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Robotics and Machine Perception

Audio-feedback experiments on Engineering Test Satellite VII and its assessment using eye-mark recorder

We get a lot of information from sound, not only from verbal utterances but also non-verbal sounds and noise. Consider the case of turning the ignition key in a car. How do you know the engine has started normally? Perhaps by the sound it makes: an engine emitting an unusual sound or noise is usually not functioning normally. Moreover you probably received information about the engine cycle aurally before you looked at the tachometer.

Audio information has fascinating features that make it potentially useful in man-machine interfaces. In particular, it can be acquired without attention, which is not true of visual information (at least the sort of information that is intentionally displayed on an interface). Humans notice changes and the tendency of change in the tone of a continuous sound very easily. Sound also increases the sense of reality and presence we get from an interface system (if we use realistic noises or sounds).

Our research is on the effect of adding meaningful sound to the operator interface of space robots operated from the ground. From 1998 to 1999, we performed more than 50 teleoperation experiments on Engineering Test Satellite VII, which was launched in 1997 and is the first telerobotic satellite developed by the National Space Development Agency of Japan. The operation of space robots is a stressful task that is dominated by concerns about safety and reliability. Collisions are the biggest worry; they may damage the robot and/or other equipment, and damaged equipment is inevitably very expensive to repair in space (and often cannot be repaired).

In particular, for safe operation of a space robot, operators must quickly analyze large amounts of information about the targets and rapidly make accurate decisions about how to proceed. The majority of this information is presented by visual cues, such as digital values, status displays, 3D computer simulations, and camera images. Complex recognition tasks that carry either high risk or huge stakes make the operator's job even more stressful and increase the likelihood of misrecognition and misoperation.

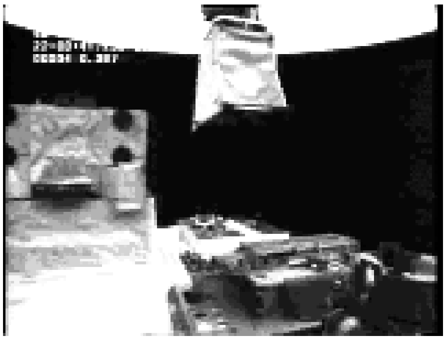

Figure 1. Downlink image during experiments on Engineering Test Satellite VII.

Based on these considerations, we thought that audio feedback could reduce operator workload and improve the reliability of space-robot teleoperation procedures. We developed an audio feedback system (AFS) to present telemetry information. It uses three computers. Computer A analyzes the telemetry data and detects changes in the status information of the robot and other equipment (for example, robot starting to move or AAM latch opening). These changes are announced by pre-recorded voices to verify the commands.

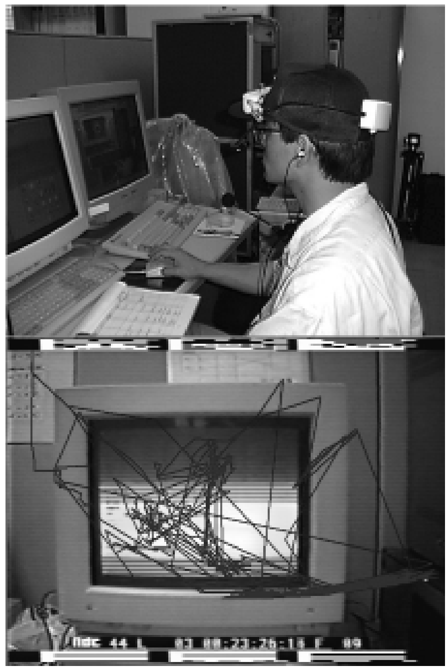

Figure 2. Experiment using Eye Mark Recorder and its readout image.

Computer B analyzes the telemetry data and detects the magnitudes of the force and torque

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Guest Editorial

Remote control of physical systems by humans through the mediation of computers has been a fascinating topic for scientists and engineers for almost four decades. Depending on the field of application and the technology involved, different terms were coined to describe the process of controlling a system at a remote site: teleoperation, tele-robotics, tele-service or telepresence are just the most often repeated terms. In the early years the development was mainly driven by space, underwater, and automation applications for hazardous areas, but especially in the recent five years, different factors have led to an increasing number of applications. The first important factor was the exponentially growing computational power, enhanced control algorithms, and new mechatronic sensors and actuators which made it possible to actively enhance the operator's—visual, acoustical and haptic—perception of the remote location; new qualities of man–machine interfaces originated from these developments. The second important factor for the increasing number of applications is the broad availability of communication networks like the Internet. The Internet makes it a snap to access remote computers. It actually takes very little to deploy a remote system and make it available to many users over the Internet—not just for "fun and fame", but also for industrial, e.g., teleservice, applications.

All developments have the aim of introducing human perception, planning, and control into a technical process. Some people tend to consider this as just an intermediate step on the way to fully autonomous systems, but the contributions in this issue clearly show that the described technologies provide a new quality of cooperation and coexistence of humans and machines—where, of course, the human always keeps control. As we are now introducing the latest insights from the fields of human perception, sensing, and cognition into telepresence systems, we are not just making the automation part of such a system smarter but we are also laying the groundwork for a broad range of intuitively comprehensible man–machine interfaces. The articles in this issue cover this aspect from different viewpoints.

Multisensory feedback

To increase the sense of reality and presence in teleoperation systems is a major issue of current developments. Besides the stimulation of the visual sense by realistic computer graphical representations of virtual worlds, the stimulation of additional senses becomes very important—and the solutions become more and more effective. The paper by Schmidt/Kron/Kammermeier outlines the developments related to providing tactile feedback for the user's arm, hand, and fingers. Different devices are being used and versatile control strategies are being developed and implemented to allow users to "feel" virtual objects. Whereas this work aims at providing a realistic sensation of physical objects, Fong/Thorpe/Bauer use haptic feedback to teleoperate a vehicle. In this case, the forces felt are artificial force fields to support the precise driving of a vehicles; virtual forces here enhance the user's intuition. In a third paper on this topic, Kimura proposes to enhance teleoperation systems by a further sensual stimulation, by audio-feedback. Find out about the psychophysical background of his suggestion in this issue.

Projective Virtual Reality

Virtual reality used to be only about immersion and interaction; the papers by Hirzinger/Landzettel/Brunner and by Freund/Rossmann add the aspect of "projection." Allowing users to handle objects in the virtual world like they would do in the real world is just the basis; the key idea then is to automatically project these actions onto robots and other means of automation. This implies that robots make exactly the changes to the physical world that correspond to the changes the user made to the virtual world. The approaches presented in both papers are different, but the aims are the same: make the teleoperation of robots safe and easy!

The idea of controling a real-world device via a graphical user interface is also pursued by Tomatis/Moreau. They describe a comprehensive web interface used to control a mobile robot. The ideas presented are made complete by the work of Lane because he summarizes the results on the effect of time delay for the control of robot manipulators over long distances.

Space Exploration

The exploration of space has always been a driving force for the development of new ideas related to teleoperation. In their paper, Pirjanian/Huntsberger/Kennedy/Schenker look into the more distant future of planetary exploration where multiple rovers are to cooperate to explore planetary surfaces. Their ambitious plans are an inspiration and a driving force for the work in this field.

Teleoperated systems pioneered space, the planets, and the deep seas. The contributions to this newsletter show how the methods and tools are now evolving to make further pioneering more intuitive, more cost-effective, and also more fun. Please read and enjoy the authors' thoughts about the present and the future in this field.

