TELE-PRESENCE INTERFACES FOR THE TELEOPERATIONS OF MOBILE ROBOTS

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Summary

The tele-operation of mobile robots offers challenging test scenarios for advanced tele-presence methods, ranging from space exploration to industrial tele-maintenance. The technology implementation for hardware and software in the different system components is summarized in this contribution, related to sensors and data processing on-board the vehicle, to the communication link via Internet and to the user interface for the teleoperator. In particular signal transmission delays and user interfaces with integrated virtual reality display and haptic feedback are analyzed. Results from tests characterizing the performance are presented.

1. Introduction

Robots are often the only way to explore and manipulate objects in hostile remote areas. Traditional applications areas are space exploration and processing plants for radioactive materials [3]. In this context for about 30 years advanced concepts for remote control approaches have been realized [13] on basis of combinations of information processing methods with control approaches to derive telepresence schemes supporting the human teleoperators [11], [1], [2].

The increasing capabilities of the telematics (telecommunication + informatics) infrastructure, in particular services provided via internet, enable nowadays a broad spectrum of commercially interesting applications, including telemaintenance of equipment in industrial production or tele-education based on remote experimental facilities [10]. For all these applications in the area of control there are concepts to be developed combining autonomous local control with telecommands from the remote operator.

This paper addresses in this context the use of virtual reality and haptic interfaces to provide a user-friendly man-machine interaction, visualizing the sensor data and using sensor data preprocessing to reduce the amount of data to be transferred. These methods are discussed in the specific application area of mobile robots. Such vehicles are often used for exploration and monitoring tasks in poorly known environments [10].

2. The MERLIN Rovers and the Tele-operations Infrastructure

In the framework of the European Space Agency's Mars rover development effort MIDD (Mobile Instrument Deployment Device) [8] the MERLIN-vehicles were initially developed as a platform for sensor and navigation tests, as well as for testing various tele-operations scenarios [7]. This vehicle infrastructure is still used as concrete application example in research on tele-presence systems.

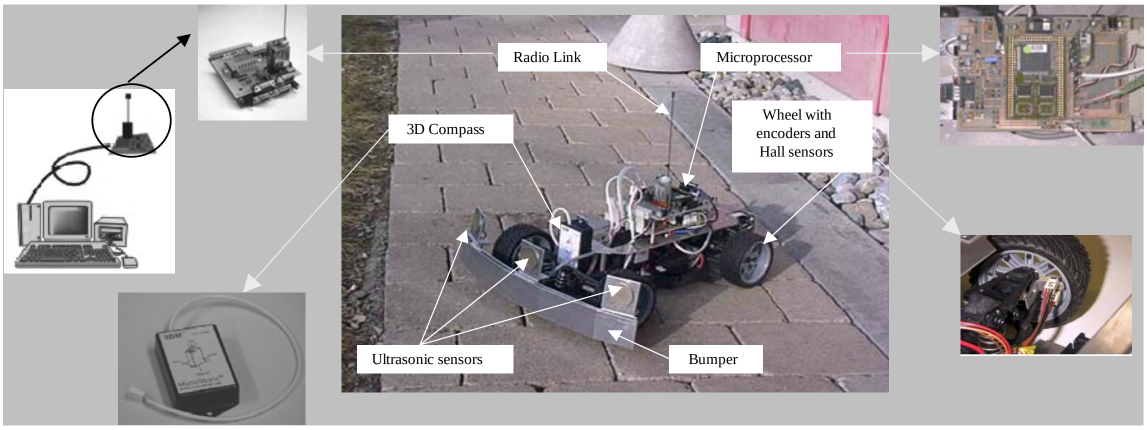


Fig. 1: The components of the MERLIN vehicle

MERLIN (Mobile Experimental Robot for Locomotion and Intelligent Navigation) is based on a 40 cm long lightweight chassis and a suspension system, enabling to drive with speeds up to 40 km/h in outdoor environments. Due to its initial purpose, it can be easily equipped with different sensor configurations in order to characterize the working environment. Its standard sensor configuration includes:

- odometry, to derive from hall sensors in the wheels by measurement of the wheel rotation and the steering angle an estimate of the current location and orientation,
- ultrasonic sensors, (3 in front, 1 in the rear) to measure distances to objects in the path,

- bumper in front, to initiate an emergency stop in case of contact.

