of the control is exercised by the teleoperator, i.e., the teleoperator is a robot. In this thesis, the term *teleoperation* refers to direct teleoperation, while supervisory control is handled under human - robot interaction. Moreover, the term *traditional teleoperation* refers to direct teleoperation over a distance without a line of sight, but with a remarkable amount of telepresence equipment. In today's digital world it has to be noted that even in the case of the direct teleoperation there usually exist control loops in the teleoperator. Typically these loops control the position or the velocity of the "directly" controlled actuators. The author has used the term *coordinated teleoperation* [Suomela 2001] to separate this case from supervisory control. Here, the teleoperator is always a moving work machine / robot. In the case of a non-moving machine – a manipulator, for example – the situation is slightly different, especially when the "onboard" situation or feeling is discussed.

3.2 *Traditional teleoperation*

When teleoperating, the operator is a constant part of a real-time control loop. He has to be more or less as involved in his task as in controlling the vehicle onboard. Due to this fact, teleoperation was earlier used only in tasks that were either too dangerous or too expensive to handle by an onboard operator; even today they are still used mainly in this way. It was not until developments in robotics made it possible to utilize teleoperation efficiently and profitable in industrial driving tasks that it was used instead of human drivers [Pulli 1999]. However, in this chapter, only continuous teleoperation is studied. Part-time teleoperation - when teleoperation is used only now and then in order to support the robot - is studied under robotic interaction in Chapter 4.

As mentioned above, the task chooses the use of teleoperation. In practice, all tasks can be executed more efficiently with better results (effectiveness) when they are operated onboard instead of being teleoperated. Therefore, the starting point is that teleoperation is chosen and the human interaction is evaluated from this point of view.

Teleoperation is an equipment-bonded sport. At the bottom is the communication. The direct teleoperation needs a low-delay, broadband – usually wireless – communication link between the operator and the teleoperator in order to transmit the control commands to the teleoperator and provide a rapid visual feedback to the operator. Humans have a good ability to compensate the transmission delays [Halme] – especially after receiving some training in a specified task – but they cannot overrun the control laws. The absolute requirements for the maximum delay and the minimum update frequency of the communication loop depend on the nominal frequency of the task. Communication has to fulfill these requirements in order to make direct teleoperation possible. From the usability point of view, the delay should not only be optimized with the nominal frequency of the task, but also minimized. The delay compensating increases the mental load of the operator.

The digital controllers and the controlled actuators also have their own delays, which are added to the total delay. Today, communication is usually not a problem in earth applications, but, in most space applications, direct teleoperation is not feasible due to the delay. Also, in the very popular Internet teleoperation, the undeterministic delay causes problems [Andreu], [Hu].

3.2.1 Improving usability

All three aspects of usability in teleoperation can usually be improved by improving the interface equipment. In the driving type of task, the teleoperator is usually a traditional work machine, which is equipped for teleoperation as in Papers I and II. In these cases, the operator environment and the control equipment usually imitates those of the traditional machine, Fig. 3. This is quite natural due to the fact that the operators are usually drivers of the traditional vehicle. However, the transfer from a manually driven machine to a teleoperator, or even the development of a teleoperator from scratch, provides a unique opportunity to improve all aspects of usability by totally new interface design, without the traditional limitations.

Figure 3: The final operator station for the LHD control presented in Paper II. The control interface (joysticks and buttons in the chair are very similar to a manual machine). – Figure provided by Sandvik Tamrock

Teleoperators with different kinds of manipulators provide many more challenges for interface design. Anthropomorphic manipulators, especially [Paper IV], [Tachi 1989], provide the possibility of very natural control by using human-connected interfaces like data gloves and generating force and haptic feedback, Fig. 4.

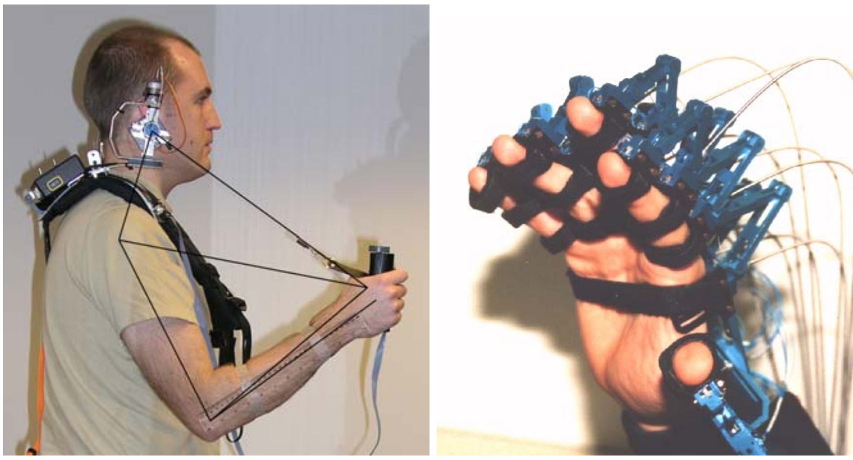

Figure 4: Mobile hand-tracker for WorkPartner manipulator control and a data-glove with force feedback

Force and haptic feedback, as well as improved perceiving equipment like head controlled servo cameras and head-mounted displays, provides a more natural feeling for the operator from the teleoperator site, i.e., they generate telepresence. From the system point of view, the operator load increases. In addition to sight, other senses like hearing and sense of feeling (both tactile and force) are utilized for feedback and more human actuators like body movements and neck muscles are used for control.

When more senses are utilized for perception and feedback it often generates synergy, which is more than the sum of the single senses. In experiments of Papers I and II it was noticed that hearing provides very important information from the state of the machine especially during loading. An experienced operator easily knows from the engine sound when the pushing has to be stopped in order to avoid the slipping of the wheels – a situation which was extremely difficult to sense automatically due to the continuous all-wheel drive. Hearing and the sense of wheeling seem to be very similar. This is a very understandable result because hearing is, in a way, the sensing of air vibrations. Air vibrations and other vibrations can also be mixed, as in the case of bone conduction microphone [Naruse]. However, it must be remembered that the usability doesn't linearly increase when the telepresence is improved. This is discussed in more detail in the following chapter.

3.3 Telepresence in teleoperation

3.3.1 Definition

"Telepresence means that the operator receives sufficient information about the teleoperator and the task environment, displayed in a sufficiently natural way, that the operator feels physically present at the remote site" – [Sheridan, 1992a]. In a way, a simple camera - monitor combination generates a feeling of presence. However, in telepresence something more is needed. This something is the operator's capability to control the pose of the (visual) sensors in the remote site. When the display is fixed relatively to the operator's head and the camera(s) in the remote site are installed in a pan-tilt drive that follows the movements of the operator's head, the feeling of presence can be achieved. Perhaps this idea was presented the first time by R. Goertz [Goertz], the developer of the first master-slave manipulator. Later, starting in the end of 80's Susumu Tachi [Tachi 1989] has made a thorough study of telepresence or, to use Tachi's term, tele-existence [Tachi 2003].