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Editorial

Welcome to this special issue of the Robotics and Machine Perception newsletter.

Our guest editor, Dr Jürgen Rossmann of the Institute of Robotics Research in Dortmund, Germany, has assembled a focused perspective on recent advances in telemanipulation and telepresence technologies in the areas of Space, Industry, and the Internet. This issue illustrates the application of robotics and machine perception techniques in developing advanced cooperative man–machine systems. I would like to thank Jürgen for his efforts in the preparation of this special issue, and my thanks also to all of the authors for their contributions.

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A new telepresence approach through the combination of virtual reality and robot control techniques

Since 1990, the application of virtual reality (VR) techniques have been investigated at the Institute of Robotics Research, leading to the development of COSIMIR/VR, IRF's 3D simulation and virtual reality system. It has been established that the potential for new virtual-reality-based approaches to man-machine interfaces is extremely promising. Such techniques offer a means of conveying information about an automation system in an intuitive manner and can combine supervisory capabilities with new, intuitive approaches to the commanding of complex technical systems over long and short distances.

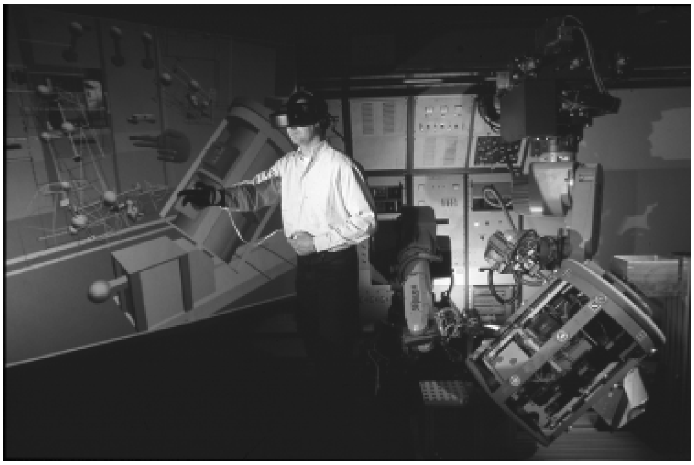

Figure 1. Telepresence by means of Projective Virtual Reality.

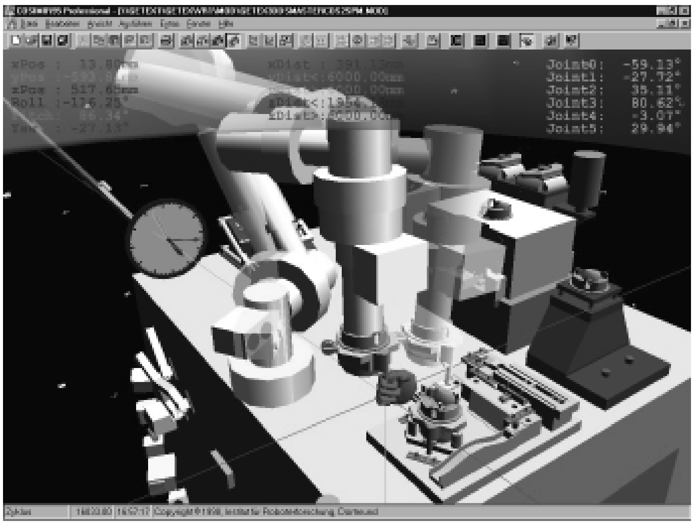

Figure 2. Teleoperation of the Japanese robot ERA on board the ETS VII satellite.

In this context, the new paradigm of *Projective Virtual Reality* has been realized as a sophisticated new approach to teleoperate and supervise robotic and automatic systems. The idea behind Projective Virtual Reality is to "project" actions that are carried out by users in the virtual world into the real world, primarily by means of robots but also by other forms of automation. Robot control technology thus provides the user in the virtual reality with a "prolonged arm" into the physical environment, paving the way for a new quality of a user-friendly man-machine interface for automation applications. Projective Virtual Reality is based on the latest results in the fields of task planning, world modelling, cooperative robot control and sensor-based robot control.

Figure 1 depicts the main idea of Projective Virtual Reality. A user is immersed into the virtual world by means of a data helmet and he interacts with the virtual objects by means of his data glove. All changes the user makes to objects in the virtual world are "evaluated" by means of a petri-net-based tracking technique that returns a high-level task description[1] like, "open heater" or "move sample from A to B" after the user has completed a task. This task description is then fed to a planning component that decomposes this task description into elementary actions and programs for the robots and automation devices involved. Using this task-oriented approach gets the user out of the real-time control loop, so that stability problems typically encountered when controlling systems over long distances do not arise. Figure 1 depicts a scenario where a user on the ground commands a robotic system: e.g. on board the Columbus module, the European contribution to the International Space Station (ISS). In such an application, the task-oriented approach has the further appeal that we can have multiple users in different virtual reality systems who all carry out tasks simultaneously. Each user thus generates task descriptions that are then sent to the planning system on board the module. The planning system then can let the robots work in a time-sharing mode for all users.

The realization shown in Figure 2 shows that the development of projective virtual reality has already left the state of laboratory experiments. In April 1999 it was used to realize the ground control station for the robot ERA on board the Japanese satellite ETS VII. This mission to control the first free-flying robot in space with our colleagues from Japan was a great success. It is described in greater detail elsewhere.[1]

In addition to being useful for commanding complex automation systems, Projective Virtual Reality also provides new features and ideas to intuitively supervise such systems. In order to make system information available "at a glance" to the user, different metaphors[1] were introduced to provide the user with important information. In Figure 1, the spheres inside the virtual robot are metaphors to visualize the robot's motor currents: at the robot's tip, a coordinate frame depicts the exerted forces and torques. In the ERA world shown in Figure 2, the numeric figures are displayed in a "visor-metaphor" (remember Geordie from the Start Trek: The Next Generation), and the translucent copy of the robot is a "look-into-the-future" metaphor—it always shows where the physical robot will be five seconds later.

Besides the two applications mentioned, Projective Virtual Reality is currently being using for different kinds of telepresence applications in space, and recently also for teleservice applications in manufacturing applications. Examples applications and more detailed descriptions can be found at our web-sites.

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References

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Intuitive haptic perception in virtual prototyping tasks

The Institute of Automatic Control Engineering (IACE) in the Department of Electrical Engineering and Information Technology at the Technische Universität München performs research in human-oriented robotics with a focus on haptic feedback technologies for multi-modal telepresence and telerobotic applications.

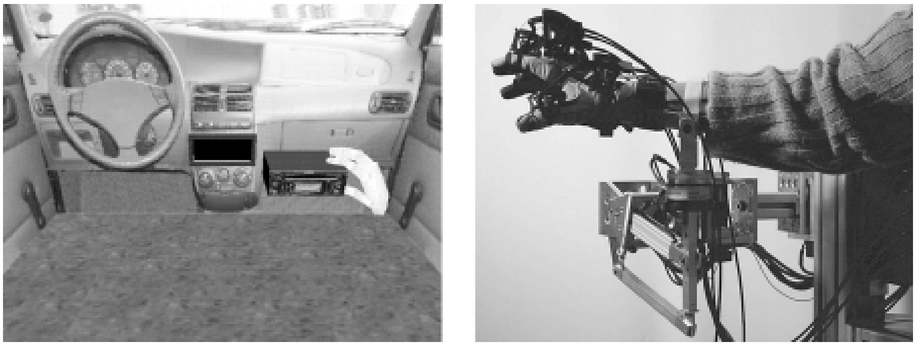

Figure 1. Multi-modal, multi-fingered installation of a virtual car radio.