Several other optional sensors have been integrated according to mission needs, such as

- gyros for monitoring of the vehicle orientation,
- a 3-D compass, consisting of a compass for the Earth's magnetic field and 2 inclinometers, to characterize the 3-dimensional orientation,
- GPS sensors to determine the position in outdoor environment by the satellites of the global positioning system,
- an active vision system combining laser and camera for distance measurements towards obstacles,
- a camera to provide environment information to the teleoperator,
- strain gauges to measure forces acting on the front of the vehicle.

The on-board control algorithms are implemented on a 16-bit microprocessor 80C167, which also coordinates the sensor data transfer via radio modem to a nearby PC. These sensors provide the inputs for telepresence and tele-control activities.

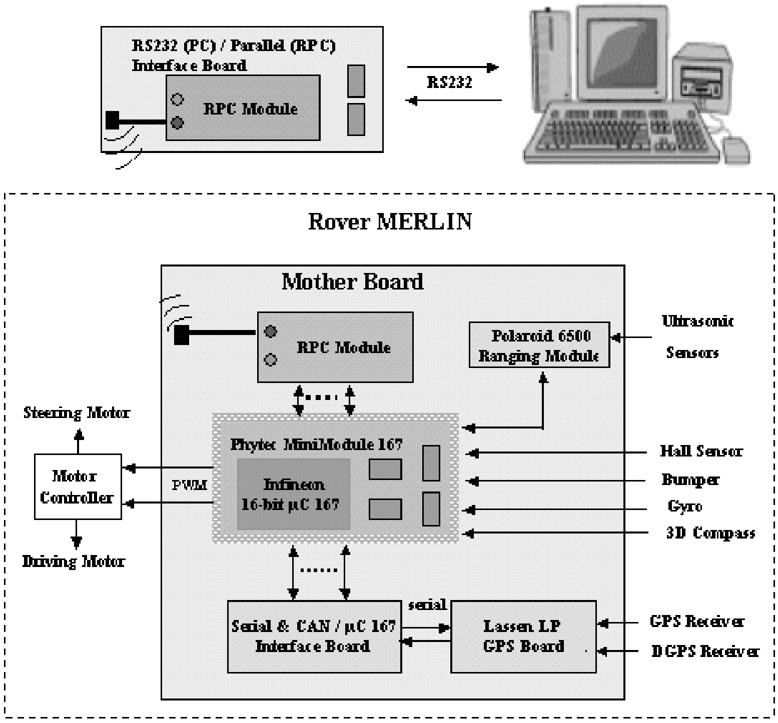


Fig. 2: The electrical architecture of the MERLIN rover

The software for vehicle teleoperations has been realized by JAVA servlets and applets. Thus on the client's side, the site of remote teleoperator, only a standard web browser needs to be available. The server is implemented on a UNIX-computer, a standby server is available, if continuous service is required. The video streaming and also chat facilities, which can be used for communication between multiple teleoperators, are implemented on separate machines for safety and performance reasons. In section 3 of this paper the remote control aspects will be further detailed, addressing in particular the effects caused by delays in data transfer.

The user interface for the teleoperator is using augmented reality methods (described in section 4) as well as a haptic interface (described in section 5) providing the teleoperator feedback on the forces encountered on the vehicle's front. This is in particular used in assembly/deassembly tasks, where objects are to be pushed by the vehicle towards target locations.

3. Effects of Delays in Tele-control via Internet

This chapter addresses remote control of mobile robots via the Internet, in particular the occurrence of delays [4]. The delay of packets transfers via Internet protocols may cause instabilities and affect the teleoperator, who is driving the remote vehicle. In the test scenario the rover had to be teleoperated by a user from a fixed start location to a given target position [cf. Fig. 1]. Test performance criteria were related to the duration to perform this task and to the accuracy of reaching the target position.

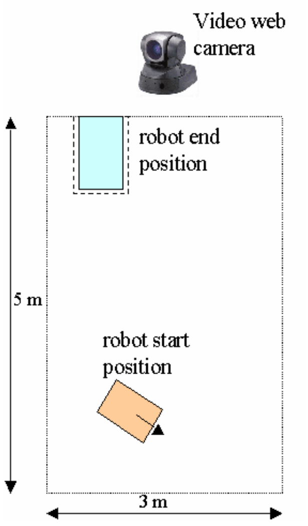


Figure: 3 The test field setup

For the teleoperator the following delays (offered to him in a random sequence) have been included in the telemetry and telecommand link :

- Constant delays of 0 ms, 200 ms, 500 ms, 1 second, and 1.5 seconds.
- Typical variable network delays with relay servers in the local network, in USA, and in Poland.