The first "Presence" journal in 1992 provides a good overview of what the feeling of presence means. According to David Zeltzer [Zeltzer] it is the number and fidelity of available sensory input and output channels. According to him, the discussion about presence is meaningless without specifying the application domain and task requirements.
Richard Held and Nathaniel Durlach [Held] claim that telepresence will increase when the operator can identify his own body within the teleoperator. This can be achieved by a high correlation between the movements of the operator, sensed by the operator via internal kinesthetic senses, and the actions of the teleoperator, sensed via the sensors.
From the author's point of view, the best general definition was made by Thomas Sheridan [Sheridan 1992b]. According to him, there are three variables that can create the feeling of presence, Fig. 5:

- *Extent of sensory information*: sensory information is the information we get through our sensors, eyes, ears, etc. More sensory information will lead to a higher level of presence.
- *Control of relation of sensors to environment*: this has to do with the ability of the subject to manipulate or to control the sensors. Control over the camera the subject looks through helps to increase the level of presence.
- *Ability to modify the physical environment*: if the subject is able to control the environment, open a door or move something around, it will help to increase the level of presence.

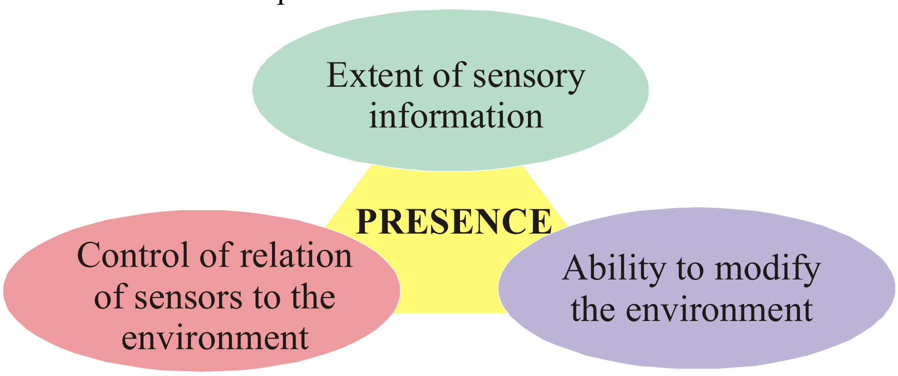

Figure 5: Three variables of presence according to Sheridan

The extent of sensory information has a much greater impact than the other two combined. However, these three factors cannot describe presence alone. Certain task variables, such as task difficulty and degree of automation, are also important to presence.
All these definitions are influenced by the "engineer's" view that there is a real place (or virtual site in the case of virtual presence) and the human feels to be present there via his ("cheated") senses. There is also a more psychological view [Biocca], [Fontaine]. They present that additionally to those two modes of presence (real presence or telepresence) there is also so-called mental presence, which is generated by the human himself without primary sensor information. Typical examples are dreaming and being immersed in a book, when humans can feel very present in a dream world or a book world even though his senses are providing information from totally different environments.

3.3.2 Measuring presence (in teleoperation)

How can presence be measured objectively? It's clear that the (tele) presence is perfect when the operator cannot say is he really present or tele/virtually present in a certain place. At the moment there is no telepresence system reported able to provide perfect presence, and it seems that implementing one would be very difficult. Mentally, humans can generate a perfect presence, during dreaming, for example, or when affected by certain drugs or in psychosis; in these cases humans cannot make a difference between the reality and the fancied world.

Schloerb [Schloerb] presents an evaluation method for telepresence systems, where the objective evaluation is to indicate how well the defined task is being performed. The subjective evaluation is based on the feeling of how good the sense of presence is from the operator's point of view. The objective evaluation includes a hypothesis that the better the feeling of presence, the better the performance of the task. In Papers I and II, the author got different results. The amount of presence did not increase the performance in all cases. It seems quite clear that any task, a driving task, for example, the performance will be best when the vehicle is driven onboard, i.e., in perfect telepresence. On the other hand, the task cannot be performed if there is no presence at all. The question is: Does the performance increase all the time relative to the feeling of presence or could the derivative of the function be negative somewhere between the ends? (Fig. 6.)

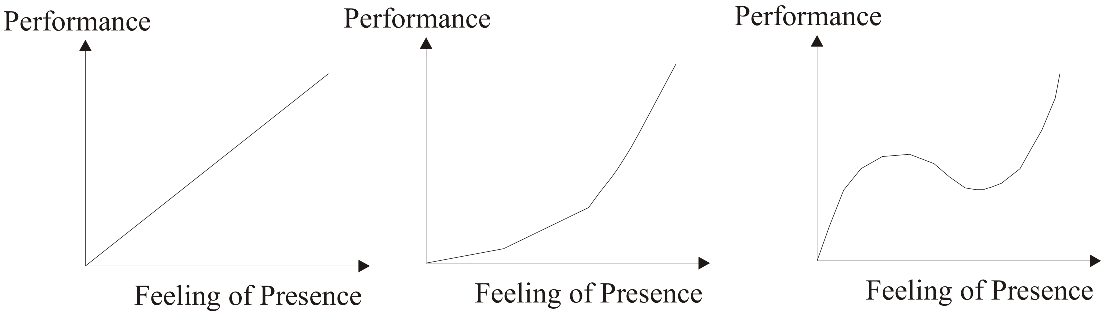

Figure 6: Possible relations between performance and the feeling of presence

The reason for the negative derivative might be very simple: in some cases "the information increases the pain" [Paper II]. It just happens that the increasing feeling of presence increases information that is not essential or is even detrimental to the task execution. The feeling of presence is greater, but the increased feeling distracts the operator's attention from the task. Most probably, the function is highly dependent on the task and the capabilities of the operator. A good example is simulator sickness (SS) [Kolasinski]. With traditional teleoperation systems, SS practically never appears, but with advanced telepresence systems the cue conflict causes SS for a remarkable number of users, especially in long-lasting tasks [Paper II].

Fontaine [Fontaine] studies the (mental) sense of presence in "intercultural and international encounters". According to him, a human is mostly present when he is operating in a totally new environment or culture. In these situations, humans are more broadly focused on the performed task or experienced environment. In routine types of tasks in familiar environments, or in an intensive "flow" type of task, the sense of presence can be quite low or very narrow. Fontaine's study was based on a questionnaire. A similar type of phenomenon was noticed in Paper I. The driving tasks in new, unfamiliar environments got the largest performance benefit from the higher level of presence. After learning, when the task and the environment were familiar, there was no difference in the performance relative to the level of presence or, in some cases, the lower level even gave better results.