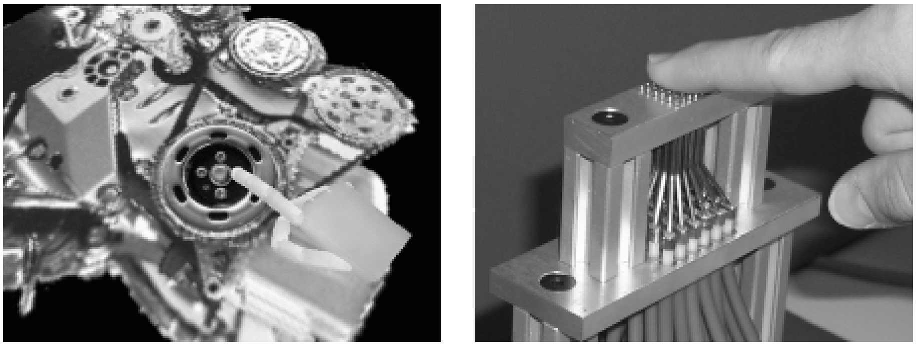

Figure 2. Tactile exploration of parts of a virtual car engine prototype.

Haptics for virtual prototyping

The need to lower time-to-market and reduce the development cost for physical prototypes has stimulated the demand for virtual prototyping techniques in the automobile and other industries. Today, highly developed 3D visualization systems are available for graphical display and animation of CAD objects or workpieces. Since such displays are constrained to the visual modality: spectators or human operators play a more or less passive role.

Because of this unsatisfactory situation, a major goal of current research in telepresence and telerobotics is to provide multi-modal sensory feedback to human operators. Technical setups in the human system interface have been developed for advanced haptic feedback and multi-fingered object manipulation. Applying this technology to virtual prototyping allows intuitive exploratory procedures to be performed: procedures that consist of more than just passively viewing an object.

Current haptic interfaces

Haptic displays, such as Sensable's PHANToM, have proven their usefulness for an improved understanding of object shapes and properties compared to vision-only systems. However, most available force-feedback systems only provide kinesthetic feedback with a single contact point for the whole hand. Devices with wider mechanical bandwidth, as e.g. the PHANToM or the Pantograph, are also capable of displaying high-frequency vibration in order to represent texture as one component of tactile information. This shift from kinesthetic to tactile display only refers to the corresponding frequency range of feedback signals in the spectrum of human haptic perception. Even if we assume ideal sensors and displays and an absolutely transparent overall system behavior, this kind of interaction only allows for an exploration "through" a rigid probe that is directly fixed to the end-effector of a kinesthetic display. Six-DoF force/moment reflection and line-based haptic rendering techniques take into account the shape of this probe.

Being restricted to touching objects through a single rigid probe, can provide a certain degree of haptic information to the human operator. However, he or she is forced to explore and manipulate objects in a not-entirely-intuitive manner. The objective of this research project is to overcome these restrictions by two major improvements: multi-finger kinesthetic feedback and distributed tactile feedback.[1]

Multi-finger kinesthetic feedback

Typical exploration and manipulation procedures carried out intuitively by humans imply the use of multiple fingers. Sampling of finger position/posture and independent force reflection to each finger enable the operator in an advanced virtual prototyping system to execute his/her intuitive motion patterns.

Besides allowing the operator intuitive finger/hand postures, a corresponding haptic feedback device must also display a multitude of forces such as varying contact forces, dynamic friction forces, or weight. This type of feedback helps to prevent the operator from penetrating objects with his/her fingers in the virtual prototyping environment.

The IACE has developed a combined Wrist Finger Kinesthetic Display (WFKD)[2] capable of displaying finger forces as well as wrist/arm forces. A commercial 5-DoF haptic glove is mounted as the end-effector on a desktop kinesthetic feedback device generating 3-DoF forces in 3D space (see Figure 1). The fixation of the lower part of the operator's arm behind the wrist allows for execution of intuitive motion patterns. Through this device, the operator can perceive separated force stimuli on fingers and wrist as a single high-fidelity force sensation. This could be demonstrated by an experiment simulating the insertion of a radio into a virtual car dash-board. In addition to visual information, the WFKD provides detailed feedback of all forces that occur during the operator's exploratory and manipulatory operations. The ability to perceive physical interactions leads to an increased degree of immersion and improved task execution.

Distributed tactile feedback

Haptic exploration means the simultaneous and consistent evocation and processing of kinesthetic and tactile information. Beyond vibration-representing textures, tactile perception comprises further components, such as small-scale shape information, that is considered to be crucial in haptic exploration tasks.

Actuator pin arrays have been proposed as a reasonable approach for representing a discrete approximation of a contact situation at

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Space exploration and the expanding domain of robotic telepresence

Figure 1. Transport of an extended container by two rovers in the arroyo at JPL. Left: Rovers in a column (offset) transport formation. Right: Rovers in a row (side-by-side) formation.

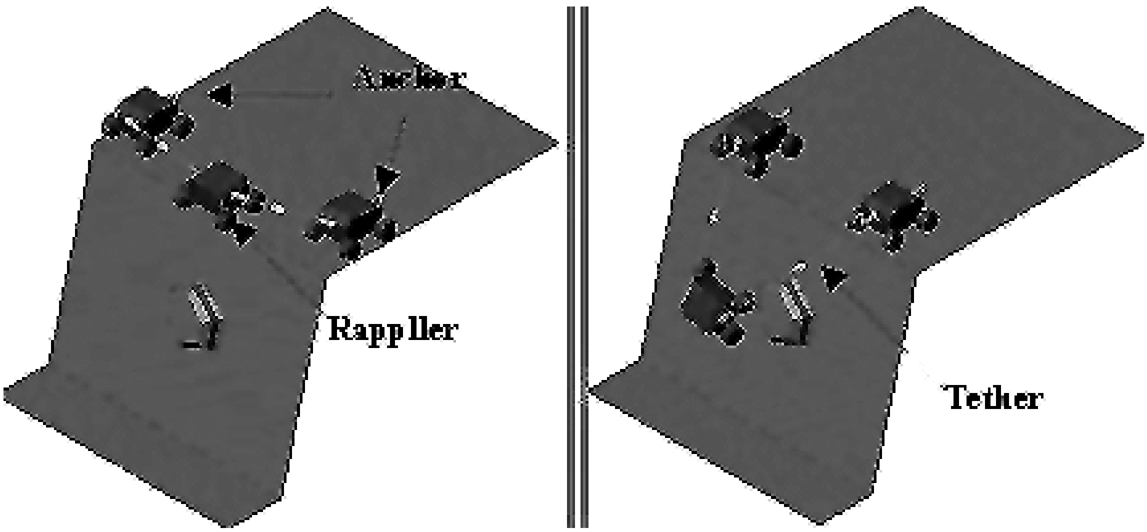

Figure 2. The All Terrain Explorer system concept for cliff descent.