The network delays are affected by variations, which vary depending on time during the day between 5 and 300 ms. Usually a test drive with the MERLIN rover is performed in approximately 10 sec. One result was that rover tele-control from Europe or from USA is feasible in such range of delays. Variation of network latency caused a gradual decrease of test performance and, simultaneously, an increase of test duration [cf. Fig. 2]. At a delay time of 2 seconds the limits for human teleoperators without additional support functionalities seemed to have been reached. In this delay scenario often the test had to be interrupted, as the vehicle left the test area.

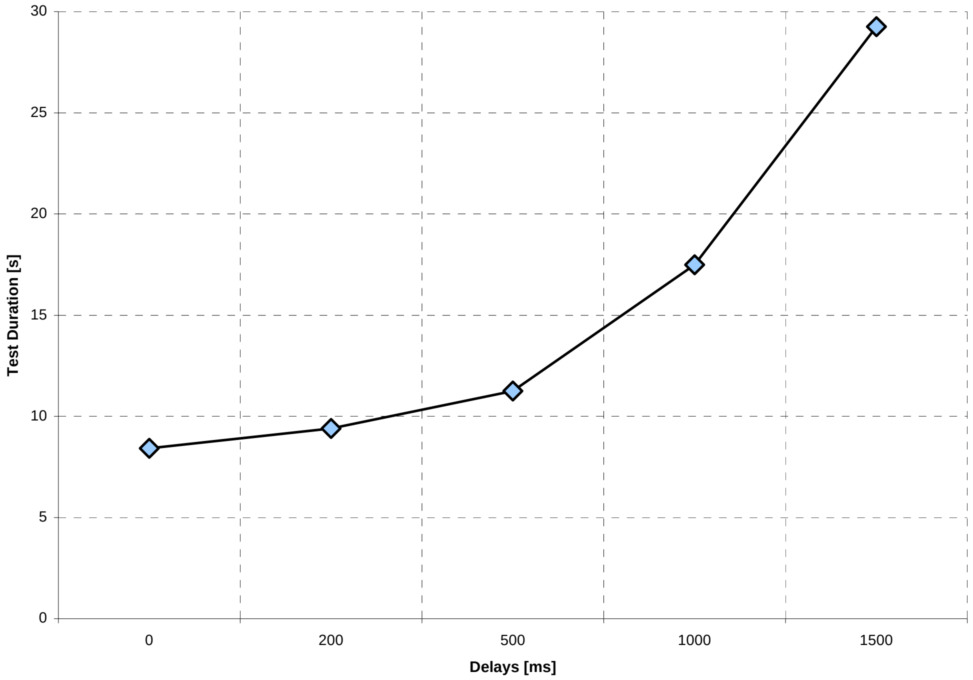


Figure 4: The duration to reach the target as a function of signal transfer delays in the telecommand link (average over 10 tests)

The tests become more complex because effects of learning and changes in control strategies had to be handled in the test setup, too. Users tried to adapt to the occurring delays by changing driving methods, slowing down and making smaller movements.

Encountered delays are affected by tuning of the network configuration parameters; factors like rerouting or loss of packets, as well as blocking can change instantaneous delay times and causes difficulties to predict the effects of delays in the teleoperated system via standard internet. In the following chapter the approach to deal with delays by predictive displays based on virtual reality methods will be addressed.