Witmer and Singer [Witmer] present a questionnaire to measure presence in virtual environments. In addition to their presence questionnaire, they have also developed an "immersive tendencies questionnaire" in order to find out the differences in the tendencies of individuals to experience presence. According to

their results, there was a clear positive correlation between the tendency to become involved or immersed and the reporting of higher feelings of presence when exposed to a particular virtual environment.
As a result, it can be noticed that measuring the task performance measures the usability (effectiveness and efficiency) of the telepresence system, but not necessarily the feeling of presence.
All references agree that the feeling of presence is a highly subjective matter and, due to this, the only way to measure the feeling of presence is by subjective evaluation by questionnaire. However, it is also possible to measure the tendency of an individual to experience presence.
It has also to be pointed out that in presence questionnaires – especially those that relate to performing a task by telepresence – it is essential to ask about the feeling of presence. Questions related to the task performance easily measure the usability (satisfaction and efficiency) of the system instead of the feeling of presence. However, from the usability point of view, the performance measurement is always more important than the feeling of presence.

4 Human - Robot Interaction

4.1 *Introduction*

As described in the Chapters 1 and 2, the novel service robots need human help as the part of the task-processing loop. The help can be occasional advice [Fong 2002], periodic teleoperation [Pulli 2003], continuous dialogue [Spiliotopoulos] or some combination of these. The most intensive operator effort is needed when new tasks are taught to the robot. The main interest is usability, i.e., how efficiently the operator can perform a task with the robot and how satisfied he is in the work process.

The evaluation of usability is started with presentation of the possible interfaces and their use in human - robot interaction. Then the differences between human and robotic cognition are discussed in order to generate the dialogue between these two entities. Finally, the methods, and the principles governing the evaluation and measurement of usability, are presented.

4.2 *Interfaces*

While controlling a service robot, the operator has several possibilities open to him when interacting with the robot. Commands can be given traditionally via a computer interface [Fong 2000], by speech [Rogalla], by gestures [Fong 2000] or even by brain waves [Amai] and the robot can be directly controlled by means of different kinds of teleoperation devices. Fong [Fong 2001] has divided the interfaces to four groups: *direct, multimodal/multisensor, supervisory control* and *novel*, according to the functional principle, except in the case of the last one, which relates to the relative novelty of the interface causing the possibility of misconceptions. The other problem is *supervisory*, which covers a very large area and causes a lot of overlapping with the others. Despite the shortcomings, the presented classification is quite clear. It is definitely difficult to classify the interfaces in closed groups. Here the interfaces are presented and classified according to the primary area of interaction they are used in. The starting point is that a service robot interface – en bloc – is always supervisory, but consists of several subinterfaces, which are classified in following way:

Command and dialogue interfaces
Interfaces to give commands other general information to the robot and receive the robot reply, questions and state information. Typical examples: computer/PDA interfaces, speech and gesture interfaces.

Direct control interfaces
Closed loop control interfaces to control movements of the robot or its manipulators. Typical examples: joysticks, manipulator controllers and telepresence equipment.

Spatial information interfaces
Interfaces to help the robot and operator to understand the environment similarly and to fix locations and objects in common coordinates. Typical examples: map interfaces, pointers and cameras.

4.2.1 Command and dialogue interfaces

The command and dialogue type of interface is always needed for a robot. To fulfill its definition, a robot should be controllable. At its simplest, the commanding interface is just an on/off button, as in vacuum cleaning robots.

4.2.1.1 Graphical User Interface (or computer interface)

A service robot can usually do several tasks in an unstructured environment and very often the robot is quite complicated. Due to this, the interface usually needs more functions than on/off. To command the robot there has to be the possibility of giving task commands and supervising the work and state of the robot. It is also easy to allow a dialogue between the robot and the operator via a computer interface [Fong 2002]. During teaching and exceptional situations, the operator might need very detailed information from the robot or to give low-level commands. A complex robot includes a huge number of subsystems and low-level actions, which should all be directly controllable. All these interfaces are easy to handle with a computer in a traditional graphical user interface tailored for the robot. One of the main benefits of a graphical interface is the shape of the information, which is always formulated exactly for the robot, i.e., there are no understanding problems that might be a problem in spoken communication. In Fig. 7, a window of WorkPartner's interface is shown. It includes state control and a detailed way of controlling the speed and attitude of the robot.

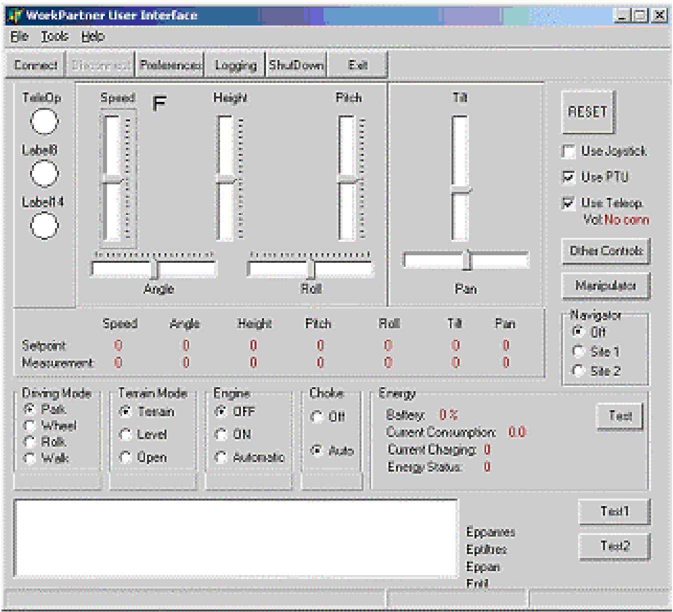

Figure 7: Attitude and mode control window of WorkPartner interface

The main problem with the graphical computer interfaces is the computer itself. It has to be carried by the operator (or the robot) and its use needs concentration on the display. Also, the interaction with the computer – like typing, touching, pointing and even the visibility of the monitor – can be a problem, especially in outdoor conditions.

The Internet extends the possibilities of computer interfaces. In addition to the control and commanding interface, the computer – anywhere – can also act as a database for new tasks, visual objects or any useful information that a similar robot in a similar task can provide.

4.2.1.2 "Natural" interfaces

As the name indicates, these interfaces should be natural for a human to use. To fulfill this requirement, interfaces should mimic human communication as much as possible. The main method for human communication is speech, but in face-to-face communication, gestures and expressions have a lot of significance, sometimes much more than we think [Krauss].

Speech is the most obvious way to transfer information to a service robot. Commercial speech (voice) control interfaces are already available in mobile phones and computers. In the case of a mobile phone, speech is used just for giving the calling command and the name (e.g., "call Bill"). New speech processing software like Philips [Philips] provides the possibility of controlling the computer by speech and even of recognizing dictation. There have also been a lot of experiments in controlling robots by speech. In recent studies, the speech was usually used for dialogue, where, in addition to commanding, the robot replies and asks questions to the operator [Papers IV and VI], [Rogalla]. Simple one- or two-word commands are relatively easy to handle, but a dialogue even with simple sentences can be a problem from the speech recognition point of view. Recognition seems still to be a problem, especially in environments with changing background noise. However, it can be expected that this problem will be solved in the near future. When the speech is recognized, it has to be processed. Processing is relatively easy if only predefined words and sentences are used. Speech generation by robots is very feasible today. In speech processing science, the biggest challenge in the future will no doubt be natural language and speech processing (NLSP). However, in robotics, NLSP is not a primary problem. When applying it in HRIs, one should be careful not to overestimate the significance of NLSP, because there are reasons, like the exactness of commands, which may keep the robot-commanding language simple and formulated anyway.