The recent development of robotics technology for space has significantly elevated both the human and robotic roles.[1] Early teleoperative manipulation has progressed to high dexterity telerobotics wherein a remote human operator shares/trades controls with robot autonomy, often guided by virtual/augmented reality displays and sensor feedback. Complementing this, planetary/lunar surface vehicular capabilities are rapidly progressing from low-level programmed automation to longer-ranging semi-autonomous navigation, exploiting on-board machine perception, and reactive control, and simple deliberative planning for hazard detection, obstacle avoidance/management, target tracking, and science sample acquisition. These technology advances will migrate into near-future flight systems such as the planned Mars Exploration Rovers of 2003 and possible later highly anthropomorphic telerobotic work stations for shuttle/space station servicing.

Looking into the more distant future, the National Aeronautics and Space Administration (NASA) is considering missions that involve not one robot, but rather an extended telepresence based on multiple cooperating robotic agents. One example is planetary outposts, wherein robot work crews act to prepare and maintain a habitat for future shared human/robot presence. Thus, there is potential for a wide-ranging telerobotic functionality spanning autonomous cooperation of remotely operating, closely interacting robots, to a later human-robot synergy and community.

Within the Planetary Robotics Laboratory at the Jet Propulsion Laboratory, Pasadena, we are developing related autonomy technologies that can enable and significantly reduce the sustaining cost of deploying, operating, and commanding such complex missions. One such development is the Control Architecture for Multi-robot Planetary OUTposts (CAMPOUT), which is a distributed, hybrid, behavior-based system in that it couples reactive and local deliberative behaviors without the need for a centralized planner.[2] It provides facilities for behavior representation, behavior generation, inter-and-intra-robot behavior coordination, and communications infrastructure for distributed robot coordination to support not only cooperative but also tightly coordinated tasks. CAMPOUT constructs a methodological framework that builds on behavior-based synthesis, multiple objective decision theory, approximate reasoning, and symbolic planning.

During 2000, we successfully demonstrated a tight, kinematics-and-force-constrained cooperation between two prototype planetary rovers (see Figure 1), SRR (Sample Return Rover) and SRR2K, for transport of an extended payload 2.5 meters long over natural terrain. Neither of the rovers is capable of transporting this simulated PV (photovoltaic tent container) without assistance. The physical constraints imposed by the physical link between the rovers and the non-holonomy constraints of each rover make this task a real challenge, especially on natural ter-

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MARCO—DLR's task-directed sensor-based teleprogramming system

DLR's telerobotics concepts have been verified in two real space-robot projects, namely in our own project ROTEX—the first remotely controlled space robot flying inside shuttle COLUMBIA[1] in April 93—and in ETS VII, the first free-flying space robot developed by Japan's space agency NASDA.

Based on the ROTEX experience, we have focused our work in telerobotics on the design of a high-level task-directed robot programming system, MARCO, that may be characterized as learning by showing in a virtual environment.[2] This system is applicable to the programming of terrestrial robots as well. The goal (see Figure 1) was to develop a unified concept for:

- A flexible, highly interactive, on-line teleoperation station based on predictive ground simulation (including sensor-based local autonomy)
- An off-line programming environment. This includes all the sensor-based control and local autonomy features as tested already in ROTEX, provides the additional possibility of programming a robotic system on an implicit, task-oriented level.

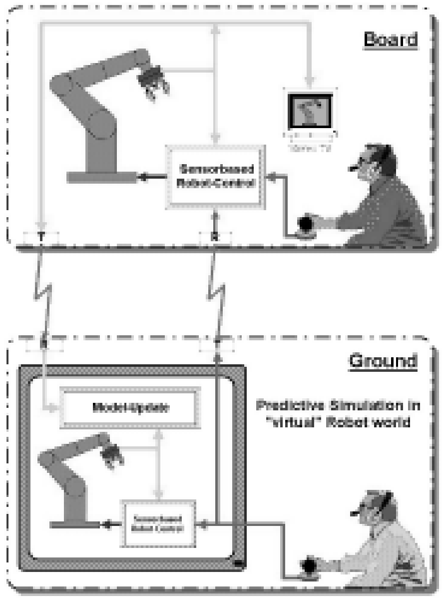

Figure 1. ROTEX telerobotic control concept.

A non-specialist user—e.g. a payload expert—should be able to remotely control the robot system in case of internal servicing in a space station (i.e. in a well-defined environment). However, for external servicing (e.g. the repair of a defect satellite), high levels of interactivity between man and machine are desirable. To fulfil the requirements of both applications, we have developed a 2-in-2-layer-model that represents the programming hierarchy from the executive to the planning level (see Figure 2).

planning

Task	implicit layer
Operation	
Elemental Operation	explicit layer
Sensor Control Phase	

execution

Figure 2. The 2-in-2-layer-model.

Based on this four-level hierarchy,[3] an operator working on the (implicit) task level no longer needs real robotic expertise. With a 3D cursor (controlled by a space mouse) or with a human-hand-simulator (controlled by a data glove) he picks up any desired object in the virtual world, releases it, moves it to a new location, and fixes it there. Sequences of these kind of operations are easily tied together as complex tasks. Before they are executed remotely, the simulated robot engaging its path planner demonstrates how it intends to perform the task (implying automatic collision avoidance). See Figure 3.

Nevertheless in the explicit layer (the learning phase) the robot expert has to show and demonstrate the elementary operations (these include the relevant sensory patterns) and, if necessary, train the mapping between non-nominal sensory patterns and motion commands that servo into the nominal patterns later on, in the real world. He performs these demonstrations by moving the robot's simulated gripper or hand (preferably without the arm) into the proximity of the objects to be handled (e.g. drawers, bayonet closures, doors in a lab environment), so that all sensory patterns are simulated correspondingly. The robot expert, at this stage, must have knowledge of position- and sensor-controlled subspaces, and must be able to define them, massively supported by MARCO function. He also has to define how operations (e.g. remove bayonet closure) are composed of elementary operations (approach, touch, grasp, turn etc.).

MARCO's two-handed VR interface concept

Thus, on the implicit as well as on the explicit layer statement, we have to move 3D-pointers or grippers / hands around in the virtual lab environment. Using classic "immersive" cyberspace techniques with data-glove and helmet were not adequate for our approach, as the human arm's reaching space is fairly small (e.g. in a lab environment). Also, with head motions, only very limited translational shifts of the simulated world are feasible. An alternative to the position control devices, the data-glove and helmet, is the velocity control device: the space mouse. This is particularly true if the robot system to be programmed has no articulated hand. Velocity control here means we may easily steer around an object in VR, over arbitrary distances and rotations, via small deflections (which command velocities) of an elastic sensorized cap. Another important point (confirmed by extensive tests of car manufacturers in the context of 3D CAD-design) is that, just as in real life, two-handed operations—when interacting with 3D-graphics—are the optimum. Indeed, whenever humans can make use of both hands, they will (e.g. when carving, modelling, cutting). In the northern hemisphere, the right hand is the working hand for around 90% of the population. The left hand is the guidance and observation hand, which holds the object to be worked (vice versa for left-handers).