4. Virtual Reality Methods for the Tele-Operator User Interface

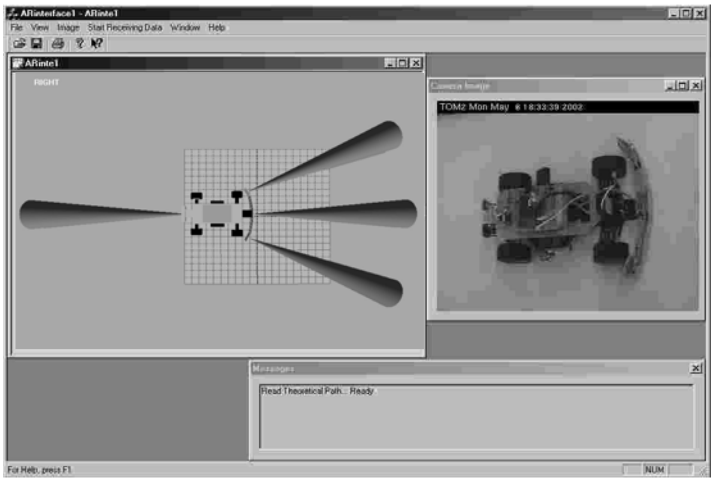
Modern information processing offer good potential to process data into user friendly information [14]. In the context of teleoperations of mobile robots in particular parameters like vehicle position and orientation, as well as distances to obstacles are to be visualized to the teleoperator in order to allow him assessment of the working environment. For this purpose models of MERLIN and of the environment have been established [5]. Thus the vehicle kinematics and dynamics, as well as the different sensor models are the basis for the rover simulation, while for the environment, architectural maps and external sensor data are composed into a model of the working area. Among the various commercially available products to design virtual reality applications, WorldToolKit (WTK) was selected, due to its capabilities to overlay simulations with live camera data.

The virtual reality framework supports in overall tele-operations scenario two objectives:

- to provide a comfortable user interface, allowing to deal with
  - signal propagation delays by predictive displays of the model based expected situations,
  - visualization of deviations between planned and measured rover activities,
- to reduce the amount of data to be transferred in the telecommunication link, when preprocessed data instead of raw sensor data are transferred, in particular for visual information.

While the first point concerns the quality of the data presentation to the tele-operator, the second point can reduce through data compression the requirements for the telecommunication link.

It is well known, that the transmission delays for sensor data and control commands lead to a degradation of teleoperator performance [13]. Of particular significance are signal propagation delays in the orders of minutes or hours in planetary exploration missions, while in terrestrial internet links, as addressed in chapter 3, this are rather fractions of a second. When a delay of T seconds is present, then the remote robot receives teleoperator commands sent T seconds before, while the robot's sensor data reach the teleoperator T seconds later. In order to coordinate the different time frames, the remote scenario predicted from model based simulations will be displayed to the teleoperator by virtual reality methods (cf. Fig.7).

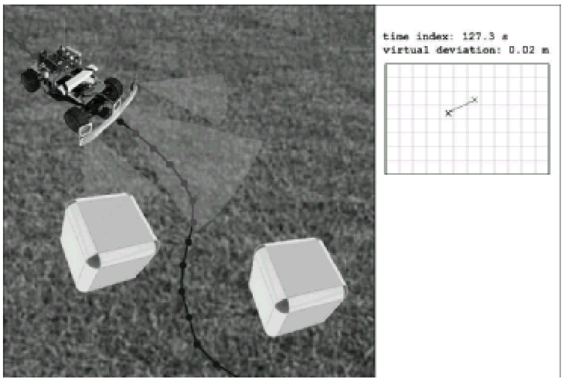


TOM2 Mon May 6 18:33:39 2002

Read Theoretical Path.: Ready

Figure 7 : *The virtual reality model of MERLIN displayed at the time scale wanted by the operator allowing comparisons with the received delayed video image at the right.*

In order to support sensor data interpretation, virtual reality methods offer the chance to overlay images of the scenery with (in reality invisible) sensor beams. Thus the teleoperator can much easier interpret the numerical sensor measurements he receives from the remote site. As displayed in Figure 8, also the planned path of the vehicle can be projected into the live image, such that deviations between planned and measured path are immediately visualized.



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time index: 127.3 s
virtual deviation: 0.02 m
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Fig. 8: *Visualization of the planned vehicle path, the beams of the ultrasonic sensors and the positions of already detected obstacles on the teleoperator screen.*

5. Haptic User Interfaces

The force feedback and haptic sensation are included in telematic systems in order to improve the user interface for the robot control. Reproduction of these remote sensor data at the tele-operator site provides additional sensory inputs to the teleoperator [2].