Gestures and expressions are a very important part of human communication. Usually they are used in addition to speech to intensify the message, but sometimes they can be the only method of communication. Typical examples of gesture communication are the sign languages of deaf people [Nakamura], the maritime signal flag signaling [SacDelta.com], the referee's signs in different sports (Fig. 8) and different gestures used in military [KT-VA] and vehicle control.

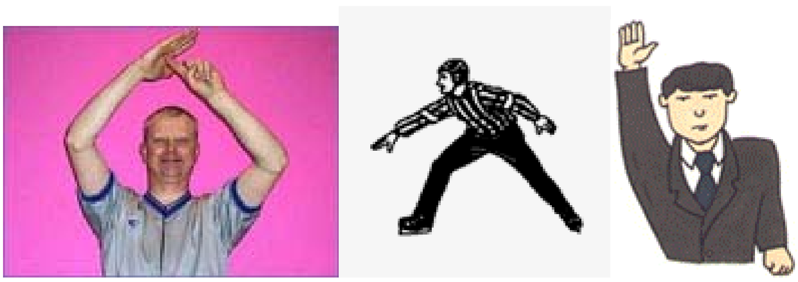

Figure 8: Referee's signals: Time out (basket ball), Goal (ice hockey), Ippon (Judo). Figures adopted from: [Basket-Ball.com], [Ice hockey], [Judo].

In robotics, gestures make communication possible, especially in noisy environments, provide a possibility for pointing [Theis] and make it possible to provide additional information, along with other communication methods [Papers IV and VI], [Fong 2000], [Waldherr], [Bonasso], [Kortenkamp]. Most of the references mentioned use visual gesture tracking, which is feasible over short distances and does not need any additional operator hardware. The author has also used mechanical hand tracking, which allows more exact resolution and is not dependent on visibility. Dynamic gestures can also be easily recognized by inertial sensors, located in hand or in handheld devices like mobile phones or PDA [Benbasat]. “Primate” or humanoid-type robot can also use their manipulators to reply or inform by gestures. Gestures can also be utilized in a very human way together with speech [Krauss]. This is close to the use of expressions and gazes presented below.

In addition to gestures, expressions and gazes are human ways of non-verbal communication. Typically all of these methods are used with speech and partly unconsciously. Some times we notice that the spoken data mismatches with the gestures and expressions and then – in most cases – we believe the non-verbal message. There have been a lot of studies of the use of human expressions for control. Heinzmann and Zelinsky [Heinzmann] used face gestures and gazes to control a robot manipulator. There has been a lot of work in the recognition of human facial expressions in general [Black], [Chibelushi]. From the robotics point of view, the topic has been studied by Bruce [Bruce], for example. Human expressions are still difficult to recognize reliably, therefore their benefit in robotics will be limited. A more feasible use for an expression interface is to make the robot imitate human expressions. Thus the robot will be more humanlike and better attract interacting humans. Good examples are MIT’s Kismet [MIT Humanoid Robotics Group], [Breazeal], Waseda’s WE-4 [Laschi], [Miwa], Fig. 9 and David Hanson’s K-Bot [Newscientist.com], [The University of Texas in Dallas]. Toyota has even take the idea into an experimental car – Toyota POD – which shows expressions by its facial looking nose and wagging its antenna [ToyotaOffRoad.com].

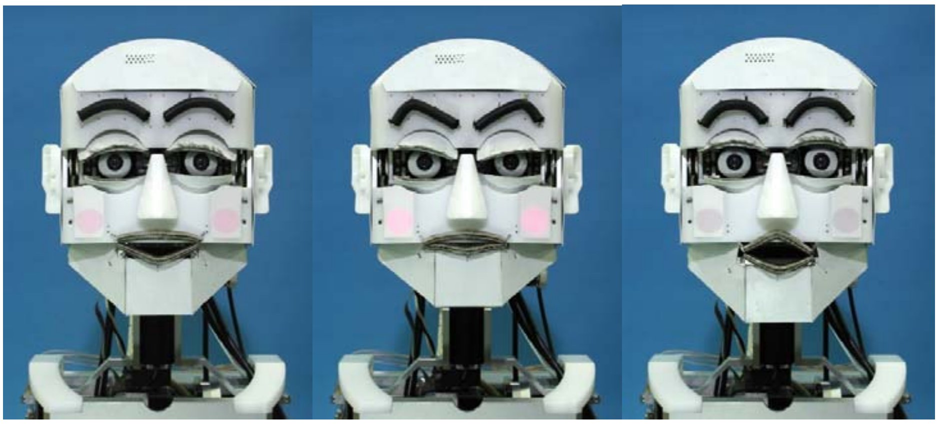

Figure 9: Emotional expressions - Happiness, anger and surprise – of WE-4 robot. Figures adopted from [Takanishi Laboratory]

By reacting through its expressions, a robot makes the human believe that it has beliefs, desires and intentions, i.e., it’s a believable social agent. Recent neurological brain research has found out that we all have specialized neurons – mirror neurons – in our brains [Buccino]. These neurons react to the gestures and expressions of our conversation partners. They activate the same parts that produce those expressions and movements in our brains. Often the opposite conversation partner – partly unconsciously – mimics these expressions and gestures thus deepening the interaction.

This human-like behavior is essential in situations where the robot is serving, not only its operator, but also a bigger audience. A good example is CMU’s Museum guide robot Minerva, which interacts with crowds of people, a typical interaction lasting about 10 minutes [Thrun 1999], [Schulte], and [Thrun 2000]. According to their results, the simple emotions shown with the caricature face of Minerva generate a positive feedback from the audience.

4.2.2 Direct control interfaces

As in the Fong's classification, direct interfaces are used in the closed loop teleoperation of a robot or its subsystem. Traditional examples are joysticks, driving wheels, pedals, mechanical hand/finger trackers like data gloves etc. The new innovations are related to gaze control and different bio controllers like myoelectric control [Williams] and brainwave control [Amai]. However the direct control principles and hardware are more or less straightforward from the technology point of view. The innovations come from the applications. In WorkPartner's interface, for example, direct control has been used for 3D pointing in order to match the coordinates of the robot and the operator during the task command dialogue (see Ch. 4.2.3).

4.2.2.1 Power assistance as a "local telepresence interface"

Old inventions can also be applied effectively in robot interfaces. In Paper III, a new application area [Suomela 2003] for the traditional power assistance interface used in power steering and electric power assisted bicycles is presented. This simple force amplifier interface provides a lot of applications in the short-distance control of service robots, as well as in human support robotics [Jane's International Defence Review] Fig. 10.