This ideal situation for a human is easily transferred to the VR interface scenario. A right-hander preferably moves around the whole virtual world in 6-DoF with a space mouse in his left hand (the guidance hand). At the same time his right hand moves around the 3D cursor with a second space mouse (velocity control) or a simulated hand with a data glove (position control). One should note that now, even for the glove, the problem of limited workspace disappears. With the left hand, the operator is always able to move the virtual lab world around such that the objects to be grasped are very close. Thus, even in position-control mode with a data glove, only small, convenient motions of the operator's

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Active interfaces for vehicle teleoperation

Since 1997, the Robotics Institute of Carnegie Mellon University and the Virtual Reality and Active Interfaces (VRAI) Group[1] of the Swiss Federal Institute of Technology have been developing tools and technology for vehicle teleoperation. The goal of our collaboration is to make such teleoperation easier and more productive for all users, novices and experts alike. Thus, we have developed a variety of active interfaces incorporating sensor-fusion displays, gesture and haptic input, personal digital assistants, and the wwweb.[2,3]

Sensor fusion displays

Perhaps the most difficult aspect of vehicle teleoperation is that the operator is unable to directly perceive the remote environment. Instead, he is forced to rely on sensors, bandwidth-limited communications links, and an interface to provide him with information. As a result, the operator often fails to understand the remote environment and makes judgement errors. Thus, we need to make it easier for the operator to understand the remote environment, to assess the situation, and to make decisions.[4]

Our approach is to develop sensor fusion displays that combine information from multiple sensors or data sources to present a single, integrated view. These displays are important for applications in which the operator must rapidly interpret multispectral or dynamic data. Figure 1 shows an example in which lidar, stereo, and ultrasonic sonar range data are fused.[5] This display is designed to direct the operator's attention to close obstacles and to improve situational awareness in cluttered environments.

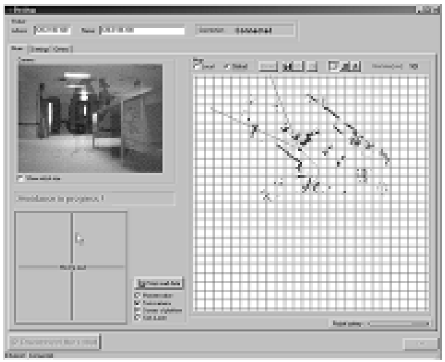

Figure 1. Sensor fusion display incorporating lidar, stereo vision, and sonar range data.

Gesture and haptic input

Almost all teleoperation interfaces rely on input devices such as joysticks or two-dimensional computer pointers (mouse, pen, etc.). One problem with this approach is that the human-machine interaction is essentially static: the form and range of input is limited to physical device properties. With computer vision, however, we can create gesture-based interfaces that provide flexible, user-adaptive interaction. Moreover, since the interpretation is software-based, it is possible to customize input processing to minimize sensorimotor workload, to accommodate operator preferences, and to adapt to the task/operator in real-time.[3]

GestureDriver is a remote driving interface based on visual gesturing (see Figure 2). Hand motions are tracked with a color and stereo vision system and classified into gestures using a simple geometric model. The gestures are then mapped into motion commands that are transmitted to the remote vehicle. In our testing, we found that GestureDriver works well almost anywhere within the vision system's field of view. Thus, users were free to move about when they were not directly commanding the robot. Additionally, GestureDriver was able to easily accommodate users of different sizes and with different control preferences.

Figure 2. GestureDriver: a visual, gesture-based interface for vehicle teleoperation.

Figure 3. HapticDriver provides force feedback for precision driving tasks.

The most difficult aspect of remote driving, as with all teleoperation, is that the operator is separated from the point of action. As a result, he must rely on information from sensors (mediated by communication links and displays) to perceive the remote environment. Consequently, the operator often fails to understand the remote environment and makes judgement errors. This problem is most acute when precise motion is required, such as maneuvering in cluttered spaces or approaching a target.[3]

HapticDriver addresses this problem by providing force feedback to the operator (see Figure 3). Range-sensor information is transformed to spatial forces using a linear model and then displayed to the operator using a large-workspace haptic hand controller (the Delta Haptic Device). Thus, HapticDriver enables the operator to feel the remote environment and to achieve better performance in precise driving tasks.

Personal interfaces

For some remote driving applications, installing operator stations with multiple displays, bulky control devices and high-bandwidth/low-latency communication links is infeasible (or even impossible) due to environmental, monetary, or technical constraints. For other applications, a range of operators having diverse backgrounds and skills drive the vehicle. In these situations, extensive training is impractical and we need interfaces that require minimal infrastructure, can function with poor communications, and do not tightly couple performance to training.

PdaDriver is a PDA-based interface for vehicle teleoperation and is shown in Figure 4. PdaDriver uses multiple control modes, sensor-fusion displays, and safeguarded teleoperation to make remote driving fast and efficient. We designed the PdaDriver user interface to minimize the need for training, to enable rapid command generation, and to improve situational awareness. The current interface is has four interaction modes: video, map, command, and sensors (see Figure 4). We have conducted a number of field tests with the PdaDriver and found the interface to have high usability, robustness, and performance.[3]

To date, we have created two Web-based systems: WebPioneer and WebDriver. The WebPioneer (developed in collaboration with ActivMedia Inc.) enables novices to explore an indoor environment. The WebPioneer, however, requires significant network resources and only provides a limited command set. We designed our second system, WebDriver, to address these problems. In particular, WebDriver minimizes network bandwidth usage, provides a dynamic user interface, and uses waypoint-

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Time delay and communication-bandwidth limitation on telerobotic control

Remote teleoperation allows humans to extend their capabilities to environments too dangerous for biological organisms. The communication between the operator and the robot needs to be fast in order to accommodate quick interaction with the environment. However, certain remote environments, such as deep-sea and space operations, impose restrictions on the communication link that limits the available bandwidth. In addition, as the distance increases, the communication between the operator and robot is further handicapped by significant time delays.

The experiment

A simulation was developed (see Figure 1) allowing an operator to control a 7-DoF manipulator to perform a manipulation positioning task. The task was to pop a target sphere with the tip of the manipulator that was commanded using a Cartesian rate controller using a pair of 3-DoF hand controllers. The operator switched between three fixed views to perform the task. The default view was an overall shot of the arm and work site, useful for coarse positioning of the manipulator. As the tip neared the target sphere, one of the two orthogonal views could be used (a side or top view) to help perform the final movements.

Four independent variables were altered during testing: time delay, the use of predictive displays, the communication bandwidth, and the manipulator velocity. Four different round-trip time delays were chosen that the operators could feasibly handle: 0s, 1.5s, 3s, and 6s. During preliminary testing, it was determined that, at 3s and 6s time delay, some form of predictive display was required to assist the operator. Three display methods were compared: an unmitigated display showing only the telemetry of the actual position, one with an added predictive display that estimated where the manipulator would move after the delay, and one that commanded the joints to move to the position as shown using an additional commanded display. Since the predictive and commanded displays were used to reduce the effects of time delay, they were only used during time-delayed treatments. The communication bandwidth between the ground and space is limited: it is, therefore, advantageous to limit the number of commands sent to the robot. Four sampling rates were used as treatments: the baseline rate (20Hz), half rate (10Hz), quarter rate (5Hz), and one-eighth rate (2.5Hz). The maximum velocity of the manipulator tip was also altered testing 6in/s and 1.3in/s.

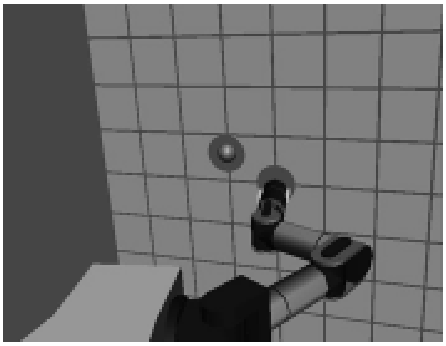

Figure 1. Modified Fitts1 law task screenshot with exaggerated size sphere.