5.1 System architecture

The haptic interface is based on the Immersion Impulse Engine 2000^{TM} joystick that controls the robot and provides accurate force-feedback to the user in two dimensions, according to two built-in motors [6]. The force applied to the joystick is proportional to measured sensation collected by strain gauges attached to the bumper on the front of the car. The communication between the remote robot and the tele-operator is comprised of UDP data packets transferred via the Internet as well as the radio link between the rover and the local PC station [cf. Fig. 9].

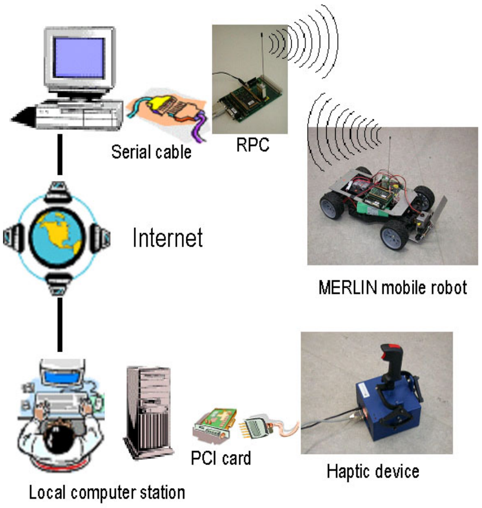

Figure 9: The haptic interface

5.2 Software architecture

Due to continuous real-time data exchange between local and remote computers over the Internet, the software section is split into joystick and robot programs. Both of the programs are, themselves, split up into client and server threads, which are responsible for sending and receiving values, respectively. The program called 'joystick' sends information from the joystick to the slave computer and listens for feedback. The robot program listens for information from the master and relays this to the robot, sending feedback information back to the master.

5.3 Robot Feedback Control

The force feedback effect is determined by a closed loop, which uses the joystick position output values to compute the joystick center force. This force, as well as that coming from the rover, is summed up for the total force and applied to the joystick drive using the stick torque. Actually only forces corresponding to effects measured by strain gauges are applied [cf. Fig. 10]. The problem of the different forces such as air resistance, acceleration, and friction acting on the rover is to be investigated, taking into consideration their significance. The work environment and intended tasks will play an important role.

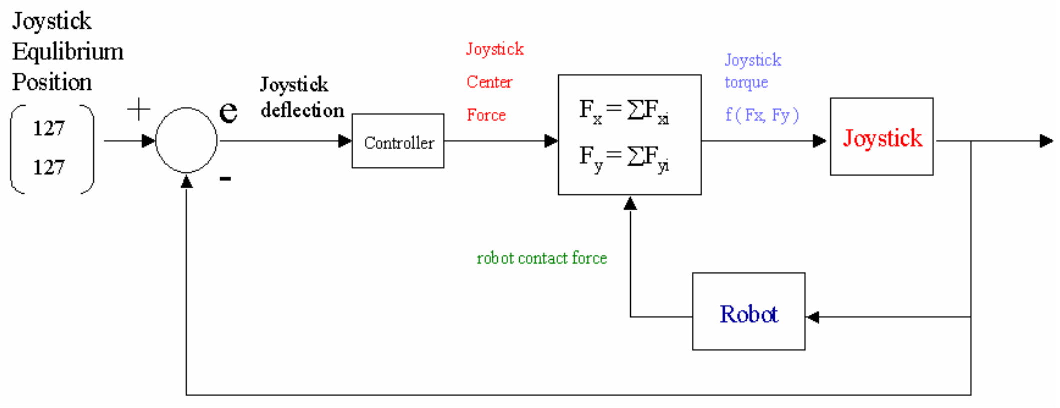

Figure 10: The feedback loop

The feedback loop provides resistance proportional to the force acting on the robot. The transfer of this effect to the user's joystick is to be calculated. It is a linear relationship with a scale factor depending on the maximum pushing force acting on the robot.

5.4 Experiments

Tests have been performed to evaluate the haptic system, taking into consideration the relation between real forces measured in experiment and the forces recorded by sensors while pushing an object forward. These trials were accomplished with three different masses. First, for calibration purposes, the bumper deformation was measured using a spring based measurement device and compared with values coming from strain gauges [cf. Fig. 4]. Force calibration produced the linear dependence. Then for each mass the friction force was evaluated, by pulling this object with a spring device [cf. Table 1].