Figure 10: Power assistant exoskeleton, adopted from [Berkeley]

The main advantage of a power assistance system (PAS) is the inbuilt force feedback. In the rowing system (Paper III), the sensitivity is so high that it can also be regarded as a haptic feedback. This is exactly as in the very first mechanical manipulators [Vertut], where the mechanic power transmission provided the natural feedback.

A typical feature of service robots is the short control distance. Unlike in traditional robotics or in heavy field robotics, the user is mostly near the robot or even working with the robot. On the other hand, direct teleoperation of the robot is needed sometimes; the control hardware on the operator should be minimized in all cases. The PAS interface fulfils all these requirements. The operator can –

without any additional hardware – control the robot or manipulator movements from a short distance and has full telepresence-level feedback, both from the environment and the controlled movement/actuator. This short-distance teleoperation with force feedback can also be classified under "local telepresence" presented under "common presence" in Ch. 4.4.

4.2.3 Spatial information interfaces

Spatial information has two features, which make it a crucial part of the HRI. Firstly, in all physical work tasks, navigation, perception and environmental awareness are the key issues; secondly, humans and robots process the position and map information in very different ways. For a robot, the environment and navigation is somehow bound to numerical coordinates, while a human relies on relative information based on perceived landmarks [Forsman]. Without additional hardware, a human simply does not know the coordinates of his environment, i.e., he cannot directly give locations to the robot. The only way is to bind the location to a known location "near the tree" or to use teleoperation or another additional interface to point out the location. The main task of spatial information interfaces is to match the environmental information of the robot and the operator. In Paper VII, the author has used the term "Common Presence", which is explained in more detail in Ch. 4.4.

Good examples of the spatial interfaces are presented in Papers IV, and VI. The WorkPartner robot can be teleoperated, or it can follow the operator to a location. For short-distance pointing there are scepters, based on visual tracking, and a teleoperated laser pointer/range finder. If the operator is carrying the computer interface, he can utilize a map interface, which visualizes the robot's map to the operator and allows pointing and even updating of the map. Additionally, separate beacons can be used to mark locations and areas manually.

4.3 Matching the cognitions

In the Paper VI, the WorkPartner interface is called a cognitive interface. In the following the concept is explained further.

The traditional human - machine interfaces mainly interpret human commands and control actions in a form that is understood by the machine, and interpret the status/state information of the robot to the operator. The situation is much more complicated in the case of service robots. A robot is not any more a simple machine with a few functions that are directly controlled by a human. By definition, a robot does not need to appear like a human, but its functions are very human like. Despite its limited "intelligence", a service robot is mobile, it navigates freely, perceives its environment, reacts to external stimulus, performs its tasks autonomously, interacts actively with its operator, and can even show emotions, etc. Due to this, it is justified to say that a service robot has cognition. However, in order to avoid misunderstanding, one must remember that the emotions or feelings mentioned are not included in cognition by definition. Definitely it is very simple to compare this to human cognition – if they can be compared – but the robot perceives the environment and processes perception data according to some kind of understanding of the environment and then plans actions based on that data. Compare this to a definition of cognition:

> *"The action or faculty of knowing taken in its widest sense, including sensation, perception, conception, etc., as distinguished from feeling and volition; also, more specifically, the action of cognizing an object in perception proper."* – [Oxford English Dictionary]

To make it possible for a human operator to give variable tasks to a robot in a changing environment, they have to have a common understanding of the tasks, objects, environment and they have to have a common language or another way to agree these matters. In practice, the need is to match their cognitions in order to have a common understanding and an ability to communicate at a symbolic level.

The cognition of a robot is very simple and made by robot designers. Its functions and performance are therefore also well known. On the other hand, human cognition has unique performance and flexibility. What the human cognition can do is well known, but how the human does it is unknown. Typically, in the interface design, the high performance and flexibility of both human cognition and manipulators have lead to a design in machine terms. In robotics, the interface should be as human like as possible, but, on the other hand, the robot cognition and "intelligence" remain far removed from that of humans. Due to this, the interface functions and hardware has to be optimized in the way that the operator and the robot can exchange information – especially perception and other environmental information – in a way that is natural for the human and understood by the robot.

4.4 Common presence

From the interface point of view, common presence is a model of the environment, which the interface interprets in a feasible form for both the operator and the robot, thus making it possible for them both to understand the environment similarly and to share position-based information with each other [Forsman]. These functions are essential for an operator and a robot working together on a physical task.

The following example makes the concept of common presence more concrete. A rescue team of cooperative human and robotic entities is presented in Paper VII. The goal of the team is to search and map a totally or partially unknown area together, with the help of an operator who is out of the search area.

The human entity – a fire fighter, for example – is moving in a more or less hostile environment in order to map the area and search for possible victims. The situation is always new and very challenging. He has to be aware of fire, hot gases and even collapsing structures. Most probably, he is very present in the ongoing situation. He is not thinking what he will eat for the dinner or dreaming about a sunny beach etc. In certain situations – heavy smoke, for example – the fire fighter is again very present but the sensor information is very limited. In the worst case, he doesn't see anything. The only way to perceive the environment is to explore the walls and floor with fingers. While exploring in the total darkness, the sense of direction will be lost rapidly. In this kind of situation, the environmental model – common presence – provides additional information from the near environment and broadens the fire fighter's feeling of presence, allowing him to execute his task more efficiently. In a way, the situation can also be described as augmented reality or "local telepresence". Therefore, the location information is also extremely crucial. It is impossible to create "tele"presence for an entity without knowing his position. The virtual world and the real world have to match.

The operator's situation is totally different. He is sitting in the operator room and controlling and supervising both the human and robotic entities in the target area. To perform his task well the operator should be as present in the target area as possible. The way to do this is by telepresence. He has the common-presence model, mapping data, video and still images sent by the entities and the verbal information from the human entities. The operator organizes this information and tries to get the best possible information from the target area. He is also

responsible of fusing the data into the common presence.
Robots are in the same situation as fire fighters. The difference is their cognition, which is very limited compared to the human entities. Robotic presence is based on common presence (filtered as a geometric map or an occupancy grid for robots) and their sensor information. In complicated situations, the operator teleoperates or commands the robots, i.e., the functions are based on the operator's telepresence. The "presence situation" of the entities and common presence are illustrated in Fig. 11.