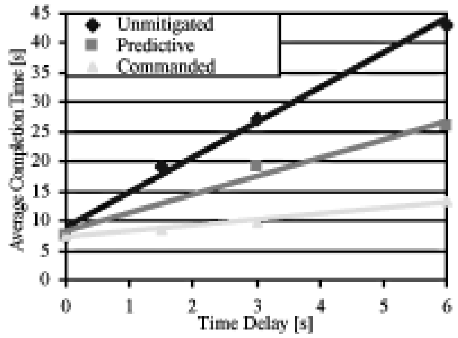

Figure 2. Linear correlation of time delay and completion time.

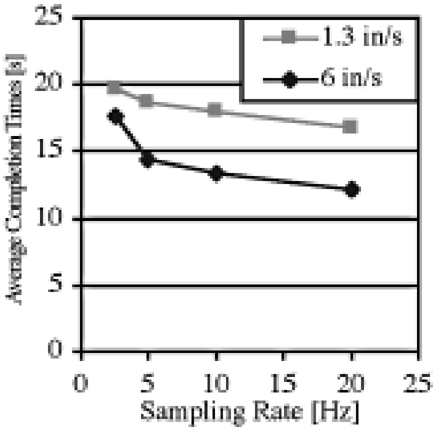

Figure 3. Comparing 1.3in/s and 6in/s manipulator speeds for changing sampling rate curves.

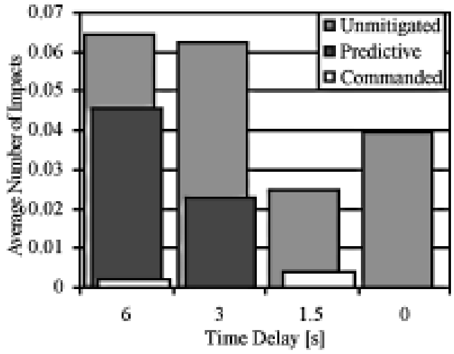

Figure 4. Number of impacts at 6in/s manipulator speed.

Results

The strongest effect on task completion time was time delay, up to a 480% increase at 6s. Figure 2 distinctly shows that completion time increases linearly with time delay. Each display method is affected by time delay differently, but all have this linear correlation. The slope of the commanded display, in Figure 2, is less than one: therefore the commanded display made up for the additional time delay. While still helpful for alleviating the time-delay effect, the predictive display was only half as effective as the commanded display. Calibration errors between the predictive display's estimated position and the actual position made the predictive display less helpful. It would be expected that any error causing a deviation between the commanded/predictive and actual output would reduce the effectiveness of the extra display. However, even with moderate errors, the predictive display still reduced the completion time considerably.

Command sampling rate was a less important factor in influencing performance. As can be seen in Figure 3, only a minor difference was found by cutting the rate in half from 20Hz to 10Hz. However, at around 5Hz, a break point was reached and performance becomes more affected by a reduction of sampling rate. More testing would likely show that further reduction of the sampling rate from 2.5Hz would significantly increase completion time.

The least influential factor was the change in manipulator velocity. It can be seen from Figure 3 that the 1.3in/s sampling rate curve is flatter when compared to the faster manipulator speed. The flatter shape of the sampling rate curve, which can be seen in Figures 16 and 17, indicates that sampling rate has less effect on the slower manipulator speed. On average, the slower manipulator speed increased the completion time by about 27%.

Overall, very few impacts were made on the work site. On average, an impact would occur

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Audio-feedback experiments

continued from cover

on the end-effector. These values are converted into MIDI tone signal commands and are transmitted to the audio sampler. A sound source of motor noise is stored in the audio sampler, and the audio sampler generates the motor noise according to the magnitudes of the force and torque. We examined several kinds of sound sources and found motor noise to be the most feasible and realistic.

Computer C analyzes the command data and detects the transmission of the command to the robot. Mac 5 announces the type of the command. This information can be used to check that the proper command was transmitted.

We chose an objective and psychophysical assessment of the AFS, the eye mark recorder (EMR), which can record an operator's eye movements in response to very small stimuli. As far as we know, this is the first experiment to deal with psychophysical phenomena during the teleoperation of space robots on board a space craft. It is important to assess the psychophysical phenomena during actual satellite operation, since the psychophysical state during actual operation is different from that of simulation-based training, even if the experimenter and operator try to maintain the same conditions.

From the experiments we found the following results.

- Operation time can be significantly reduced, and the operator can easily avoid collisions.
- The operator didn't have to concentrate on the telemetry console and thus was free to monitor other items.
- The spectrum patterns of eye movement velocity reflect the expertise level of the operators.
- The spectrum of a well-trained operator changes from a naive operator's spectrum to an astronaut's spectrum when using the AFS.

These results suggest that the audio feedback system aids in teleoperation of space robots and that the eye mark recorder is a unique and effective tool to assess interface systems.

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MARCO—DLR's task-directed sensor-based teleprogramming system

continued from p. 6

hand are required (see Figures 4 and 5).

More details on MARCO's high level user interface and Java/VRML client techniques are given in Reference 4 (see Figure 6).

The sensor-based task-level-teleprogramming system, MARCO, has reached a high level of universality. It was not only used as a ground-control station for the ETS VII experiment, but it is also being studied for Germany's Experimental Service Satellite ESS project, for remote ground-control of a new, climbing, space-station robot, and for mobile terrestrial and planetary robot projects.

Figure 3. DLR's universal telerobotic station MARCO (Modular A&R Controller).

Figure 4. Two handed VR-interface using space mouse and data glove (space-station scenario as example).

Figure 5. Two-handed VR interface using two space mice (ETS VII scenario as example).

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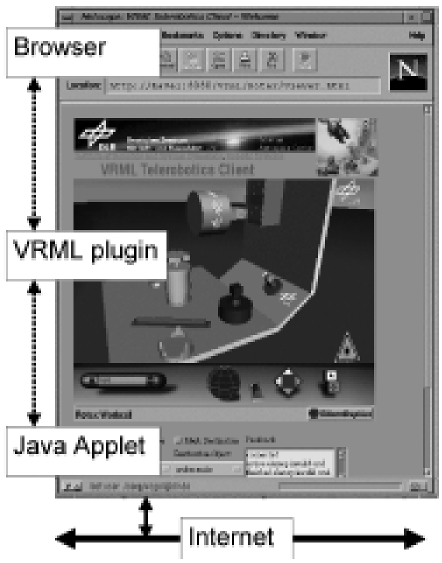

Figure 6. Internet-programming with VRML /3D Java.

Intuitive haptic perception in virtual prototyping tasks

continued from p. 4

the human fingertip. However, the ideal specification profile for such an array (which can be derived from physiological and biomechanical as well as task-oriented data) poses severe challenges in system design. The IACE has developed an actuator array with extraordinarily high pin forces and mechanical bandwidth[3] that is used for tactile representation of the interaction between the operator's fingertip and stiff objects in virtual prototyping tasks. Experiments have been performed with respect to detailed haptic exploration of an automobile engine (see Figure 2). In this scenario, the operator can examine the head of a screw to be fixed, judge the quality of workmanship at the edge of a workpiece, or localize a visually-occluded marker that indicates the assembly-rotation of a pulley.

Perspective

The benefits of including the proposed advanced haptic feedback technologies in virtual prototyping environments have been demonstrated in various laboratory experiments. Beyond the automobile industry, potential applications of this technique can be found in other industrial areas, as well as in medical simulation and education.