Test number	Mass of the pushing object [kg]	Friction force measured by hand [N]
1	0.447	2
2	1.035	4
3	1.613	7

Table 1. Measurement results

Based on the values from the Table 1 the average coefficient of motion friction was calculated. Using the mass of each object, the expected friction force was calculated and compared with the maximum force value measured by the strain gauges while driving with approximately constant velocity [cf. Table 2].

Test number	Expected force (μ_k=0.42±0.3) [N]	Max force measured by strain gauges [N]
1	1.84	1.4899
2	4.26	4.1727
3	6.64	6.5731

Table 2. Test results

The velocity in reality was changing in some small range because of joystick deflection sensitivity on user motion, presented here for the test masses 1 and 2 [cf. Fig. 11, Fig. 12].

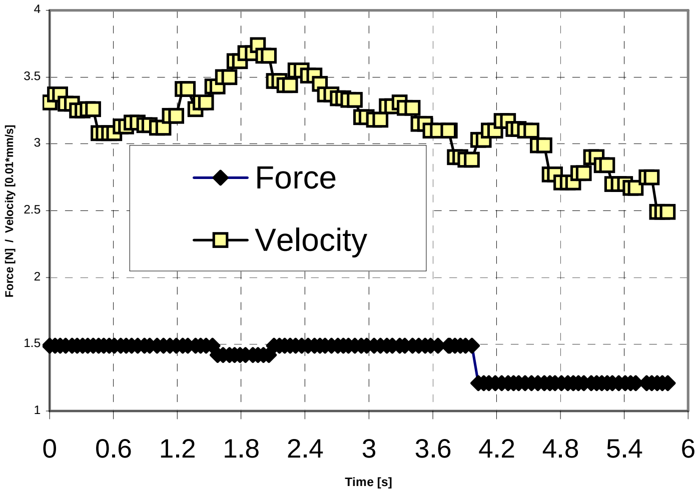

Figure 11: Force and Velocity diagram for 1^{st} test mass

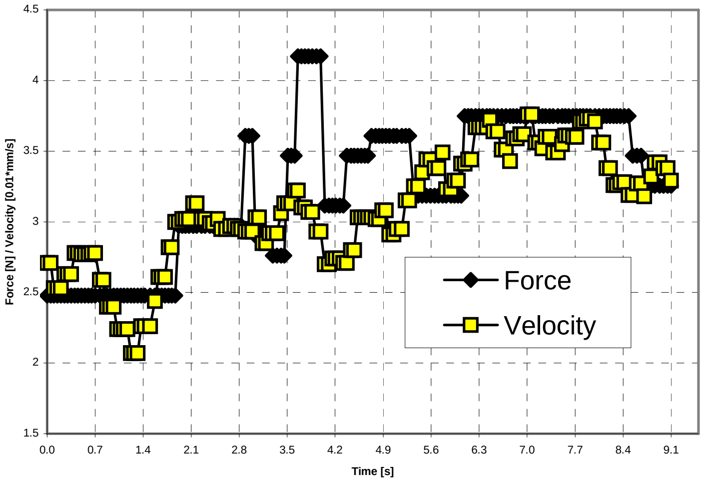

Figure 12: Force and Velocity diagram for 2nd test mass

For the third test mass the approximate maximum force was evaluated which can be applied to the rover. The results show that force measurement by strain gauges was correct in cases 1 and 2. Additional experiments are in progress, addressing the relation between Internet delays, joystick motion and user sensing.

6. Applications

This tele-operations scenario is currently intensively applied in tele-education, where students tele-operate via internet experiments with real hardware in laboratories of world-wide partner universities (cf. http://www.ars.fh-weingarten.de/team, http://www.ars.fh-weingarten.de/iecat, http://www.ars.fh-weingarten.de/vvl) [5], [9].

Further applications concern also tele-maintenance of mobile transport robots in industrial production environments [12]. Here the teleoperator sends standardized drive commands to evaluate from the observed performance the need for action and, if applicable, to analyze the cause of failures.

7. Conclusions

Virtual Reality and multi-modal feedback approaches offer in the context of telepresence applications an huge potential to improve user interfaces. This article addressed at the application example of the teleoperations of mobile robots in particular the specific problem areas of delays in the control loops and of methods for efficient data representation to the teleoperator. Thus haptic interfaces offer an interesting complement to present information to the teleoperator, while as virtual reality methods support visualization of sensor data.

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