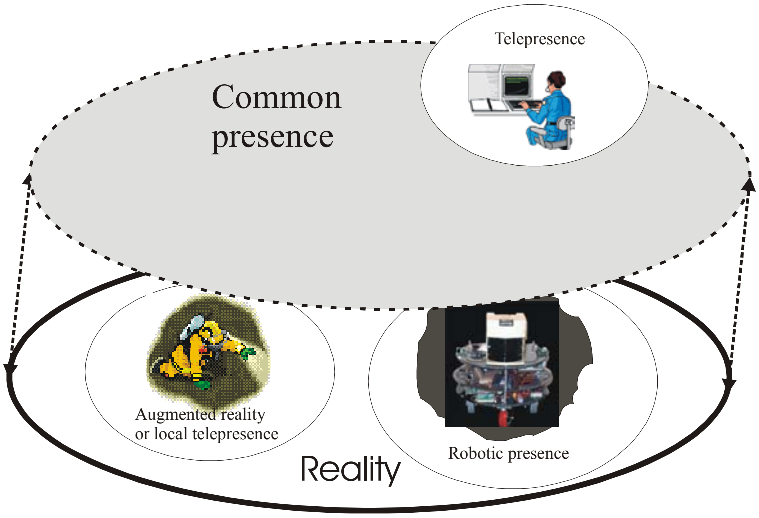

Figure 11: Presence of the PeLoTe entities

It is obvious that there is no model that would give "perfect presence" to all of these entities. But that is not the point. The key idea is to build a presence model that supports all the entities in the system. The aim of the common presence is to include all environmental information in symbolic form. Thus the common presence provides possibility to change spatial information between humans and robots and it includes the "presence" that is common to all entities i.e. an entity specific presence - topographic for a human and geometric for a robot - can easily be filtered/interpreted out from the common presence.

4.5 Usability of a HRI

Papers IV and VI present a HRI for a service robot. The focus in the publications is on the functional level. The usability of the whole system is not analyzed. The main question relates to how the usability of a service robot interface can be analyzed. As in all systems, the MMI is only a part of the system, thus the question must be widened to ask how the usability of a service robot can be analyzed. According to Chapter 2, the service robot interface asks help from the operator, including him/her as a part of the task control loop. Due to this feature, the wholeness is even more important in a traditional MMI. The functionality and the "intelligence" of the robot affect usability as much as the interface does.
Effectiveness, which is very near to the overall performance, tells how well the robot and the operator fulfill the task, but does not commit on how much operator effort is required. It is also a very task-dependent variable. Efficiency concentrates on the operator effort and, broadly, the cost efficiency of the system. Satisfaction is finally evaluated by the operator's subjective view of the interface. Usability aspects are difficult to measure in general and the service robot interfaces are not an exception. Effectiveness is definitely the easiest to evaluate. Usually, the qualitative and quantitative results of a task can be measured with generally

accepted meters. Efficiency and satisfaction are more difficult due to their multi-variable and partly subjective nature. One has to also be careful that the parameter measured is the same as that noticed in the telepresence measurements (Ch. 3.3).

4.5.1 Comparing usability in different cases

The main problem is that usability evaluation is very task-dependent. Comparison of robots can be made only when they are performing the same task. Jacoff [Jacoff] , for example, has presented a test area and performance metrics for rescue robots.

In the case of a multitask service robot, usability varies according to the task, which makes usability evaluation very difficult. If common metrics of service robot usability are needed, one approach is to measure the subtasks in the interaction process. Fong [Fong 2004] has made an effort to create common metrics for human - robot interaction. They divide the robot functions into five different task categories, which all can be performed with great human effort (teleoperation), with a high-level robot independence (full autonomy) or at any point on the interaction spectrum. The tasks are: navigational, perceptive, managerial, manipulative and social. The subtasks are then evaluated according to the usability aspects. It is, of course, clear that the whole is not always the sum of its parts, but in the case of comparison or common metrics this seems to be the only way to proceed.

As Fong [Fong 2004] pointed out, research into measuring the human - robot interaction or usability of a complicated service robot is still in the initial phase. Even with the common metrics still missing, it is crucial to pay attention to the usability of HRI design. The effectiveness and satisfaction are always measurable and comparable when the different versions of a HRI are evaluated.

In the development of the WorkPartner's cognitive interface, the usability aspect is continuously under consideration during the design and is monitored regularly by task demonstrations where a complete task – such as removal of snow or transportation of goods – is demonstrated to the public and then analyzed together with the developers and public.

5 Conclusions

Unmanned mobile working machines have developed from teleoperators to service robots during the past 40 years. The development of human-machine interfaces has taken them from teleoperation to telepresence and finally to interactive human robot interfaces. Human interaction has varied during the process and seems to be following the analogy of more developed systems – telepresence in teleoperation and the complicated service robots in robotics – that bind the operator more tightly to task processing. This is due to the fact that, at the moment, and in the near future, robotic "intelligence" cannot solve complicated tasks alone, so the operator has to be included into the control loop in order to support the execution of the complicated subtasks.

The teleoperation tests in the first two papers show that the high level of presence suits tasks that are new and need a lot of perception. In repeatable tasks, the benefit of higher presence soon becomes apparent to the operator as he learns the task. However, the most important result of these experiments is the fact that performance and the feeling of presence do not always correlate. This result emphasizes the usefulness of traditional usability factors, which separate the objective factors such as effectiveness and efficiency from subjective operator satisfaction.

The third paper, presents an application of a well-known power assistance device that should be used more in robotic interfaces. Power assistance provides a very natural and safe control system for short distances. The main benefit is the natural feedback and the common understanding of the environment – common presence – between the operator and the robot. Power assisted teleoperation strengthens the feeling of presence in the real environment, the situation that the author calls "local telepresence".

Papers IV, V, VI present the HRI of the centauroid service robot WorkPartner and the robot itself. The basic idea of the WorkPartner's interface is the matching of human and robotic cognitions by means of different interface devices and continuous interaction between the robot and the operator. The most important subinterfaces are the natural communication interfaces like speech and gestures, which are used for the fast interaction, and the interfaces for spatial cognition, which create common presence.

The last paper presents a group of cooperative humans and robots in a rescue task. This paper explains the idea of common spatial understanding – common presence – between the humans and robots. The idea of local telepresence is based on this paper.

References

Amai W., and Fahrenholtz J., Leger C., *Hands-Free Operation of a Small Mobile Robot*, Autonomous Robots, Vol. 11, No. 1, July 2001

Andreu D., Fraisse P., Roqueta V., Zapata R., *Internet Enhanced Teleoperation: Toward a Remote Supervised Delay Regulator,* ICIT'03: IEEE International Conference on Industrial Technology, 2003

Basket-Ball.com, (online) *Basketball rules - Referee's signs*, 2002-2004, [Referred 12.8.2004], available in http://www.basket-ball.com/basketball-article-207.html

Benbasat A.Y. and Paradiso J.A., *An Inertial Measurement Framework for Gesture Recognition and Applications*, "Gesture and Sign Language in Human-Computer Interaction," International Gesture Workshop, GW 2001, London, UK, 2001 Proceedings, Springer-Verlag, Berlin, 2002

Berkeley Robotics and Human Engineering Laboratory, (online), *Welcome to Bleex Project,* 2003, [Referred 12.8.2004], available in http://bleex.me.berkeley.edu/bleex.htm

Biocca, F., A *Three Pole Model of Presence*, Presented at the FET PR Venice event, Venice, Italy, May 2003, [Referred 12.8.2004] slides available online in http://www.tils.com/i-learning/contenuti/01_from_2-pole_to_3-pole_model_of_sfs_in_presence.pdf