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Active interfaces for vehicle teleoperation

continued from p. 7

based safeguarded teleoperation. WebDriver differs from other web-based driving because it is highly effective in unknown, unstructured, and dynamic environments.[6]

Future work

We believe that our tools and technologies are well-suited for tasks such as remote exploration. Thus, we are planning to apply our research to the exploration of planetary surfaces. In the next year, we intend to develop user interfaces that enable EVA crew members (e.g., suited geologists) and mobile robots to collaborate and jointly perform tasks such as surveying, sampling, and *in-situ* site characterization.

This work is partially supported by the DARPA ITO Mobile Autonomous Robot Software program (SAIC/CMU task) and the Swiss Commission for Technology and Innovation (CTI project 4327.1). Contributors include Gilbert Bouzeid, Francois Conti, Sebastien Grange, Roger Meier, and Gregoire Terrien.

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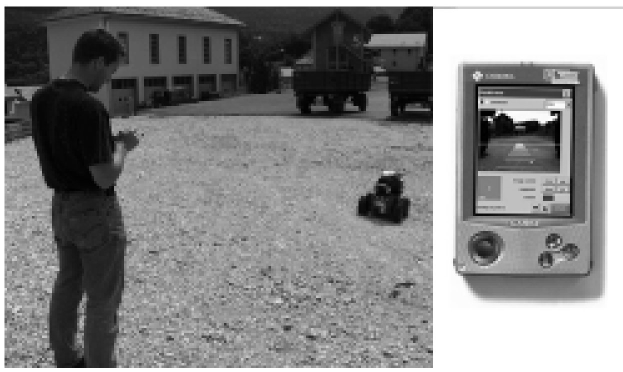

Figure 4. PdaDriver is a PDA-based interface for remote driving.

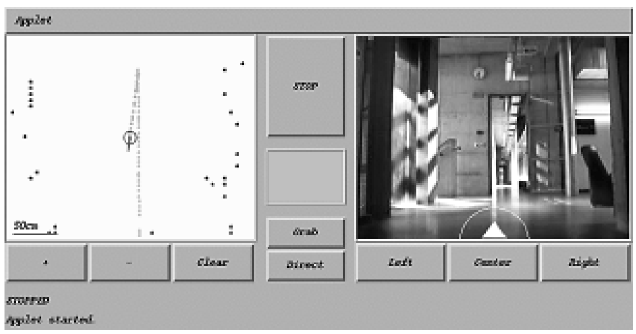

Figure 5. WebDriver enables safeguarded vehicle teleoperation via the wwweb.

Time delay and communication-bandwidth limitation on telerobotic control

continued from p. 8

0.04 times per trial, or about once in every 25 attempts at popping a sphere. More evidence showing the usefulness of the commanded display was that the number of impacts was significantly lower. When using the commanded display, the number of impacts was reduced by 95%. Operations using the commanded display were practically flawless. In all 1,440 sphere-popping trials conducted in the 6in/s manipulator speed study, impacts occurred only three times when using a commanded display. No significant difference in the number of impacts was found for the predictive display or due to changes in time delay. When the velocity was slowed from 6in/s to 1.3in/s, the probability of errors decreased by a third.

Conclusion

Each of the individual effects was ranked to determine which factors were most influential to performance. For completion times, the ranking of importance from most to least influential was the following: time delay and use of commanded display, sampling rate, and (finally) manipulator speed. A wider range of speeds may find that the manipulator speed would be more important. For number of impacts, the only conclusive effect was the use of a commanded display: all other factors had very little significance.

Continued research into determining what factors are most influential on user operation can be used to develop better interface applications to control robotics under adverse conditions. Creating an interface that is both easy to use and helpful in ameliorating time delay and communication bandwidth limitations will allow humans to effectively extend their capabilities to remote regions with the use of robotics.

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Web interfacing for task supervision and specification

continued from back cover

and correct.

- Crashes of one or more processes can cause a loss of information that would be important for the off-line analysis

On-line supervision (see Figure 1) is therefore an important tool for speeding up progress in research on applications such as mobile robotics by allowing on-line detection of characteristics of the tested approaches. Having access to the machine's perception permits us to identify the correspondence between the perception and behavior of the robot. This is done by visualizing sensory information on several levels of abstraction, using state-of-the-art web technology yielding a plug-in-free interface that can be viewed with a standard browser. It provides multi-modal information in several representations: off- and on-board vision, laser data, and odometry (see Figure 2).

This tool proved to be indispensable in the developing phase of navigation algorithms for localization, obstacle avoidance, and path planning.[3,4]

Specification

By performing public presentations and common experiments with distant labs, some limitations of our system become evident. Obscure in-line commands were used to control the robot and the only feedback was the robot behavior and some text output. This was not satisfying for people who were not familiar with this development and operating system. Including task specification in a graphical feedback interface, making the results of the robotics research accessible to potential end-users became a major aspect of the development.

For this, a means for controlling the robot—which was not a basic aim of the project—has been developed. This has been achieved by introducing modern guidelines for ergonomic interface design (like context-sensitive pop-up menus or clickable goal specification). Defining a navigation goal on a graphical interface by clicking on an image showing the known environment, makes the interface very intuitive for the end-user. In the same way, local goals near the current robot position can be defined on the image showing the neighborhood of the robot and the raw data from the laser scanner. Furthermore, the robot behavior can even be seen by distant users by means of external cameras (see Figure 2).

Its practicality has been extensively demonstrated at the 'Computer2000' exhibition, where the robot was remote-controlled using this interface for four days, in a fully autonomous mode, by visitors of the tradeshow.[2] The visitors defined 724 missions for the robot, which had to travel a total of 5.013km in order to fulfill them.

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A new telepresence approach

continued from p. 3

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Space exploration and the expanding domain of robotic telepresence

continued from p. 5

rain. However, we demonstrated that CAMPOUT provides the necessary autonomy functions to operate and command the two rovers as one single rover with capabilities for transportation of a PV tent.[3]

We are currently extending this work-scaling the concept—to develop techniques that enable command and distributed coordination of larger teams (three to tens) of agents for various space applications. As one example, the All Terrain Explorer[3] is a distributed/modular robotic system for access to high-risk, high-value locations such as cliffs, fissures, etc. This aggressive mobility platform will support operational functionality such as rappelling down a cliff, moving to a designated waypoint, and safe obstacle avoidance, all on a cliff wall (see Figure 2). The system concept consists of a tethered ensemble of three robotic entities; the rappeller, and two anchoring assistants, anchors, that will cooperatively direct and safely guide the rappeller to descend to way-points which are on the cliff-side and which are within the workspace defined by the tether lengths and the anchoring points. In this work we are using CAMPOUT to demonstrate elements including collective fused mapping, state estimation, and distributed controls.

Second, we have recently begun work in applying the same techniques for control and coordination of hundreds of satellites for tasks involving formation flying and collective data acquisition. CAMPOUT provides the core technology for a high degree of autonomy that is key to a cost-efficient deployment of such distributed satellite systems.