Black M.J., Yacoob Y., *Recognizing Facial Expressions in Image Sequences Using local Parameterized Models of Image Motion*, Journal of Computer Vision 25(1), 1997

Bonasso P., Huber E., Kortenkamp D., *Recognizing and interpreting gestures within the context of an intelligent robot control architecture*, AAAI Fall Symposium on Embodied Language and Action, 1995

Breazeal, C. and Scassellati, B., *How to build robots that make friends and influence people*, IROS99, Kyonjiu, Korea, 1999

Bruce V., *What the human face tells the human mind: some challenges for the robot--human interface*, Advanced Robotics,Volume 8, No. 4, 1994

Buccino G., Binkofski F. and Riggio L., *The mirror neuron system and action recognition,* Brain and Language, Volume 89, Issue2, 2003

Cardinal Health, (online), *Pyxis HelpMate®, the Trackless Robotic Courier*, 2004, [Referred 12.8.2004], available in http://www.pyxis.com/products/newhelpmate.asp

Chibelushi, C.C., Bourel, F., (online), *Facial Expression Recognition: A Brief Tutorial Overview*, In CVonline: On-Line Compendium of Computer Vision. R. Fisher (ed), 2002 [Referred 12.8.2004], available in http://homepages.inf.ed.ac.uk/rbf/CVonline/LOCAL_COPIES/CHIBELUSHI1/CCC_FB_FacExprRecCVonline.pdf

Electrolux (a), (online), *Trilobite*, [Referred 12.8.2004], available in http://www.trilobite.electrolux.se/

Electrolux (b), (online), *Automower,* [Referred 12.8.2004], available in http://www.automower.com/

Fong T., Conti F., Grange S., Baur C., *Novel Interfaces for Remote Driving: Gesture, Haptic and PDA*, SPIE Telemanipulator and Telepresence Technologies VII, Boston, MA, November, 2000

Fong T., Thorpe C., *Vehicle teleoperation interfaces*, Autonomous Robots, Vol. 11, No. 1, July, 2001

Fong T., Thorpe C., and Baur C., *Collaboration, Dialogue, and Human-Robot Interaction*, 10th International Symposium on Robotics Research, Lorne, Victoria, Australia, London: Springer-Verlag, 2002

Fong, T., Kaber, D., Lewis, M., Scholtz, J., Schultz, A., and Steinfeld, A., *Common metrics for human-robot interaction*, In Proc. IEEE Intl. Conf. on Intelligent Robots and Systems, Sendai, Japan, 2004

Fontaine G., *The experience of a sense of presence in intercultural and international encounters*, Presence, Vol. 1, No. 4, 1992

Forsman P., *Three-dimensional localization and mapping of static environments by means of mobile perception*, Helsinki University of Technology – Automation Technology Laboratory, Series A: Research Reports No. 23, November 2001, 145p

Glaskin M., *Does it walk? Does it roll? ... no it rolks*, New Scientist, Vol. 182, No 2443, 17 April, 2004

Goertz, R.C., *An experimental head controlled television system to provide viewing for a manipulator operator*, Proceedings of 13th RSTD Conference, 1965

Halme A., Suomela J., Rintala N., Savela M., *Liikkuuko-projekti: Liikkuvan työkoneen etäohjausasema*, Loppuraportti, Interim Report, 1997, 24p

Heinzmann J., Zelinsky A., *Visual human-robot interaction*, 3rd conference on Field and Service Robotics (FSR2001), Helsinki Finland, June 11-13, 2001

Held R.M., Durlach N.I., *Telepresence,* Presence, Teleoperations and Virtual Environments, Volume 1, Number 1, 1992

Honda, (online), *Asimo*, 2004, [Referred 12.8.2004], available in http://world.honda.com/ASIMO/

Hu H., Yu L., Tsui P.W., Zhou Q., *Internet-based Robotic Systems for Teleoperation*, International Journal of Assembly Automation, Vol. 21, No. 2, 2001

Huang H., Messina E., Albus J., *Toward a Generic Model forAutonomy Levels for Unmanned Systems (ALFUS)*, Proceedings of the NIST Performance Metrics for Intelligent Systems Workshop, Gaithersburg, MD, USA, September 16-18, 2003a

Huang H., Messina E., Albus J., *Autonomy Level Specification for Intelligent Autonomous Vehicles: Interim Progress Report*, Proceedings of the Performance Metrics for Intelligent Systems (PerMIS) Workshop, Gaithersburg, MD, September 16-18, 2003b

Husqvarna, (online), *Husqvarna Solarmower*, 2.4.1998, [Referred 12.8.2004], available in http://www.solarmower.com/

Ice hockey, (online), [Referred 12.8.2004], available in http://www.cc.jyu.fi/~ekkutvon/kasimerkit.htm

iRobot, (online), *Roomba*, 2004, [Referred 12.8.2004], available in http://www.irobot.com/consumer/

Jacoff A., Messina E., Weiss B.A., Tadokoro S. and Nakagawa Y., *Test Arenas and Performance Metrics for Urban Search and Rescue Robots,* Proceedings of the 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems, Las Vegas, NV, October 27-31, 2003

Jane's International Defence Review, *Self-powered exoskeleton assists human locomotion*, Vol. 37, May 2004

Judo, (online), *Referee Signals,* 23.2.2002, [Referred 12.8.2004], available in http://mysite.wanadoo-members.co.uk/no.1judosite/page8.html

Kolasinski E.M., Goldberg S.L., Hiller J.H., *Simulator Sickness in Virtual Environments*, Technical Report, 1027, U.S. Army Research Institute for Behavioral and Social Sciences, May, 1995

Kortenkamp D., Huber E., Bonasso R.P., *Recognizing and Interpreting Gestures on a Mobile Robot*, AAAI/IAAI, Vol. 2, 1996

Krauss R.M. and Hadar U., *The Role of Speech-Related Arm/Hand Gestures in Word Retrieval*, R. Campbell & L. Messing (Eds.), Gesture, speech, and sign. Oxford: Oxford University Press, 1999

KT-VA, (online), *Käsimerkit*, 25.9.2002, [Referred 12.8.2004], available in http://www.kt-va.org/tiedostot/kasimerkit.pdf

Laschi C., Miwa H., Takanishi A., Guglielmelli E., Dario P., "*Visuo-motor Coordination of a Humanoid Robot Head with Human-like Vision in Face Tracking*", Proceedings of the 2003 IEEE International Conference on Robotics and Automation, 2003

MIT Humanoid Robotics Group, (online), *Kismet,* [Referred 12.8.2004], available in http://www.ai.mit.edu/projects/humanoid-robotics-group/kismet/kismet.html

Miwa H., Okuchi T., Takanobu H., Takanishi A., *Development of a New Human-like Head Robot WE-4*, Proceedings of the 2002 IEEE/RSJ International Conference on Intelligent Robots and Systems, 2002

Nakamura K., *Deaf Resource Library*, 2002, [Referred 12.8.2004], available in http://www.deaflibrary.org/asl.html

Naruse K., Maeda T. and Kakazu Y., *Control of Power Assist Device by Bone Conducting Microphone*, In Proc. IEEE Intl. Conf. on Intelligent Robots and Systems, Sendai, Japan, 2004

Newscientist.com, (online), *New robot face smiles and sneers*, 17 February 03 [Referred 12.8.2004], available in http://www.newscientist.com/news/news.jsp?id=ns99993398

Parasuraman, Sheridan, T.B., Wickens, C.D., *A model for types and levels of human interaction with automation*. IEEE Transactions on Systems, Man, and Cybernetics, Vol 30, No 3, 2000

Oxford English Dictionary, (online), [Referred 12.8.2004], available in http://dictionary.oed.com/entrance.dtl

Philips, (online), *Speech Recognition Software Development Kits,* 5.4.2004 [Referred 12.8.2004], available in http://www.speechrecognition.philips.com/products/

Pulli R., Puputti J., Nurmi M., Suomela J., *Runko-ohjatun kaivoskoneen teleoperointimenetelmiä*, Automaatio 99 (Automation Days '99), Helsinki, Finland, August 14-16, 1999

Pulli R., *Kaivosautomaatio tänään - Koneet ilman kuljettajaa*, Automaatio 03 (Automation Days '03), Helsinki, Finland, September 9-11, 2003

Rogalla O., Ehrenmann M., Zoellner R.D., Becher R., Dillmann R., *Using Gesture and Speech Control for Commanding a Robot Assistant,* Proc. of the 11th IEEE Int. Workshop on Robot and Human interactive Communication, ROMAN2002, Berlin, Germany, September 25-27, 2002

SacDelta.com, (online), *International Marine Signal Flags*, 2004, [Referred 12.8.2004], available in http://www.sacdelta.com/signal-flags.htm

Schloerb D.W., *A quantitative Measure of Telepresence*, Presence, Vol. 4, No. 1, 1995

Scholtz J., Antonishek B. and Young J., *Evaluation of Operator Interventions in Autonomous Off-road Driving*, Proceedings of the NIST Performance Metrics for Intelligent Systems Workshop, Gaithersburg, MD, USA, September 16-18, 2003

Schulte J., Rosenberg C., Thrun S., *Spontaneous, Short-term Interaction with Mobile Robots,* Proc. IEEE International Conference of Robotics and Automation, ICRA, 1999

Sheridan T.B., *Telerobotics, Automation, and Human Supervisory Control*, The MIT Press, 1992a

Sheridan, T.B., *Musings on Telepresence and Virtual Presence*, Presence, Teleoperations and Virtual Environments, Volume 1, Number 1, 1992b

Siemens, (online), *Welcome at SINAS - Navigation system for autonomous service robots*, 27.03.2003, [Referred 12.8.2004], available in http://www.ad.siemens.de/sinas/index_76.htm

Sony, (online), *Aibo, Your Artificial Intelligence Companion*, [Referred 12.8.2004], available in http://www.aibo-europe.com/

Spiliotopoulos D., Androutsopoulos I. and Spyropoulos C.D., *Human-Robot Interaction Based on Spoken Natural Language Dialogue*. Presented at the European Workshop on Service and Humanoid Robots (Servicerob 2001), Santorini, Greece, 2001

Suomela J., *Telepresence aided teleoperation of semi-autonomous work vehicles*, Licentiate Thesis, Helsinki University of Technology, 2001

Suomela J., Halme A., Lappi E., Saarinen J., Soutuliikettä edistävä laitteisto ja menetelmä soutuliikkeen vahvistamiseksi, An equipment to improve oar movement and a method to assist the power of rowing, Finnish Patent, No: 111152, 2003

Tachi, S., Arai, H. & Maeda. T., *Development of Anthromorphic Tele-existence Slave Robot,* Proceedings of the International Conference on Advanced Mechatronics, Tokyo, 1989

Tachi S., *Telecommunication, Teleimmersion and Tele-existence*, Ohmsha Ltd., 2003, 163p

Takanishi Laboratory, (online), *Emotion Expression Humanoid Robot WE-4R (Waseda Eye No.4 Refined)*, 15.12.2003, [Referred 12.8.2004], available in http://www.takanishi.mech.waseda.ac.jp/eyes/index.htm

Theis C., Iossifidis I. and Steinhage A., *Image Processing Methods for Interactive Robot Control*, In Proc. of the 10th IEEE Inter. Workshop on Robot-Human Interactive Communication (ROMAN'01), Paris, France, 18 - 21 September, 2001

Thrun S., Bennewitz M., Burgard W., Cremers A.B., Dellaert F., Fox D., *MINERVA: A Second-Generation Museum Tour-Guide Robot,* Proceedings of the IEEE International Conference on Robotics and Automation (ICRA), 1999

Thrun S., Schulte J., Rosenberg C., *Interaction with mobile robots in public places,* IEEE Intelligent Systems, July/August, 2000

ToyotaOffRoad.com, (online), *Toyota's Telematic, Telepathic "POD" Smiles, Cries And Wags Its Tail At Chicago Auto Show*, 2.6.2002, [Referred 12.8.2004], available in http://www.toyotaoffroad.com/Articles/Toyota/POD/toyota_pod.htm

The University of Texas in Dallas, (online), *David Hanson*, 2003, [Referred 12.8.2004], available in http://iiae.utdallas.edu/projects/hanson.htm

U.S. Air Force, (online), *Predator Unmanned Aerial Vehicle (UAV), USA,* [Referred 12.8.2004], available in http://www.airforce-technology.com/projects/predator/

UsabilityNet, (online), *What is usability?,* 2003, [Referred 12.8.2004], available in http://www.usabilitynet.org/management/b_what.htm

Vainio, M. *Intelligence through interactions - underwater robot society for distributed operations in closed aquatic environment*. Helsinki University of Technology – Automation Technology Laboratory, Series A: Research Reports No. 21, November, 1999, 131p

Waldherr S., Thrun S., Romero R., Margaritis D., *TemplateBased Recognition of Pose and Motion Gestures On a Mobile Robot,* Proceedings of the AAAI Thirteenth National Conference on Artificial Intelligence, AAAI'98, 1998

Vertut J., Coiffet P., *Teleoperation and Robotics Evolution and Development*, Robot Technology Volume 3A, Kogan Page, 1985

Williams T.W., *One-Muscle Infant's Myoelectric Control*, Journal of Association of Children's Prosthetic Orthotic Clinics, Vol 24, Number 2, 1989

Witmer B.G. and Singer M.J., *Measuring Presence in Virtual Environments: A Presence Questionnaire*, Presence, Vol. 7, No. 3, June 1998

Yanco H.A., Drury J.L., Scholtz J., *Beyond Usability Evaluation: Analysis of Human-Robot Interaction at a Major Robotics Competition*, To appear in the Journal of Human-Computer Interaction, 2004

Zeltzer D., *Autonomy, Interaction and Presence*, Presence, Teleoperations and Virtual Environments, Volume 1, Number 1, 1992