Finally, we note in passing an effort aimed at both planetary and orbital platforms: the LEMUR (Legged Excursion Mechanical Utility Robot)[5] (see Figure 3) is being developed by us as a highly dexterous system (22 independent degrees of freedom) for assembly, inspection, and maintenance operations. Sporting six limbs that can be used for both mobility and manipulation, much like a primate, LEMUR can be reconfigured using easily exchanged end effectors to perform different tasks. To date LEMUR has been equipped with gripper, hex-key driver, and visual inspection end effectors. Eventually, we expect to show cooperative behavior between LEMUR and heterogeneous platforms, in a manner related to the robot work crew activities described above.

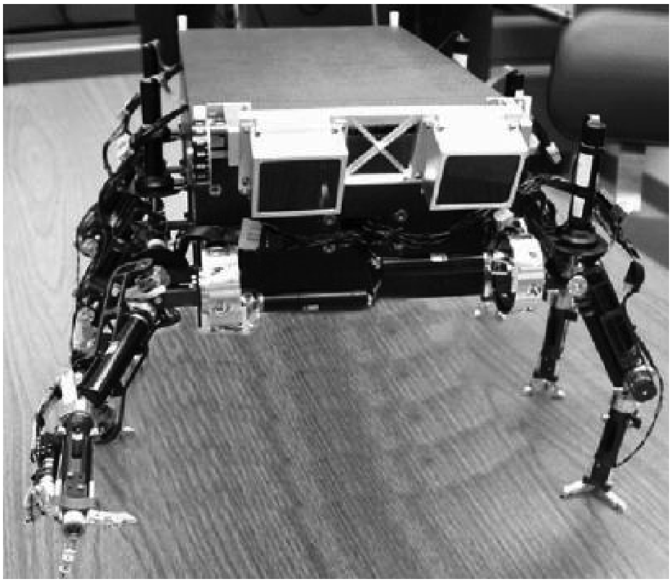

Figure 3. LEMUR with the right limb in manipulation configuration.

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Web interfacing for task supervision and specification

The Autonomous Systems Lab at the Swiss Federal Institute of Technology Lausanne (EPFL) is engaged in mobile robotics research. The lab's research focuses mainly on indoor localization and map building, outdoor locomotion and navigation, and micro mobile robotics. In the framework of a research project on mobile robot localization, a graphical web interface for our indoor robots has been developed.[1] The purpose of this interface is twofold: it serves as a tool for task supervision for the researcher, and for task specification for the end-user. Our indoor robots are fully autonomous systems based on the VME-bus standard with a six-axis robot controller carrying a PowerPC processor at 300 MHz. Among the various peripheral devices, they have three main sensors: the wheel encoders, a 360° laser range finder, and a CCD camera. The localization approach is feature based and uses an Extended Kalman Filter to integrate measurements from the encoders, the laser scanner, and the CCD camera. Features are infinite lines for the laser scanner and vertical edges for the vision system.

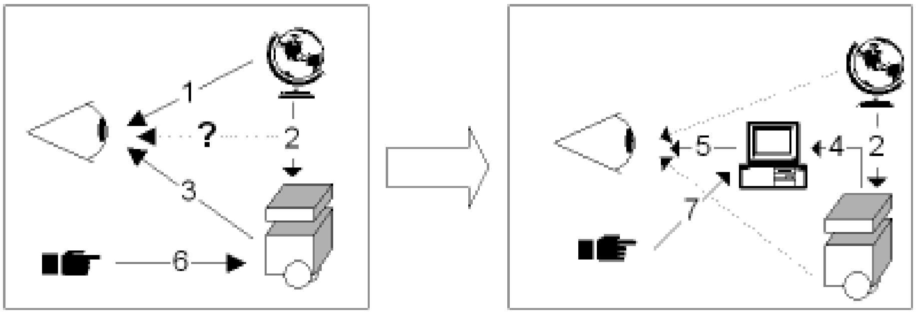

Figure 1. For research and development in mobile robotics, the correspondence between robot behavior (3) and robot perception (2) is very important. This correspondence is easier to understand by using on-line supervision, where robot perception is visualized using a graphical interface (4-5). 1: Human perception of the real world. 2: Machine perception of the real world. 3: Human perception of the robot behavior. 4: On-line transfer of the machine perception and machine states. 5: On-line visualization of the machine perception and machine states. 6: Human commands via in-line text commands. 7: Visual task specification.

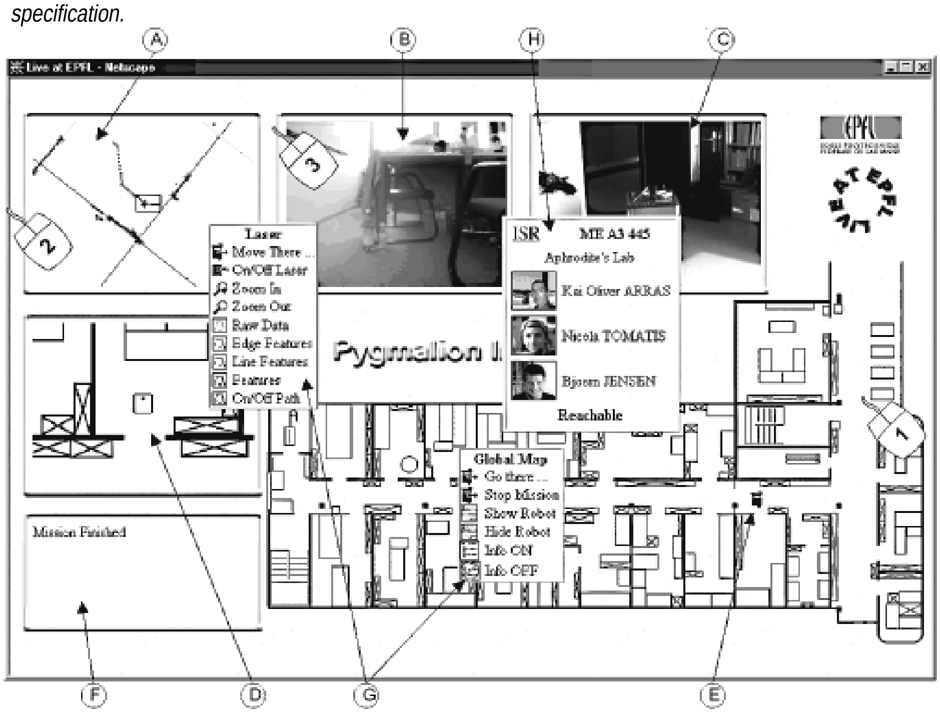

Figure 2. The web interface. A: Multi sensor localization monitor. B: On board video. C: External video. D: Local robot position (x,y,τ). E: Global robot position (x,y). F: Message window. G: Pop-up menu on each window to access corresponding functionality. H: Office information pop-up menu on global map. Numbered mice are possible way to control the robot. Mouse1: Set a room as new global goal. Mouse2: Set (x,y) as new local goal. Mouse3: Assign new orientation (τ).

Supervision

Testing algorithms like localization and obstacle avoidance on an autonomous self-contained robot[2] requires a means for the researcher to check the algorithmic reactions to the machine's perception of the world. However, the perceived data and the processing results remain embedded in the mobile vehicle until they are explicitly transferred to a local PC for analysis. This can be done by tracing the robot position (odometry), and by saving all the raw data from the sensors along with the extracted features and the results of each algorithm, then transferring this information when an experiment is finished. The analysis can then be performed off-board. Nevertheless, this procedure has several disadvantages:

- The correspondence between the behavior of the robot, and the data that caused this behavior, is difficult to identify.
- Critical states of algorithms that may cause a failure cannot be detected immediately before and are therefore difficult to isolate

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